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Review

Application of Pre-Splitting and Roof-Cutting Control Technology in Coal Mining: A Review of Technology

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Abstract: According to the development requirements of green mining of coal resources, it is imperative to improve the extraction rate of coal and the application of safe and efficient mining technology. Pre-splitting and roof cutting technology is widely used in reducing residual coal pillars and safe pressure relief mining, which has become the crucial technology for pillar-free mining methods. Therefore, it is essential to review and discuss the research hotspots, cutting-edge methods, principles of action, and application areas of the development of this technology. Above all, the research data on pre-splitting and roof-cutting development in the past ten years are summarized and outlined. The research's hot spots are pressure relief technology and gob-side entry retaining technology. Then, the functional forms of pre-splitting and roof cutting technology are discussed and compared, including explosive blasting (directional energy gathering blasting, liquid explosive blasting, and composite blasting), hydraulic fracturing, liquid CO_2 gas fracturing, and mechanized roof cutting (chain arm saw machine and directional cutting roof rig). Through the analysis of field application cases, the application field is divided into three major areas: non-coal pillar mining (gob-side entry driving with narrow coal pillar, gob-side entry retaining with the filling body, completely gob-side entry retaining, and "N00" construction method), pressure relief at working face (thick and hard main roof cracking and end area hard roof cracking), and pressure relief at roadway (gob-side roadway pressure relief and blasting pressure relief technology for roadways). By detailing the process of each application technology one by one, the principle and mode of pre-splitting in each technology are expounded. Finally, the development prospects of pre-splitting and roof cutting in new technical methods, deep pressure relief mining, intelligent unmanned mining, and green and efficient mining are prospected, providing references for similar projects.

Keywords: pre-splitting blasting; roof cutting technology; hydraulic fracturing; no-coal pillar mining; thick hard roof; pressure relief technology

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1. Introduction

In Chinese coal mining, high-intensity mine pressure in the roadway and working face has been the critical factor that endangers the average coal production [1–4]. In the past 30 years, with the rapid development of computer science and sensor technology, the study of mine pressure in the coal mining process has become more profound and transparent [5–8]. Theoretical models of mine pressure in mining fields and roadways have been proposed and gradually recognized by field engineers, such as the structural model of "masonry beam" [9,10], the mechanical model of "plate structure" of the stope [11–15], the theory of slip line of roadway floor [16], and the theory of butterfly plastic zone [17,18]. Many scholars have profoundly and extensively studied the location and causes of stress concentration areas in the mining field and the roadway through pressure monitoring in the field and numerical calculations by computer [19–22]. Among them, the stability and movement of the roof after coal mining are closely related to the regional stress concentration condition of the mining field and the roadway. Especially for the coal mining face with a hard roof, composite roof, and thick roof, when it adopts usual mining methods, many problems such as support crushing, large deformation, and strong disturbance will occur [23–27]. Simultaneously, the increase of the buried depth makes the surrounding rock conditions of the roadway increasingly bad. Under the complex surrounding rock environment, it is difficult to maintain the stability of the roadway only by support, and the application of pressure relief technology is urgently needed [28–30]. Based on this, pre-split or cutting off the roof before working face mining is gradually being implemented to study pressure relief in mining fields and roadways.

Pre-splitting and roof-cutting control technology refers to the directional pre-fracturing or cutting off of the roof of the mining field and roadway by explosive blasting or high-strength hydraulic fracturing [31–33]. As shown in Figure 1, according to its application method, it can be classified into directional blasting roof cutting technology, directional hydraulic fracturing technology, and liquid CO_2 gas fracturing technology [34–36]. According to its application object, it can be classified into pre-splitting control technology of mining field's roof and roadway's roof. According to its application scenario, it can be classified into the technology applied to roof cutting and pressure releasing of gob-side entry driving, roof cutting and pressure releasing of gob-side entry retaining, roof cutting for self-forming roadway technology, hard main roof cracking, and pressure relief on the surrounding rock of the roadway.

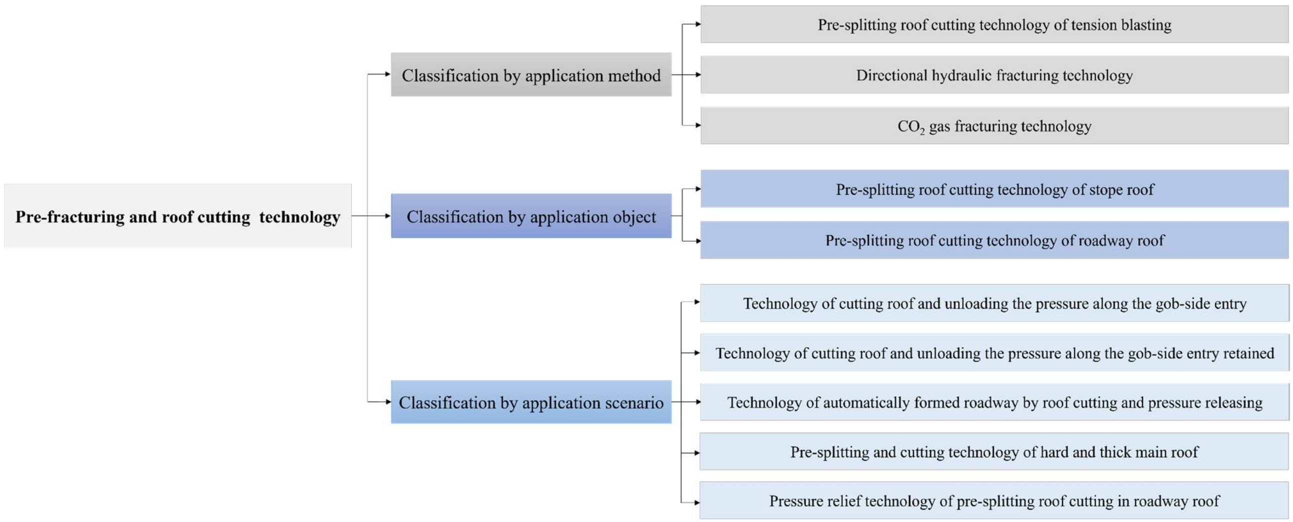


Figure 1. Category of pre-splitting and roof-cutting technology.

With the development of roof cutting and pressure relief theory, pre-split means, and supporting equipment, pre-splitting and roof-cutting technology has become essential to realize pressure relief and no pillar mining. Based on this technology, the recovery rate of coal mining increases and the roof disaster decreases, which is conducive to producing high-quality and efficient green coal mining [37–40]. The research application of pre-splitting and roof-cutting technology in the coal mining field in the past five years is analyzed by VOSviewer, as shown in Figure 2.

By counting more than 300 papers on pre-splitting and roof-cutting in the global mining industry in the past five years, we can get that the research hotspots are: ① Pre-splitting roof applied to the stability study of working face and roadway roof; ② Analysis of the mechanical mechanism of pre-cracked roof effect, including mechanical model and pressure release principle; ③ Process design and optimization of support means of pre-fractured roof technology; ④ Numerical simulation analysis study of pre-fractured roof technology, including the evolution of its plastic zone, stress, and deformation; ⑤ Application of pre-fractured roof technology, including hard-roof cracking and pressure relief, no pillar mining (gob-side entry driving and gob-side entry retaining), and self-forming roadway technology; ⑥ Research on gas and rock explosion in the process of the pre-fractured roof.

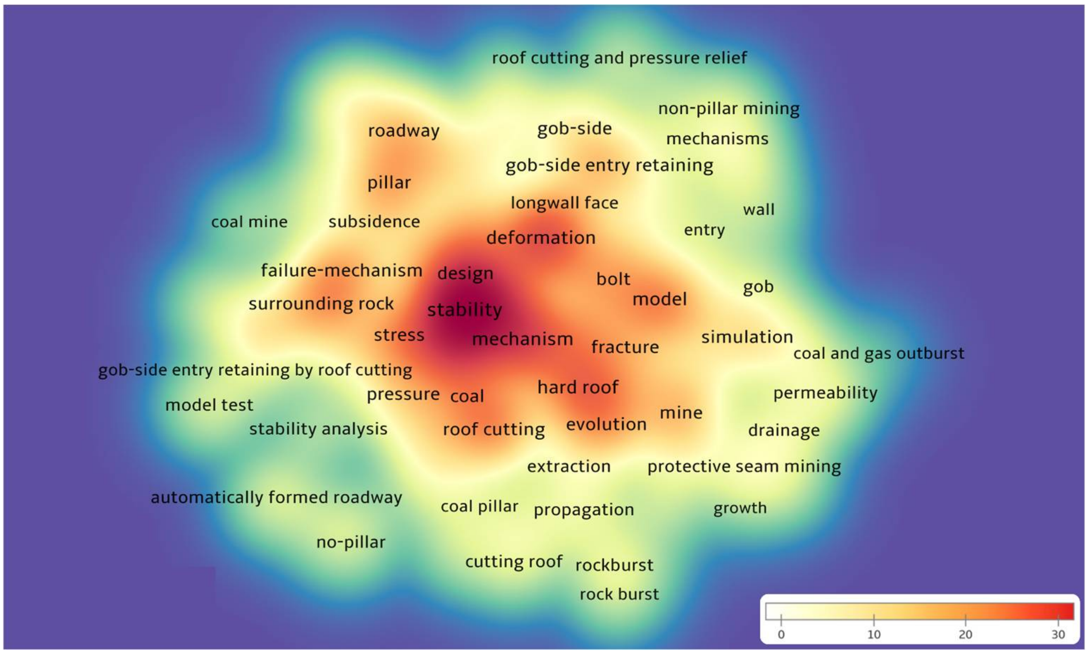


Figure 2. Research hotspot map of pre-splitting and roof-cutting technology.

China is the technological powerhouse country in coal underground mining. Pre-splitting and roof-cutting technology is extensively implemented in Chinese coal mines [2,32]. By searching the keywords "pre-splitting and roof-cutting" in CNKI (China National Knowledge Internet), 180 related papers were obtained in the past 10 years. As shown in Figure 3, the subject terms of these research papers are roof cutting and pressure relief application, gob-side entry retaining technology, pre-split blasting technology, working face pressure relief mining, technical parameter study, non-pillar mining, hard roof cracking, gob-side entry driving technology, and non-pillar self-forming roadway. Among them, the study of gob-side entry retaining through roof-cutting technology is the hot spot of research, which accounts for 56%. The deformation of the roadway along the gob is extensive and challenging to maintain [31,38]. By cutting the roof, the intense stress concentration of the roof can be released, thus significantly improving the stress environment of the roadway along the gob [34]. In addition, in the past four years, research on pre-splitting and roof-cutting has been at the forefront of the industry in the field of gob-side entry retaining and pressure relief mining at the working face. As the geological conditions of applied coal mine working faces become more diverse and complex, scholars have begun to improve the traditional pre-splitting and blasting technology, and the research on the effects of directional energy-gathered blasting has gradually increased.

With the more widespread application of pre-splitting and roof-cutting technology by Chinese and foreign scholars and engineers in coal mining sites, the technology has been comprehensively developed in the coal mining field. Furthermore, four major application scenarios have gradually been derived: roof cutting and pressure releasing for gob-side entry driving and gob-side entry retaining, non-pillar self-forming roadway, cracking of hard and thick layer roof, and pressure relief of working face and the roadway; this paper presents a comprehensive summary of this technology in coal mining in recent years and systematically describes the basic methods, technical principles, mechanical mechanisms, and application scenarios. Currently, underground coal mines advocate the development of safe and green mining technologies with high recovery rates; this technology is widely used to increase recovery rates by reducing or eliminating pillars. Therefore, this paper takes the pre-splitting and roof-cutting technology that helps coal achieve efficient and green mining as the research object of the review and comprehensively analyzes the current situation and development prospect of the application of this technology; it provides reference suggestions for the project experts who need this technology in the mining field to be applied more effectively in green coal mining.

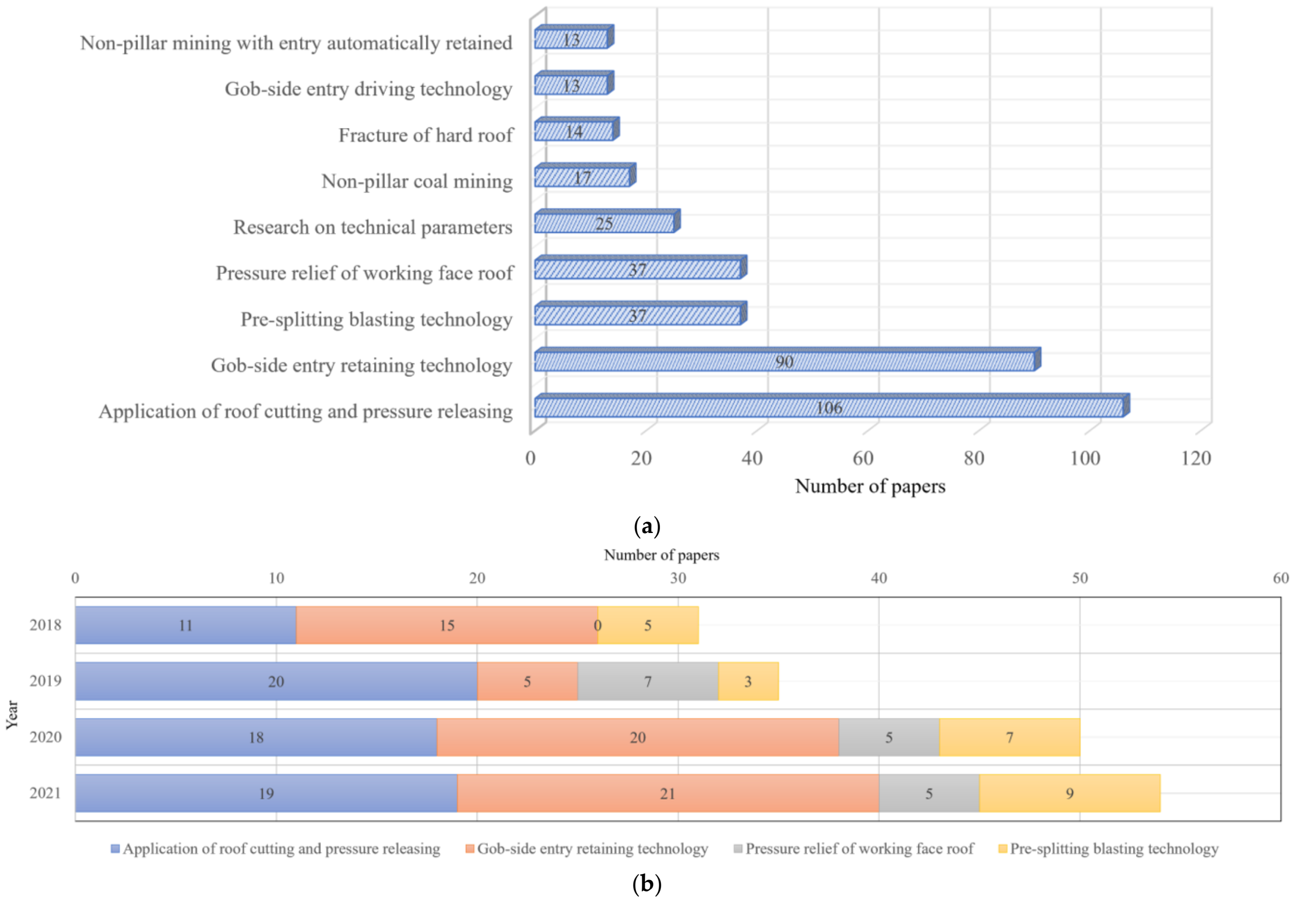


Figure 3. Category of pre-splitting and roof-cutting technology. (**a**) Nine research hotspots (**b**) Research trends in the past four years.

2. Forms of Pre-Splitting Technology for the Roof

The technology of pre-splitting and roof-cutting is to destroy the roof of the working face and roadway in advance to achieve the effect of releasing its stress concentration, and its core is to fracture the roof successfully [41]. In the field, there are four primary forms of this technology: blasting pre-split technology, hydraulic fracturing technology, liquid CO_2 gas fracturing technology, and mechanical roof-cutting technology.

2.1. Pre-Splitting Roof Technology of Explosive Blasting

2.1.1. Directional Concentrated Blasting Technology

Drill-hole blasting applied in roof-cutting is different from regular blasting. As shown in Figure 4, the blast wave and energy of ordinary blasting spread from the center of the hole to the surrounding area. Due to the anisotropy of the rock mass, the cracks around the hole are randomly extended after blasting. Although this is locally fractured in hard-roof, the blast holes are not effectively connected and do not achieve the “cut-off” effect. Therefore, most field applications of bidirectional energy-gathered tensioning and forming blasting technology. The basic principle of this technology is to control the transmission of blasting shock and stress waves through the energy-gathering pipe, which generates high-pressure gas to stretch the fracture expansion directionally [42–45]. Each blasting hole is blasted simultaneously, and the rock layer is cut off by producing directional fissures.

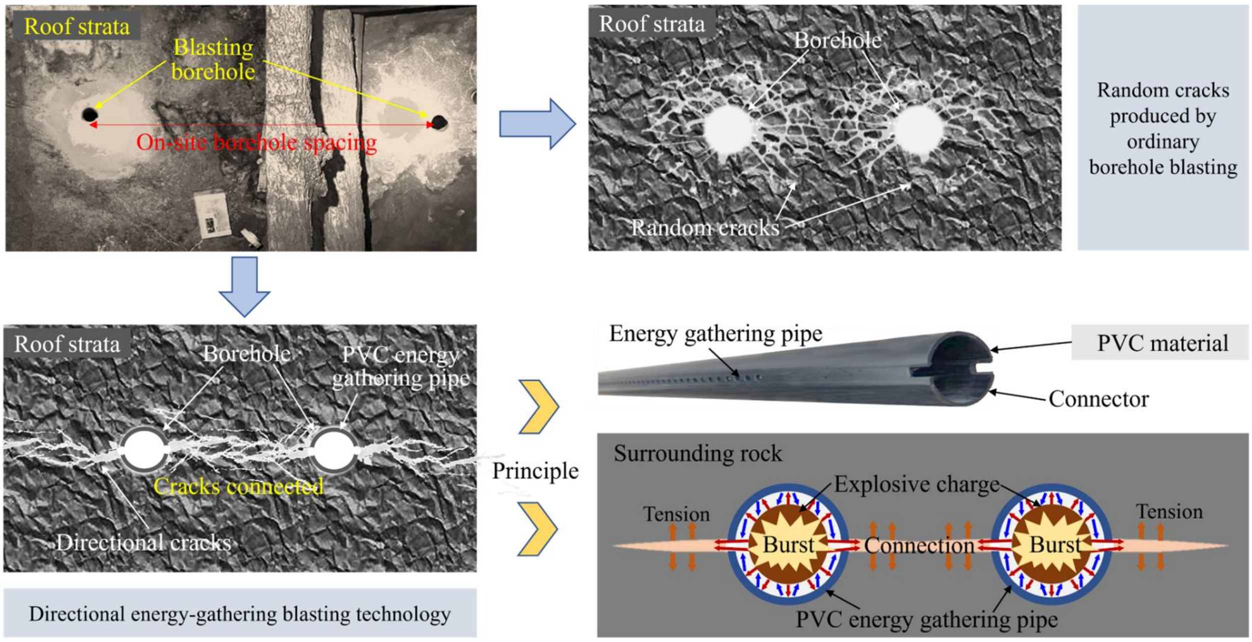


Figure 4. Directional concentrated blasting technology.

In ordinary directional energy-gathered blasting, the explosive is in a dry explosive environment, and its shock wave propagates in the air medium during blasting. Applying this method in underground coal mines generates lots of dust and toxic gases, which is not conducive to the green mining of coal. In order to overcome this drawback, the energy-gathered charge hydrodynamic blasting technology is gradually applied [46]; it is the application of the water medium filled with explosives, the use of water to spread the explosive energy, which reduces the generation of coal dust and toxic gases while enhancing the blasting effect, and it becomes a green and safe method for directional roof-cutting.

2.1.2. Directional Pre-Splitting Technology of Liquid Explosive

Ordinary solid explosives dry blasting drawbacks, improved for water-filled pressure blasting, which is effective in gas and dust control, but still shows the explosive explosion instant power and cracking range is not enough. Therefore, liquid explosives blasting technology gradually developed, the structure of the three as shown in Figure 5.

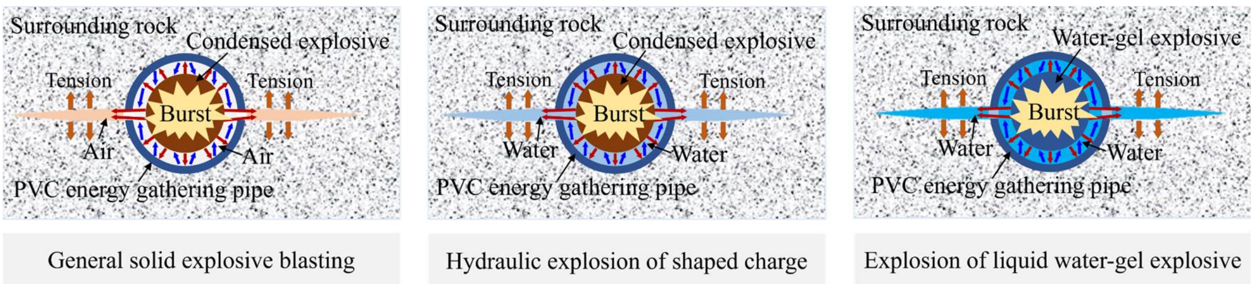


Figure 5. Charge structures of different blasting methods.

Liquid explosives to achieve the pumping method of filling the blast hole, the explosive blast energy in the fracture during the explosion is continuously supplied, the rock breaking load in the seam is robust and long duration, conducive to the full development and expansion of rock fractures. In addition, compared with hydrogel explosives and emulsion explosives, the fracture density of the borehole wall of the surrounding rock after blasting is large, and the fractures are evenly distributed [47–49]. Therefore, liquid explosives in coal mines with blasting the energy gathering pipe can achieve coupled charging in the pipe while playing the flow characteristics; its directional blasting fracturing effect and environmental protection are much better.

2.1.3. Directional Seam-Making Technology of Composite Blasting

In the actual roof-cutting work, the problem of precise and continuous fracturing of the hard and thick roof is often encountered, which requires the composite means of multiple blasting methods. For this reason, the composite blasting directional fracturing technology, which includes energy-gathered injection and high-pressure splitting, is gradually being applied in the field. The core device of this technology is a high-energy perforating gun, which needs to be installed at a certain depth of the blast hole, to be sealed after the excitation of the detonating cord to detonate the perforating bullet; its explosion also stimulates the rapid detonation of the composite propellant to produce high-pressure gas secondary splitting [50]. The result is a radially continuous fracture surface with the fusion of holes and seams to achieve precise control of rock collapse of the roof.

2.2. Hydraulic Fracturing Pre-Splitting Roof Technology

2.2.1. Hydraulic Fracturing Principle

The roadway roof is drilled according to a certain elevation angle, and the radial cutting groove is pre-fabricated on the inner wall of the borehole. After that, the hole is sealed, and the high-pressure water pump is used for water injection fracturing. The roof rock layer cracks and expands, and the crack generated by other boreholes is connected to achieve the effect of cutting off the roof; its core is that the surrounding target rock is pre-cut and fractured by high-pressure pre-water injection, thus weakening the overall strength [51,52].

As shown in Figure 6, for the pre-splitting surrounding rock, the pre-cutting groove is drilled first, and then the two sides of the groove are sealed by the packer, and then the high-pressure water is injected into the sealing fracturing section to realize fracturing of the surrounding rock. Concerning the fracture initiation mechanism, through the force analysis of the coin-shaped crack section, the initial conditions of the coin-shaped fracture in the water-saturated and natural state are obtained:

$$\begin{cases} P_W = 0.506K_{ICW}\sqrt{\frac{\pi}{a}} + \frac{\sigma_v+\sigma_h}{2} - \frac{\sigma_v-\sigma_h}{2}\left(\cos 2\alpha + (-1)^k \frac{2.418}{2-\mu_W}\sin 2\alpha\right) \\ P_N = 0.505K_{ICN}\sqrt{\frac{\pi}{a}} + \frac{\sigma_v+\sigma_h}{2} - \frac{\sigma_v-\sigma_h}{2}\left(\cos 2\alpha + (-1)^k \frac{3.056}{2-\mu_N}\sin 2\alpha\right) \end{cases} \quad (1)$$

where a is the radius of coin-type fracture, mm; σ_V and σ_h are vertical stress and minimum horizontal principal stress, respectively, MPa; α is the elevation angle of the borehole, $\alpha \in (0^\circ \sim 90^\circ)$; K_{ICW} and K_{ICN} are the type-I fracture toughness values under full water and natural state; P_W and P_N are the water pressure of groove initiation, MPa; μ_W and μ_N are Poisson's ratio; for parameter k, $\sigma_V > \sigma_h$ takes an even number, and vice versa takes an odd number. As a result, the trench inclination or borehole elevation angle α, which is most favorable for fracture initiation in hydraulic fracturing, can be calculated under different surrounding rock and stress environments [53,54].

2.2.2. Application of Hydraulic Fracturing Technology

The hydraulic fracturing technology includes fracture hole drilling, hole trenching, hole sealing, roof hydraulic fracturing, and effect monitoring [55,56]. As shown in Figure 7, the 2129 working face has a thick and hard main roof rock layer, designed to be hydraulically fractured to the full extent of the top slab prior to its mining to attenuate the impact of solid rock pressure from the hard roof.

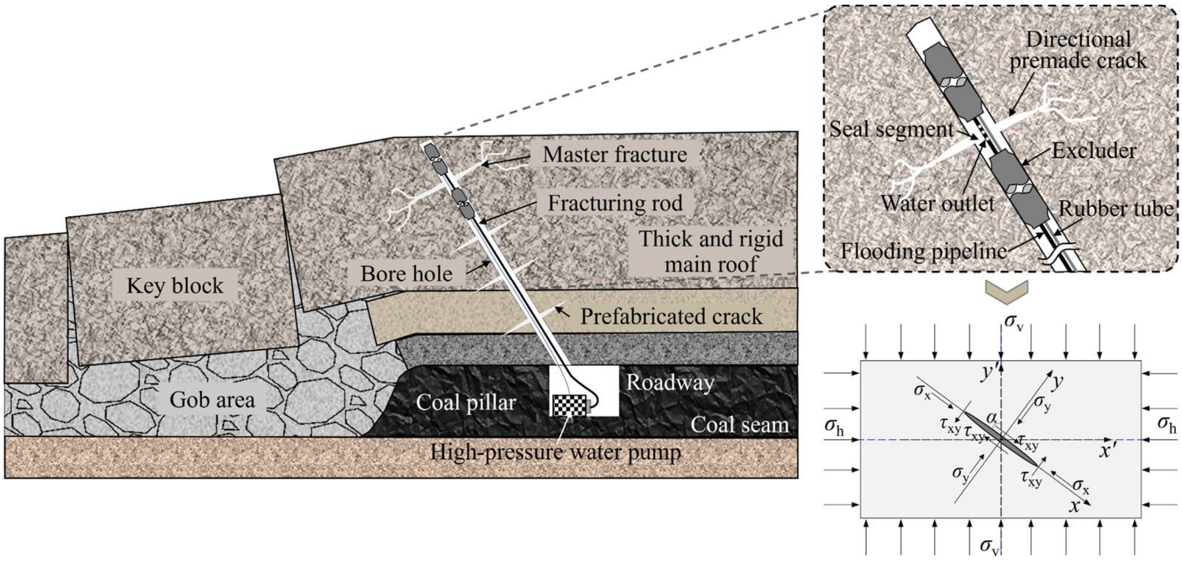


Figure 6. Principle of hydraulic fracturing rock.

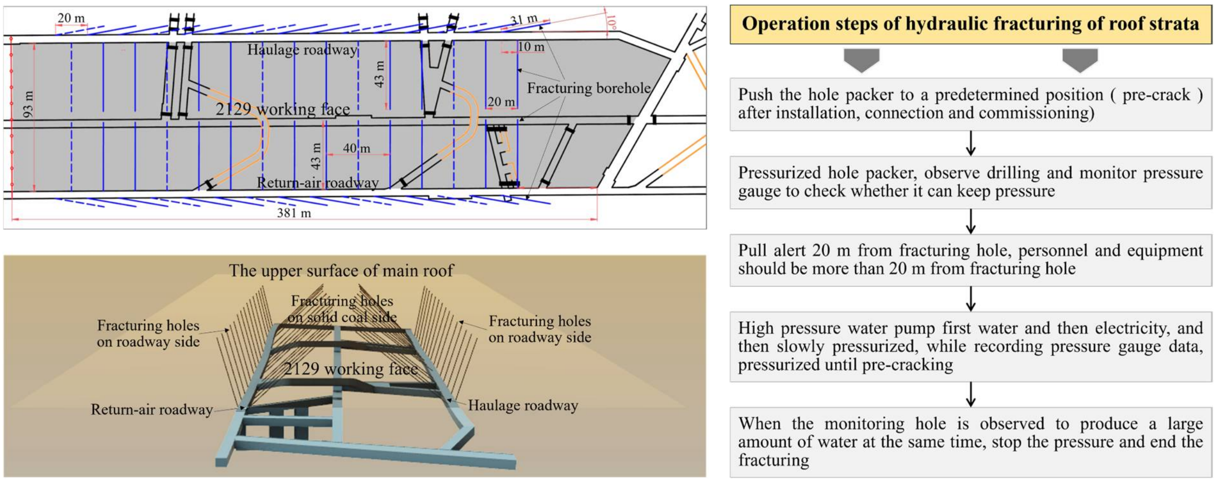


Figure 7. Hydraulic fracturing technology for roof-cutting.

The straightforward steps of the hydraulic fracturing process: firstly, drilling is carried out with a geological drilling rig, and after the drilling is completed, the drilling team will proceed with the next drilling operation. Then a sealer is installed in the completed hole, and the hole is sealed with a manual pump and an energy reservoir. Finally, a high-pressure pump is connected for fracturing. The fracturing of the coal seam to be mined and the hard roof above the roadway is achieved, after which the working face can be advanced and mined [57]; this method is safe, does not produce toxic gas and dust, and is gradually being more widely accepted at coal mine sites.

2.3. Liquid CO_2 Gas Pre-Splitting Roof Technology

CO_2 gas phase pre-fracturing refers to the rapid conversion of CO_2 from liquid to gas by a high-pressure detonation head and its instantaneous volume expansion pressure to fracture rock along the fracture face.

As shown in Figure 8, liquid CO_2 is stored in a storage tank, which requires an environment with $p > 7.35$ MPa and $T < 31$ °C to maintain the liquid form. The volume of liquid CO_2 in the fracture expands 600 times in 20 ms under the action of the heating device, creating an expansion pressure of 80–270 MPa to fracture the rock. Quick steps of liquid CO_2 blasting: After the heating device is activated, the liquid CO_2 in the storage tank expands and destroys the fixed pressure shear sheet. CO_2 is released sharply and generates low temperature and high-pressure gas to act on the pre-fractured part to realize pre-fracture blasting [58]; this method has excellent continuity, does not quickly produce a lot of dust and sparks, has apparent safety and environmental advantages, and is currently being applied in complicated rock fracturing in the excavation and recovery workings.

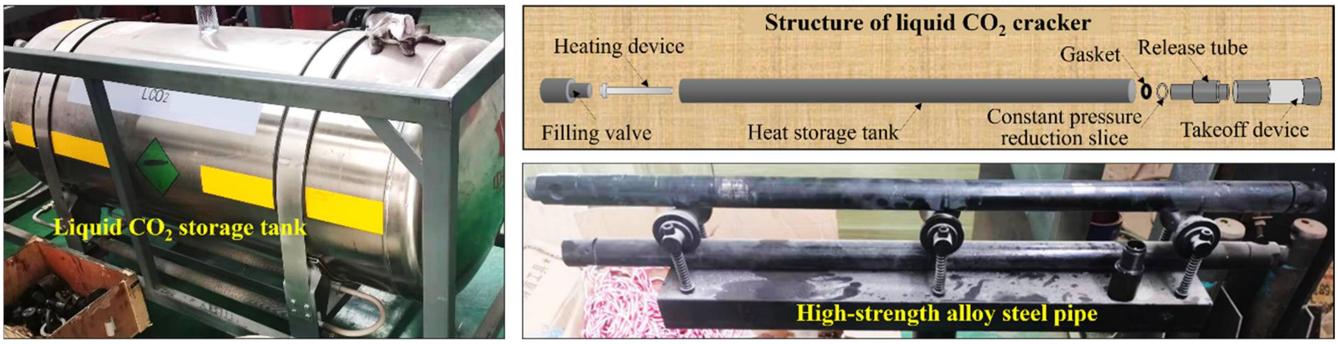


Figure 8. Liquid CO_2 storage tank and cracker.

2.4. Mechanized Directional Roof-Cutting Technology

2.4.1. Continuous Cutting Technology of Chain Arm Saw Machine

The continuous cutting machine with a chain arm saw cuts the rock in a specific direction and inclination with low-speed chipping; it considers both ductile and brittle cutting methods, and the cutting head can make extrusion and shear damage to the rock body, thus forming a continuous through-cutting slit and achieving precise directional cutting of the top slab [59].

This method has a high degree of mechanization and can directly cut the roof by remote directional control, and continuous operation reduces the time of cutting the roof. The low-speed chipping way avoids spark generation and does not consume much water; the mechanical cutting is highly accurate, and the cut surface is smooth and flat [60]. The development of mechanized roof control is an essential step to intelligent mining in coal mines, and the continuous cutting technology of chain arm saw gives an application idea.

2.4.2. Application of Directional Cutting Roof Rig

The directional roof cutting drilling rig is the mechanized roof cutting equipment developed by Academician He Manchao's "N00" construction method [32]; it has the crucial technology of simultaneous drilling in multiple holes and dynamic adjustment in multiple directions, which realizes multi-hole with the same surface and efficient cutting [61]. According to the field test, it effectively cuts off the stress transfer between the goaf's roof and the roadway's roof so that the roof of the roadway is in a specific range to form a short arm beam structure. The method is being gradually improved, popularized, and applied.

3. Pre-Splitting and Roof-Cutting Technology for Non-Pillar Mining

The method of non-pillar mining can significantly improve the coal recovery rate and reduce the waste of coal resources, which is in line with the concept of high-efficiency and green mining and has been extensively applied in the field [62,63].

3.1. Application in Gob-Side Entry Driving

Gob-side entry driving means that a narrow coal pillar (3~8 m) is set on one side of the last working face to drive the roadway of the next working face.

As shown in Figure 9a, the main roof break appears "O-X" shape in the plane when the working face is mined. The roadway and narrow coal pillar are under the "triangle" key block in gob-side entry driving [64,65]. According to the support practice of gob-side entry on-site, the gob-side entry is disturbed strongly by the superimposed stress, and its maintenance is quite tricky. The key influencing factor of mining pressure behavior in gob-side entry driving is the fracture position of the "triangle" key block. The unfavorable fracture position directly leads to large deformation of the roadway and roof collapse. Therefore, it is necessary to actively control the fracture location of critical blocks to alleviate the concentrated stress in the roadway, as shown in Figure 9b.

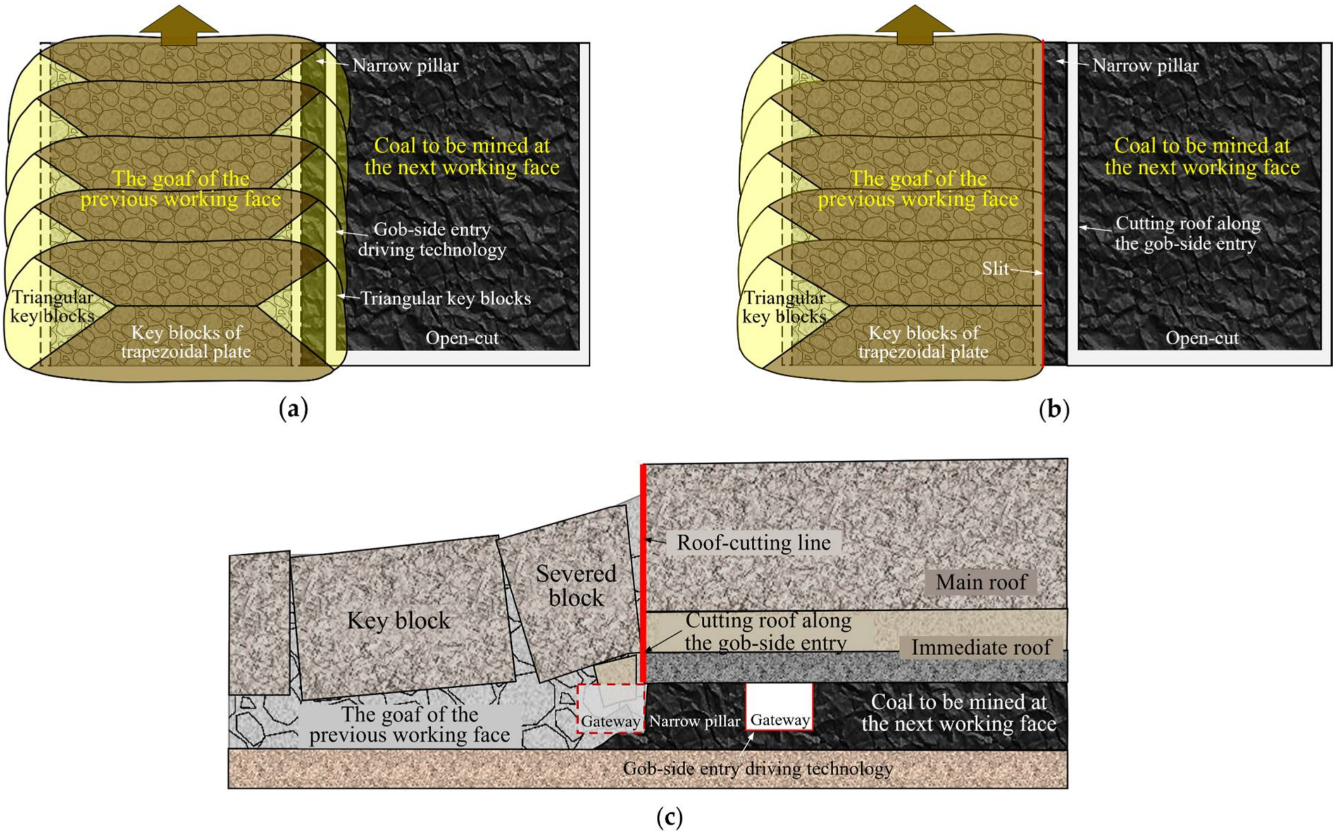


Figure 9. The schematic diagram of roof-cutting for gob-side entry driving. (**a**) Roof structure without roof cutting (**b**) Roof structure after roof cutting (**c**) Cutting roof and unloading the pressure along the gob-side entry.

As shown in Figure 9c, in the mining face, the subsequent mining face side of the roadway driving along the goaf to carry out the pre-splitting operation, the location of roof cutting is in the narrow coal pillar side of the roof. When a section of the roadway roof cutting operation is completed, and the roof collapse in the goaf is stable simultaneously, the roadway digging operation along the goaf. Attention should be paid to the replacement relationship between the mining operation of the previous working face and the tunneling operation of the next working face to ensure that the safety distance is maintained [66,67]. According to the field practice, the stress concentration degree along the empty roadway of this method is small, and the roadway support effect is practical, ensuring the roadway roof's safety.

3.2. Application in Gob-Side Entry Retaining

The gob-side entry retaining technology realizes the succession of the completely non-coal pillar between working faces, an efficient and green mining technology that is booming and applying [68].

3.2.1. Gob-Side Entry Retaining with the Filling Body

This gob-side entry retaining method uses an artificial filling body as a narrow coal pillar in gob-side entry driving. The filling bodies include high water material, paste material, and concrete [69].

(1) Delayed pre-splitting and cutting roof

As shown in Figure 10a, the force on the filling body is similar to that on the narrow coal pillar in the gob-side entry driving. At this moment, the roof structure and fracture state of the gob-side entry is similar to that of gob-side entry driving, which still leads to roadway maintenance difficulties. In order to reduce the pressure of the filling body and make the roof entirely collapse, pressure relief blasting technology with circular shallow holes is used, as shown in Figure 10b. After mining, a row of round holes is drilled towards the goaf next to the filling body about 20 cm to carry out energy-accumulating blasting [70,71]. As a result, the roof above the mining area collapses, falls, and then compacts and continues to support the overlying rock layer, as shown in Figure 10c.

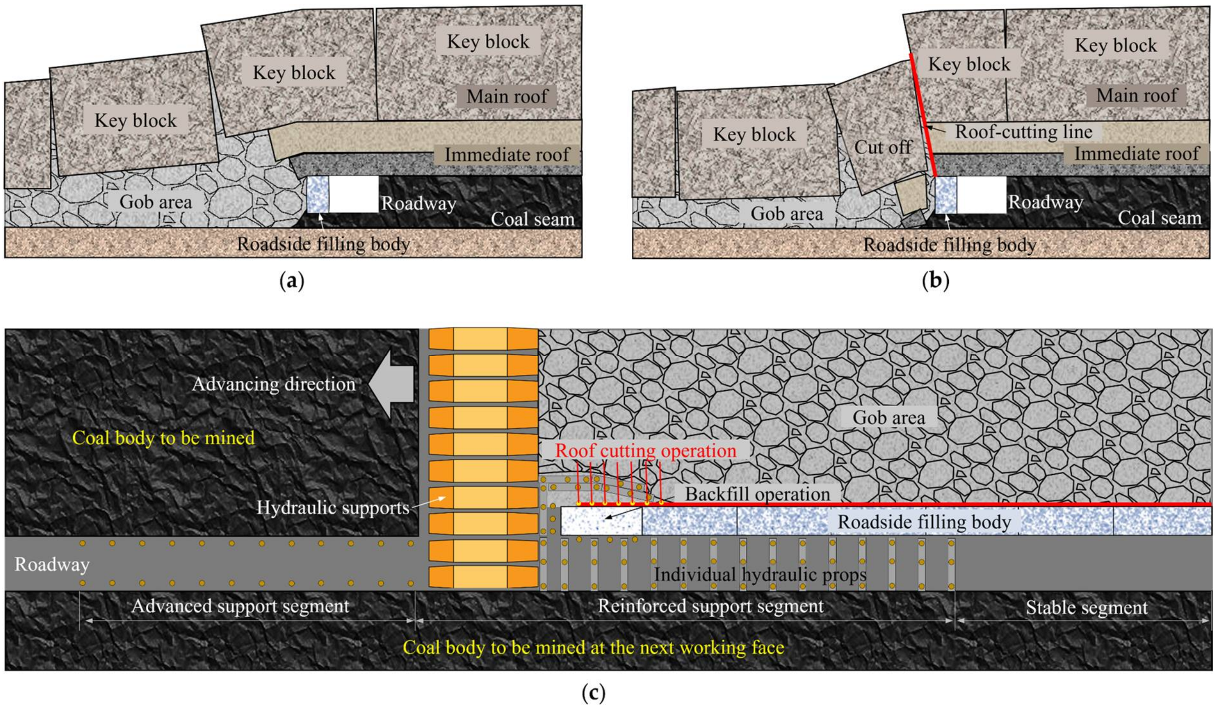
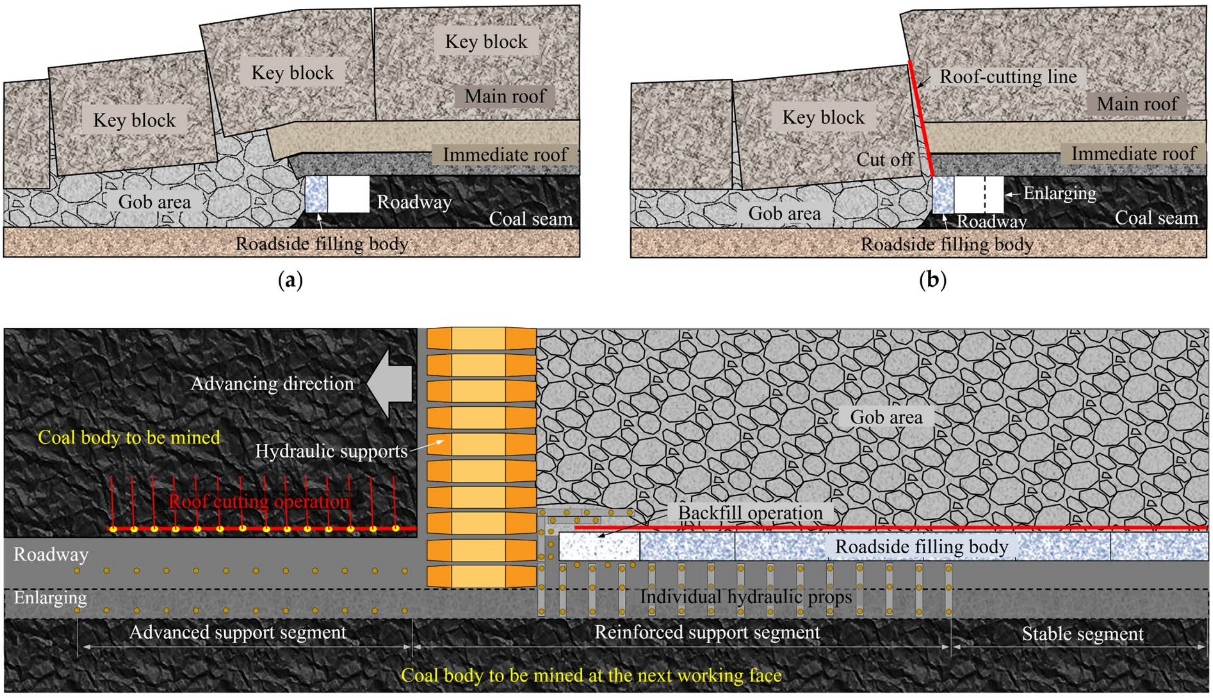


Figure 10. Delayed pre-splitting and cutting roof for gob-side entry retaining. (**a**) Gob-side entry retaining with backfill (**b**) Cutting roof on goaf side (**c**) Working methods of roof-cutting and gob-side entry retaining with backfill.

The disadvantage of this method is that it interferes with the parallel operation of mining and filling of the working face, which cannot realize the fast and high-intensity operation of the comprehensive mining face.

(2) Advance pre-splitting and cutting roof

The method of roof-cutting along the side of the roadway to be mined is the most commonly used in the field before mining the working face. As shown in Figure 11a,b, setting the filling body in the roadway for gob-side entry retaining, the main roof structure above the roadway and the filling body is more integral and stable after cutting the roof in advance [72–74]. According to the size of roadway and backfill, ample ventilation, and laneway equipment size, roadway expansion measures are often taken to ensure that the roadway size is reasonable, as shown in Figure 11c; this method can be applied in thick coal seams, soft rock, and deep high-stress environment.



(a) (b) (c)

Figure 11. Advance pre-splitting and cutting roof for gob-side entry retaining. (**a**) Gob-side entry retaining with backfill (**b**) Roof cutting operation in advance (**c**) Working methods of roof cutting in advance and gob-side entry retaining with backfill.

3.2.2. Completely Gob-Side Entry Retaining

The method of fully gob-side entry retaining means not leaving the roadside filling body, using a specific prop or single pillar to support the roof of the goaf side, and setting up gangue protection and Air leakage prevention device [75,76]. Compared with cutting the roof of retaining roadway leaving narrow coal pillar and roadside filling body, this method is more straightforward; it fully uses mining pressure and rock mass fragmentation to realize automatic lane formation.

(1) Cutting roof for retaining roadway with advance pre-splitting

During the working face mining period, pre-fracturing and roof-cutting are overrun along the solid coal side in the roadway to weaken or release the physical-mechanical connection between the roadway's roof and the gob's roof, as shown in Figure 12a,b; it is supported by a temporary prop (portal prop) with a single pillar to provide upward support resistance. The roof of the gob area is cut down as a whole by using mining pressure and artificially created roof-cutting cracks in advance. The roadway is under a complete and stable cantilevered structure, as shown in Figure 12c. According to the mechanism of roof-cutting and roadway-retaining, the site is usually divided into three operational phases: the pre-cracking and roof-cutting stage, the reinforcement support stage, and the stabilization stage of the left roadway [77–80]. The three stages correspond to different locations, so parallel operations are realized between the processes, which will significantly improve the efficiency of the left roadway. Since this method does not require the setting of a filling body, this has little effect on the advancing speed of the working face; this method is being applied under the conditions of different coal seam thickness, burial depth, dip angle, and roof conditions, and it has become a hot spot in the research of no pillar mining methods.

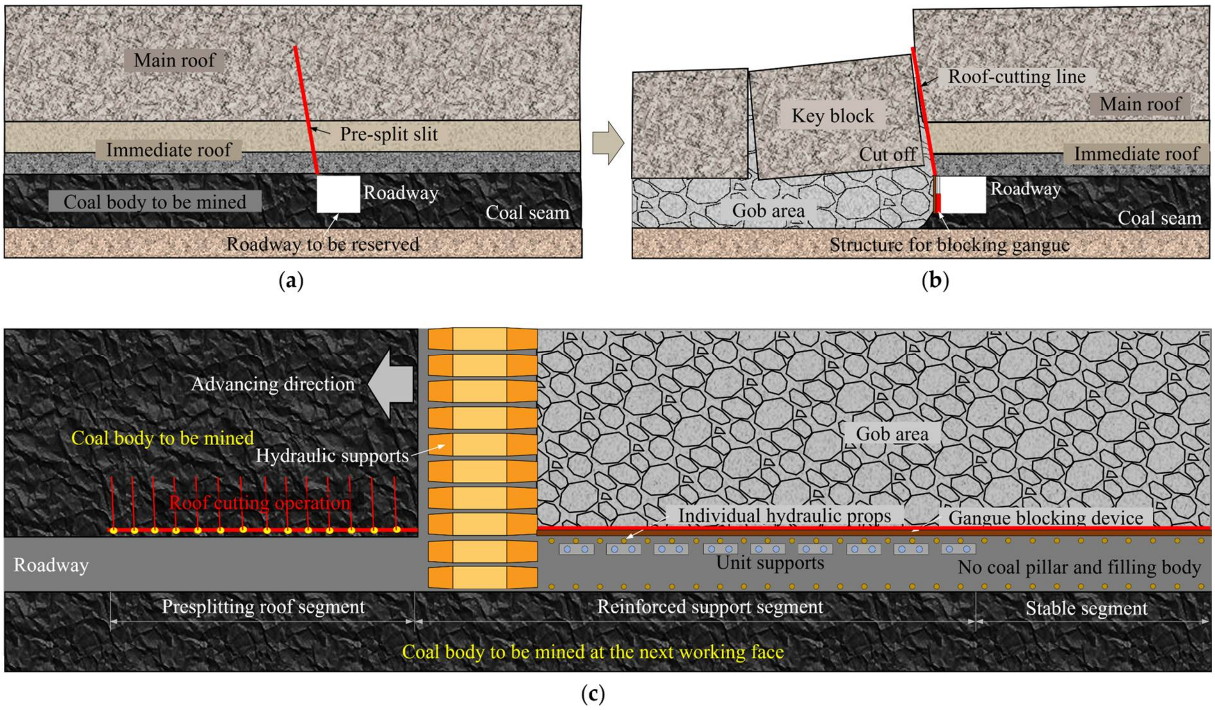


Figure 12. Gob-side entry retaining technology without coal pillar and filling body. (**a**) Pre-splitting roof in advance of the working face (**b**) Cutting roof to form roadway automatically (**c**) Working methods of roof cutting in advance and gob-side entry retaining with no-pillar.

(2) Combined support for cutting roof retaining roadway

For special roof conditions (e.g., thick direct roof), the pre-fracturing and roof-cutting can be re-optimized. For the working face with a thick immediate roof, the roof breaks down and collapses after working face mining. Due to the fragmentation of rocks, the collapsed rock can adequately fill the goaf. At this time, the combined support can be used to achieve roof cutting and roadway retaining, that is, to strengthen the support of the roadway to be retained in advance; it mainly includes the firm anchoring of the deep hole of the high-strength bolt cable on the roof and the support on the goaf side (π-shaped steel, the cross-hinged roof beam, and the single pillar of the gob-side entry retaining); they provide robust support resistance and use the mining pressure of the working face to realize the cutting of the immediate roof of the goaf side and fill the goaf to complete the roadway retaining operation. The overall approach covers four technologies: combined support roof-cutting technology, advanced-area reinforcement support technology, prevention, control technology of gangue in goaf, and beam-column auxiliary support technology of roadway [81,82].

This method directly eliminates the process of over-advance pre-fracturing and roof-cutting; meantime, it avoids the impact on the working face advancement efficiency due to blasting or hydraulic fracturing, which realizes the efficient retention of the roadway with the rapid advancement of the working face. Although its application conditions are still limited at present, its method indicates the future need to develop a mechanized way of cutting the roof and leaving the roadway without blasting.

3.3. "N00" Construction Method

The "N00" coal mining method efficiently combines the working face mining and roadway tunneling to realize the mining of N working faces, the tunneling of 0 roadways, and the retaining of 0 district sublevel coal pillars, as shown in Figure 13 [32]. In this method, the working face is mined to form the next working face's roadway, and the roadway's roof along the goaf is treated by pre-splitting and roof-cutting. The directional cutting method, such as energy-accumulating blasting, was successful at the initial test stage; however, due to the large-scale blasting operation behind the working face, there are hidden dangers to safety. After that, the team researched and developed the supporting equipment for the "N00" method and developed a directional roof-cutting rig, which is located on the side of the left-over roadway and follows the hydraulic support of the working face to push forward the roof-cutting operation [83,84].

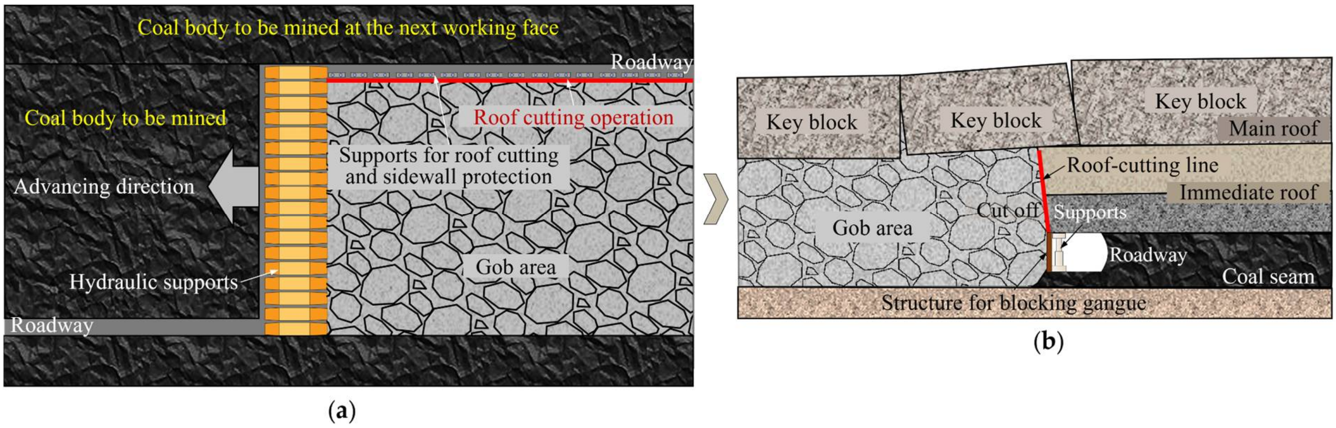


Figure 13. Cutting roof and retaining roadway technology in the "N00" construction method. (**a**) Plane diagram of "N00" construction method (**b**) The diagram of the retained roadway.

In addition, with the roof-cutting prop to support the roof on the side of the mining area of the roadway, to achieve automatic mechanical connection of coal mining, roadway formation, roof-cutting and pressure relief, support, and other processes of the working face; this method is being gradually improved and promoted in the field, providing a complete set of solutions to achieve coal pillar-free automated mining in new mining areas ultimately.

4. Pre-Splitting and Roof-Cutting Technology for Pressure Relief Mining of Working Face

The hard roof is often encountered when the long-wall working face is mined. The hard roof is difficult to collapse, and the support of the working face continues to bear the high load, which requires pre-cracking and unloading the roof [85,86].

4.1. Fracturing Operation of Thick and Hard Main Roof

The physical and mechanical properties of the main roof above the coal seam directly affect the smooth mining of the longwall working face. With the increase of mining depth, the stress level during coal seam mining gradually increases. For the coal seam with a thick and hard main roof, the weighting step and pressure of the main roof increase significantly when the working face is mined. The intense pressure threatens the safety of equipment and workers, such as hydraulic support in the working face [87–89]. Therefore, the pre-splitting operation is usually carried out before the mining face for the thick and hard main roof.

As shown in Figure 14, the main roof rock is pre-cracked by hydraulic fracturing, and the crack location includes the roof of the coal body to be mined, the roof of the roadway on both sides, and the roof of the working face's open-off cut. After the main roof's pre-splitting, the working face's coal wall pressure is slight during the weighting period. The shrinkage of the pillar is minor, and the roof collapse is closely followed by the support, indicating that the main roof activity is not intense during the fracturing [90–92]; this method has been widely used in pressure relief mining of working faces with the thick and hard main roof.

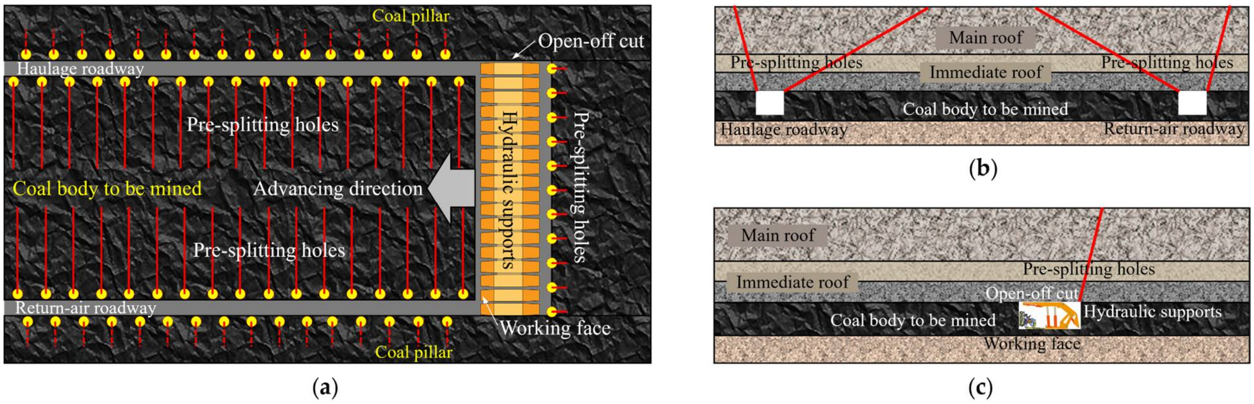


Figure 14. Fracturing operation of the thick and hard main roof. (**a**) Plane diagram of pre-splitting drilling hole (**b**) Side view of boreholes in roadway (**c**) Side view of boreholes in the open-off cut.

4.2. Fracturing Operation of Hard Roof at the End of the Working Face

For the broken roof of the longwall working face, there is a "triangle" key block structure in the end area [93,94]. When the roof of the working face is hard, it is often challenging to collapse on both sides of the roof, resulting in an excessive hanging roof area. Improper treatment will cause air leakage in the working face, gas accumulation in the goaf, and sudden caving of the sagging roof. Therefore, the hard roof at the end side should be cracked in time, and the borehole layout is shown in Figure 15. Due to the goaf behind the end support, there is a risk of explosive blasting, and hydraulic fracturing is generally used to crack the roof [95,96]. According to the field practice, in the subsequent mining process, the end top plate, after cracking, is no longer suspended but gradually collapses with the advance of the end support, which dramatically reduces the pressure of the support and achieves a good pressure relief effect.

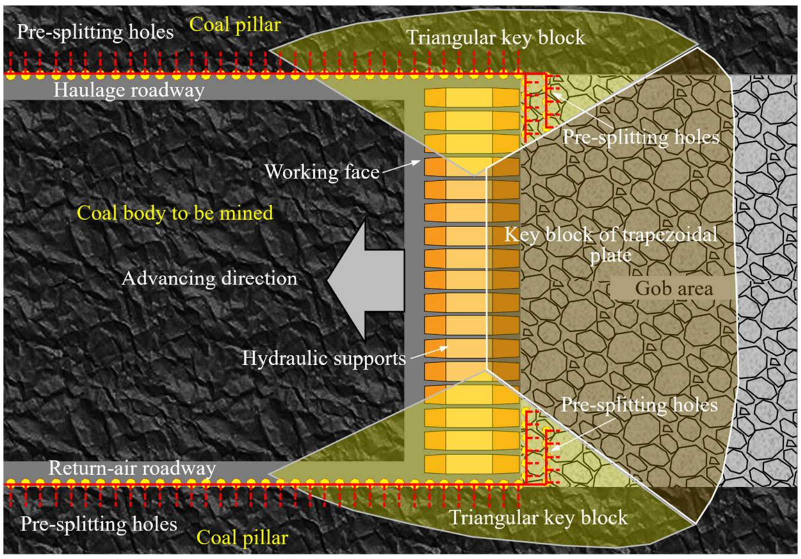


Figure 15. Fracturing operation of a hard roof at the end of the working face.

5. Pre-Splitting and Roof-Cutting Technology for Roadway's Pressure Relief

For gob-side entry, tunneling entry, and deep roadway with a high-stress environment, standard support methods are often tricky to work, and active pressure relief is needed for the position of a continuous deformation [97].

5.1. Large Deformation of Roadway along Goaf

When one side of the working face is being mined, the phenomenon of large deformation occurs in the local area of the roadway along the goaf of the adjacent digging face, especially in the roadway section within the influence of the working face mining, which rate is speedy and challenging to control [98,99]. In order to reduce the influence of mining-induced stress on gob-side entry as much as possible, pre-splitting and roof-cutting operations are designed in the adjacent roadways of this working face. The borehole layout is shown in Figure 16. By cutting the roof in advance, the continuous structure between the working face and the roof of the gob-side entry is severed, hindering mining-induced stress transmission. Thus, the surrounding rock stress environment of the roadway along the goaf is improved, and the stability of the roadway can be successfully maintained by reinforcing the support means [100–103]. Pre-splitting and cutting the roadway's roof in the overhead section of the working face to unload the pressure for the roadway along the goaf is commonly implemented in the field, which has become an important method to control the large deformation of the roadway along the goaf.

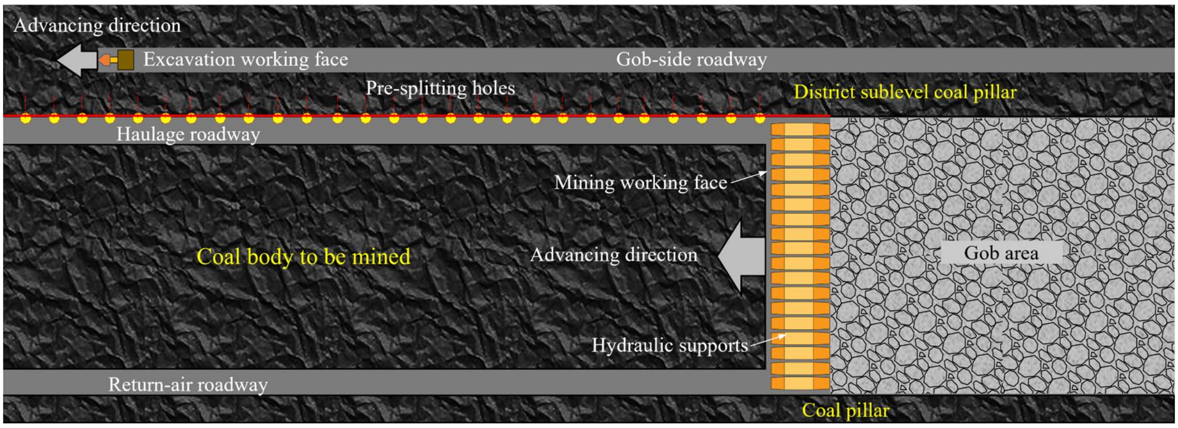


Figure 16. Pressure relief technology of roof-cutting for large deformation of roadway along goaf.

5.2. Blasting Pressure Relief Technology for Roadways

The deformation characteristics have apparent continuity and persistence for the deep high ground stress and robust rheological environment of the roadways. The general reinforcement support method cannot prevent the rheological characteristics of the surrounding rock, and the roadway needs to be expanded and repaired many times. At this point, the key to controlling deformation is to relieve pressure and cut off the transmission path of continuous high stress [104,105]. As shown in Figure 17, illustrates three blasting methods to relieve pressure to cope with substantial deformation of the roof, gangs, and floor. Blasting to relieve pressure means creating cracks by blasting to destroy the integrity and continuity of the rock to release the concentrated stress and cut off the stress transmission path to control the rheology of the surrounding rock in the roadway.

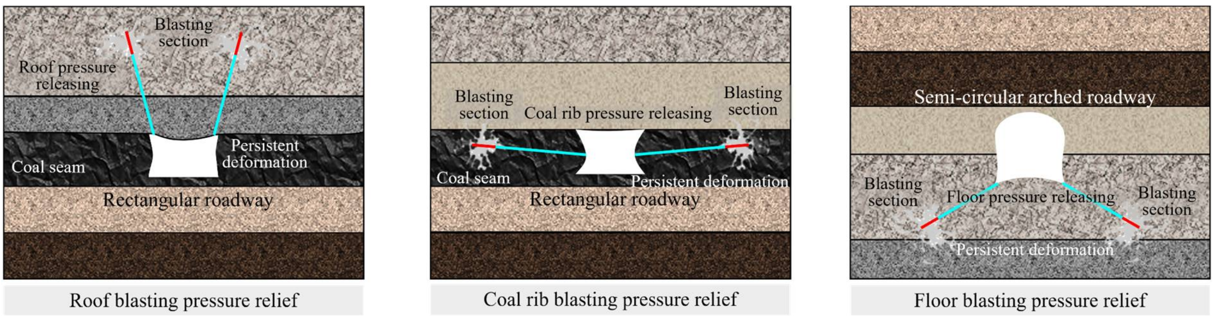


Figure 17. Blasting pressure relief technology for roadways.

For the pressure relief of the roadway under the complex high-stress environment, concentrated drilling is often carried out in the surrounding rock of the complex high-stress area. The small-scale pressure relief and fracture area are generated through the deformation and collapse of the drilling hole. At present, directional pre-splitting and roof-cutting pressure relief technologies such as concentrated energy blasting and hydraulic fracturing have been widely applied [28]. According to different surrounding rock environments and the mechanical properties of rock mass, a reasonable pressure relief method is selected to better realize the stability of the roadway under complex conditions.

With the development of the method, the internal pressure relief method and hydraulic pressure relief method of roadway surrounding rock are gradually evolved [106], which have achieved outstanding field application effect in controlling deep continuous deformation roadway.

6. Discussion

This paper summarizes the four forms of application of pre-splitting and roof cutting technology (explosive blasting, hydraulic fracturing, liquid CO_2 gas fracturing, and mechanized roof cutting) and elaborates its process in three major fields (non-pillar mining, working face's pressure relief, and roadway's pressure relief). The following conclusions and prospects are obtained:

(1) The pre-splitting method of explosive blasting has gradually developed to low pollution, low dust, high precision, and high safety. The methods of water-filled pressure blasting, liquid explosive blasting, and liquid CO_2 gas phase blasting improve environmental protection and safety significantly. The composite blasting form is committed to establishing a continuous fracture surface to achieve precise roof cutting.
(2) Hydraulic fracturing technology is gradually becoming more and more widespread in the application of hard-roof fracturing, especially in roof pre-splitting near the working face and the goaf; this method does not produce toxic gas and dust, which has high application safety for gas mines.
(3) The research hotspots of pre-splitting and roof cutting focus on pressure relief technology and gob-side entry retaining technology. For deep high-stress mining environments, applying roof pre-splitting technology will be more widely, including the safe replacement of deep coal seam working face, deep hard roof cracking, and deep roadway pressure relief.
(4) As an essential step of non-pillar mining, pre-splitting and roof cutting technology is also developing towards mechanized roof cutting, while the mining method is mechanization and automation. The research, development, and application of the chain arm saw machine and directional cutting roof rig are representative; it is anticipated that the future pre-splitting and roof-cutting technology will balance precision, automation, and greening, which will help the development of intelligent and unmanned mining.

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References

1. He, M.; Wang, Q.; Wu, Q. Innovation and future of mining rock mechanics. *J. Rock Mech. Geotech. Eng.* **2021**, *13*, 1–21. [CrossRef]
2. Yu, B.; Tai, Y.; Gao, R.; Yao, Q.; Li, Z.; Xia, H. The sustainable development of coal mines by new cutting roof technology. *R. Soc. Open Sci.* **2020**, *7*, 191913. [CrossRef] [PubMed]
3. Ma, Z.; Wang, J.; He, M.; Gao, Y.; Hu, J.; Wang, Q. Key Technologies and Application Test of an Innovative Noncoal Pillar Mining Approach: A Case Study. *Energies* **2018**, *11*, 2853. [CrossRef]
4. Wang, E.; Xie, S. Determination of coal pillar width for gob-side entry driving in isolated coal face and its control in deep soft-broken coal seam: A case study. *Energy Sci. Eng.* **2022**, *10*, 2305–2316. [CrossRef]
5. Xie, S.; Gao, M.; Chen, D.; Sun, Y.; Pan, H.; Su, H.; Lan, S. Stability influence factors analysis and construction of a deep beam anchorage structure in roadway roof. *Int. J. Min. Sci. Technol.* **2017**, *28*, 445–451.
6. Xie, S.; Pan, H.; Zeng, J.; Wang, E.; Chen, D.; Zhang, T.; Peng, X.; Yang, J.; Chen, F.; Qiao, S. A case study on control technology of surrounding rock of a large section chamber under a 1200-m deep goaf in Xingdong coal mine, China. *Eng. Fail. Anal.* **2019**, *104*, 112–125. [CrossRef]
7. Chen, D.; Wang, E.; Xie, S.; He, F.; Wang, L.; Zhang, Q.; Wu, X.; Jiang, Z.; Li, Y.; Shi, S. Roadway surrounding-rock under multi-coal seam mining: Deviatoric stress evolution and control technology. *Adv. Civil Eng.* **2020**, *2020*, 9891825. [CrossRef]
8. Kang, H.; Zhang, X.; Wang, D.; Tian, J.; Yi, Z.; Jiang, W. Strata control technology and applications of non-pillar coal mining. *J. China Coal Soc.* **2022**, *47*, 16–44.
9. Qian, M.; Miao, X.; Xu, J. Theoretical Study of Key Sratum in Ground Conrol. *J. China Coal Soc.* **1996**, *21*, 2–7.
10. He, S.S.; Xie, S.R.; Song, B.H.; Zhou, D.Q.; Sun, Y.D.; Han, S. Breaking laws and stability analysis of damage main roof in close distance hypogynous seams. *J. China Coal Soc.* **2016**, *41*, 2596–2605.
11. He, F.L.; Chen, D.D.; Xie, S.R. The kDL effect on the first fracture of main roof with elastic foundation boundary. *Chin. J. Rock Mech. Eng.* **2017**, *36*, 1384–1399.
12. Chen, D.D.; Guo, F.F.; Wu, Y.Y. Study on the first fracture of the main roof plate structure with one side goaf and elastic-plastic foundation boundary. *J. China Coal Soc.* **2021**, *46*, 3090–3105.
13. Chen, D.D.; He, F.L.; Xie, S.R.; Zeng, J.C. Time-space relationship between periodic fracture of plate structure of main roof and rebound in whole region with elastic foundation boundary. *Chin. J. Rock Mech. Eng.* **2019**, *38*, 1172–1187.
14. Xie, S.; Cheng, D.; Ceng, J.; Gao, M.; Zhang, T.; Liu, J. First fracturing characteristics of main roof plate structure considering coal pillars and elastic coal foundation on both sides of stope. *J. China Coal Soc.* **2019**, *44*, 115–126.
15. He, F.; He, W.R.; Chen, D.D.; Xie, S.R.; Li, H.; He, C.X. First fracture structure characteristics of main roof plate considering elastic-plastic deformation of coal. *J. China Coal Soc.* **2020**, *45*, 2704–2717.
16. Li, Z.; Changzhi, Z.; Xie, H.; Yang, F. Similar simulation test for breakage law of working face floor in coal mining above aquifer. *Chin. J. Rock Mech. Eng.* **2011**, *30*, 1571–1578. [CrossRef]
17. Zhao, Z.; Ma, N.; Guo, X.; Zhao, X.; Fan, L. Falling principle and support design of butterfly-failure roof in large deformation mining roadways. *J. China Coal Soc.* **2016**, *41*, 2932–2939.
18. Guo, X.F.; Guo, L.F.; Ma, N.J.; Zhao, Z.Q.; Li, C. Applicability analysis of the roadway butterfly failure theory. *J. China Univ. Min. Technol.* **2020**, *49*, 646–653.
19. Tao, Z.; Zheng, X.; Zhu, C.; Zhang, H.; Zhang, X. Framework and engineering application of large data monitoring system for a non-pillar mining method with gob-side entry formed automatically. *J. China Univ. Min. Technol.* **2021**, *50*, 983–991.
20. Xie, S.; Guo, F.; Wu, Y. Control Techniques for Gob-Side Entry Driving in an Extra-Thick Coal Seam with the Inflence of Upper Residual Coal Pillar: A Case Study. *Energies* **2022**, *15*, 3620. [CrossRef]
21. Wang, Q.; Jiang, B.; Xin, Z.X.; He, M.C.; Li, S.C.; Zhang, P.; Wang, Y.; Jiang, Z.H. Development of a 3D geomechanical model test system for non-pillar mining with automatically formed roadway and its engineering application. *Chin. J. Rock Mech. Eng.* **2020**, *39*, 1582–1594.
22. Xie, S.; Wu, Y.; Chen, D.; Liu, R.; Han, X.; Ye, Q. Failure analysis and control technology of intersections of large-scale variable cross-section roadways in deep soft rock. *Int. J. Coal Sci. Technol.* **2022**, *9*, 19. [CrossRef]
23. Liu, X.; He, M.; Wang, J.; Ma, Z. Research on non-pillar coal mining for thick and hard conglomerate roof. *Energies* **2021**, *14*, 299. [CrossRef]
24. Chen, X.; Li, L.; Guo, Z.; Chang, T. Evolution characteristics of spontaneous combustion in three zones of the goaf when using the cutting roof and release pressure technique. *Energy Sci. Eng.* **2019**, *7*, 710–720. [CrossRef]
25. Wang, Q.; Qin, Q.; Jiang, B.; Jiang, Z.; He, M.; Li, S.; Wang, Y. Geomechanics model test research on automatically formed roadway by roof cutting and pressure releasing. *Int. J. Rock Mech. Min. Sci.* **2020**, *135*, 104506. [CrossRef]
26. Chen, X.; Du, Y.; Wang, L.; Zhao, S. Evolution and application of airflow permeability characteristics of gob in roof cutting and pressure releasing mining method. *Energy Sci. Eng.* **2020**, *8*, 2073–2085. [CrossRef]

27. Wu, Y.; Xie, S.; Zhang, Y. Research on stability control of roadway intersections with nested variable cross-section in deep mine. *J. Min. Sci. Technol.* **2022**, *7*, 720–729.
28. Li, G.; Yang, S.; Sun, Y.; Xu, J.; Li, J. Research progress of roadway surrounding strata rock control technologies under complex conditions. *Coal Sci. Technol.* **2022**, *50*, 29–45.
29. Yang, S.; Li, G.; Bi, R.; Yao, B.; Feng, R.; Sun, Y. The Stability of Roadway Groups under Rheology Coupling Mining Disturbance. *Sustainability* **2021**, *13*, 12300. [CrossRef]
30. Sun, Y.; Bi, R.; Sun, J.; Zhang, J.; Taherdangkoo, R.; Huang, J.; Li, G. Stability of roadway along hard roof goaf by stress relief technique in deep mines: A theoretical, numerical and field study. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2022**, *8*, 45. [CrossRef]
31. Wang, Q.; Wang, Y.; He, M.; Jiang, B.; Li, S.; Jiang, Z.; Wang, Y.; Xu, S. Experimental research and application of automatically formed roadway without advance tunneling. *Tunn. Undergr. Space Technol.* **2021**, *114*, 103999. [CrossRef]
32. Zhang, Q.; He, M.; Guo, S.; Qi, J.; Yang, J.; Wang, C.; Xia, M.; Li, L. Investigation on the key techniques and application of the new-generation automatically formed roadway without coal pillars by roof cutting. *Int. J. Rock Mech. Min. Sci.* **2022**, *152*, 105058. [CrossRef]
33. Wang, Y.; He, M.; Yang, J.; Wang, Q.; Liu, J.; Tian, X.; Gao, Y. Case study on pressure-relief mining technology without advance tunneling and coal pillars in longwall mining. *Tunn. Undergr. Space Technol.* **2020**, *97*, 103236. [CrossRef]
34. Li, Z.; Tao, Z.; Meng, Z.; He, M. Longwall mining method with roof-cutting unloading and numerical investigation of ground pressure and roof stability. *Arab. J. Geosci.* **2018**, *11*, 697. [CrossRef]
35. Yang, J.; Liu, B.; Bian, W.; Chen, K.; Wang, H.; Cao, C. Application Cumulative Tensile Explosions for Roof Cutting in Chinese Underground Coal Mines. *Arch. Min. Sci.* **2021**, *66*, 421–435.
36. Xie, S.R.; Pan, H.; Chen, D.D.; Zeng, J.C.; Song, H.Z.; Cheng, Q.; Xiao, H.B.; Yan, Z.Q.; Li, Y.H. Stability analysis of integral load-bearing structure of surrounding rock of gob-side entry retention with flexible concrete formwork. *Tunn. Undergr. Space Technol.* **2020**, *103*, 103492. [CrossRef]
37. Wang, Q.; He, M.; Yang, J.; Gao, H.; Jiang, B.; Yu, H. Study of a no-pillar mining technique with automatically formed gob-side entry retaining for longwall mining in coal mines. *Int. J. Rock Mech. Min. Sci.* **2018**, *110*, 1–8. [CrossRef]
38. Tao, Z.; Song, Z.; He, M.; Meng, Z.; Pang, S. Principles of the roof cut short-arm beam mining method (110 method) and its mining-induced stress distribution. *Int. J. Min. Sci. Technol.* **2018**, *28*, 391–396. [CrossRef]
39. Fan, D.; Liu, X.; Tan, Y.; Yan, L.; Song, S.; Ning, J. An innovative approach for gob-side entry retaining in deep coal mines: A case study. *Energy Sci. Eng.* **2019**, *7*, 2321–2335. [CrossRef]
40. Wang, Q.; He, M.; Li, S.; Jiang, Z.; Wang, Y.; Qin, Q.; Jiang, B. Comparative study of model tests on automatically formed roadway and gob-side entry driving in deep coal mines. *Int. J. Min. Sci. Technol.* **2021**, *31*, 591–601. [CrossRef]
41. Tu, M.; Zhao, G.; Zhang, X.; Bu, Q.; Dang, J. Fracture Evolution between Blasting Roof Cutting Holes in a Mining Stress Environment. *Minerals* **2022**, *12*, 418. [CrossRef]
42. Zhang, Q.; He, M.; Wang, J.; Guo, S.; Guo, Z.; Liu, X.; Hu, J.; Ma, Z.; Fan, L.; Guo, P. Instantaneous expansion with a single fracture: A new directional rock-breaking technology for roof cutting. *Int. J. Rock Mech. Min. Sci.* **2020**, *132*, 104399. [CrossRef]
43. Hua, X.Z.; Liu, X.; Huang, Z.G.; Yang, P.; Ma, Y. Stability mechanism of non-pillar gob-side entry retaining by roof cutting under the coupled static-dynamic loading. *J. China Coal Soc.* **2020**, *45*, 3696–3708.
44. Ma, X.; He, M.; Sun, J.; Wang, H.; Liu, X.; Zhen, E. Neural Network of Roof Cutting Blasting Parameters Based on Mines with Different Roof Conditions. *Energies* **2018**, *11*, 3468. [CrossRef]
45. Fan, D.; Liu, X.; Tan, Y.; Song, S.; Gu, Q.; Yan, L.; Xu, Q. Roof Cutting Parameters Design for Gob-Side Entry in Deep Coal Mine: A Case Study. *Energies* **2019**, *12*, 2032. [CrossRef]
46. Zhang, Q.; Wang, J.; Guo, S.; Gong, W.; Feng, L.; Wang, H.; Ming, C.; Ma, Z. Shaped Charge Hydraulic Blasting: An Environmental, Safe, and Economical Method of Directional Roof Cutting. *Geofluids* **2021**, *2021*, 5511081. [CrossRef]
47. Wang, Q.; Jiang, Z.; Jiang, B.; Gao, H.; Huang, Y.; Zhang, P. Research on an automatic roadway formation method in deep mining areas by roof cutting with high-strength bolt-grouting. *Int. J. Rock Mech. Min. Sci.* **2020**, *128*, 104264. [CrossRef]
48. Zhang, X.; Hu, J.; Xue, H.; Mao, W.; Gao, Y.; Yang, J.; He, M. Innovative approach based on roof cutting by energy-gathering blasting for protecting roadways in coal mines. *Tunn. Undergr. Space Technol.* **2020**, *99*, 103387. [CrossRef]
49. Wang, Y.; Yang, J.; He, M.; Tian, X.; Liu, J.; Xue, H.; Huang, R. Test of a liquid directional roof-cutting technology for pressure-relief entry retaining mining. *J. Geophys. Eng.* **2019**, *16*, 620–638. [CrossRef]
50. Yang, T. *3D Breaking Characteristics of Overlying Strata and Stress Field Evolution Law in Stope with Directional Hard Roof Cutting*; China University of Mining and Technology: Xuzhou, China, 2021.
51. Wang, Q.; Zhang, P.; Jiang, Z.; He, M.; Li, S.; Wang, Y.; Jiang, B. Automatic roadway formation method by roof cutting with high strength bolt-grouting in deep coal mine and its validation. *J. China Coal Soc.* **2021**, *46*, 382–397.
52. Pan, J.F.; Ma, W.T.; Liu, S.H.; Jiaming, G. A prevention technology of rock burst based on directional presplitting of water jet prefabricated slot in hard roof. *Chin. J. Rock Mech. Eng.* **2021**, *40*, 1591–1602.
53. Tang, T.; Liu, D.; Cui, Z.; Han, Z.; Liu, B.; Wang, Z. Initiation pressure evaluation of coal mine roof hydraulic fracturing based on fracture mechanics. *J. China Coal Soc.* **2020**, *45*, 727–735.
54. Lin, J.; Guo, K.; Sun, Z.; Wang, T. Study on fracturing timing of hydraulic fracturing top-cutting and pressure relief in roadway with strong dynamic pressure. *J. China Coal Soc.* **2021**, *46*, 140–148.

55. Huang, B.; Chen, S.; Zhao, X. Hydraulic fracturing stress transfer methods to control the strong strata behaviours in gob-side gateroads of longwall mines. *Arab. J. Geosci.* **2017**, *10*, 236. [CrossRef]
56. Guo, S.; Zhang, Q.; He, M.; Wang, J.; Liu, J.; Ming, C.; Guo, L.; Fan, L. Numerical investigation on rock fracture induced by a new directional rock-breaking technology. *Eng. Fract. Mech.* **2022**, *268*, 108473. [CrossRef]
57. Wu, Y. *Study on De-Stressing Mechanism of Directional Hydraulic Fracturing to Control Deformation of Reused Roadway in Longwall Mining with Two Gateroad Layout and Its Onsite Practices*; China Coal Research Institute: Beijing, China, 2018.
58. Zhang, J.; Gao, Z.; Zhang, H. Parameters determination of coal-rock HJC model and research on blasting characteristics by liquid CO_2. *Chin. J. Rock Mech. Eng.* **2021**, *40* (Suppl. 1), 2633–2642.
59. Kuang, T. *Research on Overlying Rock Structure and Near-Far Roof Control Technology in Extra Thick Coal Seam*; China University of Mining and Technology: Xuzhou, China, 2021.
60. Tai, Y.; Yu, B.; Xia, B.; Li, Z.; Xia, H. Research on stress release for the gob-side roadway using the roof-cutting technology with a chainsaw arm. *R. Soc. Open Sci.* **2020**, *7*, 191663. [CrossRef]
61. Wang, Q.; Feng, H.; Tang, P.; Peng, Y.; Li, C.; Jiang, L.; Mitri, H.S. The structure characteristics and deformation of "short cantilever beam" using a non-pillar mining method with gob-side entry formed automatically. *J. China Univ. Min. Technol.* **2019**, *48*, 718–726.
62. Sun, X.; Liu, Y.; Wang, J.; Li, J.; Sun, S.; Cui, X. Study on three-dimensional stress field of gob-side entry retaining by roof cutting without pillar under near-group coal seam mining. *Processes* **2019**, *7*, 552. [CrossRef]
63. Yang, J.; Wang, H.; Gao, Y.; Wang, J.; Liu, H. Fracture characteristics of the roof in gob-side entry retaining with roof cutting and pressure release. *J. Min. Saf. Eng.* **2019**, *36*, 1137–1144.
64. Tian, C.; Wang, A.; Liu, Y.; Jia, T. Study on the migration law of overlying strata of gob-side entry retaining formed by roof cutting and pressure releasing in the shallow seam. *Shock Vib.* **2020**, *2020*, 8821160. [CrossRef]
65. Chen, D.; Guo, F.; Xie, S.; Wang, E.; Wu, Y.; Jiang, Z.; Wang, L.; Cui, J.; Zhang, X.; Liu, R. Mining-induced failure characteristics and surrounding rock control of gob-side entry driving adjacent to filling working face in the deep coal mine. *Energy Sci. Eng.* **2022**, *10*, 2593–2611. [CrossRef]
66. Zhang, B.S.; Wang, P.F.; Cui, S.Q.; Fan, M.Z.; Qiu, Y.M. Mechanism and surrounding rock control of roadway driving along gob in shallow-buried, large mining height and small coal pillars by roof cutting. *J. China Coal Soc.* **2021**, *46*, 2254–2267.
67. Song, X. *Pressure Relief at Cutting Top of Mining Face Study on the Regularity of Mine Pressure in Retaining Small Coal Pillar*; Taiyuan University of Technology: Taiyuan, China, 2021.
68. Wang, F.; Shang, J.; Zhao, B.; Cao, Q. Surrounding rock structural characteristics and anchor-cable strengthened support technology of the gob-side entry retaining with roof cutting and pressure releasing. *Chin. J. Rock Mech. Eng.* **2021**, *40*, 2296–2305.
69. Zhang, Y.; Xu, H.; Song, P.; Sun, X.; He, M.; Guo, Z. Stress evolution law of surrounding rock with gob-side entry retaining by roof cutting and pressure release in composite roof. *Adv. Mate. Sci. Eng.* **2020**, *2020*, 1961680. [CrossRef]
70. Wang, K. *Study on Surrounding Rock Control of Gob-Side Entry Filling in Lingzhida Hard Top Plate Working Face*; China University of Mining and Technology: Xuzhou, China, 2020.
71. Zhen, E.; Gao, Y.; Wang, Y.; Wang, S. Comparative study on two types of non-pillar mining techniques by roof cutting and by filling artificial materials. *Adv. Civil Eng.* **2019**, *2019*, 5267240. [CrossRef]
72. Li, H.; Zu, H.; Zhang, K.; Qian, J. Study on filling support design and ground pressure monitoring scheme for gob-side entry retention by roof cutting and pressure relief in high-gas thin coal seam. *Int. J. Environ. Res. Public Health* **2022**, *19*, 3913. [CrossRef]
73. Xie, S.; Wang, E.; Chen, D.; Li, H.; Jiang, Z.; Yang, H. Stability analysis and control technology of gob-side entry retaining with double roadways by filling with high-water material in gently inclined coal seam. *Int. J. Coal Sci. Technol.* **2022**, *9*, 52. [CrossRef]
74. Xie, S.; Wang, E.; Chen, D.; Sun, Y.; Cheng, Q.; Ji, C.; Yan, Z.; Xiao, H. Failure analysis and control mechanism of gob-side entry retention with a 1.7-m flexible-formwork concrete wall: A case study. *Eng. Fail. Anal.* **2020**, *117*, 104816. [CrossRef]
75. Liu, X.; Hua, X.; Yang, P.; Huang, Z. A study of the mechanical structure of the direct roof during the whole process of non-pillar gob-side entry retaining by roof cutting. *Energ. Explor. Exploit.* **2020**, *38*, 1706–1724. [CrossRef]
76. He, M.; Ma, X.; Yu, B. Analysis of strata behavior process characteristics of gob-side entry retaining with roof cutting and pressure releasing based on composite roof structure. *Shock Vib.* **2019**, *2019*, 2380342. [CrossRef]
77. Gao, Y.; Wang, J.; Gao, H.; Yang, J.; Zhang, Y.; He, M. Mine pressure distribution and surrounding rock control of gob-side entry formed by roof cutting and pressure release under the influence of faults. *Chin. J. Rock Mech. Eng.* **2019**, *38*, 2182–2193.
78. Liu, H.; Zhao, Y.; Ren, T.; Wang, F.; Li, Z. Characteristics of overburden failure and fracture development in gob of mining with gob-side entry formed by cutting roof. *J. China Univ. Min. Technol.* **2022**, *51*, 77–89.
79. Li, L.; Li, G.; Gong, W.; Wang, J.; Deng, H. Energy evolution pattern and roof control strategy in non-pillar mining method of goaf-side entry retaining by roof cutting—A case study. *Sustainability* **2019**, *11*, 7029. [CrossRef]
80. Wang, Q.; Guo, Z.; Ouyang, Z.; Yin, S.; Peng, R. The influence of crushed rock size on bearing-deformation performance of gangue rib of gob-side entry retaining formed by roof fracturing. *J. China Univ. Min. Technol.* **2022**, *51*, 100–106.
81. Xie, S.; Wu, X.; Chen, D.; Sun, Y.; Zeng, J.; Zhang, Q.; Ji, C.; Cheng, Q.; Wang, E.; Ren, Y. Automatic roadway backfilling of caving gangue for cutting roofs by combined support on gob-side entry retaining with no-pillars: A case study. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 8736103. [CrossRef]
82. Chen, D.D.; He, F.L.; Xie, S.; Gao, M.M.; Song, H.Z. First fracture of the thin plate of main roof with three sides elastic foundation boundary and one side coal pillar. *J. China Coal Soc.* **2017**, *42*, 2528–2536.

83. Wang, Y.; He, M.; Wang, Q.; Yang, J.; Wang, J.; Liu, H.; Chen, F. Design of equipment system and surrounding rock control for N00 mining method without coal pillar left and roadway excavation. *J. China Coal Soc.* **2022**. [CrossRef]
84. Wang, J.; Gao, R.; Yu, G.; Gong, W.; Zhu, D. Experimental study on infrared radiation characteristics of overburden movement of self-forming roadway under pressure relief. *J. China Coal Soc.* **2020**, *45*, 119–127.
85. He, H.; Dou, L.; Fan, J.; Du, T.; Sun, X. Deep-hole directional fracturing of thick hard roof for rockburst prevention. *Tunn. Undergr. Space Technol.* **2012**, *32*, 34–43. [CrossRef]
86. Yan, S.; Liu, T.; Bai, J.; Wu, W. Key Parameters of Gob-Side Entry Retaining in A Gassy and Thin Coal Seam with Hard Roof. *Processes* **2018**, *6*, 51.
87. Liu, H.; Dai, J.; Jiang, J.; Wang, P.; Yang, J. Analysis of Overburden Structure and Pressure-Relief Effect of Hard Roof Blasting and Cutting. *Adv. Civ. Eng.* **2019**, *2019*, 1354652.
88. Zhang, L.; Zhao, J.; Zang, C.; Wang, S. An Innovative Approach for Gob-Side Entry Retaining by Roof Cutting in Steeply Pitching Seam Longwall Mining with Hard Roof: A Case Study. *Min. Metall. Explor.* **2020**, *37*, 1079–1091.
89. Yang, H.; Liu, Y.; Cao, S.; Pan, R.; Wang, H.; Li, Y.; Luo, F. A caving self-stabilization bearing structure of advancing cutting roof for gob-side entry retaining with hard roof stratum. *Geomech. Eng.* **2020**, *21*, 23–33.
90. Gao, K.; Huang, P.; Liu, Z.G.; Liu, J.; Wang, F.; Shu, C.M. Pressure Relief by Blasting Roof Cutting in Close Seam Group Mining under Thick Sandstone to Enhance Gas Extraction for Mining Safety. *Processes* **2021**, *9*, 693.
91. Hu, J.; He, M.; Wang, J.; Ma, Z.; Wang, Y.; Zhang, X. Key Parameters of Roof Cutting of Gob-Side Entry Retaining in a Deep Inclined Thick Coal Seam with Hard Roof. *Energies* **2019**, *12*, 934.
92. Ma, X.; He, M.; Wang, J.; Gao, Y.; Zhu, D.; Liu, Y. Mine Strata Pressure Characteristics and Mechanisms in Gob-Side Entry Retention by Roof Cutting under Medium-Thick Coal Seam and Compound Roof Conditions. *Energies* **2018**, *11*, 2539.
93. Chen, D.D.; Guo, F.F.; Wu, Y.Y. Study on the first fracture of the main roof plate structure with the long side goaf and elastic-plastic softening foundation boundary. *J. China Coal Soc.* **2022**, *47*, 1473–1489.
94. Chen, D.D.; Xie, S.R.; He, F.L.; Zeng, J.C.; Xie, F.X.; Cheng, Q. First fracturing of thin plate of main roof with elastic foundation boundary on both sides of the long side of goaf (coal pillars). *J. China Coal Soc.* **2018**, *43*, 3273–3285.
95. Guo, Z.; Wang, H.; Ma, Z.; Wang, P.; Kuai, X.; Zhang, X. Research on the transmission of stresses by roof cutting near gob rocks. *Energies* **2021**, *14*, 1237.
96. Li, P.; Lai, X.; Gong, P.; Su, C.; Suo, Y. Mechanisms and applications of pressure relief by roof cutting of a deep-buried roadway near Goafs. *Energies* **2020**, *13*, 5732. [CrossRef]
97. Yang, X.; Liu, C.; Sun, H.; Yue, S.; Ji, Y.; Zhang, X.; Hou, L. Research on the deformation mechanism and directional blasting roof cutting control measures of a deep buried high-stress roadway. *Shock Vib.* **2020**, *2020*, 6742504. [CrossRef]
98. Wang, Y.; Wang, H.; He, M.; Wang, Q.; Qiao, Y.; Yang, J. Mine pressure behavior characteristics and control methods of a reused entry that was formed by roof cutting: A case study. *Shock Vib.* **2020**, *2020*, 4276730. [CrossRef]
99. Wang, Q.; Jiang, B.; Wang, L.; Liu, B.; Li, S.; Gao, H.; Wang, Y. Control mechanism of roof fracture in no-pillar roadways automatically formed by roof cutting and pressure releasing. *Arab. J. Geosci.* **2020**, *13*, 274. [CrossRef]
100. Wang, Y.; Gao, Y.; Wang, E.; He, M.; Yang, J. Roof deformation characteristics and preventive techniques using a novel non-pillar mining method of gob-side entry retaining by roof cutting. *Energies* **2018**, *11*, 627. [CrossRef]
101. Ma, Q.; Tan, Y.; Zhao, Z.; Xu, Q.; Wang, J.; Ding, K. Roadside support schemes numerical simulation and field monitoring of gob-side entry retaining in soft floor and hard roof. *Arab. J. Geosci.* **2018**, *11*, 563. [CrossRef]
102. Sun, B.J.; Hua, X.Z.; Zhang, Y.; Yin, J.; He, K.; Zhao, C.; Li, Y. Analysis of roof deformation mechanism and control measures with roof cutting and pressure releasing in gob-side entry retaining. *Shock Vib.* **2021**, *2021*, 6677407. [CrossRef]
103. Guo, J.G.; Li, Y.H.; Shi, S.H.; Jiang, Z.S.; Chen, D.D.; He, F.L.; Xie, S.R. Self-forming roadway of roof cutting and surrounding rock control technology under thick and hard basic roof. *J. China Coal Soc.* **2021**, *46*, 2853–2864.
104. Zhao, S.K.; Deng, Z.G.; Qi, Q.X.; Li, H.Y. Theory and application of deep hole floor-break blasting in floor rock burst coal mine. *J. Min. Saf. Eng.* **2016**, *33*, 636–642.
105. Liu, S.; Feng, M.; Pan, J.; Wang, S. Experimental analysis on vibration of roadway with strong probability of rock burst subjected to pressure relief blasting. *Chin. J. Rock Mech. Eng.* **2016**, *35*, 906–918.
106. Xie, S.R.; Wang, E.; Chen, D.D.; Jiang, Z.S.; Li, H.; Liu, R.P. Collaborative control technology of external anchor-internal unloading of surrounding rock in deep large-section coal roadway under strong mining influence. *J. China Coal Soc.* **2022**, *47*, 1946–1957.