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APPLICATION CUMULATIVE TENSILE EXPLOSIONS FOR ROOF CUTTING IN CHINESE UNDERGROUND COAL MINES

Cumulative blasts are an important controlled blasting method used to control the propagation of cracks in the predetermined direction. However, traditional cumulative blasts are associated with long processing times and poor blasting effects. A simple blasting technology called bilateral cumulative tensile explosion (BCTE) is proposed in this paper. There are two application types where BCTE is used. The first application is used to control the stability of high-stress roadways in both Wangzhuang mine 6208 tailgate and Hongqinghe mine 3-1103 tailgate. The second application is used to replace the backfill body in gob-side entry retaining (GER) in Chengjiao mine 21404 panel, Jinfeng mine 011810 panel and Zhongxing mine 1200 panel. The first application type reveals that BCTE can significantly reduce the deformation of the surrounding rock and reduce the associated maintenance cost of the roadways. Whereas the second application type, the roadway deformations are smaller, the process is simpler, and the production costs are lower, which further promotes GER and is of significance towards conserving resources.

Keywords: cumulative blast, bilateral cumulative tensile explosion, roof cutting and pressure relief technology, gob-side entry retaining

1. Introduction

Roof blasting and hydraulic fracturing [1,2] are often used in coal mine production, to eliminate mining hazards [3,4]. Compared with ordinary blasting, controlled blasting can break rocks within a predetermined range and reduce rock damage outside this range [5-7]. The force

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of the explosions around the drilled explosives hole is the same and will produce cracks in the predetermined direction as well as other directions. Therefore, several problems result from controlled blasting, which includes a poor blasting profile, large unit consumption of explosives and significant influence on the rock that surrounds the blasting section.

In blasting construction, it is often necessary to produce a smooth blasting surface. Therefore, a variety of cumulative blasts are proposed. Foster [8] proposed cutting a "V" -shaped groove in the wall of the blast hole to control the direction of the burst expansion. U. Langefor [9] analysed the blasting effects of different blast hole shapes and thought that cutting out the "V" shaped groove was beneficial to control the generation and propagation of blasting cracks. W.L. Fourney [10] carried out the blasting test of the notched blastholes on plexiglass and achieved a satisfactory effect of directional blasting control. Costin [11] carried out experiments using this method on oil shale and achieved exceptional results. Kabiesz [4] used a newly designed device to create a wedge-shaped notch in the vertical direction of the borehole, resulting in the effect of a concentrated blasting. Bjarnholt G. [12] introduced an energy-concentrated charge into the rock blasting. Guo [13] designed two kinds of energy-concentrated charges to improve the permeability of coal seam and gas extraction rate. Wang [14] applied energy-collecting tube blasting to the field, with good results. Generally speaking, at present, there are three kinds of cumulative blasts: notched blasting, i.e. changing the shape of the blast hole [15]; energy concentrated charge blasting, i.e. changing the charging structure; and energy-collecting tube blasting, i.e. adding special devices, as shown in Figure 1.

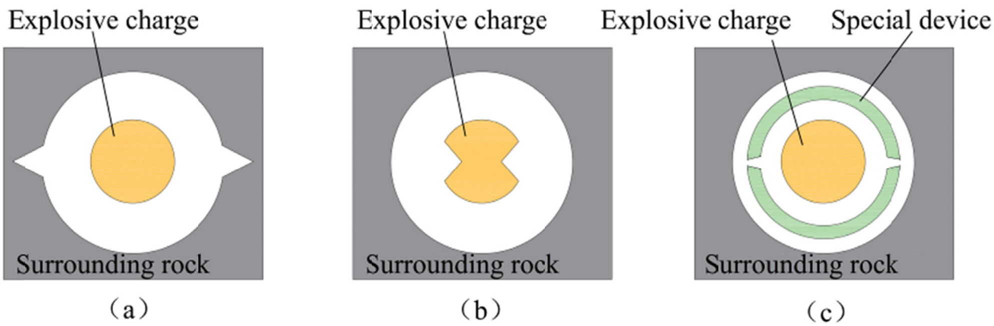


Fig. 1. Types of cumulative blasts: (a) notched blasting, (b) energy-concentrated charge blasting, (c) energy-collecting tube blasting

The first method requires a specific construction for the shape of the blastholes, whereas the second method requires the processing of blasting rolls with particular shapes, which are relatively complicated. He et al. [16] proposed BCTE, a kind of energy-collecting tube blasting. There are small holes in the energy-collecting tube. Detonation gas is blown out from the small holes to achieve cracks in the rock mass. BCTE is very effective. Zhu [17] proved that pre-split blasting achieves satisfactory results in the condition of extra-thick coal seams and multiple hard roofs. In recent years, it has been widely used in China's coal mining, chamber excavation [18], complex jointed rock mass blasting [19], and national defence engineering [20]. Especially in coal mining, it has been one of the most popular technologies. This article will introduce the technology comprehensively and show the latest engineering applications of the technology.

2. Bilateral Cumulative Tensile Explosions

2.1. Technical principle

In BCTE, the explosive cartridges are packed in an energy-collecting tube that has densely distributed small holes. After the explosive cartridges explode, an enormous shock wave acts on the whole wall of the blasthole along the direction, causing the rock to crack in the set direction, as shown in Figure 2.

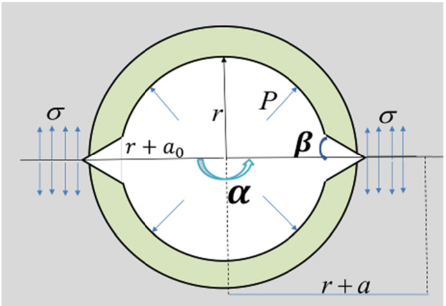


Fig. 2. Principle of Bilateral Cumulative Tensile Explosions

In Figure 2, P is the pressure acting on the tube, $r + a_0$ is the distance from the initial crack tip to the centre of the circle, and σ is the stress acting on the crack. α is the angle between the two rows of small holes, and β is the angle of energy accumulation. According to fracture mechanics [21], in the direction of energy accumulation, the stress intensity factor K_1 at the tip of the crack during the crack growth process is as shown in equation (1), where F is the correction coefficient.

$$K_1 = P \cdot F\sqrt{\pi\left(r + a_0\right)} + \sigma\sqrt{\pi a_0} \tag{1}$$

σ is caused by the detonation gas, and this value can be ignored in the non-aggregated energy direction. Therefore, in non-aggregated energy direction, the stress intensity factor K_2 at the tip of the crack during the crack growth process is as shown in equation (2).

$$K_2 = P \cdot F\sqrt{\pi\left(r + a_0\right)} \tag{2}$$

The fracture occurs when the stress intensity factor is greater than the fracture toughness K_{IC}. In the direction of energy accumulation, the pressure required for detonation P_1 is as formula (3). In the non-aggregated energy direction, the pressure required for detonation P_2 is as shown in formula (4). Therefore, in the direction of energy accumulation, the stress produced by detonation gas reduces the required pressure for crack initiation and propagation, which is conducive to the preferential development of cracks in the direction of energy accumulation.

$$P_1 > \frac{K_{IC} - \sigma\sqrt{\pi a_0}}{F\sqrt{\pi\left(r + a_0\right)}} \tag{3}$$

$$P_2 > \frac{K_{IC}}{F\sqrt{\pi\left(r + a_0\right)}} \tag{4}$$

SPH is selected to simulate ordinary blasting and BCTE. The angle α is equal to 180°, and the angle β changes. The results are shown in Figure 3, and the following conclusions can be drawn: (1) under the same charge, the cracks produced by ordinary blasting are not obvious, but obvious cracks produced by BCTE. (2) The smaller the angle β, the better the energy accumulation effect, and a crack is generated in the direction of energy accumulation. The larger the angle β, the worse the energy accumulation effect, and two crossed cracks are formed. With the increase of the energy accumulation angle β, the included angle of the cross fissures first increases and then remains unchanged.

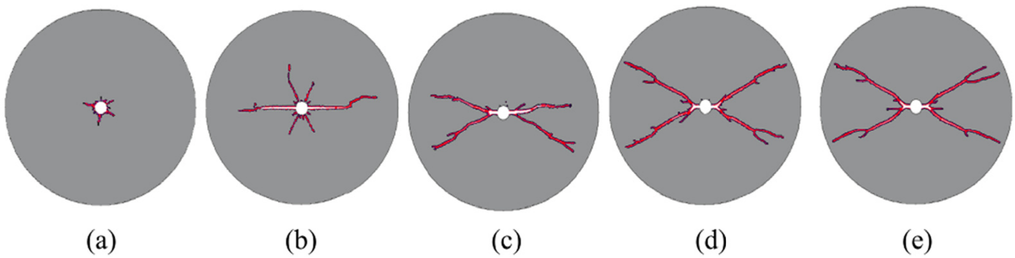


Fig. 3. Comparison of ordinary blasting and BCTE:
(a) ordinary blasting (b) BCTE, $\beta = 15°$, (c) BCTE, $\beta = 25°$, (d) BCTE, $\beta = 35°$, (e) BCTE, $\beta = 45°$

The angle β is equal to 15°, and the angle α varies. The results are as shown in Figure 4, and the following conclusions can be obtained: (1) under the same charge, the cracks produced by ordinary blasting are not obvious, but obvious cracks produced by BCTE. (2) Under different angle α, cracks are produced in the direction of energy accumulation, which shows that BCTE can effectively control the direction of cracks and has a better guiding effect.

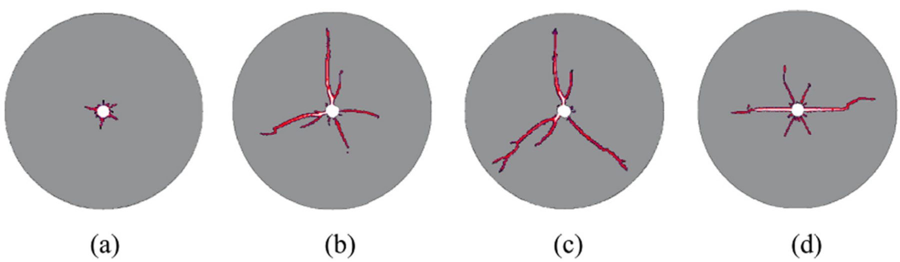
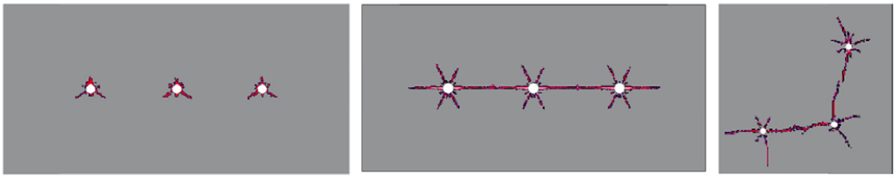


Fig. 4. Comparison of ordinary blasting and BCTE:
(a) ordinary blasting (b) BCTE, $\alpha = 90°$, (c) BCTE, $\alpha = 120°$, (d) BCTE, $\alpha = 180°$

The comparison of ordinary joint hole blasting and joint BCTE is shown in Figure 5, and the following conclusions can be obtained: (1) BCTE produces obvious directional cracks, and the unit consumption is small. (2) By reasonably designing the angle α in the joint hole blasting, BCTE can effectively control the crack direction.



(a) (b) (c)

Fig. 5. Comparison of joint blasting: (a) ordinary blasting (b) BCTE, $\alpha = 180°$, (c) BCTE, $\alpha = 90°$

2.2. Parametric design

BCTE has been widely used in China's underground coal mining in recent years, mainly used for cutting roofs. The blasting is required to produce a smooth and flat surface, $\alpha = 180°$ and $\beta = 15°$ are used. In addition, the outer diameter of the energy-collecting tube is 42 mm, and the inner diameter is 36.5 mm.

The explosive cartridge is 200 mm in length and 32 mm in diameter. According to the lithology of the roof, the number of explosive cartridges per meter in the blasting hole can be selected according to Table 1 or can be determined by field tests. In addition, mud is used for hole sealing, and the length of it should be 1.5 m-2.5 m.

TABLE 1

Explosive cartridge per meter of the energy-collecting tube

Drilling lithology	Shale	Mudstone	Sandstone	Sand-mudstone interlayer
Number of explosive cartridges	1-2	1-3	2-5	1-5

The angle γ between the blasthole and the plumb line, as well as the height *HF* of the blasthole, should be determined in combination with the actual site effect. Among them, when BCTE is applied to the GER, the technology is relatively mature. The angle γ and the height *HF* of the blasthole can be determined according to equations (5) and (6), respectively. In addition, the diameter of the blasthole is 46-48 mm, and the distance between the blastholes can be selected according to Table 2.

$$\gamma = \begin{cases} 15° - 20°, \ H_c \le 1m \\ 10° - 15°, \ H_c > 1m \end{cases} \tag{5}$$

Among them, H_c is the height of mining.

$$H_F = 2.6H_c \tag{6}$$

Among them, H_F is the height of blasthole.

TABLE 2

Distance between blasting holes

Roof characteristics	Hard rock roof	Soft rock roof	Broken roof	Composite roof
Distance between blasting holes /mm	450-550	500-600	550-650	450-650

2.3. Tools and processes of BCTE

The main materials and equipment of BCTE are shown in Figure 6(a-d), and the operation process is shown in Figure 6(e-i). Among them, the most commonly used explosive is the mine emulsified explosive, and the most commonly used stemming is mud. Blasting and roof cutting, using roof cutting machinery, simultaneously produces blasting holes in the roof. Then, the explosive is charged into the energy collecting tube according to blasting network and charging parameters, and the end of the energy collecting tube is blocked by mud. Finally, the explosive and the energy collecting tube are sent into the blasthole together, and the normal direction of the energy collecting tube's hole is the same as the direction of the roadway.

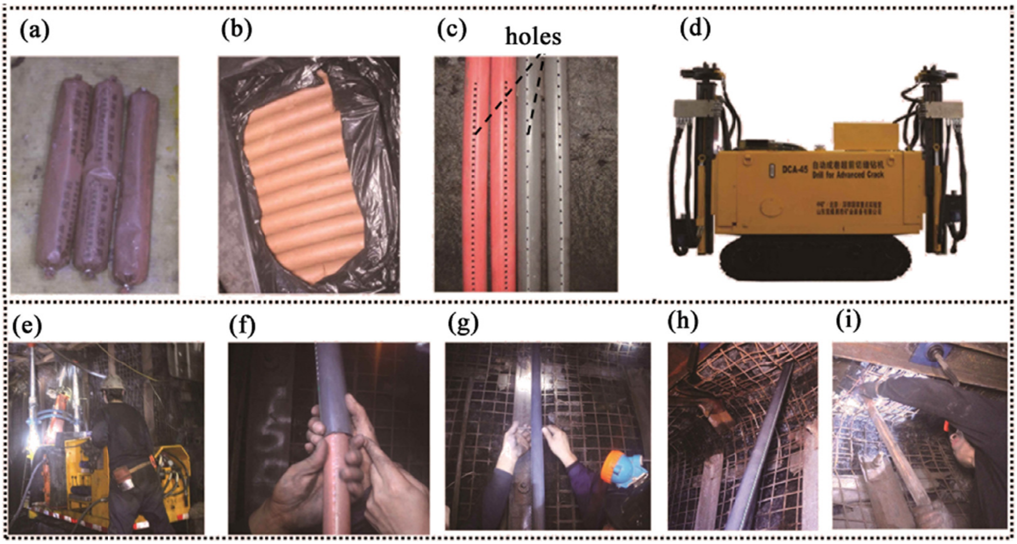


Fig. 6. Device, material, technological process of BCTE: (a) explosive cartridge, (b) stemming, (c) energy-collecting tube, (d) roof cutting machinery, (e) drill holes, (f) stuff the explosive cartridge into the energy-collecting tube, (g) fix the explosive cartridge, (h) insert explosive cartridge and energy-collecting tube into boreholes, (i) sealing boreholes with stemming

3. The application of BCTE

After mining along the longwall face, the distribution of the lateral abutment pressure affects the layout of the roadway for the adjacent working face [22-25]. The distribution of the abutment pressure before the basic roof above the roadway breaks is shown in Figure 7. To facilitate roadway stability, it is necessary to arrange the roadway in the region with a low abutment pressure. For example, the rock stress area (position 1) is far from the gob, and the pressure reduction area (position 2) is very close to the gob.

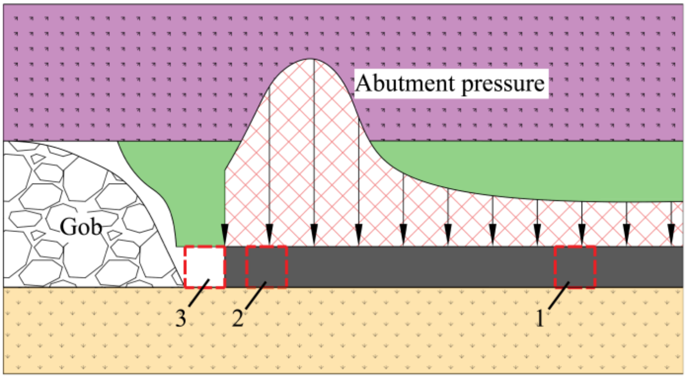


Fig. 7. Lateral abutment pressure and selection of roadway position

One possible roadway arrangement requires large coal pillars between the roadway and the gob. In some places, such as the Hongqinghe coal mine in Inner Mongolia, even though the width of the coal pillar approaches 30 m, the roadway stability is still very poor [26]. If the coal pillar width is further increased, there will be more significant coal resource waste. A second roadway arrangement only requires a small coal pillar that must be in a plastic state. However, this readily leads to instability after there is a main roof fracture disturbance above the roadway. A third roadway arrangement is to use a GER. In this method, the roadway is also in the pressure reduction area, which not only reduces the coal resource waste but also reduces the roadway excavation requirements.

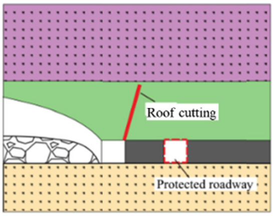
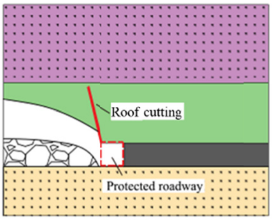
In the GER, support is established near the gob to cut off the roof of the gob side, which is called roadside support. The roadside support can be divided into two categories: permanent and removable. For the permanent type, the roadway support masonry exists and produces stress concentration, which comes with significant risks of outburst and close coal seams. The removable type, such as a single pillar and support, is a kind of roadway support that avoids the problems associated with a permanent approach. However, this approach has problems of insufficient cutting off resistance.

The lateral abutment pressure is the most important factor that affects roadway stability. If the continuity of the overlying strata can be actively cut off, the stress condition of the roadway can be reduced. Therefore, BCTE is widely used to cut off the continuity of the roof. Currently, BCTE is applied in the two cases shown in Table 3.

The BCTE has significant advantages over ordinary blasting, which has promoted its widespread use in coal mines. In particular, the application of BCTE to roadways along gobs is denoted as the third mining technology revolution in China [27-30].Our group has coordinated with more than 100 mines to apply the BCTE process to coal mine production. The statistics from some mines using this technology are shown in Figure 3.

TABLE 3

The applications of BCTE

Roadway layout	Reason for roof cutting	Schematic diagram	Description
Type 1 or type 2	The two roadways are simultaneously excavated, and the mining effect on one side of the working face makes the right roadway deform significantly (the coal pillar width is unreasonable).		Roof cutting is performed on the upper right or left sides of the roadway beside the gob, while the roof cutting is vertical or inclined. The BCTE can avoid further impact damage of ordinary blasting to protect the roadway.
Type 3	No new roadways are excavated, and the GER is used.		Roof cutting is performed on the upper left side of the roadway, and the roof cutting is vertical or inclined relative to the gob. The use of BCTE can avoid damaging the roof integrity of the retained roadway and can form a flat cutting surface, which is conducive to the timely collapse of the strata in the gob. The application of BCTE in the GER overcomes the shortcomings of an insufficient cutting off resistance when a single pillar and support are used as the roadside support.

As seen in Figure 8, BCTE has been applied primarily to mines with preferred geological conditions, such as with medium-thick coal seams, low gas, small dip angle coal seams, or in shallow burial conditions. The mines were located mainly in Shanxi and Shaanxi. However, with the maturity of BCTE and its advantages, the technology has been increasingly applied under more adverse conditions. For example, (1) when the mining height is large, the stability of the filling body in the GER is poor. However, BCTE reduces the cutting off resistance required by the GER for its use in thick coal seams. (2) At greater buried depths, there are larger stress concentrations at the coal pillar and higher risks of coal and gas outbursts. In the three types of roadway arrangements described in Table 1, the implementation of BCTE can effectively reduce the risk of protrusion. This technology has been fully extended to such mines in Sichuan Province, suggesting this technology can be used increasingly often in deep mines.

4. Application cases

4.1. Application of BCTE in stability control of high-stress roadways

Based on the descriptions in Table 1, the roadway position can avoid high abutment pressure zones by setting wide or narrow coal pillars between adjacent panels. However, for different geological conditions, the reasonable width of the coal pillars can vary. If the width of the coal pillar is not suitable, the roadway will be significantly affected by the lateral abutment pressure.

Fig. 8. The applications of BCTE in China

The 6208 tailgate of Wangzhuang mine and the 3-1101 tailgate of Hongqinghe mine are used as examples. Table 4 shows the basic conditions for these two panels, and Figure 9 shows the destruction conditions of the roadway before the adoption of BCTE.

TABLE 4

Basic conditions for two types of panels

	Mining method	**Buried depth**	**Coal pillar width and roadway layout**	**Phenomenon**
Wangzhuang mine 6208 tailgate	Top coal mining	>400 m	5 m (Type 2)	The coal seam of the roadway roof is broken, and there are serious deformations of the roadway.
Hongqinghe mine $3^{-1}103$ tailgate	Large mining height mining	>650 m	30 m (Type 1)	The roadway side is bulging, and breaking sounds are often emitted from the coal pillar.

To reduce the influence of the lateral abutment pressure on the roadway of the subsequent panel, BCTE was adopted to cut the roof of the GER. The depth of the blasting hole in the Wangzhuang mine is 19 m and is laterally deflected by 25° to the gob. The depth of the blasting hole

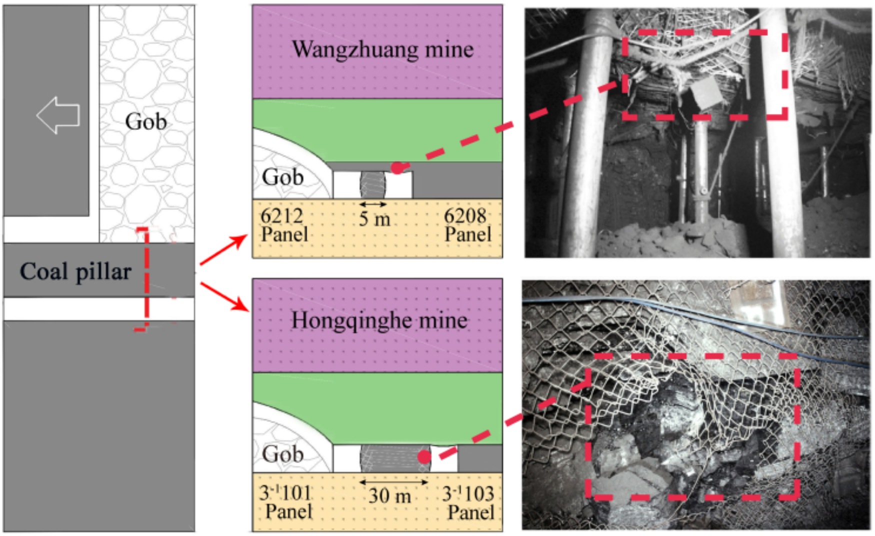


Fig. 9. Roadway damage before using BCTE

in Hongqinghe mine is 10 m and is laterally deflected by 15° to the coal wall. The roof-to-floor convergence and the convergence of the two ribs for the tailgate [26,31,32] in the two coal mines are shown in Figure 10. It can be seen that adopting BCTE to control the stability of a high-stress roadway can be used to good effect.

4.2. Contrast between the RCPR and GERF

There are usually two techniques when the roadway layout adopts the GER using BCTE technology: gob-side entry retained by filling (GERF) and roof cutting and pressure relief (RCPR). The current popular GERF includes flexible formwork, pump concrete (FFPC) and high-water-content packing (HWCP). To compare the advantages and disadvantages of the GERF and RCPR, relevant field tests were conducted in the Chengjiao mine, Jinfeng mine and Zhongxing mine [33-38]. Table 5 shows the basic conditions of panels from the above three mines.

TABLE 5

Basic conditions of three panels to compare the GERF and RCPR

	Buried depth: m	Mining height: m	GERF			RCPR		
			Type	Thickness: m	Length: m	Height: m	Angle: °	Length: m
Chengjiao mine 21404 panel	915	3.0	FFPC	1.2	1700	8	15	580.7
Jinfeng mine 011810 panel	214-330	3.75	FFPC	1.0	230	9	20	550
Zhongxing mine 1200 panel	350	2.3	HWCP	2.5	130.5	6	15	142.5

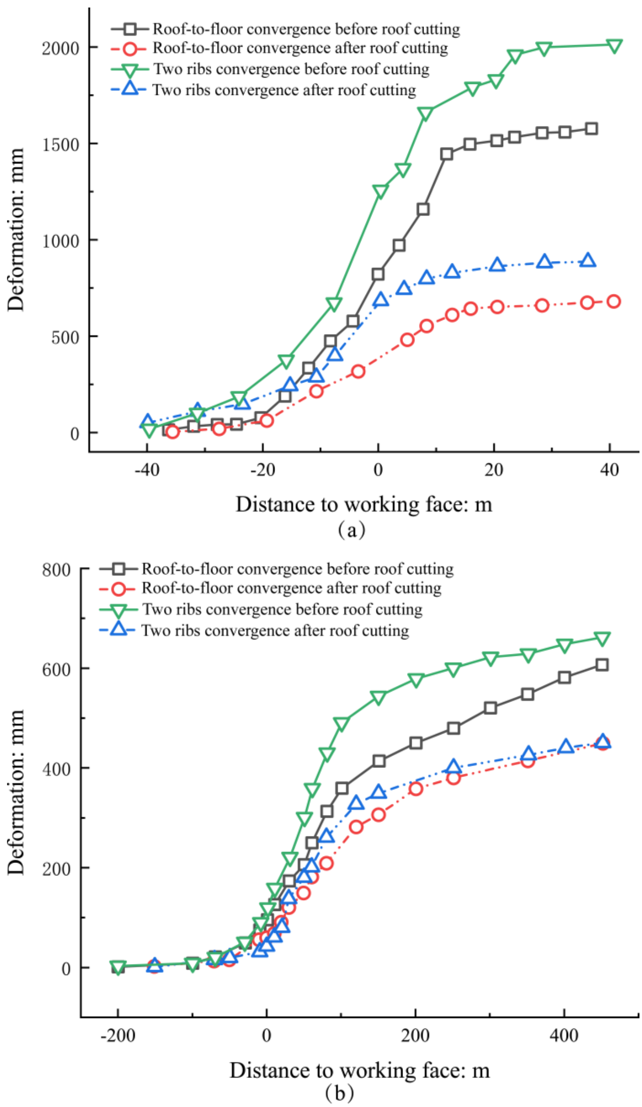


Fig. 10. Roof-to-floor convergence and convergence of the two ribs for tailgates:
(a) Wangzhuang mine and (b) Hongqinghe mine

The effects of the GERF and RCPR on the entry retaining, construction difficulty and economic benefits are described below. For brevity, only some results are shown here.

4.2.1. Entry retaining effects

The 21404 panel of the Chengjiao mine is buried deep with a high lateral abutment pressure. Figure 11(a) shows a large deformation in some areas when the FFPC is used in the Chengjiao mine, as well as the effects of entry retaining with RCPR. The roof and floor of the 1200 panel from Zhongxing mine are both soft strata. Figure 11(b) shows the phenomenon of the expansive filling pack in some areas when using the HWCP, as well as the effects of entry retaining when using the RCPR. After BCTE was adopted, the GER could achieve satisfactory results in relatively harsh environments.

Fig. 11. Comparison of FFPC and RCPR: (a) Chengjiao mine and (b) Zhongxing mine

The GERF and RCPR were adopted in the 011810 panel of the Jinfeng mine. The roof-to-floor convergence and the convergence of the two ribs can be seen in Figure 12. The roof-to-floor convergence is more significant, and the RCPR has a greater effect than the GERF in controlling deformations of the rock surrounding the roadway.

4.4.2. Construction difficulty and economic benefit

The GERF requires the building of a filling wall with a complex construction process, a significant amount of labour and high labour intensity. Unlike the RCPR, which can be ahead of the working face, the masonry of the filling wall can only be carried out behind the working face, which cannot utilise parallel operation.

In addition, the RCPR also exhibits significant economic benefits. To illustrate this, Table 6 shows the cost of RCPR based on the 21404 panel of Chengjiao mine is 65.9% that of the FFPC, while the cost of the RCPR for the 1200 panel of Zhongxing mine is only 59.2% of the HWCP.

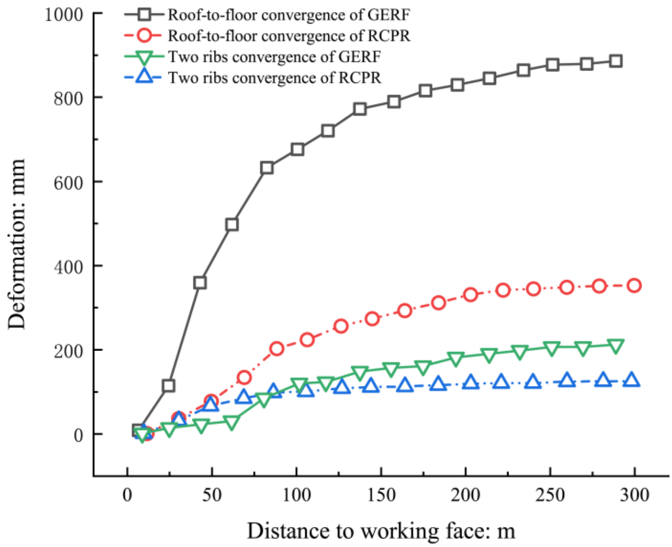


Fig. 12. Roof-to-floor convergence and the convergence of the two ribs in haulageway of Jinfeng mine

TABLE 6

Comparison of economic benefits

	Cost of gob-side entry retaining: yuan/m		
	FFPC	**HWCP**	**RCPR**
Chengjiao mine 21404 panel	10137	—	6684
Zhongxing mine 1200 panel	—	8380	4959

5. Discussion

The BCTE is a popular new technique to control the stability of the surrounding rock in high-stress roadways and for the GER. The former has only recently been applied in coal mining, and the application conditions are not restricted. Thus, it is expected to be a widely used technique in the future. The latter has attracted considerable attention from coal mines all over China in recent years, which have conducted industrial tests of the RCPR and promoted its use for all mines. However, there are still problems in the extension of the RCPR for some geological conditions. (1) For coal seams prone to spontaneous combustion, it is necessary to ensure the closed quality of the gob and the normal advanced speed of the working face. (2) When the RCPR is performed on a top-coal caving working face, reasonable data for the explosive fill should be further studied to weaken the impact of blasting on the top coal and supporting components above the retaining roadway. (3) When ascending mining is adopted in an inclined coal seam, it is necessary to prevent pumping at the top of the retaining roadway. When descending mining is adopted in an inclined coal seam, special attention should be given to the gob support. The solution to these problems will be focused on in future research to ensure the application of BCTE is more widely applicable in GER.

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