Experimental Study on Presplitting Blasting of Roof Cutting Along Goaf with Thick and Hard Roof Plate

Jianquan Tang1,2, Hongliang Liu1,* and Anfa Chen1
1College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao, China
2Institute of Mining Engineering, Shandong University of Science and Technology, Taian, China
*Corresponding author: hongliangliu@sdust.edu.cn

Abstract. In order to explore the reasonable blasting parameters of the gob-side entry retaining technology under the specific conditions of thick and hard roof, and realize successful roof cutting and safe roadway retaining, the thick and hard roof of the XV1306 working face in the first panel of Yixin Coal Mine is used as the research background. The drilling parameters of blasting are analyzed, which contains the depth of slitting, angle of slitting and spacing of blasting holes. And the influence of charge structure and charge amount on the effect of presplitting blasting was studied through underground blasting tests. The results show that when the blast hole depth is 10m, the drilling angle is 15°, and the blast hole spacing is 500 mm, with adopting the "2+3+4+4+3+2" method to the deep-hole charge structure, the top-cut crack rate is more than 90%. The penetration effect of top-cut crack is good, which can meet the needs of roof cutting for pressure relief and control of surrounding rock in roadway retaining.

Keywords: Gob-side entry retaining, thick and hard roof, roof cutting and pressure relief, shaped charge blasting, blasthole parameter.

1. Introduction
Academician He Manchao, based on the theory of "top-cut short arm beam", put forward the mining technology without coal pillar with top-cut roadway along goaf [1, 2]. After the coal mining operation system was formed, the roof of advanced roadway was reinforced and supported by anchor cable with constant resistance and large deformation, and then the weak surface of advanced roof was directionally pre-cracked along the mining side by drilling shaped charge blasting technology. When the working face is pushed over, the overhanging rock mass on the presplitting face is cut into a roof along the weak face under the action of mine pressure, thus cutting off the stress connection between the roof of goaf and the roof of retaining roadway. The roof of mined-out area falls in time and fully, which not only relieves the pressure of surrounding rock of retaining roadway, but also controls the final position of basic roof subsidence. Roof cutting changes the mechanical structure of roadway roof, optimizes the internal stress distribution of surrounding rock, and achieves the goal of safe roadway formation by combining active and passive support. This process can not only improve the resource
recovery rate, but also have obvious benefits for rock burst and gas prevention, which is an important development direction for safe and efficient mining of coal resources.

In recent years, Chinese experts, scholars and field technicians have carried out in-depth research on the basic theory and related technologies of gob-side entry retaining, and made a lot of achievements, which are mainly divided into the following aspects: First, based on the mine pressure theory, the mining technology of roof cutting and pressure relief without coal pillars was put forward [3-6]. Second, by using theoretical analysis, numerical calculation and industrial test, the parameters such as presplitting height of roof, cutting angle and blasting hole spacing are analyzed [7-9]. Thirdly, according to the specific engineering geological conditions and mining environment, the mining technology without coal pillar by roof cutting and pressure relief has been adaptively improved [10,11]. The above research has laid a foundation for the popularization and application of gob-side entry retaining technology by roof cutting and pressure relief. However, the geological structure of coal mines in China is complex and diverse, and the scheme of retaining entry under specific engineering geological conditions should be explored according to local conditions.

In this paper, the parameters of roof presplitting blasting are analyzed on the background of gob-side entry retaining project under the condition of thick and hard roof in XV1306 working face of Yixin coal mine. Based on this, a large number of field tests are carried out, and finally the presplitting blasting parameters suitable for Yixin coal mine are obtained, which plays an important role in promoting the successful roof cutting and safe entry retaining under this geological condition.

2. Engineering survey

XV1306 working face in Yixin coal mine is located in No.15 coal area, with XV1307 working face in the east, solid coal in the west, security pillar in the south and track alleys in the north. the working face is 461m long and 200m long. The thickness of the coal seam is 2.0~2.6m, the average thickness is 2.3m, the thickness of the gangue in the middle is 0.3m, the dip angle is 2°~9° and the buried depth is 182~356m, the occurrence condition is stable and the structure is single. The basic roof of the working face is K2 limestone with a thickness of 8.9m, which exists directly above the coal seam, followed by sandy mudstone with a thickness of about 1.7m, coal line with a thickness of 0.4m and K3 limestone with a thickness of 5m. The direct bottom is mudstone with a thickness of 1.8m. Lithological characteristics of coal seam and roof and floor are shown in Table 1.

Table 1. Lithological characteristics of coal roof and floor

| Name of roof and floor | Rock name     | Thickness/m | Lithologic characteristic description                                      |
|------------------------|---------------|-------------|---------------------------------------------------------------------------|
| Main roof              | K2 Limestone  | 8.9         | Gray, Thick layered, Containing flint nodules and lumps, Hard, Muddy and bioclastic |
| 15# coal               | Coal seam     | 2.01        | Black, Mainly bright coal                                                 |
| Immediate floor        | Mudstone      | 1.80        | Gray-black, Carbonaceous and soft                                         |
|                        | Fine sandstone| 0.44        | Gray, Fine grain structure, Hard quality, Sand and argillaceous cementation|
| Main floor             | Alumina mudstone | 18.26  | Gray, Thick layered, Soft, Dense and delicate                             |

3. Presplitting weak surface blasting technology

3.1. Slotting principle of shaped charge blasting

Two-way shaped charge tension blasting technology [12,13] is one of the key technologies to successfully realize top entry retaining along goaf. Two-way shaped charge tensile blasting is a directional blasting method combining shaped charge pipe with explosives. The shaped charge pipe is used to charge the borehole, and the detonation wave is restrained around the shaped charge pipe and
the detonation energy (including explosive products and explosive gases) is released directionally at the opening in the set direction. Finally, the cracks between holes penetrate through the rock mass to form weak planes. The whole process of fracture generation and development is essentially the process of rock mass destruction: (1) After explosive explosion, the shaped charge flow is released directionally under the action of shaped charge pipe, which is mainly the dynamic load effect of high-speed and high-energy explosion products, which crushes the rock mass at the pre-crack in the hole and forms directional cracks. (2) The shock wave evolves into the stress wave acting on the rock mass, and the existence of the stress wave changes the stress state of the surrounding rock in the hole. Although the strength is not enough to cause the rock mass to produce compressive failure, the reflected wave strength can cause the rock mass to produce tensile failure, and continue to expand the initial fracture under the guidance of the directional fracture. (3) After the attenuation of shock wave and stress wave, it is mainly the gas wedge effect of explosion gas quasi-static pressure $P_0$ in the primary fracture, which produces tensile force on the rock mass and continues to tear the fracture by taking advantage of the "low tensile strength" of the rock mass. The cutting principle of shaped charge blasting is shown in Fig. 2.

![Figure 1](image)

**Figure 1.** Principle of directional presplitting technology in shaped charge blasting: (a) Compression model of shaped charge blasting on XOY plane; (b) Tension model of shaped charge blasting on XOY plane

3.2. Blasting parameter analysis

3.2.1. Analysis of cutting top height. If the height of roof cutting is too small, the caving gangue is not enough to fill the whole mining space, and the basic roof is bound to have a large turning and sinking, and the final position of the key blocks above is difficult to control, which increases the disturbance degree of the roof covering rock activities in the retaining roadway. If it is too large, the control of the basic top position of caving zone gangue will not be improved after reaching the best state with the increase of the top cutting height, but the supporting effect on the "short arm beam" above the roadway will be weakened, which undoubtedly increases the difficulty of controlling the roof support in the roadway. Too large or too small can easily lead to poor pressure relief effect, unstable surrounding rock structure, and difficult deformation control. Reasonable design of roof cutting height is the key element of presplitting roof cutting.

(a) Design height according to the theory of fragmentation and swelling of caving rock mass

The critical design formula of cutting height $H_{f1}$ of presplitting weak surface is as follows:

$$H_{f1} = \frac{M - \Delta H_1 - \Delta H_2}{K - 1}$$

In the formula: $H_{f1}$ is the cutting height (m), $M$ is the mining height (m), $\Delta H_1$ is the roof subsidence (m), $\Delta H_2$ is the bottom heave (m), and $K$ is the swelling coefficient of the falling gangue.
stratum above the coal seam in Yixin Coal Mine is K₂ limestone, which has high hardness. Based on the previous mining data, it is determined that the crushing expansion coefficient of the fallen waste rock is 1.4. According to the data of supplementary drilling, the thickness of No.15 coal seam has little change, and the maximum mining height is 2.6m when the subsidence of roof and floor heave are neglected, which can be obtained from formula (1): \[ H_f = 6.5 \text{m} \]

(b) Analyze the lithologic characteristics of roof and optimize the design of roof cutting height

The presplit rock stratum is thick and hard limestone. If the cutting height \( H_f = 6.5 \text{m} \), and the thickness \( H_0 = 2.4 \text{m} \) of limestone above which is not penetrated by weak plane, the tensile stress is concentrated there, as shown in Figure (2). Under the condition that the whole stress structure is unchanged, the joint of \( H_0 \) is less likely to be broken. If the tensile stress is increased by the subsidence activity of overlying rock, it will inevitably bring severe influence to the surrounding rock and support in the roadway. There is a layer of 1.7m mudstone and a layer of 0.4m coal line a above the K₂ limestone. Compared with the upper and lower limestones, its thickness, rigidity and strength are also smaller. Damage occurred under the combined action of limestone pulling and overlying limestone sinking.

Although the destruction of the roof in goaf and the development of caving zone are from bottom to top, the sinking activity of the roof above the cutting seam and the caving activity of the rock mass below the cutting seam are synchronized to a certain extent. Only when the rock mass within the cutting seam falls and breaks as quickly as possible can a better roadway protection effect be achieved. Therefore, it is finally determined that the cutting height is 10.0m to penetrate limestone and some mudstone.

![Figure 2. Influence of cutting seam on roof movement](image)

3.2.2. Top cutting angle design. The top cutting angle determines whether the roof of the goaf can fall smoothly after the working face is pushed. From the perspective of pressure relief, the closer the angle \( \theta \) between the slit and the plumb line is to 0°, the larger the volume of the cut rock block. For the top cutting height of 10m, when the top cutting angle is 20°, the overhanging length of the short arm beam of the top cutting will reach 3.6m Both its dead weight and the disturbance caused by the subsidence of overlying rock will act on the roof and the coal in the upper part of the roadway, resulting in poor pressure relief effect and difficult control of surrounding rock support.

But the cutting angle is not as small as possible. If \( \theta \) is too small, the dynamic load effect caused by large gangue caving will bring stress disturbance to roadway roof, and even break the bend to block gangue support. In addition, the rock block B above the irregular caving zone will form an articulated structure with the rock block A above the roadway roof at the cutting plane (as shown in Figure 3). Under the self-weight and overburden load, the rock block B will exert the squeezing force \( F_j \) pointing to the lower left on the rock block A, which leads to the increase of the internal stress of the surrounding rock and the load of the supporting structure. There will be an "underjoint" problem.
between the collapsed gangue and the rock block B that has not slipped smoothly, which will seriously affect the stability of surrounding rock of gob-side entry and the final effect of retaining roadway, especially for the geological conditions of near-horizontal coal seam and thick and hard roof in Yixin Coal Mine.

According to the S(sliding)-R(rotation) stability principle of masonry beam and surrounding rock structure, when considering the angle $\theta$ between the cracking movement direction of basic roof rock and the direction of plumb hammer, the overall stress balance relationship of rock block engagement point is shown in Figure 3.

![Figure 3. Mechanical model of roof rock beam structure by cutting roof behind working face:](image)

(a) Schematic diagram of structural model; (b) Mechanical model

Therefore, if rock block b is cut off smoothly, $\theta$ shall satisfy:

$$\theta = \varphi - \arctan \frac{2(h_m - \Delta S)}{L}$$  \hspace{1cm} (2)

Where: $L$ is the length of the basic top rock block B (m); $\Delta S$ is the rotational subsidence of the rock block B (m); $h_m$ is the thickness of the rock layer (m); $\varphi$ is the friction angle between the rock blocks ($^\circ$). Studies have shown [14]: The friction angle between rocks is mostly $25^\circ$~$35^\circ$, and when the environment is humid, it decreases by $2^\circ$~$4^\circ$, with an average of $3^\circ$ C. Considering the humid environment in the coal mine, the friction angle $\varphi$ between the basic top rock blocks is $22^\circ$~$32^\circ$, with an average of $27^\circ$.

The principle of choosing the top-cutting angle should be to select a smaller value from all $\theta_i$ satisfying the above formula, and $\theta$ has a negative correlation with the length $L$ of the rock block B. When the length of $L$ is the largest, that is, when the rock block B reaches the limit collapse step, the obtained $\theta$ meets the condition. From the geological conditions of the XV1306 working face of Yixin Coal Mine, we can get: $\varphi=27^\circ$, $L=16m$, $\Delta S=0.65m$, $h_m=8.9-H_f=2.4m$, substituting the formula (2) into the equation: $\theta=14.6^\circ$. Taking into account the feasibility of actual construction, the pre-cracking slit angle $\theta$ is taken as $15^\circ$. 
3.2.3. Determination of hole spacing in shaped charge blasting. Two-way shaped charge blasting is one of the key factors that directly affect the cutting effect. Rock mass between boreholes expands cracks under the action of explosion load, and forms weak planes after penetration. The condition for judging whether the presplitting section of directional blasting can be successful is that the depth of damage crack between two shaped charge blasting holes is greater than the distance between the holes [15]. The following formula can be used as the critical criterion for selecting blasting hole spacing:

\[
d \leq 2\gamma_b \left( \frac{\lambda p_b}{(1 - D_0)\sigma_t + p} \right) \frac{1}{\delta}
\]  

(3)

Where: \(d\) is the borehole center distance; \(\gamma_b\) is the hole radius; \(\lambda\) is the lateral pressure coefficient of the rock mass, \(\lambda = \mu / (1 - \mu)\); \(\mu\) is the Poisson's ratio of the roof rock mass; \(p_b\) is the peak pressure of the blasthole wall shock wave; \(D_0\) is the initial damage parameter of the rock mass; \(\sigma_t\) is the uniaxial tensile strength of the rock; \(\delta\) is the attenuation coefficient of the explosion stress wave, \(\delta = 2\mu / (1 - \mu)\).

From the engineering practice of the 1306 working face of Yixin Coal Mine: \(\gamma_b = 24\text{mm}\); \(\mu = 0.3\); \(p = 19\text{MPa}\), \(p_b = 2000\text{MPa}\), \(D_0 = 0.6\), \(\sigma_t = 1.2\text{MPa}\), and substituting into the formula (3) can be obtained: \(d \leq 624\text{mm}\).

The distance between blast holes and the charge structure in the holes are the direct factors that determine the cutting effect. If the design of hole spacing is too large, only by changing the charging structure to strengthen the effect of cutting, the hole wall may be broken but the crack is still not penetrated. Therefore, 500mm is taken as the hole spacing for presplitting blasting test of thick and hard roof in XV1306 working face of Yixin coal mine.

4. Field test of pre-split blasting

4.1. Shaped energy blasting test plan

The shaped charge pipe with an outer diameter of 42mm and an inner diameter of 36.5mm and a pipe length of 1500mm is used for roof drilling shaped charge blasting. The explosive is mine-used secondary emulsion explosive, with the specification of φ32×200mm per roll, and 6 bidirectional shaped charge pipes are installed in each hole. According to the previous field blasting test experience, shaped charge blasting adopts the way of forward charging and joint hole blasting, and the hole sealing length is not less than 1.75m. The structure of deep hole charge is shown in Figure 4. Four schemes are adopted in this blasting test, and the test scheme is shown in Table 2.
Table 2. Field test plan of shaped energy blasting

| Programme | Energy collecting tube/m | Charge quantity | Mudcap/m | Blasting method     |
|-----------|--------------------------|-----------------|----------|--------------------|
| I         | 1.5+1.5+1.5+1.5+1.5+0.75 | 5-4-4-3-3-1     | 1.75     | Four-hole explosion|
| II        | 1.5+1.5+1.5+1.5+1.5+0.75 | 3-3-3-3-2-2     | 1.75     | Four-hole explosion|
| III       | 1.5+1.5+1.5+1.5+1.5+0.75 | 3-3-4-3-2-2     | 1.75     | Four-hole explosion|
| IV        | 1.5+1.5+1.5+1.5+1.5+0.75 | 2-3-4-4-3-2     | 1.75     | Four-hole explosion|

4.2. Analysis of blasting test results

After blasting, CXK6 mine borehole imaging detector was used to observe the cracks in the borehole from the blasting results of four test schemes. CXK6 mine borehole imager has the function of imaging the whole borehole and expanding the imaging along the tangential direction, which can visually and comprehensively display the cracks in the borehole and make quantitative statistics and analysis. Figure 5 shows the results of borehole inspection and crack propagation under four blasting parameters.

![Figure 5. Crack effects of energy-controlled blasting in hole](image)

(a) image of crack inside blasthole; (b) image of crack inside blasthole for unfloded plane

When blasting in the first scheme, "5-4-4-3-3-1" charging mode, the local section in the hole appeared crisp and crumbled, and the hole bottom collapsed, indicating that the local charge was too large, which destroyed the integrity of the rock mass structure within the range, and the resulting fracture zone and plastic zone were not conducive to controlling the stability of the rock stratum. When blasting in the second scheme, namely "3-3-3-3-2-2" charging mode, no obvious cracks appeared in local sections, the effect of presplitting weak surfaces was poor, and it was difficult to cut off the roof in time and fully after mining, and even the overlapping masonry structure was formed under the geological conditions of hard roof. In the third scheme, namely "3-3-4-3-2-2" charging mode, symmetrical cracks can be seen in the hole, but the cracks at the bottom of the hole are not obvious. In scheme 4, namely "2-3-4-4-3-2" charging mode, obvious symmetrical cracks can be seen in the hole, the cracks are consistent to the end, and the overall crack rate is more than 90%.

Compared with the above four different charge structures, under the condition of the same drilling parameters, sealing length and other factors, the charge quantity and the distribution of cartridge in the hole are the main factors that determine the blasting cutting effect. In the first scheme, the charge is 20 rolls/hole, and the bottom of the hole is fried and crisp under the charge of 5 rolls. In scheme 2, the
charge is 16 rolls/hole, and the presplitting effect of local section is poor, and the detonation energy is insufficient; Thus, the charge in a single shaped charge tube in the hole is controlled to be less than 5 rolls and the total charge in each hole is between 17 and 19 rolls. At the initial stage of the fracture in the hole, the hole wall was crushed and destroyed by directional detonation wave, and then the hole wall and rock mass between holes in the air column section were torn by stress wave and high-pressure gas under the primary fracture. Therefore, according to the degree of hole wall breakage and crack opening, the charging parameters, including the charge volume and air column length of each shaped charge tube, are improved, and finally the scheme which can achieve the expected presplitting effect is determined, that is, "2+3+4+4+3+2" charging structure.

5. Conclusions
(1) After drilling and blasting, the weak surface can penetrate through the rock mass between holes without damaging the roof structure and the strength of supporting body, which is the basis of successful roof cutting and roadway retaining. Unreasonable parameters will easily cause the hole wall to be fried, the hole bottom to collapse or the crack to be inconspicuous, which will affect the top cutting effect.

(2) Through theoretical calculation and field experiment, the pre-reasonable crack parameters of retaining roadway under the condition of thick and hard roof in Yixin Coal Mine are determined as follows: the top cutting height is 10m, the angle is 15, and the blast hole spacing is 500mm.

(3) Under the same roof cutting parameters, the blasting effect will determine the slitting effect. By adjusting four blasting test schemes in the field, it is found that when the charging structure of the blast hole is "2-3-4-4-3-2", the crack development degree in the hole is high, the crack rate reaches over 90%, and the penetration effect is good, which can cut off the roof smoothly behind the working face, laying a foundation for the successful roof cutting and safe roadway retaining in the working face.

References
[1] Manchao He, Guolong Zhu, Zhibiao Guo. Longwall mining “cutting cantilever beam theory” and 110 mining method in China——The third mining science innovation [J].Journal of Rock Mechanics and Geotechnical Engineering,2015,7(05):483-492.
[2] Manchao He, Zhenqi Song, An Wang, et al. Theory of longwall mining by using roof cutting shortwall team and 110 method——the third mining science and technology reform [J].Coal Science&Technology Magazine,2017(01): 1-9+13(in Chinese).
[3] Yidong Chen, Xuebin Li, Jingwu Wang, et al. Application of advanced blasting roof cutting and pressure relieving technology in 50104 working face roadway of Hecaogou Coal Mine [J].Coal Engineering,2017,49(07): 72-74(in Chinese).
[4] Manchao He, Yubing Gao, Jun Yang, et al. Engineering experimentation of gob-side entry retaining formed by roof cutting and pressure release in a thick-seam fast-extracted mining face [J].Rock and Soil Mechanics,2018,39(01):254-264(in Chinese).
[5] Xiaoliang Liu, Guofeng Zhang. Technology of Roof Cutting Pressure Relief Gob-side Entry Retaining in Soft Fractured Stratum [J].Coal Science and Technology,2013,41(S2):133-134(in Chinese).
[6] Xiaolong Wang, Zhiyong Dong. Application research on technology of non-pillar gob-side entry retaining formed by roof cutting and pressure release in high gas coal seam [J].Industry and Mine Automation,2019,45(07): 97-101(in Chinese).
[7] Baosuo Chi, Kaifang Zhou, Manchao He, et al. Optimization research on supporting parameters of roof cutting entry retaining with large mining height face [J].Coal Science and Technology,2017, 45(08):128-133(in Chinese).
[8] Manchao He, Zimin Ma, Zhibiao Guo, et al. Key parameters of the gob-side entry retaining formed by roof cutting and pressure coal seams [J].Journal of China University of Mining&Technology,2018,47(03):468-477(in Chinese).
[9] Shangyuan Chen, Fei Zhao, Hongjian Wang, et al. Determination of key parameters of gob-side entry retaining by cutting roof and its application to a deep mine [J]. Rock and Soil Mechanics, 2019, 40(01): 332-342+350 (in Chinese).

[10] Aijun Li, Xifan Li. Application of Layered Grouting Process in Surrounding Rock Reinforcement of Cutting Roof [J]. Coal Engineering, 2019, 51(10): 50-53 (in Chinese).

[11] Xiaojie Yang, Eryu Wang, Min Zhang, et al. Research on technique of forming roadway by advanced roof cutting and pressure releasing in depth buried coal seam with broken roof [J]. Coal Science and Technology, 2017, 45(09): 86-91 (in Chinese).

[12] Manchao He, Wufu Chao, Renliang Shan, et al. New Blasting Technology——Bilateral Cumulative Tensile Explosion [J]. Chinese Journal of Rock Mechanics and Engineering, 2003, 22(12): 2047-2051 (in Chinese).

[13] Manchao He, Yubing Gao, Jun Yang, et al. An energy-gathered roof cutting technique in no-piller mining and its impact on stress variation in surrounding rocks [J]. Chinese Journal of Rock Mechanics and Engineering, 2017, 36(6): 1314-1325 (in Chinese).

[14] Qingxiang Huang, Pingwu Shi, Minggao Qian. Experiment study on the coefficients of friction and inserting of main roof block corner [J]. Rock and Soil Mechanics, 2000, 21(1): 60-63 (in Chinese).

[15] Hu Jia, Ying Xu. Study on Stress Damage Zone in Excavation of Rock Mass [J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(S1): 3489-3492 (in Chinese).