Coal Pillar Stress Weakening Technology and Application by Gob-Side Entry Driving and Hydraulic Roof Cutting in Deep Shafts Mines

Zhi Zhang¹,2, Jianguo Ning¹,2,*, Jun Wang¹,2, Kun Wang¹,2,*, Shang Yang¹,2, Ruyu Yan¹,2, Guoqing Sun¹,2 and Minghao Du¹,2

¹ State Key Laboratory of Mining Disaster Prevention and Control Co-founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao 266590, China; zhangzhi@sdust.edu.cn (Z.Z.); wjun@sdust.edu.cn (J.W.); yangshang@sdust.edu.cn (S.Y.); yry@sdust.edu.cn (R.Y.); sungq@sdust.edu.cn (G.S.); dmh@sdust.edu.cn (M.D.)
² College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China

* Correspondence: njglxh@126.com (J.N.); wkun@sdust.edu.cn (K.W.)

Abstract: To solve the problems of serious deformation and support difficulty of deep and narrow gob-side coal pillars, an optimized hydraulic roof cutting structural model for the roof structure of narrow gob-side coal pillars in kilometer–deep shafts was established based on the 6302 working face of the Xinhe coal mine. The influence of factors such as the angle and height of hydraulic roof cutting on the stress evolution of narrow gob-side coal pillars was analyzed, the principle of the pressure relief of hydraulic roof cutting of narrow gob-side coal pillars in kilometer–deep shafts was revealed, and an industrial application was conducted. The results of the study show that, first, the hydraulic roof cutting of narrow gob-side coal pillars in a kilometer–deep shaft transfers the roof load only to the gob area, but not to the solid-side deep coal body; and second, there is an optimal height for roof cutting and pressure relief, i.e., the effect of roof cutting and pressure relief will not be improved after the second critical layer is exceeded. An industrial application was carried out along the gob-side entry at the 6302 working face of the Xinhe coal mine, which showed that the strength of the roof was weakened, the stress concentration in the coal pillars was relieved, and the deformation of the rocks surrounding the roadway was controlled after hydraulic roof cutting and pressure relief. This study provides some technical guidance for the stability control of gob-side entries under similar conditions.

Keywords: gob-side entry driving; hydraulic roof cutting; pressure relief effect; industrial practice

1. Introduction

In recent years, under the dual requirement of a high coal resource recovery rate and rock burst disaster prevention and control, the gob-side narrow coal pillar entry protection technology has been widely promoted in the mining of thick coal seams in kilometer–deep shafts [1–3]. Narrow gob-side coal pillars in deep shafts are not only subject to a high static load, but also subject to the squeezing pressure generated by the movement of overburdened rock rotation and uneven settlements, which leads to the common occurrence of the tensile failure of anchor ropes and tearing of the metal mesh and W–type steel strip [4–7]. Therefore, multiple renovations are needed to meet the requirements of ventilation, personnel passing, and transportation. Therefore, it is of great practical significance to carry out research on the stability control of the surrounding rocks during the gob-side entry driving of kilometer–deep shafts for their safe and efficient mining [8,9].

At present, China’s traditional pressure relief methods for gob-side entry driving mainly include large-diameter drilling and deep hole blasting [10,11]. Although these
pressure relief methods have some effect, they involve a large amount of work implemented on site and present difficulties for safety control, which restrict their widespread use. The directional hydraulic fracturing roof-cutting pressure relief technology implements active structural transformation of the coal–rock mass by artificially adding cracks in it, weakening the bearing characteristics of the coal–rock seam, and achieving local and regional improvement of the high stress environment [12–15].

At present, many domestic and foreign scholars have conducted in-depth studies on the hydraulic fracturing roof cutting and pressure relief technology using theoretical analyses, indoor tests, and numerical simulations [16–19]. Based on the theory of hydraulic fracturing, Hongpu Kang et al. [20] used the true triaxial hydraulic fracturing test system to study the law of hydraulic fracture initiation and extension of the coal–rock mass under the action of various stresses, such as in situ stress, mining-induced stress and gas pressure, and established the guideline of fracture extension of the coal–rock mass. Shugang Li et al. [21] used the RFPA numerical simulation software to study the changes in hydraulic fracture pressure and fracture extension under different ground stress differences, and concluded that the larger the stress difference was, the more homogeneous the fracture pattern, the more obvious the direction, and the larger the extension of the main fracture. Geng Ma et al. [22] used the hydraulic fracturing test system to conduct a physical simulation test of hydraulic fracture with similar materials as those of the research objects, and derived the law that the fracture pressure gradually decreases and the fracture time gradually shortens with the increase in the main stress difference. Based on indoor tests and numerical simulations, Weishu Li [23] carried out a study on the water-cooled fracture mode and hydraulic fracture expansion pattern of high-temperature granite and analyzed the hydraulic fracture expansion pattern of granite under different conditions of temperature, confining pressure, and stress difference. Tongshe Zheng et al. [24] analyzed the effect and applicability of the antireflective hydraulic fracturing technology for coal–rock through experiments, optimized its implementation process, and improved the gas extraction rate in the coal seam. Pedro R. Cleto et al. [25] proposed the mesh fragmentation technique (MFT) to extend the application of the HAR element, and introduced this type of element between the standard finite elements of typical meshes to simulate more general problems involving the formation of hydraulic fractures in rocks. Ingrid Tomac et al. [26] adopted the discrete element method (DEM) to discrete the rock mass space into discrete disc particles, and combined with the solver to simulate the flow of fluid through the connected pore network, conducted a meso-mechanical study on the fluid-structure interaction (H-M) behavior of brittle rock in the process of hydraulic fracturing.

The above research status shows that a large amount of research has been performed by previous scholars on the mechanical properties of coal–rock fracture, fracture expansion patterns, and control methods, and useful research results have been achieved and widely used and guided in the field [27–31]. However, the relevant mechanisms are still unclear, for example, does hydraulic roof cutting relieve the pressure by transferring the roof load to the depth of the coal mass, or does it cut off the stress transfer path to transfer it to the gob area? It is still unclear how to choose the location for implementing hydraulic fracturing roof cutting and controlling the stability of the surrounding rock of gob-side entries.

To this end, this study proposes a hydraulic fracturing roof cutting and pressure relief control technology based on the technical conditions of gob-side entry mining of the 6302 working face of the Xinhe coal mine, analyzes the principles of hydraulic roof cutting and pressure relief, determines the key seam of hydraulic roof cutting, and carries out an industrial application.

2. Project Overview

2.1. Project Geological Conditions

The Xinhe coal mine is located in Jining City, Shandong Province, and its 6302 working face has a strike length of 818 m, an inclined width of 110 m, and an elevation of −947 to −1035 m. The 6301 working face has been mined to the west of it, leaving small coal pillars
of 5 m in the middle, whereas the 630 mining area of Xinhe Mining and the 630 mining area of the Tangkou Coal Industry are mined to the east and north, respectively. Their specific locations are shown in Figure 1.

![Figure 1. 6302 working face layout diagram.](image)

The thickness of the No. 3 coal seam in the 6302 working face is 9 m. The immediate roof mainly consists of mudstone and fine sandstone, which is an unstable roof with fissures. The basic roof consists of medium–fine sandstone, fine sandstone, etc., with less developed fissures, and is a stable to very stable roof. The immediate floor of No. 3 coal is dominantly mudstone and siltstone, and it is an unstable to more stable floor, with more developed fissures. The details of the roof and floor are presented in Table 1.

Table 1. Strata description of the 6302 working face.

| Rock Strata         | Thickness/m | Strata Characteristics                                      |
|---------------------|-------------|-------------------------------------------------------------|
| Basic roof          |             |                                                             |
| Siltstone (third key stratum) | 17.0        | Dark gray, soft, with fossilized plants and charcoal chips |
| Fine sandstone (second key stratum) | 10.6        | Gray to dark gray, laminar, hard, and dense                |
| Medium–fine sandstone (first key stratum) | 7.8         | Off–white to off–white, siliceous cementation, hard         |
| siltstone           | 5.9         | Dark gray, soft, with fossilized plants and charcoal chips  |
| Immediate roof      |             |                                                             |
| mudstone            | 6.7         | Grey, clay cementation, flimsy                              |
| fine sandstone      | 8.3         | Gray to dark gray, laminar, hard, and dense                |
| Coal seam           |             |                                                             |
| No. 3 coal          | 9.0         | Black, shiny, with internal fissure development             |
| Floor               |             |                                                             |
| mudstone            | 4.9         | Grey, clay cementation, flimsy                              |
| siltstone           | 12.4        | Dark gray, soft, with fossilized plants and charcoal chips  |

2.2. Field Measurements of the Entry Deformation Failure of 6302 Track

The 6302 working face track entry is a gob-side entry driving. Its cross–section is a rectangle with a width of 4.5 m and a height of 3.7 m. The direct roof is dominantly composed of fine sandstone and mudstone, and it has a high fissure development. The surrounding rocks of the entry have different degrees of time–dependent deformation under high stress. This is mainly manifested in more serious deformation and failure of the entry-side coal pillar than those of the solid coal side, and the overall deformation is non–uniform and non–symmetrical. The deformation and failure characteristics of the surrounding rock of the entry are summarized as follows:

1. Roof bulging. The surrounding rock of the roof and shoulder are broken, and “net pockets” appear, accompanied by sinking of the roof (Figure 2a,b).
2. Buttock shear slip. It mainly occurs at the coal pillar–coal–rock junction, where the buttock is squeezed inward and the shoulder experiences shear slip (Figure 2c).
(3) Sinking roof. The roof sinks significantly, the anchor bolt (rope) load increases, and the anchor net tears (Figure 2d).

(4) Anchor bolt (rope) breakage. The anchor bolt (rope) in the shoulder of the coal pillar is subjected to compound stress of tension, bending, and shear, and it breaks beyond the strength limit, which is accompanied by pallet out-turning deformation (Figure 2e,f).

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Figure 2. Deformation and failure of surrounding rock of roadway; (a) Roof bulging; (b) Appear “net pocket”; (c) Buttock shear slip; (d) Sinking roof; (e) Anchor bolt (rope) breakage.; (f) Pallet out-turning deformation.

The main reason for the above deformation characteristics is that the lateral roof of the gob-side entry rotates and sinks, and it squeezes the coal pillars, causing them to enter a state of plastic failure. This leads to a reduction in the integrity and bearing capacity of the coal pillars. The shallow plastic cracking zone develops to the deep part of the coal pillar, which expands the range of the plastic cracking zone. This further aggravates the deformation of the entry, with crushing and expansion, leading to a large deformation of the surrounding rock and failure of the supporting elements.

3. Analysis of the Principle of Hydraulic Fracturing Roof Cutting and Pressure Relief of Gob-Side Entry Driving

After the upper section of the working face is mined, the lateral immediate roof collapses into the gangue in the gob area. The lateral basic roof is fractured inside the coal mass and in the gob area to form the rock beam B. The rock beam B rotates and sinks along the lateral fracture line until it touches the gangue and compacts the gangue, forming a stable hinge joint structure. Under the cover of the upper hinge joint structure, gob-side entry driving is performed at the lower section of the working face and the support system.
is used to form an anchor structure to bear the external load. After driving the gob-side entry, the coal wall, set coal pillars, and gangue in the gob area jointly carry the weight of the immediate roof, basic roof, and overburden to maintain the stability of the surrounding rock of the empty gob-side, and its structural model is shown in Figure 3a.

Figure 3. Deformation and failure of surrounding rock of roadway; (a) Before hydraulic fracturing roof cutting; (b) After hydraulic fracturing roof cutting.

Related studies reveal that the hydraulic fracturing of rock of the roof of the gob-side driving entry can form a fracture network, shorten the length of the lateral roof overhang, and promote the collapse of the lateral roof in the gob area. Without discussing the fracture expansion pattern of the lateral roof hydraulic fracturing, this can be approximated as follows: after the hydraulic fracture of the roof along the empty roadway, part of the lateral basic roof falls directly across the mining void area, and the force model of the surrounding rock along the empty roadway is shown in Figure 3b.

Before cutting the roof, it is assumed that the gravity of the rock strata along the centerline of the gob-side entry to the fracture line of the basic roof is applied to the solid coal, and that the rock fracture line on the roof within the solid coal runs through the rock beams of the immediate roof and the basic roof. Then, for the entire structural body in Figure 3a, it is known by the mechanical equilibrium condition that

\[
\left\{ \begin{array}{l}
\sum F = 0 \\
\sum M = 0
\end{array} \right. \tag{1}
\]

i.e.,

\[
\begin{align*}
q_S \cdot \frac{1}{2} + q_F \cdot (L_0 + a + \frac{1}{2}b) + q_G \cdot L_G - G_Z \cdot \frac{1}{2}(L_0 + a + b) - G_E \cdot \frac{1}{2}L_G &= 0 \\
q_S + q_F + q_G - G_Z - G_E &= 0 \tag{2}
\end{align*}
\]

where: \(F\): force, kN; \(M\): moment of force, kN·m; \(q_S\): support force of solid coal, kN; \(q_G\): support force of coal pillar, kN; \(q_F\): support force of gangue, kN; \(G_Z\): gravity of immediate roof, kN; \(G_E\): gravity of the rock beam of the basic roof, kN; \(L_0\): length from the lateral line of the basic roof to the buttck of the entry, m; \(a\): width along the gob-side entry, m; \(b\): width of the coal pillar, m; and \(L_G\): length of the rock beam of the basic roof, m. The width \(L_0\) from the lateral line of the basic roof to the buttck of the entry can be obtained from the following formula:

\[
L_0 = \frac{h}{2\xi f} \ln \frac{K \gamma H + C \cot \phi}{\xi C \cot \phi} \tag{3}
\]

where \(\xi = \frac{1 + \sin \phi}{1 - \sin \phi} \tag{4}\)
where \( h \): mining height, \( m \); \( C \): coal adhesion, MPa; \( f \): internal friction factor of the coal seam; \( \psi \): internal friction angle, \( ^\circ \); \( K \): stress concentration coefficient, generally taken as 1.5; \( H \): buried depth of coal, \( m \); and \( \gamma \): volumetric weight of the roof, kN/m\(^3\).

According to the research results of Guozhi Lu et al., when the pushing distance is greater than or equal to the inclination length, the length \( L_G \) of the rock beam of the basic roof is equal to the step size of the periodic pressure of the transmitting rock beam \[32\].

The support force of the solid coal \( q_s \) can be expressed as

\[
q_s = (\gamma_Z m_Z + \gamma_E m_E)(L_0 + \frac{1}{2}a) \tag{5}
\]

where \( \gamma_Z \): volumetric weight of the immediate roof, kN/m\(^3\); \( m_Z \): thickness of the immediate roof, \( m \); \( \gamma_E \): volumetric weight of the basic roof, kN/m\(^3\); \( m_E \): thickness of the basic roof, \( m \).

The gravity \( G_Z \) of the immediate roof of the upper part of the gob-side entry and the gravity \( G_E \) of the rock beam of the basic roof can be approximated as

\[
G_Z = \gamma_Z m_Z (L_0 + a + b) \tag{6}
\]

\[
G_E = \gamma_E m_E L_G \tag{7}
\]

Equation (2) is solved to obtain the support force from the gob-side small coal pillars and the gangue in the gob area to the lateral roof, which is expressed as

\[
q_F = \frac{G_Z \left[ L_G - \frac{1}{2}(L_0 + a + b) \right] + G_E \frac{1}{2} L_G - q_s \left( L_G - \frac{1}{2} L_0 \right)}{L_G - L_0 - a - \frac{1}{2} b} \tag{8}
\]

\[
q_G = \gamma_Z m_Z \left( \frac{1}{2} a + b \right) + \gamma_E m_E \left( L_G - L_0 - \frac{1}{2} a \right) - q_F \tag{9}
\]

According to the structural model of the roof of the gob-side entry after hydraulic fracturing, the mechanical equilibrium equation of “gangue in the gob area–gob-side coal pillar–solid coal” is established as follows:

\[
\sum F = q_s + q_F' - G_Z - G_E' = 0 \tag{10}
\]

Similarly, the gravity of the immediate roof and the rock beam of the lateral basic roof after hydraulic fracturing can be obtained as

\[
G_Z = \gamma_Z m_Z (L_0 + a + b) \tag{11}
\]

\[
G_E' = \gamma_E m_E (L_0 + a + b) \tag{12}
\]

Then, the force on the coal pillar and gangue is

\[
q_F' = (\gamma_Z m_Z + \gamma_E m_E)\left( \frac{1}{2} a + b \right) \tag{13}
\]

\[
q_G' = q_G + \gamma_E m_E (L_G - L_0 - a - b) \tag{14}
\]

Combining Equations (8) and (13) yields the reduction in load of gob-side coal pillars after hydraulic fracturing, i.e.,

\[
q_F - q_F' = \gamma_E m_E (L_G - L_0 - a - b) \tag{15}
\]

From the stress analysis of the surrounding rock of the gob-side entry, it can be observed that the overburden load of the coal pillar is reduced after the implementation of hydraulic fracturing roof cutting. Therefore, hydraulic fracturing roof cutting has a positive impact on improving the stress environment of the gob-side small coal pillar,
and its pressure relief principle is to transfer the overburden load of the small coal pillar to the gob area so as to control the stability of the surrounding rock of the gob-side entry.

4. Analysis of the Impact of Hydraulic Fracturing Roof Cutting Pressure Relief on the Stress of the Surrounding Rocks of Gob-Side Entry Driving

The full name of UDEC is the Universal Distinct Element Code [33]. It is a calculation and analysis software based on the theory of the discrete element method. It mainly solves the problems of geometric failure, large deformation, various geological structures and geotechnical constitutive models, and groundwater simulation [34].

4.1. Modeling

The UDEC numerical analysis model was established according to the technical conditions of mining at the 6302 working face. The model is 220 m long and 180 m high, as shown in Figure 4. Discontinuities such as the bedding plane and cross joints were considered in the model, and the Mohr–Coulomb model was used for the constitutive relationship of surrounding rocks. To avoid unstable model runs, a stepwise mining method was used to simulate the mining of the working face, in which each advance was of 10 m. For each stage, sufficient time was required to run to relieve the unbalanced stresses and allow the roof to collapse. A total of 110 m of working face advance was simulated.

![Figure 4. Diagram of UDEC model.](image)

4.2. Mechanical Parameter Calibration

The mechanical properties of the coal–rock mass material in the UDEC are controlled by the mechanical properties of the block and contact surfaces. Therefore, it is necessary to calibrate the mechanical parameters of the block and contact surfaces to match the mechanical response of the coal–rock mass.

First, the uniaxial compressive strength of coal–rock samples was obtained in the laboratory. However, often there are fractures, joint fractures, and discontinuity surfaces inside the coal–rock mass, which weaken its strength. Therefore, it is unreasonable to use the mechanical parameters of the coal–rock samples obtained from the indoor tests for the analysis of the mechanical response of the coal–rock mass in numerical calculations. For this reason, the mechanical parameters (such as uniaxial compressive strength and modulus of elasticity) of the coal–rock samples obtained from the indoor tests can be converted into the mechanical parameters of the coal–rock mass based on the rock quality designation (RQD),
which can be derived based on Equations (16) and (17). The mechanical parameters of the coal–rock mass are presented in Table 2.

\[
E_m = E_r \cdot 10^{0.0186RQD - 1.91}
\]

\[
\sigma_m = \sigma_r \cdot \left[ \frac{E_m}{E_r} \right]^n
\]

where \(E_m\) and \(\sigma_m\) are the modulus of elasticity and compressive strength of coal–rock samples, respectively; \(E_r\) and \(\sigma_r\) are the modulus of elasticity and compressive strength of the coal–rock mass, respectively; \(n\) is a constant and, according to the relevant research \([25,35,36]\), it is often taken as 0.63; and RQD is the quality designation of the coal–rock mass, which can be determined by taking the rock core from the borehole in the field.

Table 2. Mechanical properties of the complete rock mass and computational rock mass.

| Strata                | Complete Rock Samples | RQD | Rock Mass |
|-----------------------|-----------------------|-----|-----------|
|                       | \(E_r\) (GPa) | \(\sigma_r\) (MPa) | \(E_m\) (GPa) | \(\sigma_m\) (MPa) |
| Fine sandstone        | 17.3                | 53.8           | 94 | 12.44 | 43.72 |
| Medium–fine sandstone | 10.8                | 34.6           | 91 | 6.83  | 25.93 |
| Siltstone             | 9.6                 | 28.9           | 90 | 5.81  | 21.08 |
| Mudstone              | 5.2                 | 17.6           | 87 | 2.54  | 11.21 |
| Coal                  | 2.8                 | 8.6            | 70 | 0.75  | 3.75  |

In addition, calibration is still required to determine the mechanical parameters (normal stiffness \(k_n\) and shear stiffness \(k_s\)) of the contact surfaces in the UDEC numerical analysis. From the UDEC User Manual, the normal stiffness \(k_n\) and shear stiffness \(k_s\) of the contact surface can be expressed as follows:

\[
k_n = 10 \left[ \frac{K + \frac{3}{4}G}{\Delta z_{\text{min}}} \right]
\]

\[
k_s = 0.4k_n
\]

where \(K\) and \(G\) are the bulk modulus and shear modulus of the block in the UDEC model, respectively. \(\Delta z_{\text{min}}\) is the minimum distance of the region adjacent to the contact point in the normal direction.

Finally, the mechanical properties of the coal–rock mass were calibrated using the stress–strain curves obtained from the uniaxial compression test with indoor tests using UDEC numerical simulations, as shown in Figure 5. The calibrated mechanical parameters are listed in Table 3, and these parameters can be used for the subsequent simulation analysis.

Table 3. Mechanical parameters of the rock mass used in the UDEC model.

| Lithology            | Block Mechanical Parameters | Contact Mechanical Parameters |
|----------------------|-----------------------------|------------------------------|
|                      | Density/(kg m\(^{-3}\)) | \(K\)/(GPa) | \(G\)/(GPa) | \(k_n\)/(GPa m\(^{-1}\)) | \(k_s\)/(GPa m\(^{-1}\)) | Cohesion/(MPa) | Friction/(\(^{\circ}\)) | Tensile Strength/(MPa) |
| Fine sandstone       | 2030                        | 7.26                        | 4.91           | 33.60 | 13.44 | 4.18 | 34/30 | 2.35 |
| Medium–fine sandstone| 2560                        | 4.72                        | 2.69           | 26.25 | 10.50 | 2.64 | 36/33 | 1.76 |
| Siltstone            | 2720                        | 4.02                        | 2.30           | 21.48 | 8.59  | 1.75 | 31/26 | 1.94 |
| Mudstone             | 2400                        | 2.10                        | 1.87           | 9.33  | 3.73  | 0.62 | 35/30 | 1.14 |
| Coal                 | 1800                        | 0.51                        | 0.33           | 21.18 | 8.47  | 1.08 | 30/25 | 0.57 |
| Fracturing area      | ——                          | ——                          | ——             | 26.00 | 10.40 | 0    | 20    | 0    |
were set up in the simulation process; namely, in the solid side, above the coal pillar, and in the gob area, as shown in Figure 6a; (ii) the hydraulic fracturing locations were kept constant in the simulation, and three different stratahorizon were set up, respectively, in the 1st key stratum, in the 1st and 2nd key strata, and in the 1st to 3rd key strata, as shown in Figure 6b.

To investigate the influence of hydraulic fracturing location, stratahorizon, and other factors on the effect of roof cutting and pressure relief, two types of simulation schemes were set up as follows: (i) three types of hydraulic fracturing locations were set up in the simulation; namely, in the solid side, above the coal pillar, and in the gob area, as shown in Figure 6a; (ii) the hydraulic fracturing locations were kept constant in the simulation, and three different stratahorizon were set up, respectively, in the 1st key stratum, in the 1st and 2nd key strata, and in the 1st to 3rd key strata, as shown in Figure 6b.

In addition, it is known from the hydraulic fracturing theory, that the hydraulic fracture failure of the coal–rock mass is caused by the expansion and interpenetration of its internal natural fractures with the hydraulic fractures [17,19,31,33,37–39]. To characterize only the hydraulic fracture failure of the coal–rock mass and ignore the expansion pattern of hydraulic fractures, the contact surface mechanical parameters were weakened in the numerical analysis so that the coal–rock mass could undergo tensile or shear failure at the contact location. According to the related research results, the cohesion and tensile strength of the contact surface were set to zero and the friction angle was reduced to 20°. The specific parameters are presented in Table 3. In addition, during the simulation process, measurement points were arranged in the solid coal–gob-side entry–coal pillar to analyze the influence of this factor on the stress of the surrounding rock of the gob-side entry.
4.4. Analysis of the Effect of Roof Cutting Angle on Surrounding Rock Stress

According to the simulation scheme, the effect of different roof cutting angles on the surrounding rock stresses of the gob-side entry driving was simulated, and then the vertical stresses of the monitoring points at two sides of roadway were obtained. The distribution form is shown in Figure 7. Figure 7a shows the vertical stress at different distances from the roadway sidewall in the solid coal. Figure 7b shows the vertical stress at different distances from the roadway sidewall in the coal pillar.

![Graphs showing stress distribution](image)

**Figure 7.** The effect of different roof cutting angles on the surrounding rock stresses of the gob—side entry; (a) Vertical stress at solid coal side of roadway; (b) Vertical stress at coal pillar side of roadway.

Figure 7 shows the effect of different roof cutting angles on the stress distribution of the surrounding rock of the gob-side entry driving. From Figure 7, it can be observed that Option 1 (roof cutting on the solid side) only changes the degree of stress concentration on the solid side significantly. Compared with roof cutting, the stress reduction on the solid side reaches 9.7%, while the reduction on the gob-side small coal pillar is only 5.2%. However, it increases the small coal pillar load. This is because roof cutting on the solid side cuts the cantilever beam of the basic roof on the solid side, and the broken rock beam shifts towards the gob area causing the coal pillar load to increase. Option 2 (cutting the roof above the gob-side small coal pillar) has a positive effect on improving the stress environment of the gob-side small coal pillar, because fracturing above the small coal pillar breaks and collapses the part in which the basic roof hinge joints the beam in the gob area, so that the load of the small coal pillar is released to some extent. Option 3 (lateral roof cutting in the gob area) does not work to improve the stress environment of the surrounding rock of the gob-side entry. Because the broken rock beam of the basic roof in the gob area is basically supported by the gangue in the gob area, its load is basically borne by the gangue, and only a small part is transferred through the hinge joint point to the surrounding rock of the gob-side entry. It is difficult for this part of the force to constitute the main control force source of the gob-side entry. For this reason, although the rock beam load transfer effect can be weakened by fracturing in the gob area, the stress reduction of the surrounding rock of the gob-side entry is very little.

4.5. Analysis of the Effect of Roof Cutting Height (Stratahorizon) on Surrounding Rock Stress

According to the simulation schemes, the effect of the height of roof cutting (strata-horizon) on the vertical stress of the surrounding rock of the gob-side entry driving was simulated, and then the vertical stresses of the monitoring point at two sides of the roadway
were obtained. The distribution form is shown in Figure 8. Figure 8a shows the vertical stress at different distances from roadway sidewall in the solid coal; Figure 8b shows the vertical stress at different distances from roadway sidewall in the coal pillar.

Figure 8. The effect of different roof cutting heights (stratahorizon) on the surrounding rock stresses of the gob-side entry; (a) Vertical stress at solid coal side of roadway; (b) Vertical stress at coal pillar side of roadway.

Figure 8 shows the form of vertical stress distribution of the gob-side entry at different roof cutting heights (stratahorizon). The specific analysis in relation to Figure 8 is as follows:

1. Overall, whether or not the roof is cut, the form of stress distribution in the surrounding rock of the gob-side entry is basically the same. The difference is whether the degree of stress concentration is improved, thus indicating that with hydraulic fracturing roof cutting it is difficult to change the form of stress distribution in the surrounding rock of the gob-side entry, but it can play a role in local pressure relief. From the theory of the transfer rock beam, it is known that along the gob-side entry, the internal stress field is generally under the control of the fracture arch, and the internal stress distribution form is controlled by the load transfer of the transfer rock beam in the fracture arch and the support state of the gob area. Thus, the above situation occurs.

2. As the height of the roof cutting increases, both the solid side stress and the vertical stress of the coal pillar of the gob-side entry are gradually reduced, and the reduction rate is also gradually reduced. The details are as follows: compared with no roof cutting, the vertical stress reduction of the small coal pillar in Option 1 (roof cutting of the first key stratum) is 15.8%, while the reductions in Options 2 (roof cutting until the second key stratum) and 3 (roof cutting until the third key stratum) are 22.4% and 23.7%, respectively, but the stress gradually reduces and tends to be stable. For the solid side, the change in height of the roof cutting cannot shift the high stress on the solid side to the deep coal mass but can only reduce it.

3. When reducing the vertical pressure of the gob-side small coal pillar as the core, the best stratum for roof cutting can be found, that is, it is difficult to reduce the coal pillar stress continuously after the height of roof cutting reaches a certain stratum. For example, the coal pillar stress is basically the same as that in Option 2 in the numerical simulation when the roof cutting height (stratahorizon) reaches the 3rd key stratum. Therefore, taking the 6302 working face of the Xinhe coal mine as an example, the best height for small coal pillar roof cutting to relieve pressure is the 2nd key stratum.
From the analysis of the surrounding rock stress, it can be found that hydraulic fracturing roof cutting has a certain control effect on the deformation of the surrounding rock of the gob-side entry, but its control effect has a certain relationship with the roof cutting angle. The effect is the most obvious when the roof cutting is carried out in the area above the coal pillar. Therefore, it is recommended that fracturing should be carried out in the area above the gob-side coal pillar to weaken the overburden rock load of the gob-side small coal pillar and control the deformation of the surrounding rock of the gob-side entry.

5. Field Application and Effect test of Hydraulic Fracturing Roof Cutting of Gob-Side Entry Driving

5.1. Composition of Hydraulic Roof Cutting Equipment

The technical parameters of the main equipment for hydraulic roof cutting and pressure relief are shown in Table 4.

| Name                               | Technical Parameters                                                                 |
|------------------------------------|--------------------------------------------------------------------------------------|
| High pressure water tail           | Working pressure 0–100 MPa, flow rate 0–420 L/min, rotational speed 0–600 r/min. |
| Diamond hydrodynamic slitting drill bits | Φ113 mm                                                                         |
| Super high-pressure hose           | Inner diameter 18.8 mm, working pressure 0–150 MPa                                 |
| Shallow threaded drill pipe for hydrodynamic slit | Φ73 mm, pressure–bearing over 100 MPa                                      |
| High pressure jet                  | Φ75 mm, high– and low– pressure conversion threshold: 15 MPa                      |
| Super high pressure clarified water pump | Rated flow rate 132 L/min, rated pressure 105 MPa                           |
| Hole sealer                        | Pressure–bearing 1–20 MPa; hose contraction coefficient: 60%                     |

5.2. Hydraulic Cut Top Pressure Removal Site Implementation

From 25 May 2021 to 20 June 2021, hydraulic roof cutting was carried out in the 6302 track entry of the Xinhe coal mine, and the main equipment and technical parameters are presented in Table 4. Within the range of 400–450 m from the open–off cut, hydraulic roof cutting was carried out every 10 m along the lateral roof of the gob-side entry. The length of the roof cutting hole was 47 m, the angle was 78°, and the construction position was as shown in Figure 9. First, 90 MPa high–pressure water was used to cut the slit (the effect is shown in Figure 10a); then, segmental hydraulic fracturing was carried out at the slit location. It was found that the hydraulic fracturing pressure was only approximately 20 MPa through the hydraulic fracturing pipeline. A crisp fracture sound was first emitted from the roof during the fracturing process, and then water drenching appeared in the adjacent borehole.
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Figure 9. Construction position.

Figure 10. Construction position; (a) Drilling TV detection; (b) Water pressure monitoring data.

5.3. Effectiveness Test

(1) Fracture extension monitoring of hydraulic fracturing

The electrical resistance of the coal–rock mass is reduced due to the intersection of hydraulic fractures and natural fractures in the roof, which reduces the integrity of the coal–rock mass. For this reason, the effect of hydraulic roof cutting was monitored using the cross-hole electromagnetic wave CT technique (Figure 11). First, electromagnetic wave CT equipment was used to detect the electromagnetic wave absorption between two adjacent holes before hydraulic roof cutting; then, tests were conducted after the hydraulic roof cutting to compare the difference in electromagnetic wave absorption before and after fracturing. The specific detection results are shown in Figure 12.

Figure 11. Electromagnetic wave CT detection; (a) Electromagnetic wave CT detection equipment; (b) Field Construction of electromagnetic wave CT detection.

Figure 12 shows the comparison of electromagnetic wave CT detection results before and after hydraulic fracturing roof cutting, where the horizontal coordinate is the hole distance, the vertical coordinate is the borehole depth, and the chromatogram is the electromagnetic wave absorption coefficient. The analysis of Figure 12 shows that before fracturing (Figure 12a), the electromagnetic wave absorption coefficient of the rock mass...
between the boreholes was low, indicating that the rock integrity between the two boreholes before fracturing was good and there were few preexisting fractures. After fracturing (Figure 12b), the electromagnetic wave absorption coefficient of the rock mass between the boreholes increased significantly compared with that before fracturing, and the maximum increase reached 21 dB/m, especially in the area of borehole depth between 10–23 m. This indicates that the preexisting fractures in this area were further extended and expanded under the action of hydraulic cutting–fracturing, and they finally interpenetrated. Through the above analysis, it can be found that hydraulic fracturing can produce a certain range of fractures in the rock mass between the boreholes, and the fractures in some areas penetrate each other, which can change the physical properties of the working surface roof to a certain extent, weaken the strength of the working surface roof, and promote stress release.

![Figure 12](image_url)

Figure 12. Comparison of electromagnetic wave CT detection results before and after hydraulic fracturing; (a) Before hydraulic fracturing roof cutting; (b) After hydraulic fracturing roof cutting.

(2) Stress detector monitoring in small coal pillar boreholes

Borehole stress detectors were used to monitor the stress variation in the small coal pillar in the 6302 track entry (gob-side entry). Representative monitoring results were selected (as shown in Figure 13), where the #1 stress detector was located in the unfractured area and the #2 stress detector in the fractured area.

![Figure 13](image_url)

Figure 13. Stress monitoring data of small coal pillar; (a) #1 stress detector data; (b) #2 stress detector data.

From Figure 13a, it can be observed that the stress detector of the small coal pillar borehole in the unfractured area, approximately 110 m away from the working face, showed a small increase in coal pillar load under the influence of the advanced abutment pressure,
and then the stress was basically smooth and stable at 6 MPa. On the contrary, the stress data from the small coal pillar borehole stress detector in the fractured area started to drop after the completion of fracturing on 20 June 2021, with a maximum drop of 27.3%, as shown in Figure 13b. Subsequently, the stress in the coal mass of this area remained basically stable although the small coal pillar in this area was within the influence of the advanced pressure of the 6302 working face. In summary, hydraulic fracturing roof cutting has obvious pressure relief effect on gob-side small coal pillars, which is consistent with UDEC numerical simulation results.

(3) Monitoring of deformation of the surrounding rocks of the entry

After the implementation of hydraulic fracturing roof cutting, the convergence of the roof, floor, and the two buttocks of the entry were measured by the crossing method using a laser distance measuring instrument on 3 July 2021 to compare and analyze the deformation of the surrounding rocks of the entry in the area with and without hydraulic fracturing roof cutting. Within 400–500 m from the open–off cut, a total of 10 measurement points were arranged along the 6302 track entry with 10 m spacing.

From the measured data of the convergence of the roof, floor, and the two buttocks of the entry in Table 5, it can be observed that, compared with the unfractured area, their convergence in the fractured area was significantly reduced after the implementation of hydraulic fracturing roof cutting. The average reduction in convergence was of 0.26 m in the roof and floor and 0.09 m in the two buttocks. This indicates that the implementation of hydraulic fracturing roof cutting has a positive effect on controlling the surrounding rock deformation of gob-side entries.

Table 5. Measurement data of the convergence of roof, floor, and two buttocks of the entry.

| Measurement Point Serial Number | Fractured Area | Unfractured Areas |
|---------------------------------|----------------|-------------------|
|                                | Convergence of the Roof and Floor/m | Convergence of the Two Buttocks/m | Measurement Point Serial Number | Convergence of the Roof and Floor/m | Convergence of the Two Buttocks/m |
| 1                               | 1.032           | 0.592             | 6                                | 1.069           | 0.637             |
| 2                               | 0.869           | 0.577             | 7                                | 0.966           | 0.643             |
| 3                               | 0.774           | 0.515             | 8                                | 1.187           | 0.657             |
| 4                               | 0.825           | 0.560             | 9                                | 1.142           | 0.671             |
| 5                               | 0.806           | 0.571             | 10                               | 1.251           | 0.658             |

6. Conclusions

(1) With the background of mining geological conditions at the 6302 working face of the Xinhe coal mine, a structural model of drill–cut–pressure roof cutting and pressure relief of the gob-side entry was established. By calculating the bearing capacity of gob-side small coal pillars before and after roof cutting, the analysis found that roof cutting helps to reduce the load of gob-side small coal pillars, and this effect is obtained by transferring the overburden rock load of the small coal pillars to the gob area.

(2) Using the UDEC numerical analysis software, a numerical analysis model was established for roof cutting and pressure relief of gob-side entry at the 6302 working face of the Xinhe coal mine. By monitoring the stress change characteristics of the surrounding rock of the gob-side entry, the following was found: First, roof cutting above the gob-side small coal pillar to relieve pressure has a positive effect on improving the stress environment of the gob-side small coal pillar. Second, there is an optimal stratum for roof cutting, that is, it is difficult to continue reducing the coal pillar load after the height of roof cutting reaches a certain level.

(3) The effect of fracturing, roof cutting, and pressure relief was examined using electromagnetic wave CT detection, borehole stress detector monitoring, and taking measurements of the deformation of the surrounding rocks of the entry. From the analysis, it was found that hydraulic fracturing and roof cutting can weaken the strength of the working face roof and promote stress release, which not only has an obvious effect on the
pressure relief of gob-side small coal pillars, but also has a positive effect on controlling the deformation of the surrounding rock of the gob-side entry.

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