International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 5, Number 1, Year 2025
DOI: https://doi.org/10.62051/ijmee.v5n1.08
Journal homepage: https://wepub.org/index.php/IJMEE/index

# Numerical Simulation Research on Layer-Crossing Directional Hydraulic Fracturing Technology

Weilong Zhou *

Henan Polytechnic University, Jiaozuo Henan, 454003, China
* Corresponding author Email: s1534153730@gmail.com

## ABSTRACT

This paper focuses on the prevention and control of coal and gas outbursts in high-gas, high-stress, and low-permeability coal seams. Through numerical simulation methods, the crack propagation mechanism and engineering application of cross-strata directional hydraulic fracturing technology are studied. Based on the RFPA (Rock Failure Process Analysis) system, a two-dimensional plane strain model is established to analyze the influence of in-situ stress, injection pressure, and coal seam gas pressure on the initiation and propagation of fractures. The research results show that the coal seam gas pressure significantly weakens the effect of high-pressure water injection. The higher the gas pressure, the greater the difficulty of coal body fracture and the higher the initiation pressure, and the injection pressure needs to be increased to optimize the fracturing effect. The directional hydraulic fracturing technology can effectively control the crack propagation along the preset path by arranging guide holes, forming a penetrating crack network, and avoiding the stress concentration and disordered crack problems caused by single-hole fracturing. The simulation shows that the directional fracturing technology has achieved the improvement of coal body pressure relief and gas drainage efficiency in the field application of Chengzhuang Mine, providing a safe and efficient permeability enhancement and pressure relief method for areas without protective layer mining conditions. This technology, by optimizing the crack direction and propagation behavior, has the dual advantages of improving oil and gas recovery efficiency and reducing environmental risks, and has significant engineering value for the development of unconventional reservoirs.

## KEYWORDS

Cross-strata Directional Hydraulic Fracturing; Prevention and Control of Coal and Gas Outbursts; Numerical Simulation; Crack Propagation Mechanism.

## 1. INTRODUCTION

The research and application of through-layer directional hydraulic fracturing technology have received significant attention in the oil and gas industry in recent years, especially in the development of unconventional reservoirs. This technology optimizes the efficiency of oil and gas extraction by controlling the direction of hydraulic fractures to enable them to traverse different geological layers.

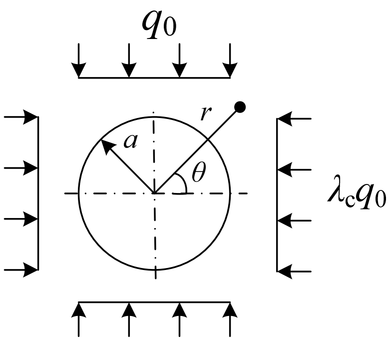
Interlayer directional hydraulic fracturing technology refers to the process of controlling the initial direction and propagation path of fractures through specific engineering means (such as directional perforation) during hydraulic fracturing, enabling them to traverse multiple geological layers. This method is particularly suitable for layered reservoirs, such as those composed of alternating layers of shale and sandstone. In standard hydraulic fracturing, fractures typically propagate along the direction of the minimum principal stress, which may be vertical. However, in layered formations, fractures may interact in complex ways due to the nature of the interfaces between layers. For instance, studies have shown that fractures may be restricted when encountering layers with higher toughness, and may cross or deviate at interfaces with significant stress contrasts [1]. Directional fracturing ensures that fractures propagate along the designed path by adjusting the perforation direction, making it especially applicable to horizontal or inclined wells.

This technology plays a crucial role in the development of unconventional oil and gas reservoirs, such as shale gas and tight sandstone gas. These reservoirs typically have low permeability and thin-layer structures, and traditional vertical well fracturing is difficult to effectively connect all production layers. Layer-crossing directional hydraulic fracturing creates a fracture network that traverses multiple layers in horizontal wells, significantly increasing the contact area between the reservoir and the wellbore, thereby enhancing oil and gas flow. For example, in shale gas fields, directional fracturing can ensure that fractures traverse multiple shale layers, connecting dispersed storage spaces and increasing total production [2]. Additionally, this technology can prevent fractures from extending to aquifers, reducing environmental risks such as groundwater pollution.

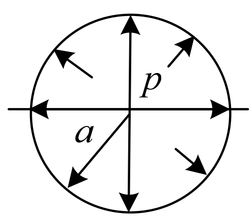
The current research mainly focuses on the propagation mechanism of fractures in layered formations. Studies have shown that rock properties (such as elastic modulus and toughness), in-situ stress state, viscosity of fracturing fluid and injection rate all have significant influences on fracture propagation. For instance, the friction coefficient and conductivity of interlayer interfaces determine whether fractures will cross or be confined [3]. Additionally, the angle and position of directional perforations also affect the initial direction and complexity of fractures [4]. Numerical simulation tools such as the finite element method (FEM) and discrete element method (DEM) are widely used to study fracture propagation behavior. These models can simulate the interaction between fractures and interlayer interfaces, and predict the fracture morphology under different geological and engineering conditions. For example, a study utilized a three-dimensional FEM model to analyze the vertical growth of fractures in layered rocks, revealing the influence of toughness contrast on the fracture crossing mode [5].

Through-the-layer directional hydraulic fracturing technology is an important tool for the development of unconventional reservoirs in the oil and gas industry. The current research status shows a deep understanding of the fracture propagation mechanism and continuous improvement in engineering control. Despite the challenges of geological complexity and prediction, recent directional perforation technology offers new opportunities for optimizing production. In the future, through model refinement and technological innovation, this technology is expected to further enhance efficiency and environmental sustainability. To ensure effective and safe operations and achieve the overall pressure relief effect of fracturing, it is necessary to conduct research on directional hydraulic fracturing technology.

## 2. MECHANISM OF INITIATION OF THROUGH-LAYER BOREHOLES




(a) Original Stress




(b) Inner Water Stress

**Figure 1.** Stress of Bore in Drilling Wall under Original Stress and Inner Water Stress

(1) The stress state at any point in the surrounding rock of a cross-strata borehole

Due to the influence of the thickness of each coal seam and the changes in bedding, and also because it is difficult to ensure that the drilling holes remain parallel to the coal seam bedding during the drilling operation, the hydraulic fracturing holes are actually mostly cross-seam holes, as shown in Figure 1. According to the solution process of H. Kastner, the stress at any point in the surrounding rock of the drilling hole before water injection fracturing is [6]:

$$\begin{cases} \sigma_r = \dfrac{1+\lambda_c}{2} q_0 (1-\dfrac{a^2}{r^2}) - \dfrac{1-\lambda_c}{2} q_0 (1-4\dfrac{a^2}{r^2}+3\dfrac{a^4}{r^4}) \cos 2\theta \\ \sigma_\theta = \dfrac{1+\lambda_c}{2} q_0 (1+\dfrac{a^2}{r^2}) + \dfrac{1-\lambda_c}{2} q_0 (1+3\dfrac{a^4}{r^4}) \cos 2\theta \\ \tau_{r\theta} = \dfrac{1-\lambda_c}{2} q_0 (1+2\dfrac{a^2}{r^2}-3\dfrac{a^4}{r^4}) \sin 2\theta \end{cases} \tag{1}$$

In the formula, $\sigma_r$, $\sigma_\theta$, and $\tau_{r\theta}$ represent the radial stress, tangential stress, and shear stress at any point within the rock mass surrounding the borehole, respectively; $\lambda_c$ is the lateral stress coefficient in the direction perpendicular to the borehole axis in the original rock stress field; $a$ is the borehole radius; $r$ is the distance from any point to the center of the borehole; $\theta$ is the direction angle of the point; and $q_0$ is the self-weight stress.

The stress under the action of internal water pressure alone is：

$$\begin{cases} \sigma_r = \dfrac{a^2}{r^2} p \\ \sigma_{\theta r} = -\dfrac{a^2}{r^2} p \\ \tau_{r\theta} = 0 \end{cases} \tag{2}$$

Considering the dual effects of the in-situ stress of the original rock and the high-pressure water in the borehole on the fracture holes simultaneously, by comparing Equations (1) and (2), the stress expression at any point in the surrounding rock of the borehole can be obtained as follows:

$$\begin{cases} \sigma_r = \dfrac{1+\lambda_c}{2} q_0 (1-\dfrac{a^2}{r^2}) - \dfrac{1-\lambda_c}{2} q_0 (1-4\dfrac{a^2}{r^2}+3\dfrac{a^4}{r^4}) \cos 2\theta + \dfrac{a^2}{r^2} p \\ \sigma_\theta = \dfrac{1+\lambda_c}{2} q_0 (1+\dfrac{a^2}{r^2}) + \dfrac{1-\lambda_c}{2} q_0 (1+3\dfrac{a^4}{r^4}) \cos 2\theta - \dfrac{a^2}{r^2} p \\ \tau_{r\theta} = \dfrac{1-\lambda_c}{2} q_0 (1+2\dfrac{a^2}{r^2}-3\dfrac{a^4}{r^4}) \sin 2\theta \end{cases} \tag{3}$$

(2) Determination of the Initiation Pressure and Position for Layer-Crossing Drilling and Water Injection

The boreholes for cross-layer fracturing are composed of multiple coal seams along the axial direction, with each section having different surrounding rock properties. Besides overcoming factors such as in-situ stress, the fracture of the fracturing boreholes mainly involves overcoming the tensile strength at the weakest point of the borehole. Based on this, the author explores from both the radial and axial directions of the fracturing boreholes.

Assumption: Along the axis of the fractured borehole, the surrounding rock in each section is homogeneous and isotropic, but the properties of the surrounding rock vary from section to section.

If the borehole of the interlayer fracturing fractures around a certain cross-section of the borehole, the effect of the axial horizontal stress can be ignored, and only the vertical stress $q_0$ and the horizontal radial stress $\lambda_c q_0$ need to be considered, as shown in Figure 2. Then:

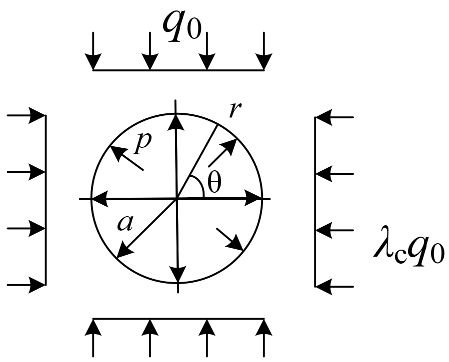



**Figure 2.** Stress Analysis along Bore's Radial

At this point, Equation (3) can still represent the tangential stress at any point within the surrounding rock of the fracture hole. Substituting $r = a$ into the expression of $\sigma_r$, the tangential stress on the fracture hole wall is:

$$\sigma_\theta\big|_{r=a} = (1+\lambda_c)q_0 + 2(1-\lambda_c)q_0\cos 2\theta - p \tag{4}$$

If the borehole fractures, $\sigma_\theta\big|_{r=a}$ must be tensile stress, and:

$$\sigma_\theta\big|_{r=a} > |R_t| \tag{5}$$

In the formula: $R_t$ represents the tensile strength of stratified coal.

Combining the above two equations, the initiation fracturing injection pressure is obtained:

$$p > (1+\lambda_c)q_0 + 2(1-\lambda_c)q_0\cos 2\theta + \min\{R_{ti}\}(i = 1, 2, \ldots, m) \tag{6}$$

In the formula: $R_{ti}$ represents the tensile strength of the $i$-th stratified coal; $m$ is the number of coal and rock strata penetrated by the fracturing hole.

Therefore, at this time, the initiation water injection pressure can be expressed as:

$$p_{H1} = (1+\lambda_c)q_0 + 2(1-\lambda_c)q_0\cos 2\theta + \min\{R_{ti}\}(i = 1, 2, \ldots, m) \tag{7}$$

In summary, the through-layer hydraulic fracturing borehole fractures under the dual action of the in-situ stress and high-pressure water. This pressure not only depends on the magnitudes of the axial and radial horizontal stresses of the fracturing hole, but also on the physical and mechanical properties of the coal and rock mass around the borehole before and after the construction. Regarding the fracture initiation position, in the axial direction, it is determined by the related factors of the weakest bedding plane; in the radial direction, it is determined by factors such as $\min\{R_{ti}\}$ and $\lambda_c$.

## 3. HYDRAULIC FRACTURING FRACTURE PROPAGATION MECHANISM BASED ON RFPA

After analyzing the action mechanism of cross-layer directional hydraulic fracturing, numerical simulation can be adopted to simulate directional hydraulic fracturing, which can further deeply study the behavior characteristics and control factors of fracture propagation in directional hydraulic fracturing. The following is a numerical simulation study of directional hydraulic fracturing based on the RFPA system。

### 3.1. Model Establishment

This model takes the 2236 auxiliary roadway of Chengzhuang Mine, Jincheng Anthracite Mining Group as the object. The coal seam is approximately 4 meters thick. The mechanical parameters of the coal and rock strata are shown in Table 1. The material properties of the coal and rock strata are assigned according to the Weibull distribution, and the elastic finite element method is applied for stress analysis. The yield criterion adopts the modified Coulomb criterion (including tensile truncation).

**Table 1.** Physical Parameters of Coal and Rock

| Mechanical and seepage parameters | coal seam | Rock strata (roof and floor) |
|---|---|---|
| Homogeneity | 3 | 4.5 |
| Mean elastic modulus $E_0$/GPa | 5 | 60 |
| Mean compressive strength $\sigma_0$/MPa | 35 | 90 |
| Poisson's ratio μ | 0.25 | 0.20 |
| angle of friction /° | 23 | 28 |
| Strength compression-tension ratio | 20 | 15 |
| Attenuation coefficient of intensity $B_s$ | 0.2 | 0.25 |
| Permeability coefficient，$m^2/(MPa^2 \cdot d)$ | 0.2 | 0.005 |
| Gas content coefficient $A_w$ | 2.5 | 0.05 |
| Liquid-solid coupling coefficient β | 0.3 | 0.15 |

To better eliminate the boundary effect, the model was built as a two-dimensional model of 40m×40m. As the angle between the fracture hole and the coal seam dip varies from 30° to 90°, considering the universality and pertinence of the field test, the thickness of the coal seam in the model was taken as 8m. The physical model is shown in Figure 3.

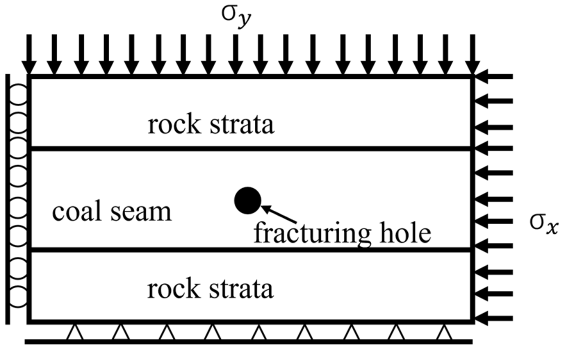



**Figure 3.** Hydraulic Fracturing Modelling

It is regarded as a two-dimensional problem and a plane strain mechanics model is established. The model is subjected to a vertical stress of approximately 19 MPa and a horizontal stress of 17 MPa. The entire model is divided into 400×400 elements, and its numerical calculation model is shown in Figure 4. The initial gas pressure of the model is 2.85 MPa. The initial pressure of water injection for hydraulic fracturing is 1 MPa, increasing by 0.5 MPa each step, with a total of 60 steps of operation.

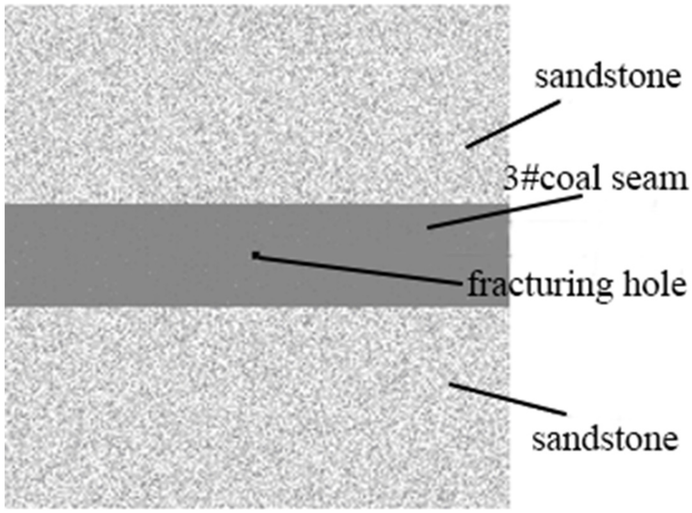



**Figure 4.** Model Calculation of the Single Drilling Hydraulic Fracturing Diagram

## 3.2. Simulation Results

### 3.2.1. Simulation Results of Unconventional Hydraulic Fracturing (Single Well)

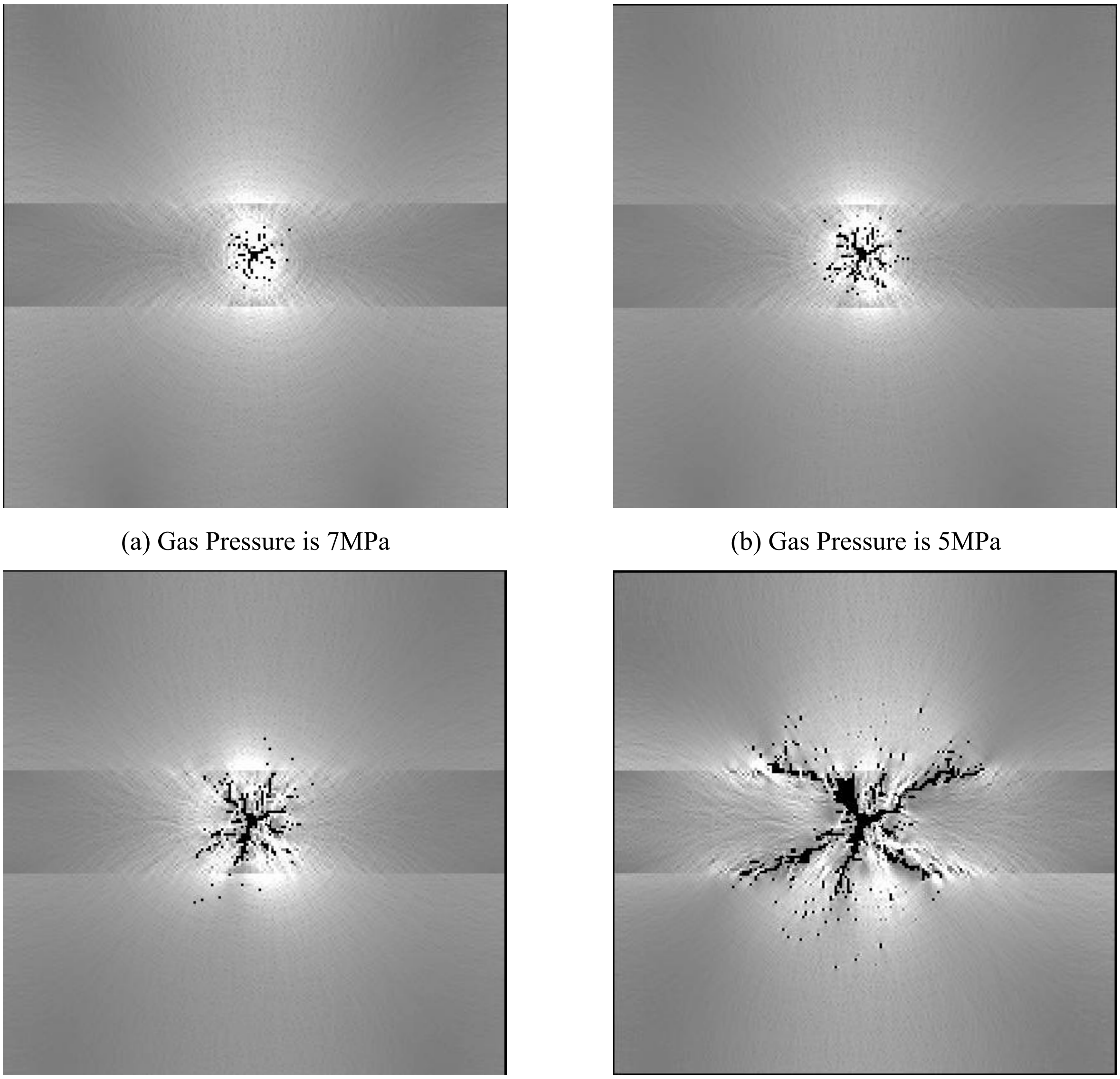
To explore the influence of gas pressure on coal seam hydraulic fracturing, the author excluded the effect of in-situ stress and established four different calculation models with gas pressures of 1 MPa, 3 MPa, 5 MPa and 7 MPa based on the parameters in Table 1. The model size was 40m×40m, with a coal seam thickness of 8m and a top and bottom strata thickness of 16m each. The grid was divided into 400×400 cells. In all models, a fracturing hole was constructed at the center and water was injected at high pressure to simulate the hydraulic fracturing process. To facilitate comparison and analysis, the water injection pressure was uniformly set at 10 MPa, so as to simulate the coal seam fracture process under the same fracturing conditions but different gas pressures

The following are the stress diagrams of coal body fracturing under different gas pressures:

From the above four models, it can be seen that the coal seam gas pressure reduces the high-pressure water injection effect of hydraulic fracturing and offsets part of the injection pressure. The greater the gas pressure, the more difficult it is for the coal body to break. When implementing the hydraulic fracturing technology on site, it is recommended to appropriately increase the injection pressure during hydraulic fracturing in high-gas mines to achieve the expected fracturing effect.

### 3.2.2. Simulation Results of Directional Hydraulic Fracturing

Through numerical simulation of unidirectional hydraulic fracturing (single hole), the relationship between the injection pressure of hydraulic fracturing and the process and degree of coal and rock mass fracture was well investigated, the stress-strain relationship around the fracturing hole and the water flow condition around the fracturing hole were analyzed, the effect of coal seam gas pressure on hydraulic fracturing was discussed, and finally, the law of coal seam fracture pressure and the influence radius of hydraulic fracturing were quantitatively studied. This section will mainly conduct corresponding research and discussion on directional hydraulic fracturing.



(a) Gas Pressure is 7MPa (b) Gas Pressure is 5MPa

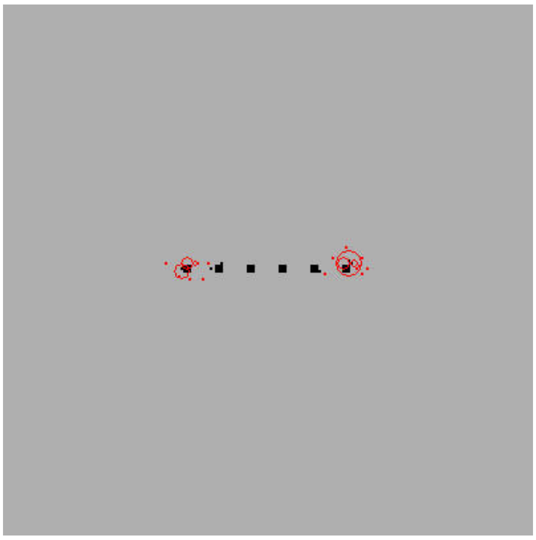
(c) Gas Pressure is 3MPa (d) Gas Pressure is 1MPa

**Figure 5.** Pressure Distribution of Different Gas Pressure in Condition of the Same Water Pressure

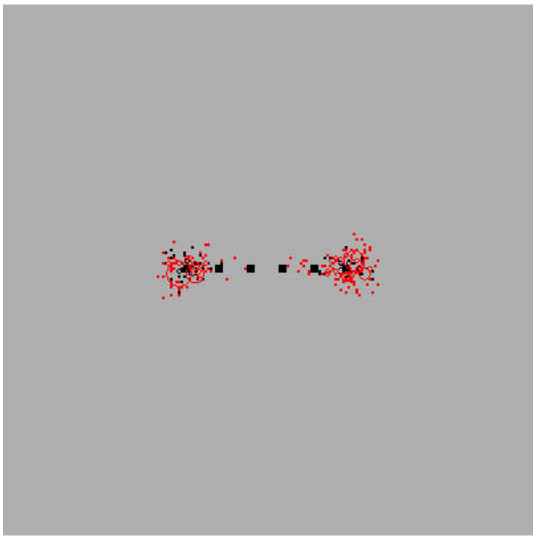
The most significant drawback of single-hole hydraulic fracturing is that the fracturing direction is uncontrolled, which can easily lead to stress concentration and the formation of high-pressure energy storage zones. In severe cases, it may cause coal and gas outburst accidents due to stress concentration. To ensure effective and safe operations and achieve the overall pressure relief effect of fracturing, it is necessary to implement directional hydraulic fracturing. Therefore, it is highly necessary to explore and study the technology of directional hydraulic fracturing.

The propagation direction of rock mass hydraulic fracturing fractures is controlled by the stress field around the borehole. However, in actual engineering, it is necessary for the fracturing fractures to expand in a certain direction, which has led to the development of directional hydraulic fracturing technology. Based on the gas geological conditions of the 2238 auxiliary roadway in Chengzhuang Mine, a relatively simple and practical directional borehole directional technology was selected, that is, directional fracturing was carried out by constructing a row of directional boreholes within the influence radius of the fracturing borehole. Good fracturing effects were achieved in the on-site industrial test.

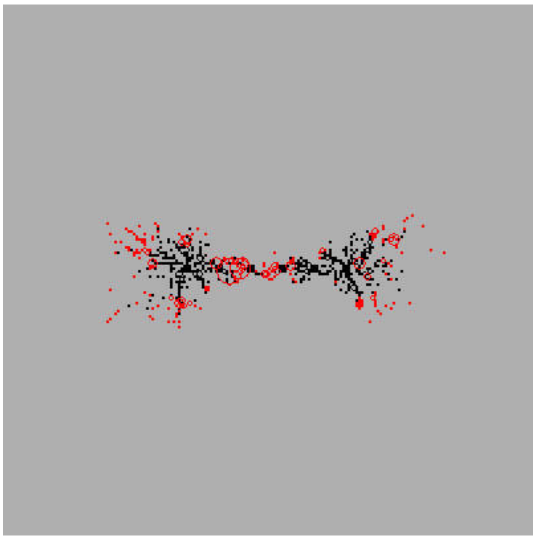
The following simulates the situation of four hydraulic fracturing directional control holes in the middle when two water injection holes are arranged at the left and right ends with a distance of 15m. The model is 40m×40m, with a coal seam thickness of 8m and the upper and lower top and bottom plates are both 16m. The entire model is divided into 400×400 units, and a two-dimensional plane strain mechanical model is established.



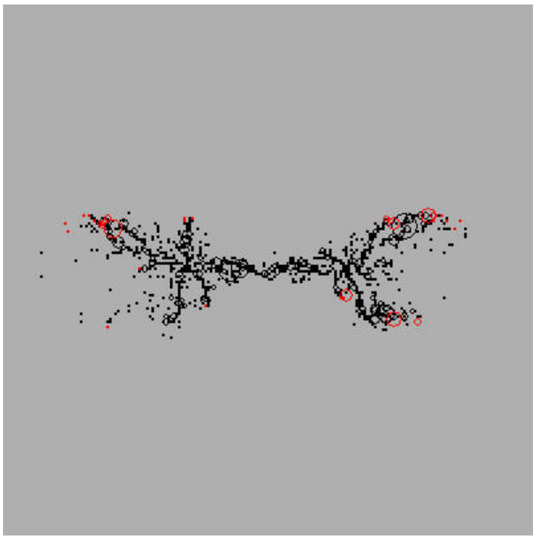
(a) AE Diagram (Water Pressure is 10MPa)



(b) AE Diagram (Water Pressure is 14MPa)



(c) AE Diagram (Water Pressure is 21MPa)



(d) AE Diagram (Water Pressure is 25MPa)

**Figure 6.** AE Diagram of Fractrue Initiation and Stead Propagation during Directional Hydraulic Fracturing

The acoustic emission results in Figure 6 show that the initiation, development and propagation process of hydraulic fracturing fractures starts from stress accumulation (Figure 6-a), followed by the stable growth of micro-fractures (Figure 6-b), the formation of local fracture bands (Figure 6-c), and finally the expansion and penetration of local fracture bands (Figure 6-d).

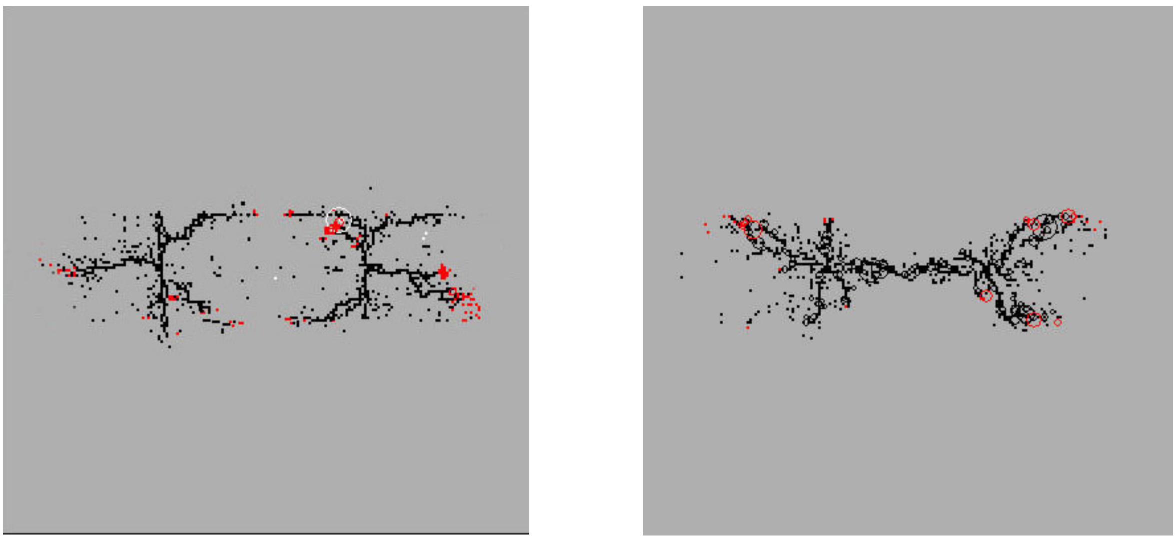
Due to the guiding effect of the directional holes, the result of the fracturing is the formation of an approximately cylindrical compression and crushing zone around the fracturing holes within the coal and rock mass and a penetrating fracturing crack surface along the line connecting the centers of the fracturing holes and the directional holes. This effectively achieves the purpose of controlling the fracturing, avoiding the disorderly flow of high-pressure water in the coal mass, and eliminating the safety issues such as partial pressure relief and partial stress concentration in non-directional hydraulic fracturing. Although the concentration of gas drainage has increased, the stress concentration left behind for later mining has been eliminated.

### 3.2.3. Analysis of the Fracturing Process in Directional Hydraulic Fracturing

To study the dual-hole fracturing problem from a perspective of connection, the following simulation was conducted on the related conditions of hydraulic fracturing with and without directional control holes when the distance between two water injection holes is 15m. The models are all 40m×40m, with a coal seam thickness of 8m and the upper and lower top and bottom plates are both 16m. The entire model is divided into 400×400 units, and a two-dimensional plane strain mechanics model is established.

Figure 7 shows the acoustic emission patterns at the end of the dual-hole unidirectional and dual-hole directional hydraulic fracturing. It can be clearly seen that the hydraulic fracturing with directional holes generates more fractures than that without directional holes. Moreover, due to the existence of directional holes, more fractures are produced around the directional holes along the line connecting the centers of the fracturing holes and the directional holes, and these fractures are connected to the radial fractures generated by the fracturing holes along the line connecting the centers.

Because the resistance that needs to be overcome for the generation of fractures in the direction of the oriented hole is smaller than that encountered by the development of fractures in other directions, that is, the fractures along the line connecting the centers restrict the generation and expansion of fractures in other directions. In this sense, the oriented hole is a guide for radial fractures - a continuous fracture surface is generated along the line connecting the centers of the hydraulic fracturing hole and the oriented hole, as shown in Figure 7(b). That is to say, the result of the dual-hole hydraulic fracturing is the formation of a cylindrical compression crushing zone around the hydraulic fracturing hole in the coal and rock mass and a continuous hydraulic fracturing fracture surface along the line connecting the centers of the hydraulic fracturing hole and the oriented hole.



(a) Without Directional Drilling (b) With Directional Drilling

**Figure 7.** AE Diagram of Two Drillings after Hydraulic Fracturing

Through the reasonable spatial arrangement of multiple directional holes, after directional hydraulic fracturing, a series of weak planes centered on the fracturing holes and extending to the multi-level weak planes of the guiding holes can be generated in the coal and rock mass above the tunneling face. This can fully release the in-situ stress and cause a uniform redistribution of stress. Additionally, the connection of the fracture surfaces and the directional holes enables the high-pressure gas within the coal and rock mass above the working face to be fully discharged, effectively enhancing the permeability of the coal seam and preventing coal and gas outbursts.

## 4. CONCLUSION

1)The application of cross-stratum directional hydraulic fracturing technology in the prevention and control of coal and gas outbursts in high gas, high stress and low permeability coal seams has been carried out, and the form of cross-stratum hydraulic fracturing has been determined, providing a new way for pressure relief and permeability enhancement in areas where the conditions for mining protective layers are not available.

2)Among the various factors influencing hydraulic fracturing, the gas pressure in coal seams is a significant one. The gas pressure in coal seams reduces the high-pressure water injection effect of hydraulic fracturing and offsets part of the injection pressure. The higher the gas pressure, the more difficult it is for the coal body to fracture, and the corresponding initiation pressure for fracturing also increases. When implementing hydraulic fracturing technology in the field, it is recommended to appropriately increase the injection pressure for hydraulic fracturing in high-gas mines to achieve the expected effect of eliminating outbursts through fracturing.

## REFERENCES


[1] Wang F ,Liu W ,Deng J , et al.Hydraulic fracture propagation research in layered rocks based on 3D FEM modeling and laboratory experiments[J].Geoenergy Science and Engineering, 2024, 2342 12670-.

[2] Karlov I V ,Krykhtin I Y .Analysis of Technical Solutions for a High-Power Drive for a Pumping Unit Designed for Hydraulic Fracturing of Reservoir Bridges in Isolated Oil/Gas Cavities[J].Russian Engineering Research,2024, 44(6): 810-814.

[3] Liuke H ,Egor D ,Haifeng F , et al.Hydraulic fracture height growth in layered rocks: Perspective from DEM simulation of different propagation regimes[J].International Journal of Solids and Structures,2022,238

[4] Liu L ,Li L ,Elsworth D , et al.The Impact of Oriented Perforations on Fracture Propagation and Complexity in Hydraulic Fracturing[J].Processes,2018,6(11):213-213.

[5] Garcia, X., Nagel, N., Zhang, F., Sanchez-Nagel, M., and B. Lee. Revisiting Vertical Hydraulic Fracture Propagation Through Layered Formations-A Numerical Evaluation. Paper presented at the 47th U.S. Rock Mechanics/ Geomechanics Symposium, San Francisco, California, June 2013.

[6] Zhang S ,Wang Z ,Zhao Y , et al.Study on the design of gas extraction drilling angle of crossing coal layer drilling in the floor rock roadway considering the boreholes superposition effect[J].Fuel,2024,378132981-132981.