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Article

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Research and Application of Directional Fracturing Roof Cutting for Lateral Thick and Hard Roofs in Shallow-Buried Large-Section Roadways

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Abstract: Aimed at the severe strata behavior hazards caused by the occurrence of lateral thick and hard roofs in shallow-buried large-section roadways, a directional fracturing and roof cutting technology for lateral thick and hard roof zones in shallow-buried large-section coal mine roadways is proposed. Key technologies of directional fracturing for such roof regions are investigated using a comprehensive approach including theoretical analysis, numerical simulation, and field testing. The results show that: compared with the minimum principal stress direction, the perforation direction acts as a relatively weak plane and can guide fracture initiation and propagation. Fluid pressure inside arrayed perforations weakens the dominance of the in-situ stress field, promotes fracture connectivity between adjacent perforations, and forms vertical sheet-like fractures around the borehole. Increasing the injection rate and perforation diameter enhances the guidance capacity of arrayed perforations and promotes vertical fracture propagation. As the injection rate increases from 0.12 m³/min to 1.2 m³/min, the fracture height increases by 310.83%; as the perforation diameter increases from 2 cm to 8 cm, the fracture height increases by 31.44%. However, increasing the perforation spacing weakens the influence of fluid pressure inside adjacent perforations, resulting in fracture-free zones between perforations and inhibiting the formation of connected fractures. An arrayed perforation directional fracturing technology for lateral thick and hard roofs in shallow-buried large-section roadways is proposed, with the following parameters: perforation diameter of 8 cm, perforation length of 50 cm, injection rate of 1.2 m³/min, and perforation spacing of 20 cm. Industrial application tests were carried out in the 122105 working face of Caojiatan Coal Mine. Monitoring and evaluation of the perforation-guided fracturing effect were conducted using microseismic monitoring, roadway section scanning, and bolt/cable stress measurement. The results indicate that arrayed perforation-guided fracturing can promote timely caving of the thick and hard roof, effectively reduce strata behavior intensity, and mitigate roadway deformation. This study can provide a reference for the prevention and control of severe strata behavior hazards associated with lateral thick and hard roofs in shallow-buried large-section roadways.

Keywords: discrete lattice method; vertical sheet fractures; arrayed perforation; shallow-buried thick and hard roof; directional hydraulic fracturing

Highlights:

- A mechanical model of perforation-guided fracturing was established, which clarified that perforations act as weak directions to guide fracture initiation and propagation. Verified by true triaxial hydraulic fracturing experiments, perforation-guided fracturing can mitigate the influence of the in-situ stress field, reduce the fracture initiation pressure, and direct fracture propagation in the desired direction.
- To form vertical sheet fractures in the lateral thick and hard roof of shallow-buried large-section roadways, an adjacent perforation stress model was established. It was determined that the key influencing factors of arrayed perforations are water injection pressure, perforation diameter, and perforation spacing.
- The key parameters of arrayed perforation-guided fracturing were optimized by simulation. Industrial application tests of arrayed perforation-guided fracturing were carried out underground in coal mines, which confirmed that arrayed perforation-guided fracturing can effectively reduce the degree of strata pressure manifestation and minimize roadway deformation.

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1 Introduction

During the retreat mining of coal mine working faces, thick and hard roof strata cannot fracture effectively, resulting in large-area suspended roofs and the accumulation of substantial elastic energy. When the thick and hard roof fractures and collapses, a large amount of energy is released and acts on the surrounding rock mass, which easily triggers problems such as rock bursts, roadway deformation, and floor heave ^[1-3]. To reduce the energy released during the fracture of thick and hard roofs, pressure relief techniques are required for strata control ^[4]. The key to controlling thick and hard roofs lies in destroying the integrity of the roof, weakening its strength, and reducing both the static load induced by large-area suspended roof sections and the dynamic load generated during fracture impact ^[5-8]. In response to the above problems, hydraulic fracturing, as a technical measure for strata control, exhibits the advantages of being clean, safe, and highly applicable ^[9-10].

However, hydraulic fracturing technology is plagued by high initiation pressure and fracture propagation direction controlled by the in-situ stress field. For instance, in shallow coal seams, hydraulic fracture networks are dominated by horizontal fractures, which lead to stratification of the thick hard roof and fail to effectively cut the roof. In view of this, scholars worldwide have proposed directional hydraulic fracturing technology. At present, there are two main types of directional hydraulic fracturing techniques: one is prefabricated fracture directional hydraulic fracturing, in which artificial prefabricated fractures are created in fracturing boreholes before hydraulic fracturing is performed, allowing fractures to propagate under the guidance of the prefabricated fractures and form a directional fracture network ^[11-15], the other is guide hole-controlled fracture propagation, which arranges guide holes near the fracturing hole to induce fractures to propagate toward the guide holes ^[16-17].

In terms of directional hydraulic fracturing with prefabricated fractures, the main technical methods include mechanical slotting and high-pressure jet slotting. Xia ^[18] and Zhou ^[19] applied abrasive jet prefabricated fractures in roadway fracturing boreholes before fracturing, which separated the roadway roof from the working face roof and realized effective caving. Rui ^[20] and Wu ^[21-22] used mechanical tools to create annular prefabricated fractures, which can guide the formation of horizontal fractures, divide thick and hard strata into two layers, and weaken the rock mass. Cong ^[23] found through laboratory experiments that prefabricated fractures can effectively guide directional fracture propagation and reduce fracture complexity.

In terms of directional hydraulic fracturing using guide holes: Lu ^[24] and Li ^[25] connected the plastic zone of the fracturing hole with that of the guide holes, allowing fractures to propagate continuously within the plastic zone and effectively controlling the propagation direction of the main fracture. Lu ^[26], Lu ^[27] and Zhao ^[28] found that the interaction between holes weakens the influence of in-situ stress on fracture propagation and guides fractures to extend toward the guide holes. Liu ^[29] revealed that the number of guide boreholes is positively correlated with the effect of directional fracture propagation, which controls the directional propagation range of hydraulic fractures. Yan ^[30] and Guo ^[31] arranged multiple small-diameter guide holes near fracturing holes and found that such holes alter the magnitude and direction of the three-dimensional in-situ stress in the rock mass, reduce the stress required for fracture propagation, and effectively control the propagation direction of the main fracture.

The above scholars have conducted in-depth research on the directional control mechanism, methods and influencing parameters of hydraulic fracturing, and achieved abundant results, which

are of great significance to the development and application of directional hydraulic fracturing technology. However, in the application of directional fracturing roof-cutting technology in thick and hard roof areas, perforations are formed around boreholes by abrasive jet tools, and multiple perforations constitute prefabricated fractures to guide fracture propagation. Among them, the roof-cutting effect of thick and hard roofs is affected by geological conditions and perforation parameters. The applicability of perforation-guided fracturing technology and equipment under shallow coal seam conditions still needs to be continuously improved and optimized. Based on this, in order to form vertical continuous fractures inside the thick and hard roof laterally in shallow buried large-section roadways and control roof caving, this paper takes the 122105 working face of the Caojiatan Coal Mine as the engineering background. A directional hydraulic fracturing model under key factors such as different injection rates, perforation diameters and perforation spacings is established based on the discrete lattice method, and the propagation law of directional fracture networks under different influencing parameters is clarified. On this basis, a multi-hole fracture-forming directional fracturing method is proposed, which explores a new approach for the formation of large-angle directional fracture networks inside thick and hard roofs in underground coal mines.

2 Engineering overview

Caojiatan Coal Mine No. 122105 working face adopts fully-mechanized top-coal caving mining, and the goaf roof is managed by the full caving method. The buried depth ranges from 255 to 338 m, the strike length is 2981.4 m, and the dip length is 300 m. The average coal thickness of the working face is 11.3 m, the designed mining height is 5.9 m, the top-coal caving height is 5.9 m, and the coal seam dip angle is less than 1° . The general layout of the working face is shown in Figure 1. The main roof and immediate roof are dominated by sandstone. The main roof thickness is 5.8–25.9 m, and the immediate roof thickness is 2.75–17.25 m. The immediate floor is mainly siltstone with a thickness of 2.98–14.26 m.

Due to the occurrence characteristics of thick and hard roof in the mine, large-area suspended roofs form during working face extraction. According to previous ground pressure monitoring data from working faces in the Caojiatan Mine, the lateral roof of the roadway exhibits strong activity. During the retreat of the 122108 and 122107 working faces, the energy proportion released by the fracture of the lateral goaf roof reached 33.96 % and 44.31 %, respectively. The roadway is affected not only by the lateral roof of the current working face but also by the lateral roof of the adjacent goaf. Severe strata behavior caused by lateral roof fracture is prominent, resulting in serious roadway deformation, hydraulic support damage, and floor heave, as shown in Figure 2. Therefore, perforation-guided hydraulic fracturing is adopted to weaken or cut off the rear and lateral suspended roofs behind the working face, so as to reduce the influence of strata behavior on the roadway. It is necessary to clarify the influence of perforation parameters on hydraulic fracture propagation, so as to effectively form vertical continuous fractures inside the lateral roof of the roadway and block the energy transfer caused by roof fracture, as illustrated in Figure 3.

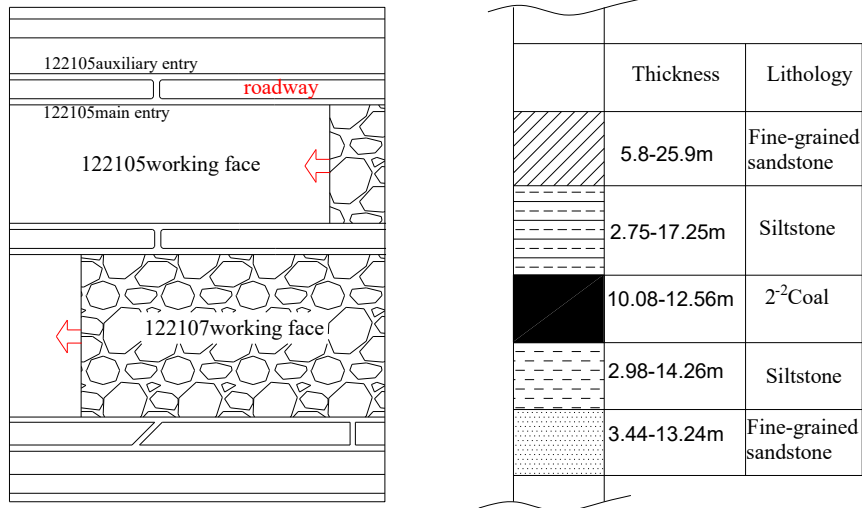


Fig.1 122105 working face



Fig.2 Roadway deformation

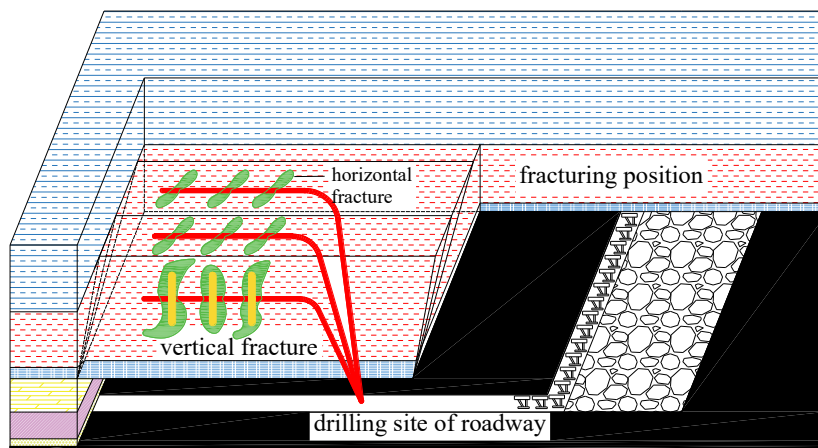


Fig3 Crack network expansion

2 Theoretical analysis of perforation-guided fracturing

To investigate the influence of perforations on hydraulic fracture propagation, a two-dimensional mechanical model of perforated fracturing is established, which is governed by the in-situ stress field and water pressure. The model can be decomposed into three sub-models: a hydraulic pressure model under isobaric in-situ stress, a hydraulic pressure model under counter-pressure in-

situ stress, and a mechanical model of perforated holes, as shown in Figure 4. Tensile stress is defined as positive and compressive stress as negative.

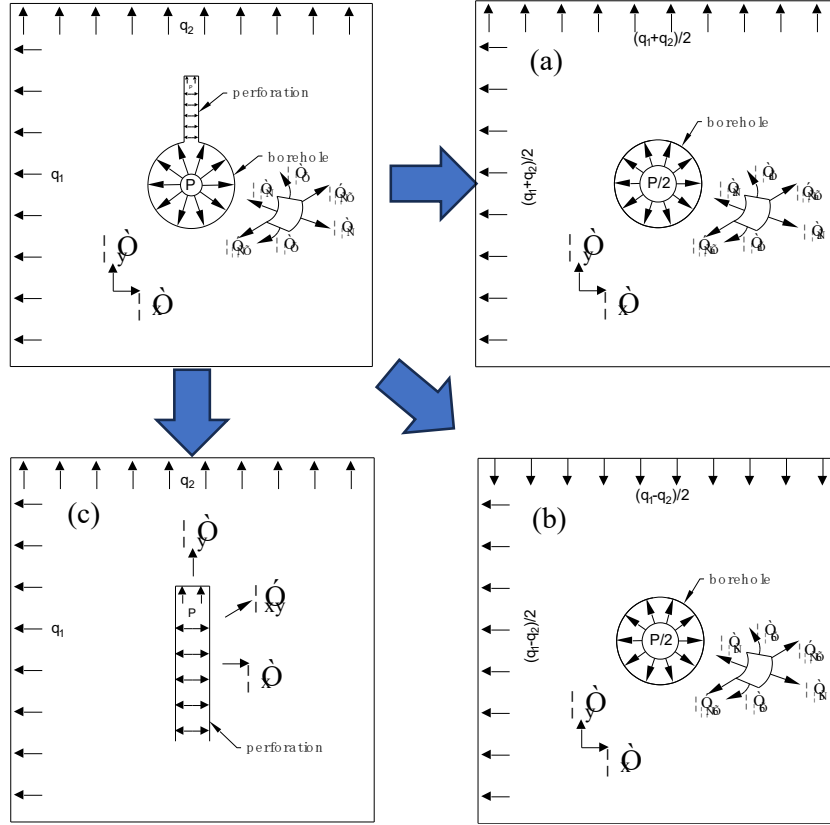


Fig.4 The fracturing mechanical model of perforation in array type

Based on the theory of elasticity, for the model subjected to water pressure under isobaric in-situ stress:

$$\begin{cases} \sigma_{pa} = \left(1 - \frac{r^2}{\rho^2}\right) \frac{q_1 + q_2}{2} - \frac{r^2}{\rho^2} \frac{P}{2} \\ \sigma_{qa} = \left(1 + \frac{r^2}{\rho^2}\right) \frac{q_1 + q_2}{2} + \frac{r^2}{\rho^2} \frac{P}{2} \\ \tau_{pqa} = 0 \end{cases} \quad (1)$$

Where: σ_{pa} is radial stress of the borehole, MPa. σ_{qa} is circumferential stress of the borehole, MPa. r is radius of the borehole, m. ρ is distance from the stress element to the borehole center, m. q_1 is maximum principal stress, MPa. q_2 is minimum principal stress, MPa. P is water pressure, MPa. τ_{pqa} is shear stress of the borehole, MPa.

In the model under water pressure with counter-pressure in-situ stress:

$$\begin{cases} \sigma_{pb} = -\left\{-\frac{q_1 - q_2}{2} + \left[-P + 2(q_1 - q_2)\right] \frac{r^2}{\rho^2} + \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2)\right] \frac{r^4}{\rho^4}\right\} \cos 2\varphi \\ \sigma_{qb} = \left\{-\frac{q_1 - q_2}{2} + \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2)\right] \frac{r^4}{\rho^4}\right\} \cos 2\varphi \\ \tau_{pqb} = \left\{-\frac{q_1 - q_2}{2} - \left[-\frac{P}{2} + (q_1 - q_2)\right] \frac{r^2}{\rho^2} - \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2)\right] \frac{r^4}{\rho^4}\right\} \sin 2\varphi \end{cases} \quad (2)$$

Where: σ_{pb} is radial stress of the borehole, MPa. σ_{qb} is circumferential stress of the borehole, MPa. τ_{pqb} is shear stress of the borehole, MPa. φ is angle between the stress element and the horizontal direction.

By adding equations (1) and (2) from the two models, the formula for stress variation around the borehole under sustained water pressure is obtained as follows:

$$\begin{cases} \sigma_{pc} = \left(1 - \frac{r^2}{\rho^2}\right) \frac{q_1 + q_2}{2} - \frac{r^2}{\rho^2} \frac{P}{2} - \left\{ -\frac{q_1 - q_2}{2} + \left[-P + 2(q_1 - q_2) \right] \frac{r^2}{\rho^2} + \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2) \right] \frac{r^4}{\rho^4} \right\} \cos 2\varphi \\ \sigma_{qc} = \left(1 + \frac{r^2}{\rho^2}\right) \frac{q_1 + q_2}{2} + \frac{r^2}{\rho^2} \frac{P}{2} + \left\{ -\frac{q_1 - q_2}{2} + \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2) \right] \frac{r^4}{\rho^4} \right\} \cos 2\varphi \\ \tau_{pqc} = \left\{ -\frac{q_1 - q_2}{2} - \left[-\frac{P}{2} + (q_1 - q_2) \right] \frac{r^2}{\rho^2} - \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2) \right] \frac{r^4}{\rho^4} \right\} \sin 2\varphi \end{cases} \quad (3)$$

Where: σ_{pc} is radial stress of the borehole, MPa. σ_{qc} is circumferential stress of the borehole, MPa. τ_{pqc} is shear stress of the borehole, MPa.

In the mechanical model of perforations:

$$\begin{cases} \sigma_x = q_1 \sin^2 \varphi + q_2 \cos^2 \varphi - P \\ \sigma_y = q_2 \sin^2 \varphi + q_1 \cos^2 \varphi - P \\ \tau_{xy} = -(q_1 - q_2) \sin \varphi \cos \varphi - P \end{cases} \quad (4)$$

Where: σ_x is radial stress of the perforations, MPa. σ_y is circumferential stress of the perforations, MPa. τ_{xy} is shear stress of the perforations, MPa.

Substituting $r=\rho$ and adding Equation (3) and Equation (4), the circumferential stress at the contact point between the borehole wall, perforations and the borehole can be obtained as:

$$\sigma_{qc} = \frac{P}{2} (\cos 2\varphi + 1) + q_1 (1 - 2 \cos 2\varphi) + q_2 (1 + 2 \cos 2\varphi) \quad (5)$$

$$\sigma_{qs} = \frac{P}{2} (\cos 2\varphi - 1) + q_1 (1 - 2 \cos 2\varphi + \cos^2 \varphi) + q_2 (1 + 2 \cos 2\varphi + \sin^2 \varphi) \quad (6)$$

Where: σ_{qz} is circumferential stress on the borehole wall, MPa. σ_{qs} is circumferential stress at the contact point between perforation and borehole, MPa.

According to the in-situ stress data measured on site, the minimum principal stress is the vertical stress, and fractures initiate and propagate horizontally along the borehole to form horizontal fractures. At this time, by setting $\varphi=0$, the formula for circumferential stress in the horizontal direction of the borehole wall is obtained as:

$$\sigma_{q0} = P - q_1 + 3q_2 \quad (7)$$

Subtracting Equation (6) from Equation (7) yields:

$$\sigma_{qs} - \sigma_{q0} = p (\cos^2 \varphi - 1) + q_1 + 3 \sin^2 \varphi (q_1 - q_2) \quad (8)$$

Since $q_1 - q_2 \geq 0$, $p(\cos^2 \varphi - 1) \geq 0$, Equation (8) is always greater than zero, indicating that the circumferential stress at the perforation–borehole contact point is consistently higher than that at the horizontal weakness zone of the borehole wall. During the fracture initiation stage, the perforation–borehole contact points act as relative weak points, which control the fracture initiation direction and reduce the fracture initiation pressure.

Substituting $\rho > r$ and $\varphi=90^\circ$ into Equations (3) and (4) yields the circumferential stress formula of perforations under the combined action of fracturing borehole, water pressure and in-situ stress field:

$$\sigma_{qsk} = \left(1 + \frac{r^2}{\rho^2}\right) \frac{q_1 + q_2}{2} + \frac{r^2}{\rho^2} \frac{P}{2} - \left\{ -\frac{q_1 - q_2}{2} + \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2) \right] \frac{r^4}{\rho^4} \right\} + q_2 - P \quad (9)$$

Where: σ_{qsk} is circumferential stress of the perforation, MPa.

Subtracting the borehole circumferential stress formula in Equation (3) from Equation (9)

yields the formula for the circumferential stress difference $\Delta\sigma$ between the perforation and the borehole:

$$\Delta\sigma = q_2 - P - \left\{ -\frac{q_1 - q_2}{2} + \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2) \right] \frac{r^4}{\rho^4} \right\} (1 + \cos 2\varphi) \quad (10)$$

Since $q_1 - q_2 \geq 0$, $\cos 2\varphi + 1 \geq 0$, and $P < 0$, Equation (10) is always greater than zero, indicating that the circumferential stress of the perforation is consistently higher than that of the borehole. During the fracture propagation stage, the perforation direction becomes a relatively weak path, which controls and guides fractures to propagate toward the perforation direction to form vertical fractures.

A comparison between conventional fracturing and single-perforation fracturing was conducted using true triaxial hydraulic fracturing equipment^[32], as shown in Figure 5. The experimental system mainly consists of a mainframe, triple oil source, servo oil source, pressurizer cylinder, and data measurement and control system. Roof sandstone specimens from the Caojiatan Coal Mine were prepared into cubic samples with dimensions of 200 mm × 200 mm × 200 mm. According to the in-situ stress test report, $\sigma_v - \sigma_H - \sigma_h = 7 \text{ MPa} - 11 \text{ MPa} - 9 \text{ MPa}$, and the perforation was oriented toward the σ_v direction. Clean water was used as the fracturing fluid at a injection rate of 10 ml · min⁻¹. From the fracturing curves, compared with conventional fracturing, the peak water pressure of perforation-guided fracturing decreased by 22.5 %, reaching approximately 14.8 MPa. Three-dimensional fracture reconstruction shows that the fracture surfaces are uneven to some degree. Conventional fractures are generally perpendicular to the σ_v direction, whereas perforation-guided fracturing weakens the influence of the in-situ stress field and guides fractures to propagate toward the σ_v direction.

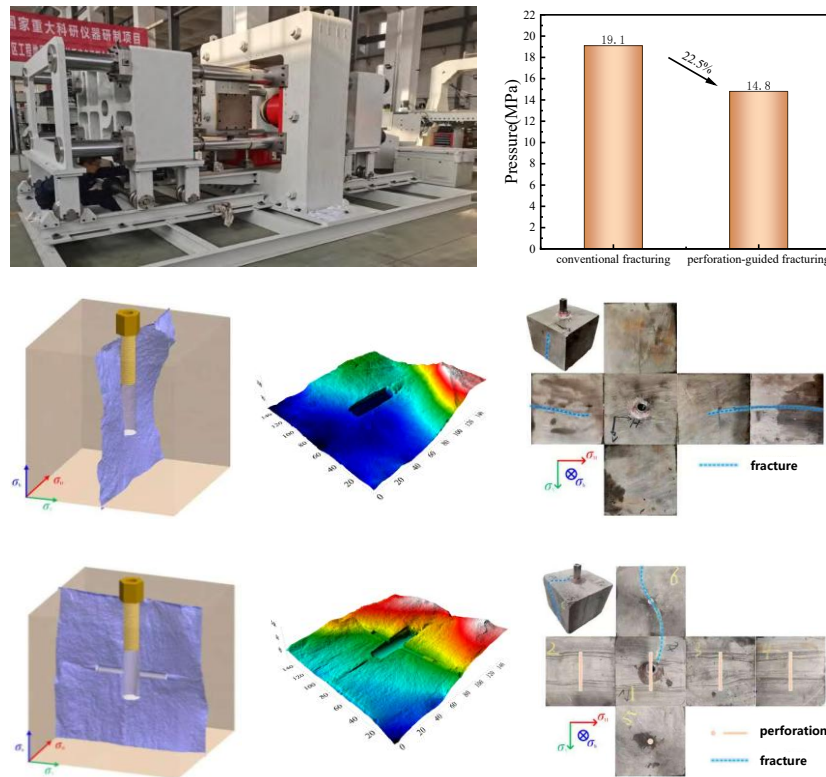


Fig.5 Hydraulic fracturing experiment

As shown in Figure 6, to form vertical continuous fractures along the borehole axis, a perforation-array directional fracturing method is proposed. In this method, the radial stress of one

perforation acts on adjacent perforations. According to Equation (3), the formula for the radial stress influence of adjacent perforations is:

$$\sigma_{ps} = q_1 + \frac{r_s^2}{d^2} \frac{P}{2} - 2(q_1 - q_2) \frac{r_s^2}{d^2} + \left[\frac{P}{2} - \frac{3}{2}(q_1 - q_2) \right] \frac{r_s^4}{d^4} \quad (11)$$

Where: σ_{ps} is radial stress of the perforation, MPa. r_s is radius of the perforation, cm. d is perforation spacing, cm.

It can be seen from Equation (11) that σ_{ps} is positively correlated with P and r_s and negatively correlated with d . In the perforation-guided model, the perforation direction is weaker than the bore-hole, thus becoming the dominant propagation direction of fractures. However, the parameters P , r_s and d in arrayed perforations affect the stress distribution around perforations and control the dominant propagation direction of fractures. Therefore, it is necessary to clarify the influences of P , r_s and d on arrayed perforation-guided fracturing.

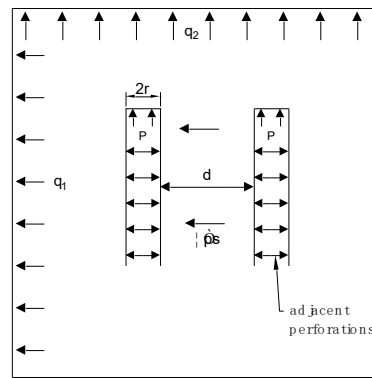


Fig.6 Adjacent perforation mechanical model

3 Simulation of arrayed perforation-guided fracturing

3.1 Model establishment

Rock mechanical parameters were obtained through uniaxial compression tests and other measurement methods, as shown in Figure 7 and Table 1. The vertical stress (σ_v), maximum horizontal principal stress (σ_H), and minimum horizontal principal stress (σ_h) of the target rock formation obtained by the small-diameter hydraulic fracturing method were 7 MPa, 11 MPa, and 9 MPa, respectively.

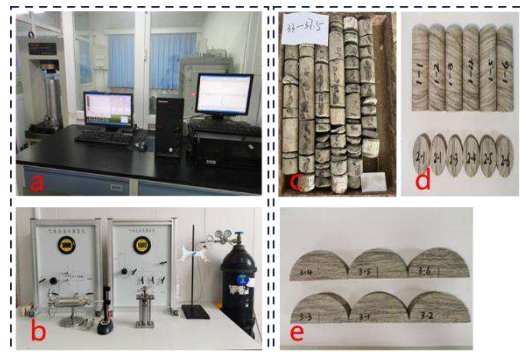


Fig.7 Rock mechanics parameter testing. (a)uniaxial compression test equipment; (b)permeability test equipment; (c)rock core; (d)the specimen of uniaxial compression test; (e)brazilian splitting test

Based on the geomechanical parameters, physical properties, and horizontal well perforation parameters of the Caojiatan Coal Mine, a numerical model for directional fracturing with arrayed

perforations was established using the XSite numerical simulation software [33–37], as shown in Figure 8. The model is a cube with a side length of 2 m. A horizontal borehole is arranged along the y-axis (σ_h direction) with a diameter of 12 cm. To form vertical fractures, perforations in the model are oriented along the z-axis (σ_v direction) with a perforation depth of 50 cm and a diameter of 2 cm. Left and right perforations are parallel to each other, and upper and lower perforations are symmetrically arranged, with a perforation spacing of 10 cm. The injection rate is $1.2 \text{ m}^3 \cdot \text{min}^{-1}$, clean water is used as the fracturing fluid, and fluid loss is neglected.

Table.1 Rock mechanics parameter

Sandstone parameters	Values
Density (g/cm^3)	2.43
Compressive strength (MPa)	95.43
Tensile strength (MPa)	6.63
Elastic modulus (GPa)	16.22
Poisson's ratio	0.248
Fracture toughness ($\text{pa} \cdot \text{m}^{0.5}$)	34440.42
Porosity%	10.42
Permeability (10^{-3}um^2)	0.012

3.2 Model validation

Based on the engineering conditions and rock geomechanical parameters of the Caojiatan Coal Mine, the reliability of the numerical model established in this paper was verified by comparing the 3D penny-shaped fracture geometric properties obtained by discrete lattice numerical simulation with theoretical solutions under the same conditions, and by comparing the simulated fracture morphology with that obtained from experiments [38–39]. Through true triaxial hydraulic fracturing experiments, the propagation characteristics of fracture networks under non-perforated and single-perforated conditions were compared. It is clarified that a single perforation can weaken the influence of the in-situ stress field and guide fracture propagation, turning the fracture network from being perpendicular to the vertical stress to aligning with the minimum horizontal stress ($\sigma_v - \sigma_H - \sigma_h = 7 \text{ MPa} - 11 \text{ MPa} - 9 \text{ MPa}$). Non-perforated fracturing and single-perforated fracturing were simulated using XSite and compared with experimental results. The simulated fracture morphology is consistent with that of experimental specimens, indicating that the numerical model in this paper can reasonably explain fracture propagation behavior, as shown in Figure 9.

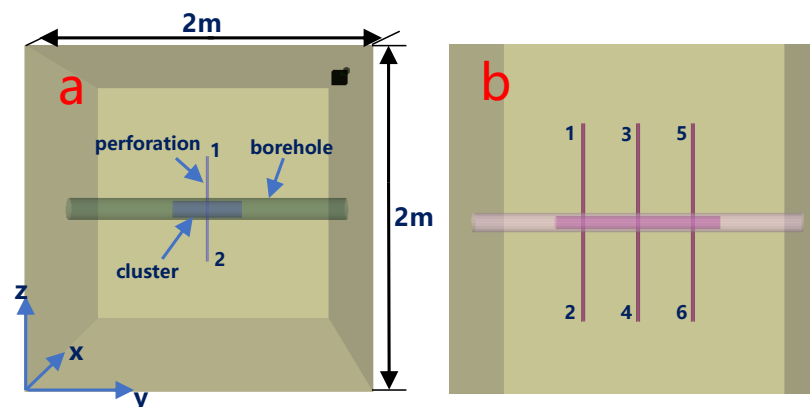


Fig.8 Perforation model; (a)single-hole fracturing model; (b)the local enlargement diagram of arranged perforation

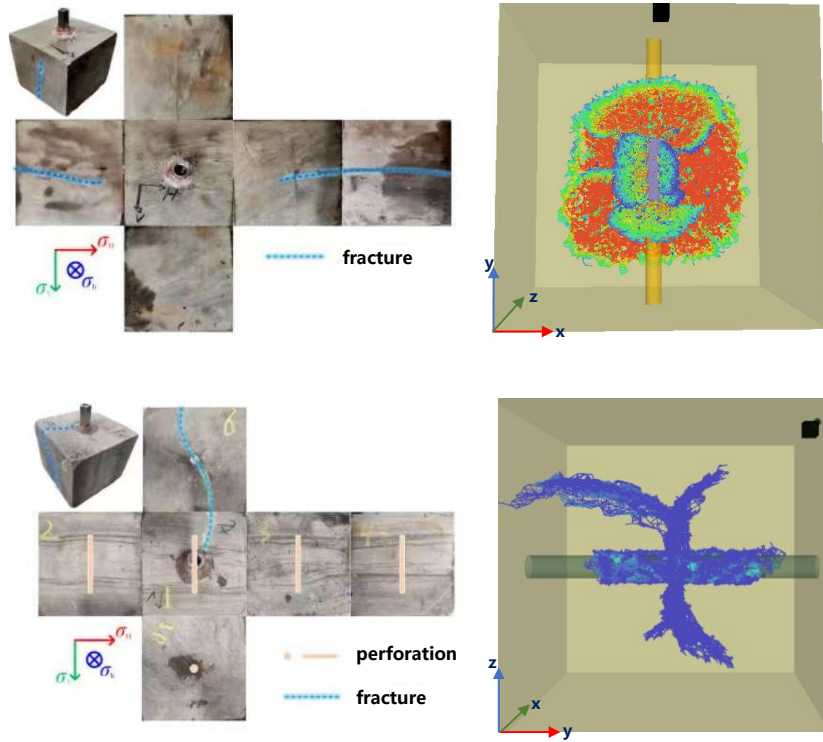


Fig.9 Model validation

3.3 Propagation of hydraulic fracture networks guided by arrayed perforation

Compared with conventional fracturing and single-perforation fracturing, arrayed perforations provide multiple fluid pressure channels and form multiple "stress sources" acting on the rock mass. The increased number of fluid channels around the borehole raises the fluid pressure, weakens the influence of the in-situ stress field, and strengthens the guiding effect of perforations. Under the guidance of adjacent perforations, fractures between perforations connect to form continuous vertical fractures along the borehole, as shown in Figure 10.

Figure 11 shows the fracture propagation pattern under arrayed perforation fracturing. At time A, a large number of microcracks form around the perforations starting from the perforation roots, and fracture propagation is suppressed under the fracture stress shadow of adjacent perforations, forming a fracture blank zone. At time B, microcracks between adjacent perforations propagate and connect. At time C, inter-perforation fractures further develop and propagate, the fracture area increases, and fractures near the perforation tips propagate toward the maximum principal stress direction under the influence of the in-situ stress field. At time D, dominant fractures propagate rapidly, forming a complex fracture network around the borehole. By comparing the fracture network propagation characteristics of non-perforated, single-perforated, and arrayed perforation conditions, it is clarified that arrayed perforations can form continuous vertical fracture networks around the borehole under the condition of thick and hard roof in shallow buried roadways, thus destroying the integrity of the roof.

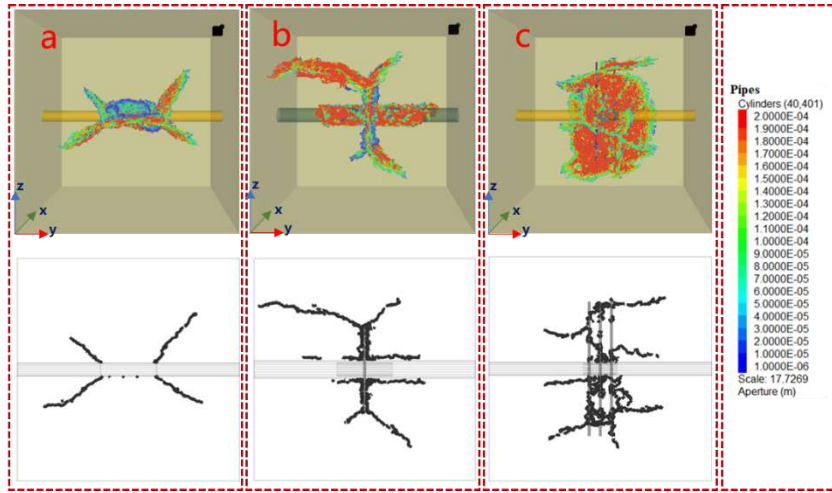


Fig.10 Model diagram

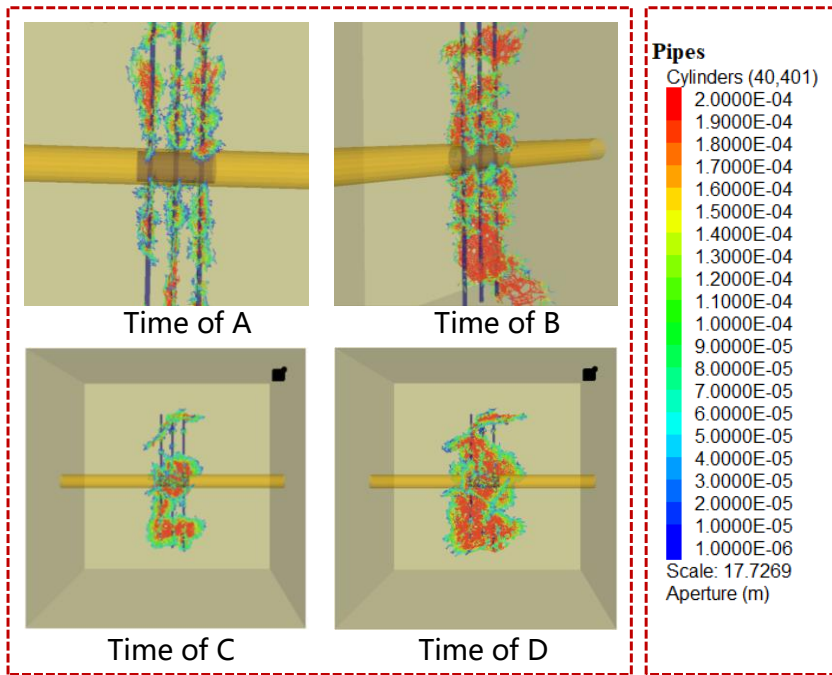


Fig.11 Fracture propagation in arranged perforation fracturing mod

4 Key parameters for fracture network guided by arrayed perforation

Compared with conventional fracturing and single-perforation-guided fracturing, arrayed perforation-guided fracturing can form continuous vertical fractures along the borehole axis. However, the radial stress generated by perforations affects the stress field around adjacent perforations. Based on the stress derivation of adjacent perforations, P , r_s and d are identified as the key factors. Two indicators, namely vertical average fracture height and continuous fracture range, were proposed. The effects of P , r_s and d on the fracture network propagation in arrayed perforation-guided fracturing were analyzed based on the vertical continuity indicator. As shown in Figure 12, the simulation schemes are presented in Table 2.

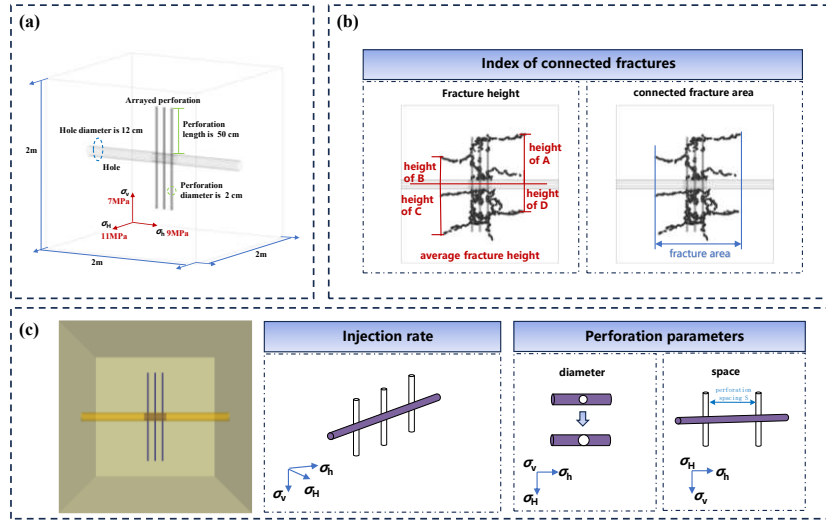


Fig.12 Model of perforation-guided fracturing with arrayed perforations. (a) model establishment; (b) index of vertical sheet fractures; (c) key influencing factors

Table.2 Simulation plan of arrayed perforation-guided fracturing

Model	σ_v - σ_H - σ_h MPa	Injection rate $\text{m}^3 \cdot \text{min}^{-1}$	Arrayed perforation	
			Diameter, cm	Space, cm
P #1-3	7-11-9	0.012,0.12,1.2	2	10
D #1-3	7-11-9	1.2	4,6,8	10
S #1-3	7-11-9	1.2	8	0,20,30

4.1 Injection rate

Injection rate serves as the driving force for hydraulic fracture propagation. With the replacement of downhole pump units, the injection rate has gradually increased to $1\text{--}2 \text{ m}^3 \cdot \text{min}^{-1}$, making it necessary to investigate the relationship between different injection rates and directional fracture network propagation under arrayed perforations. Figure 13 shows the fracture propagation morphology of arrayed perforation directional fracturing at injection rates of $0.012 \text{ m}^3 \cdot \text{min}^{-1}$, $0.12 \text{ m}^3 \cdot \text{min}^{-1}$, and $1.2 \text{ m}^3 \cdot \text{min}^{-1}$.

When the injection rate was set at $0.012 \text{ m}^3 \cdot \text{min}^{-1}$, the fluid pressure inside the arrayed perforations was insufficient to exert a strong guiding effect. Consequently, the direction of the minimum principal stress became the relative weak path, and the fracture network propagated perpendicular to the minimum principal stress to form horizontal fractures, as shown in Figure 13(a). When the injection rate was increased to $0.12 \text{ m}^3 \cdot \text{min}^{-1}$, the direction of the minimum principal stress still remained the dominant path for horizontal fracture propagation. However, the higher fluid pressure generated by the increased rate significantly enhanced the perforation-guided effect, leading to the initiation of fractures along the perforation direction, as depicted in Figure 13(b). Compared to the $0.012 \text{ m}^3 \cdot \text{min}^{-1}$ rate, the fracture height increased by 46.34%. As the injection rate was further raised to $1.2 \text{ m}^3 \cdot \text{min}^{-1}$, the substantial fluid pressure inside the perforations effectively weakened the influence of the in-situ stress field. This made the perforation direction the primary weak path, guiding fractures to propagate vertically along it, as shown in Figure 13(c). Compared to the $0.12 \text{ m}^3 \cdot \text{min}^{-1}$ rate, the fracture height saw a significant increase of 310.83%. The results indicate that increasing the injection rate strongly enhances the guiding capability of arrayed perforations and promotes vertical fracture growth. However, it has a negligible effect on expanding the continuous fracture range; the range only varied by 1.4% when the rate increased from $0.012 \text{ m}^3 \cdot \text{min}^{-1}$ to $1.2 \text{ m}^3 \cdot \text{min}^{-1}$, as illustrated in Figure 14.

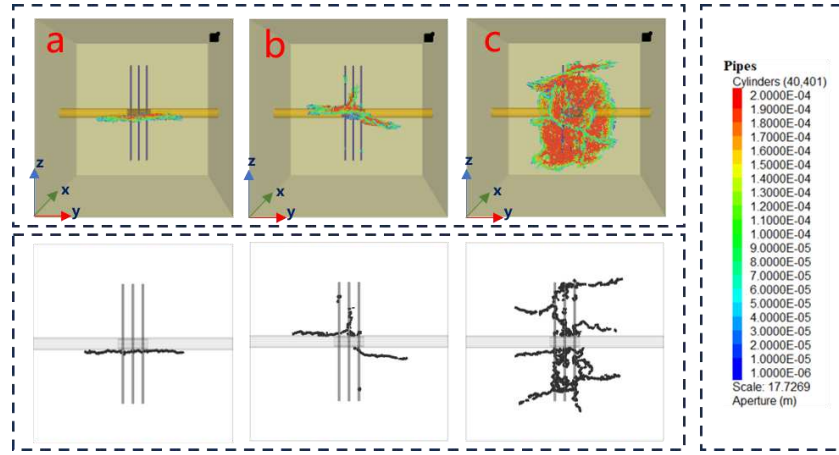


Fig.13 Fracture initiation and propagation under different injection rate; (a) $0.012 \text{ m}^3 \cdot \text{min}^{-1}$; (b) $0.12 \text{ m}^3 \cdot \text{min}^{-1}$; (c) $1.2 \text{ m}^3 \cdot \text{min}^{-1}$

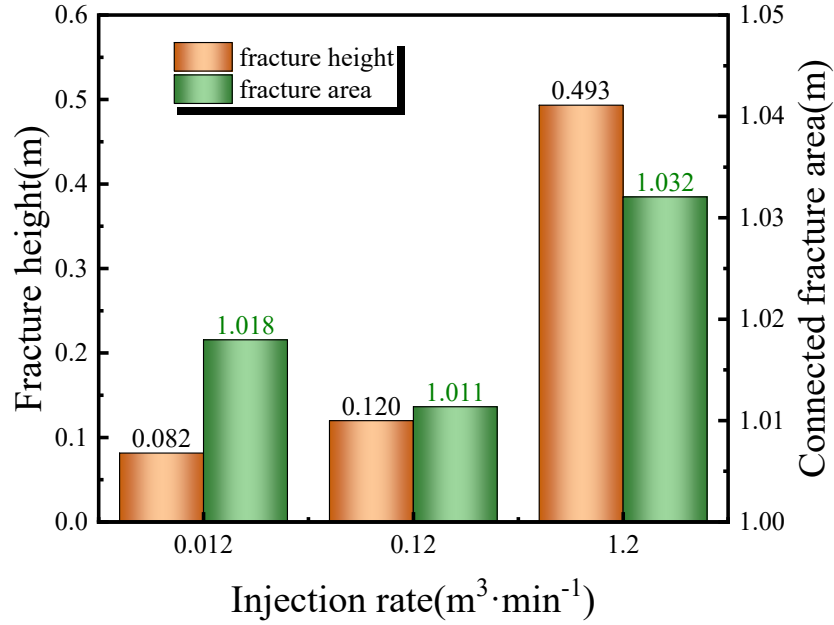


Fig.14 Index of vertical sheet fractures under different injection rates

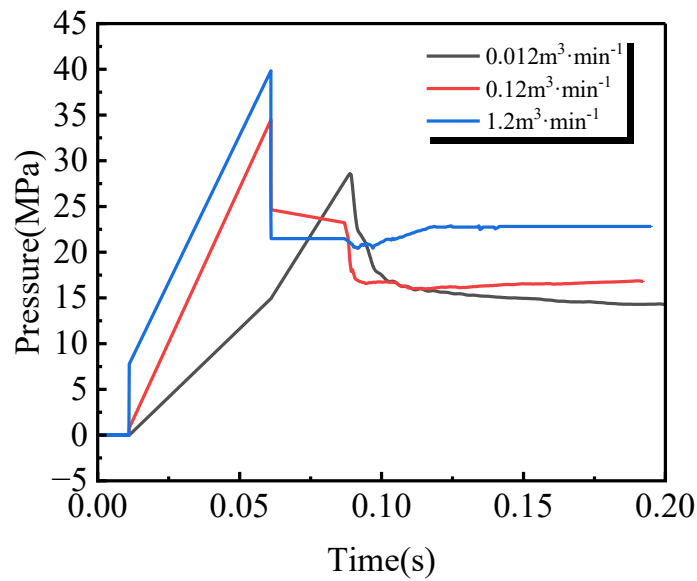


Fig.15 Fracturing curve under different injection rate

Figure 15 compares the fracturing curves at injection rates of $0.012 \text{ m}^3 \cdot \text{min}^{-1}$, $0.12 \text{ m}^3 \cdot \text{min}^{-1}$, and $1.2 \text{ m}^3 \cdot \text{min}^{-1}$. It can be seen from the figure that as the injection rate increases, the peak fluid pressure inside the arrayed

perforations rises, weakening the influence of the in-situ stress field and making the perforation direction the relative weak path. At a injection rate of $0.012 \text{ m}^3 \cdot \text{min}^{-1}$, the minimum principal stress direction is the relative weak path, and the fracture initiation pressure is 28 MPa. As the injection rate increases to $1.2 \text{ m}^3 \cdot \text{min}^{-1}$, the relative weak path shifts to the perforation direction. Since fracture initiation is affected by the minimum horizontal stress, the initiation pressure increases by 42.86% to 40 MPa. Therefore, the injection rate is optimized to $1.2 \text{ m}^3 \cdot \text{min}^{-1}$.

4.2 Diameter of arrayed perforation

Figure 16 shows the fracture network propagation morphology at perforation diameters of 2 cm, 4 cm, 6 cm, and 8 cm. As the perforation diameter increases, the influence range of fluid pressure around perforations expands, promoting the development and connection of fractures between adjacent perforations, strengthening the guiding effect of neighboring perforations, and forming continuous vertical fractures. When the perforation diameter increases from 2 cm to 8 cm, the fracture height increases by 31.44%, while the continuous fracture range only increases by 7.27%, as shown in Figure 17.

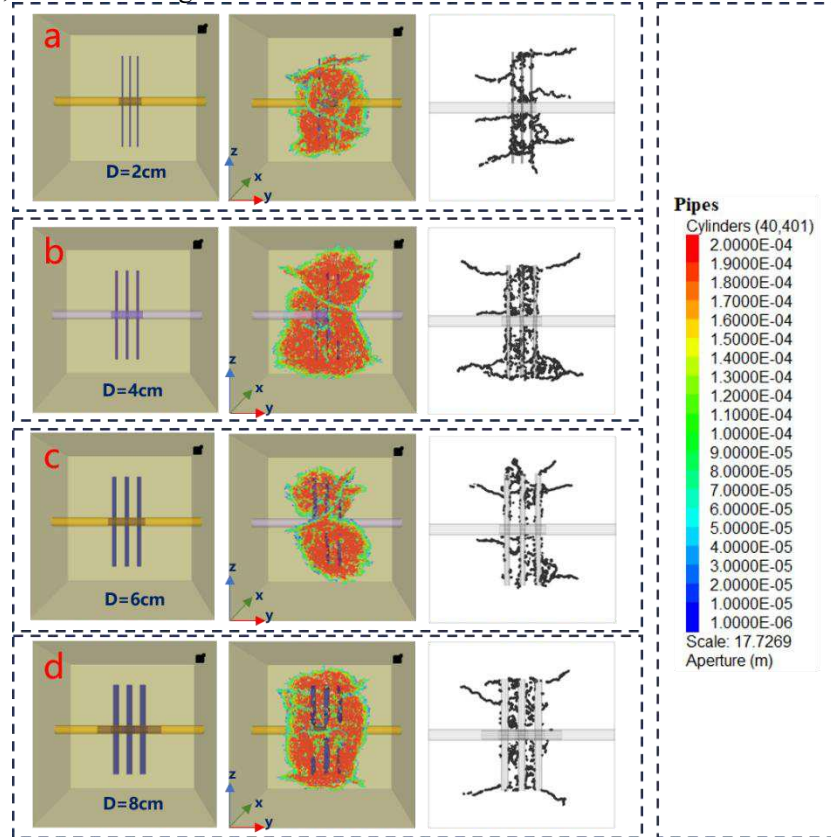


Fig.16 Fracture propagation under different perforation diameter

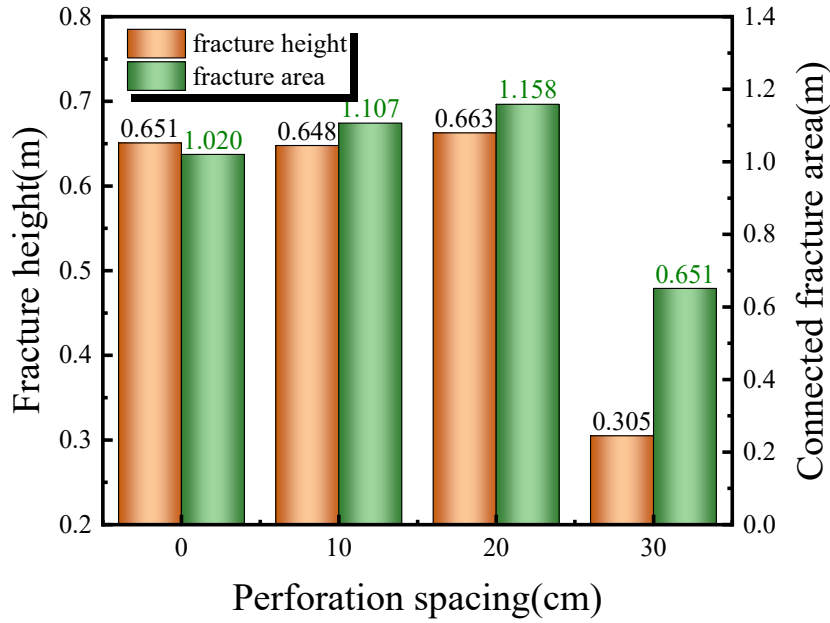


Fig.17 Index of vertical sheet fractures under different perforation diameters

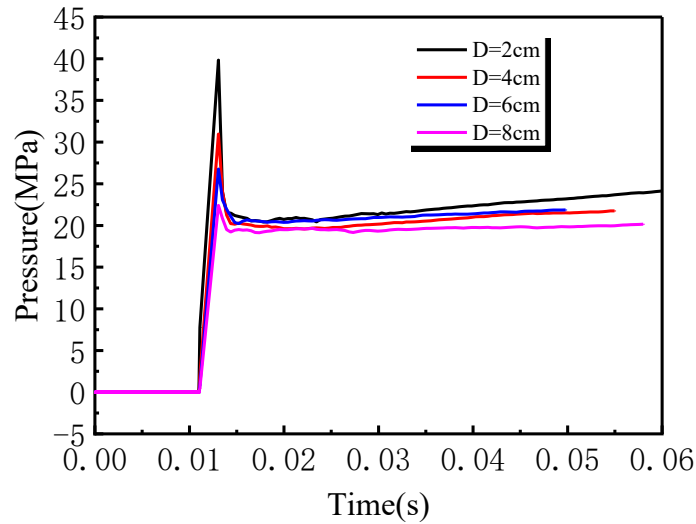


Fig.18 Fracturing curve under different perforation diameter

Figure 18 compares the fracturing curves at perforation diameters of 2 cm, 4 cm, 6 cm, and 8 cm. It can be seen from the figure that increasing the perforation diameter strengthens the influence of internal fluid pressure on the rock mass between perforations, reduces the fracture initiation pressure, and promotes the connection of fractures among perforations. When the perforation diameter increases from 2 cm to 8 cm, the fracture initiation pressure decreases from 40 MPa to 22 MPa, a reduction of 45%. Therefore, the perforation diameter is optimized to 8 cm.

4.3 Space of arrayed perforation

Figure 19 shows the fracture network propagation morphology at perforation spacings of 0 cm, 10 cm, 20 cm, and 30 cm. At a perforation spacing of 0 cm, adjacent perforations merge into a rectangular integral slot. Under rectangular fluid pressure, fractures initiate at the perforations on both ends of the slot and propagate along the perforation direction, as shown in Figure 19(a). As the perforation spacing increases to 10 cm and 20 cm, fractures initiate and propagate under perforation guidance. Driven by the fluid pressure between adjacent perforations, fractures connect with each other to form continuous vertical fractures along the borehole axis, as shown in Figures 19(b) and 19(c). However, when the perforation spacing is further increased to 30 cm, the influence of fluid pressure between neighboring perforations is weakened, resulting in fracture blank zones between perforations. This

suppresses the formation of connected fractures and reduces the guiding capability of arrayed perforations, as shown in Figure 19(d). When the perforation spacing is less than 20 cm, its increase has little effect on fracture height and continuous fracture range. As the spacing increases from 0 cm to 20 cm, the fracture height and continuous range change by only 1.84% and 13.53%, respectively. However, when the spacing increases to 30 cm, the fracture height and continuous range decrease by 54% and 43.78%, respectively, as shown in Figure 20.

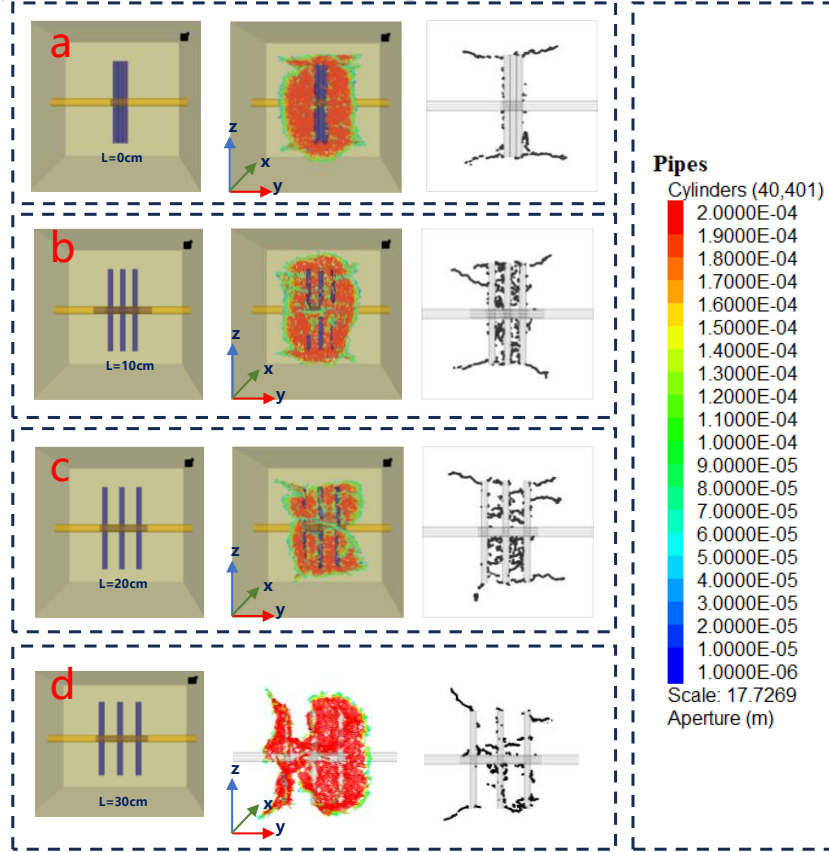


Fig.19 Fracture propagation under different perforation spacing

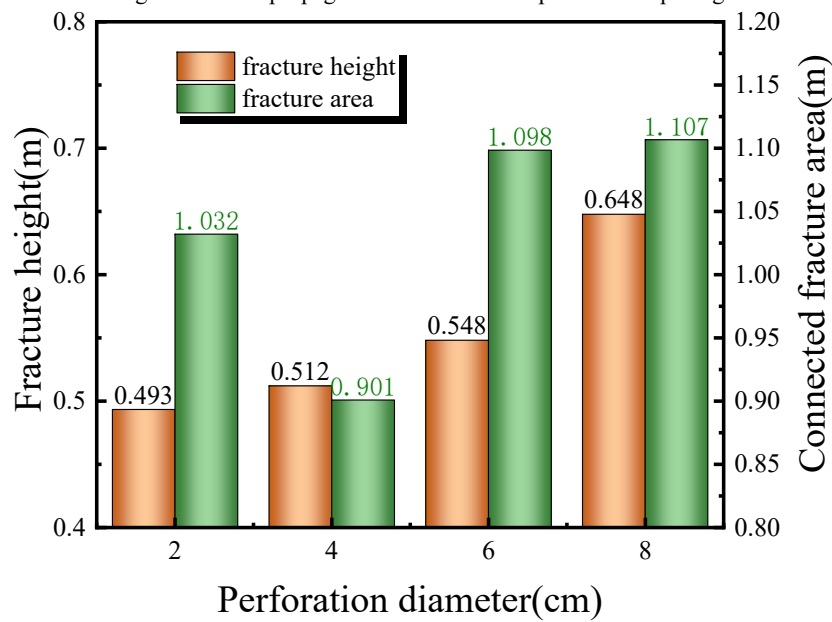


Fig.20 Index of vertical sheet fractures under different perforation spacing

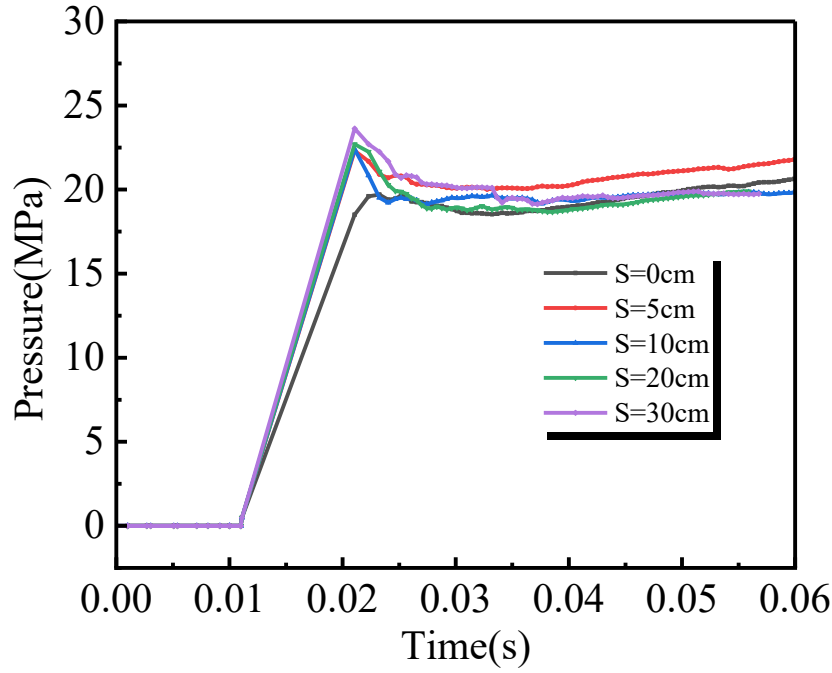


Fig.21 Fracturing curve under different perforation spacing

Figure 21 compares the fracturing curves at perforation spacings of 0 cm, 10 cm, 20 cm, and 30 cm. It can be seen from the figure that at a perforation spacing of 0 cm, adjacent perforations connect to form a rectangular slot. Under the internal fluid pressure, fractures initiate and propagate at both ends of the slot, with an initiation pressure of 19.8 MPa. As the perforation spacing increases, the rectangular fluid space separates, and the fluid pressure inside each perforation affects neighboring perforations, resulting in an increase in fracture initiation pressure. At perforation spacings of 10 cm and 20 cm, the initiation pressure reaches 22 MPa, an increase of 11.11 MPa compared with 0 cm spacing. As the spacing further increases to 30 cm, the guiding effect between adjacent perforations is weakened, and the initiation pressure rises to 24 MPa. Therefore, the perforation spacing is optimized to 20 cm.

Based on the simulation results of fracture network propagation guided by arrayed perforations, the key parameters of arrayed perforation-guided fracturing were optimized. The optimized parameters are as follows: injection rate is $1.2 \text{ m}^3 \cdot \text{min}^{-1}$, perforation diameter is 8 cm, and perforation spacing is 20 cm.

5 Industrial test

5.1 Principle and technology of abrasive jet perforation guided hydraulic fracturing

The fundamental principle of abrasive waterjet technology is to use high-pressure waterjet mixed with abrasive particles to impact rock at high velocity before hydraulic fracturing, creating a cutting effect and forming holes of a certain size. During hydraulic fracturing, these prefabricated holes induce hydraulic fractures to propagate along their orientation, thereby achieving directional stimulation of the thick and hard roof. The equipment is shown in Figure 22.



Fig.22 Abrasive water jet equipment

The technological process of abrasive waterjet slotting technology is as follows: ① Start the pump and increase the flow rate to the designed value; the outlet pressure of the pump shall match the sand-blasting pressure. ② Add sand and viscosity enhancer, stabilize the sand proportion at 5%~7%, and inject the viscosity enhancer at a predetermined flow rate. ③ Perform perforation, with the perforation duration no less than 10 minutes. ④ Stop sand addition once the designed perforation time is reached. ⑤ Displacement: after stopping sand addition, flush the pipeline with clean water or suspension to ensure no sand accumulation between the fracturing pipe and perforations. ⑥ Stop the pump and shut down the high-pressure water pump after confirming no sand residue in the pipeline. ⑦ Conduct the next section of perforation: shorten the length of the fracturing string, retract the spray gun to the next position, and repeat steps ①~⑥ until the last section is completed. ⑧ Continuous perforation: adopt retractable perforation (from deep to shallow). The technological process of retractable staged hydraulic fracturing technology is as follows: ① Design and assemble hydraulic fracturing tools, then convey them to the designed position by a drilling rig. ② Start the fracturing pump and monitor the pumping pressure and flow curves to ensure the packer sets normally. ③ After packer setting, increase the displacement to conduct fracturing operation until the designed fluid volume is injected. ④ Stop the pump, unset the packer, and drag the tool string to the next fracturing section for operation. ⑤ Repeat the above steps until the fracturing of the entire borehole section is completed^[40-41]. The processes are shown in Figures 23 and 24.

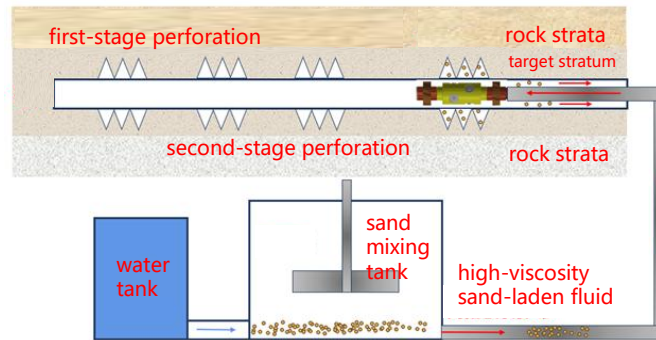


Fig.23 Diagram of continuous perforation^[40-41]

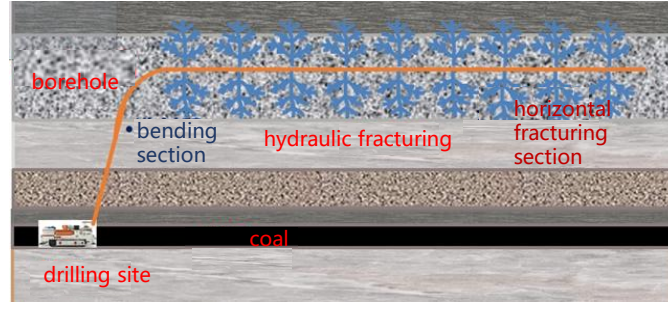


Fig.24 Hydraulic fracturing diagram of long horizontal hole directional drilling^[40]

5.2 Scheme of hydraulic fracturing guided by arrayed perforation

An industrial test was conducted at the 122105 working face of Caojiatan Coal Mine. Arrayed perforations were formed in the underground mine using an abrasive waterjet spray gun. Based on site conditions and construction requirements, a scheme for roof cutting via arrayed perforation-guided fracturing was designed. Five directional long boreholes were arranged in the siltstone layer at 14 m and the fine-grained sandstone layer at 24 m above the working face, respectively. The boreholes have a diameter of 0.12 m and a total length of 500 m, with a horizontal section of 400 m. The distance between the arrayed perforation-oriented hydraulic fracturing roof cutting and the belt transport entry is 10 m, and the perforation direction is perpendicular to the vertical stress direction. Each borehole is equipped with 14 fracturing stages, with a spacing of 15 m between stages, as shown in Figure 25.

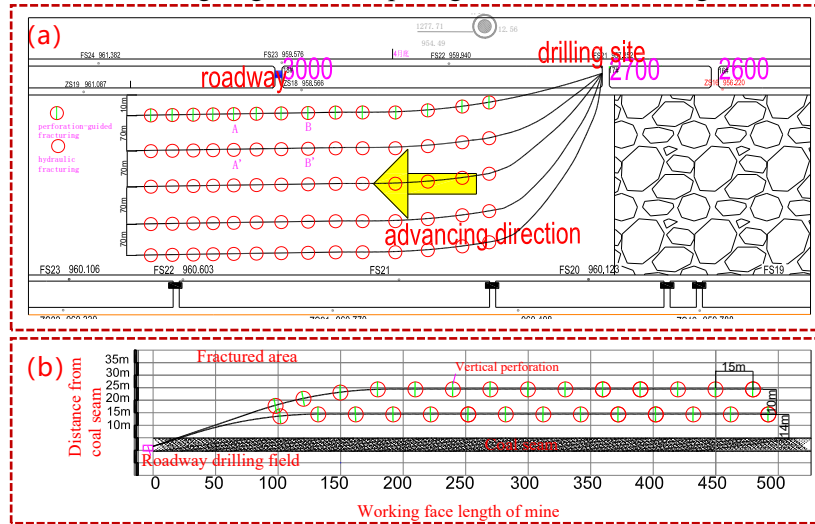


Fig.25 The borehole layout of fracturing. (a) top view; (b) section view

5.3 Monitoring of fracturing effect guided by arrayed perforation

To monitor the field application effect of the fracturing scheme, monitoring points were arranged in both the arrayed perforation-guided fracturing section and the unfractured section to continuously monitor roof fracture energy, stress of rock bolts (cables), and roadway deformation.

It can be seen from the planar distribution of microseismic events in the non-fractured and fractured sections in Figure 26 that a total of 325 microseismic events occurred in the fractured section, including 73 events with energy magnitude of 10^3 J and above, accounting for 22.46%. In the non-fractured section, 270 microseismic events occurred, including 96 events with energy magnitude of 10^3 J and above, accounting for 35.56%. In terms of roof fracture intensity, high-energy microseismic events were mainly concentrated in the non-fractured section, while the spatial density of high-energy events in the fractured section was relatively low. The fractured section generally showed a trend of high frequency and low energy, indicating that arrayed perforation-guided fracturing effectively induced frequent roof fracturing, reduced the roof caving interval, and released the elastic energy accumulated in the roof.

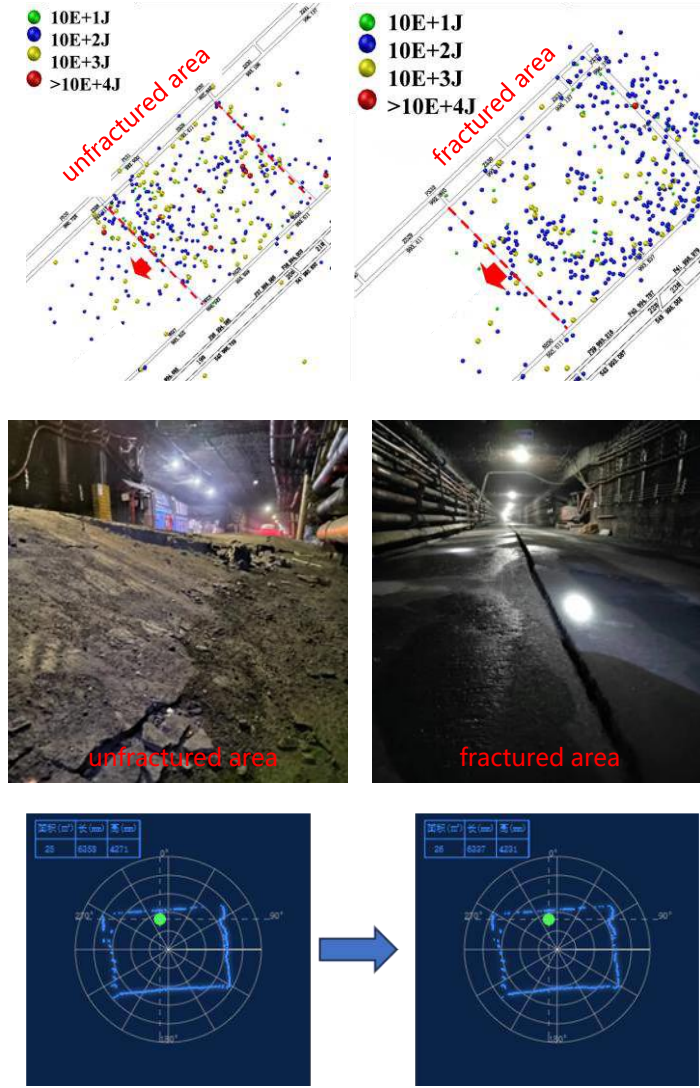


Fig.26 The deformation measurement of roadway

6 Conclusions

In this paper, theoretical analysis and numerical simulation were used to investigate the fracture propagation behavior of perforation-guided fracturing in shallow buried large-section roadways. Field tests were carried out at the 122105 working face of Caojiatan Coal Mine, and the main conclusions are as follows:

(1) To form continuous vertical fractures inside the thick and hard roof of shallow buried large-section roadways, formulas for perforation-guided fracture network propagation and stress influence between adjacent perforations were derived based on elasticity. True triaxial hydraulic fracturing tests show that perforations can weaken the influence of the in-situ stress field and guide fracture propagation, with the fracture initiation pressure reduced by 22.5% compared with conventional fracturing. An oriented fracturing method using arrayed perforations is proposed, and the key parameters are identified as injection rate, perforation diameter, and perforation spacing.

(2) XSite numerical simulation was used to compare fracture network propagation characteristics under non-perforated, single-perforated, and arrayed perforation conditions. Results show that fluid pressure within arrayed perforations interacts along the borehole axis, causing fractures between perforations to connect and form continuous vertical fractures along the borehole.

(3) Based on fracture height and continuity indicators, increasing pumping rate and perforation diameter enhances the guiding capability of arrayed perforations and promotes vertical fracture growth. When the injection rate increased from $0.12 \text{ m}^3 \cdot \text{min}^{-1}$ to $1.2 \text{ m}^3 \cdot \text{min}^{-1}$, fracture height increased by 310.83%; when perforation diameter

increased from 2 cm to 8 cm, fracture height increased by 31.44%. Increasing perforation spacing weakens the fluid pressure interaction between adjacent perforations, creating blank fracture zones and suppressing connected fractures. The optimized arrayed perforation parameters for shallow buried large-section roadways are: perforation diameter 8 cm, pumping rate $1.2 \text{ m}^3 \cdot \text{min}^{-1}$, and perforation spacing 20 cm.

(4) An industrial test of arrayed perforation-guided fracturing was conducted at the 122105 working face of Caojiatan Coal Mine. Microseismic monitoring, roadway section scanning, and bolt (cable) stress monitoring were used to compare the effects of untreated and fracturing zones. Compared with the unfractured area, events with energy of 10^3 J and above decreased by 23.96%. The results demonstrate that arrayed perforation-guided fracturing can damage the integrity of the roof strata and block lateral roof fracture stress in shallow buried large-section roadways.

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CRediT authorship contribution statement

Yu Wang: Writing-original draft, Conceptualization, Writing-review & editing, Data curation. Yanjun Feng: Supervision, Conceptualization. Kaikai Zhao: Investigation.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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