Hindawi
Shock and Vibration
Volume 2022, Article ID 3044121, 13 pages
https://doi.org/10.1155/2022/3044121

Research Article

Mechanism and Numerical Simulation of Vertical Fracture Propagation in Composite Coal Rock

Fan Zhang[1,2] **Hanjin Wan,**[1] **Yan Liu,**[1] **Shuwei Li,**[1] **and Zijiang Li**[1]

[1]*School of Resources and Safety Engineering, Henan University of Engineering, Zhengzhou, Henan 451191, China*
[2]*Research Institute of Mine Safety and Green Mining, Henan University of Engineering, Zhengzhou, Henan 451191, China*

Correspondence should be addressed to Fan Zhang; 379591198@qq.com

Received 13 June 2022; Revised 29 July 2022; Accepted 4 August 2022; Published 27 August 2022

Academic Editor: Xue-Qiu He

Vertical fracture propagation mechanism is important to understand the effect of hydraulic fracturing on the roof of outburst coal seams. In this paper, the differences in physical parameters and in situ stress between an outburst coal seam and its roof strata were compared, and influencing factors of roof-fracturing fractures connecting coal seams were vertically analyzed. The impact of different fracturing strata and injection rates on fracture propagation was studied by numerical models. Results show that the horizontal principal stress of an outburst coal seam is less than that of roof strata, and the fracture length of roof fracturing is larger than that of an outburst coal seam. Roof-fracturing fracture of an outburst coal seam has the material conditions to communicate downward with the coal seam. The downward propagation height of roof-fracturing fracture is positively correlated with the minimum horizontal stress difference between an outburst coal seam and its roof strata. Soft coal fracturing cannot form a long fracture dominated by tensile failure, so the coal seam can be communicated by transforming the roof strata of soft coal to form vertical fractures. The injection rate affects the failure location, fracture width, and fracture-propagation path of the numerical model. Construction parameters should be reasonably designed in accordance with the physical parameters of coal and rock, construction displacement, and in situ stress. These research results can provide a theoretical basis and data support for the design, and optimization of construction parameters of roof fracturing in outburst coal seams.

1. Introduction

Coal plays an important role in the present and future energy structure of China, and the coal-mining depth is still increasing [1]. Deeply buried coals have the characteristics of low permeability, low gas saturation, high gas content, difficult extraction, and large gas emission [2, 3]. Most domestic coal mines use layer-crossing boreholes for gas predrainage, but defects exist, such as a long gas governance period, high construction cost, and a large amount of construction [4–6]. To improve the efficiency of gas drainage, roof-fracturing technology on outburst coal was proposed, and a good gas-drainage effect in the field was achieved [7–9]. The application of this technology is affected by the in situ stress of coal and rock reservoirs, mechanical parameters, interfacial properties, and other factors [1, 10]. Therefore, it is necessary to study fracture-propagation paths under different conditions to select reasonable construction parameters and improve fracturing effects.

Many experts and scholars have conducted in-depth research on roof-fracturing technology of outburst coal seams and achieved fruitful research results [11–14]. The mechanism of stress difference, fracturing layer, interlayer stress difference, lithology difference, interfacial property, fracturing fluid displacement, and horizontal good distance on multistage fracturing has been revealed by physical and numerical simulation tests [3, 11, 12, 14]. It has been concluded that the stress difference between a roof and outburst coal seam plays a key role in fracture layer-crossing propagation, and determines whether hydraulic fracture in the roof of an outburst coal seam can pass through the coal-rock interface and communicate with the coal seam. In addition, many experts have compared the effects of influencing factors on multistage fracturing and conducted field tests in different coal mines [14, 15]. By comparing multifracturing technology and traditional gas-control methods, it has been observed that gas-drainage concentration and purity-gas-drainage volume can be greatly improved.

Although, Chinese experts and scholars have carried out a significant amount of research work on roof-fracturing technology, due to different in situ stresses, mechanical parameters, interfacial properties of coal seams and rock, physical simulation tests, and field tests cannot be used to intuitively observe the fracture-propagation path and morphology. In the work described in this paper, Coal Seam No 21 of Zhongmacun Coal Mine in Jiaozuo City, China was taken as the research object. Through theoretical analysis and numerical simulation, the influencing factors of vertical expansion of hydraulic fracture in the roof of an outburst coal seam were studied, and the fracture-propagation path under different fracturing strata and different injection rates was analyzed. The research results can provide a theoretical basis and data support for the design, and optimization of construction parameters of roof fracturing in the outburst coal seam.

2. Mathematical Model

The value and orientation of in situ stress affect the permeability of coal seam and the occurrence and migration of coalbed methane in addition to playing a decisive role in fracture morphology and affecting the final effect of gas drainage. In situ stress is composed of gravity stress and tectonic stress, which is generally characterized by maximum horizontal stress (σ_H), vertical stress (σ_v), and minimum horizontal stress (σ_h) [16].

It is assumed that the coal seam comprises isotropic homogeneous elastic bodies, and there is no relative displacement between one reservoir and an adjacent one during sedimentary movement and late tectonic movement. The horizontal stress can be calculated using equation (1) due to the influence of tectonic stress, pore fluid pressure, and upward pressure on horizontal in situ stress [17].

$$\begin{cases} \sigma_H = \dfrac{v}{1-v}\left(\sigma_v - \alpha p_p\right) + \dfrac{E\varepsilon_H}{1-v^2} + \dfrac{vE\varepsilon_h}{1-v^2} + \alpha p_p, \\ \sigma_h = \dfrac{v}{1-v}\left(\sigma_v - \alpha p_p\right) + \dfrac{E\varepsilon_h}{1-v^2} + \dfrac{vE\varepsilon_H}{1-v^2} + \alpha p_p, \end{cases} \tag{1}$$

where v is Poisson's ratio; α is Biot's porous elastic coefficient, P_p is the pore fluid pressure, in MPa; ε_H is the strain in the direction of maximum horizontal stress, in %; ε_h is the strain in the direction of minimum horizontal stress, also in %.

It can be seen from equation (1) that, when other parameters are fixed, the maximum and minimum horizontal stresses increase with increasing elastic modulus. That is to say, the horizontal stress is positively correlated with the elastic modulus of coal and rock. Combined with the mechanical parameters of the roof and floor of a coal seam, the elastic modulus of roof strata is mostly greater than that of the outburst coal seam. Therefore, the horizontal stress of the outburst coal seam is smaller than that of roof strata.

Figure 1 shows the fracture-propagation path under different stress conditions. When $\sigma_v > \sigma_H > \sigma_h$, the hydraulic fracture is vertical fracture; when $\sigma_v > \sigma_H > \sigma_h$, the hydraulic fracture is horizontal fracture.

The two-dimensional Perkins–Kern–Nordgren (PKN) model (Figure 2) was first proposed in 1961 [18]. This model assumes that fracture height is constant, and a fracture section propagates elliptically. This model is suitable for low filtration coefficient and short-term fracturing design.

In the PKN model, fracture width at any position of hydraulic fracture in coal and rock can be calculated by the following equation [17]:

$$W = 2\alpha\left[\left(\frac{1}{60}\right)\frac{(1-v^2)Q\mu L}{E}\right]^{0.25}, \tag{2}$$

where W is the fracture width, in mm; α is the flow coefficient of fracturing fluid; v is Poisson's ratio of coal and rock in different directions; Q is the displacement of fracturing fluid, in L/min; μ is the viscosity of fracturing fluid, in Pa·s; L is the fracture length, in m; E is the elastic modulus of coal and rock in different directions, in GPa.

It can be seen from equation (2) that fracture widths are different due to different physical parameters, such as bedding direction and lithology. In the target fractured coal reservoir studied, the fracture width parallel to the bedding direction is greater than that perpendicular to it. In accordance with the law of conservation of energy, the fracture length parallel to the bedding direction is smaller than that perpendicular to it. Generally, the elastic modulus of roof strata is greater than that of an outburst coal seam, the fracture width in the roof strata of an outburst coal seam is smaller than that in an outburst coal seam, and the change rule of fracture length is the opposite. In summary, roof-fracturing fracture of an outburst coal seam has the material conditions to communicate downward with a coal seam.

The key to roof fracturing in outburst coal seams lies in whether the hydraulic fracture in roof strata can connect the outburst coal seam and the range of hydraulic fractures entering the outburst coal seam, which is closely related to fracture height. Hydraulic fracture first cracks and propagates in the roof strata of an outburst coal seam. Assuming that the hydraulic fractures propagate symmetrically before entering the outburst coal seam (Figure 3), the upper and lower hydraulic fracture heights can be calculated by the following equation:

$$h_1 = h_2, = h(0,t), = q(0,t)\frac{4\pi}{K_{IC_1}^4}\left(\frac{E_1}{1-v^2}\right)^3\mu_1 y, \tag{3}$$

where h_1 is the upper fracture height and h_2 is the lower fracture height, in m; $h(0, t)$ is the fracture height at $y = 0$ at t moment, in m; $q(0, t)$ is the volume flow rate of the hydraulic fracture section at $y = 0$ at t moment, in m^3/min; y represents the fracture-length coordinates, in m; K_{IC1} is the fracture toughness of the roof strata of the outburst coal seam; $E1$ is

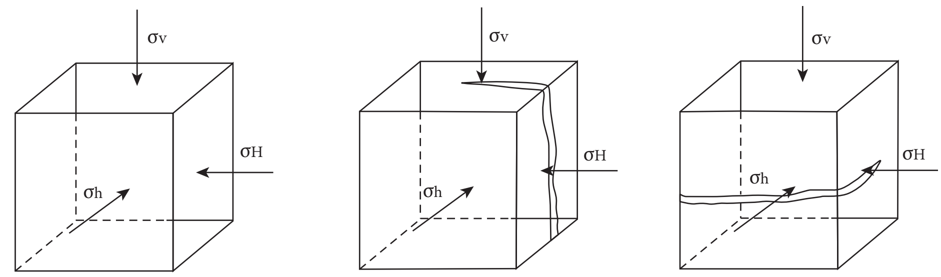


Figure 1: Fracture propagation path.

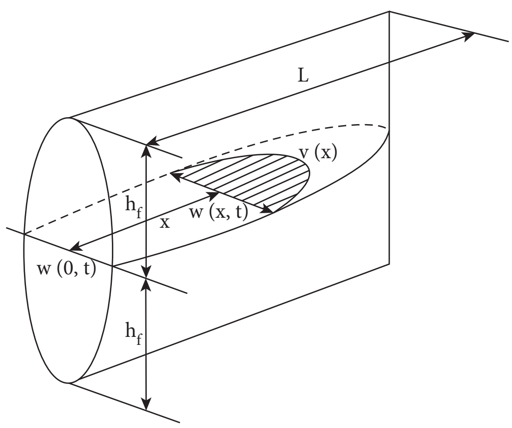


Figure 2: Model PKN.

the elastic modulus of the roof strata of the outburst coal seam, in GPa; μ_1 is Poisson's ratio of the roof strata of the outburst coal seam.

As the fracturing fluid continues to pump into a hydraulic fracture, the vertical fracture continues to propagate in the roof of the outburst coal seam. The constraints of minimum horizontal stress and tensile strength must be overcome simultaneously in the process of vertical fracture propagation [17]. It can be seen from (1) that the minimum horizontal stress and tensile strength of the roof strata of an outburst coal seam are greater than those of the outburst coal seam itself. When the coal-rock interface is well cemented and the interface does not slide, the hydraulic fracture eventually passes through the lower end of the roof strata of the outburst coal seam and enters the outburst coal seam (Figure 4), and the water pressure at the fracture tip increases. At this time, the fracture propagation in the outburst coal seam is directly related to the structural properties of the coal seam, and there is a possibility that the outburst coal seam cannot be pressed through.

As shown in Figure 4, the upper and lower ends of hydraulic fracture propagate asymmetrically in the roof strata and outburst coal seam under different stresses. The lower fracture height can be obtained from the following equation [19]:

$$h_2 = \frac{p_{\text{net}}^2 + 4/\pi\left(\sigma_{h2} - \sigma_{h1}\right)^2\left[\arccos\left(H/h_1 + h_2\right)\right]^2 + 2p_{\text{net}}2/\pi\arccos\left(H/h_1 + h_2\right)}{K_{IC_2}^2}\pi, \quad (4)$$

where p_{net} is the water pressure in hydraulic fracture, in MPa; σ_{h1} and σ_{h2} are the minimum horizontal stresses of the roof strata and outburst coal seam, respectively, in MPa; H is the thickness of the outburst coal seam, in m; K_{IC2} is the fracture toughness of the outburst coal seam.

It can be seen from equation (4) that the lower fracture height is positively correlated with the minimum horizontal stress difference between the roof strata and outburst coal seam. That is to say, the greater the minimum horizontal stress difference, the greater the lower fracture height, and the greater the vertical distance of hydraulic fracture into the outburst coal seam. Fracture height is also related to water pressure, permeability, natural fractures, fracturing fluid displacement, fracturing fluid viscosity, and other factors [20–22].

If the hydraulic fracture in the outburst coal seam passes through the coal-rock interface into the floor strata ($h_2 > h + H$) of the outburst coal seam, the constraint of minimum horizontal stress and tensile strength of the floor strata should also be overcome in the process of fracture propagation. However, due to the minimum horizontal stress and tensile strength of the floor strata of an outburst coal seam being greater than that of the outburst coal seam itself, the hydraulic fracture water pressure decreases, hindering vertical fracture propagation in the outburst coal seam.

3. Numerical Simulation

Coal Seam No. 21 of Zhongmacun Coal Mine in Jiaozuo City, Henan Province, China was taken as the research object of the present work, and the real failure process analysis system (RFPA2D-flow system) was used to carry out hydraulic fracturing simulation experiments under different fracturing strata and different injection rates. Measurement results show that the buried depth of Coal Seam No. 21 is

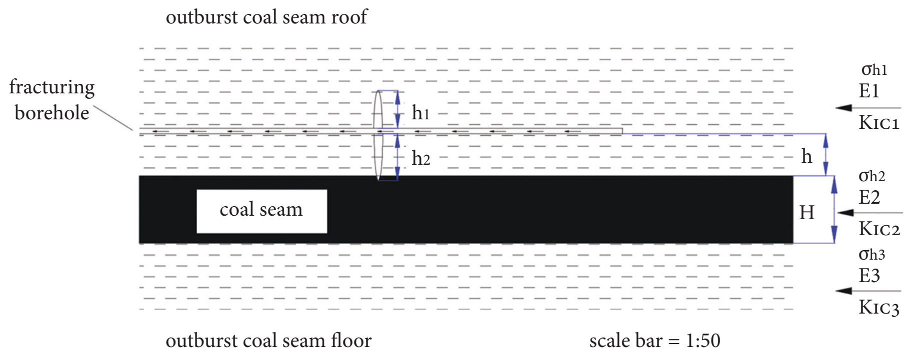


Figure 3: Symmetrical hydraulic fracture propagating in the roof of the outburst coal seam.

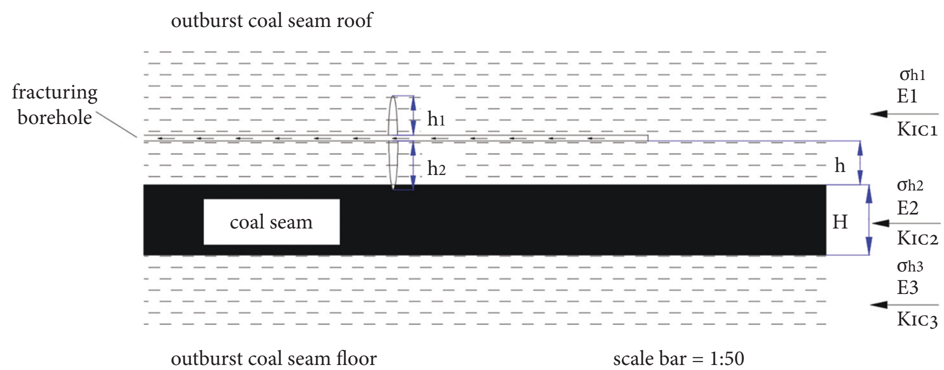


Figure 4: Asymmetric hydraulic fracture propagating after fracture enters outburst coal seam.

approximately 480 m, the maximum horizontal stress approximately 14 MPa, the vertical stress approximately 9 MPa, and the minimum horizontal stress approximately 12 MPa. The mechanical parameters of the numerical model are shown in Table 1. The model size is 300 m × 300 m and is divided into 300 × 300 = 90,000 cells. The model was loaded by confining pressure, and a plane simplified model was used as the plane strain model.

4. Results and Discussion

4.1. Effect of Different Strata on Fracture Propagation. Fracturing strata are very important for hydraulic fracturing in outburst coal seams. In the present work, both soft-coal and medium-sandstone fracturing were simulated separately, and the propagation characteristics of hydraulic fractures were compared and analyzed. The confining pressure stress parameters were as follows: vertical loading stress (σ_v) 9 MPa and lateral loading stress (σ_H) 14 MPa. The radius of the fracturing hole at the center of this model was 0.3 m, and the initial water pressure in the fracturing hole was 10 MPa, increasing in steps to 0.5 MPa. Figures 5 and 6 show the fracture morphology of soft-coal and medium-sandstone fracturing, respectively.

Figure 5(b) is a diagram of acoustic emission in the soft-coal fracturing process. In the figure, the acoustic emission circle is based on the energy of acoustic emission, and the white circle is the acoustic emission generated by shear failure. The size of the acoustic emission circle represents the energy released by hydraulic fracturing. Figure 5 shows that soft-coal fracturing failed to form a long fracture propagating along with the direction of maximum stress, and no tensile failure occurred. It can be seen that the permeability improvement effect of soft coal under compaction and water sensitivity is limited, and the strengthening effect is generally poor. Analysis shows that the soft coal has been destroyed into plastic materials, which is a kind of dispersion. When the fracturing fluid enters this kind of coal seam, the fracturing fluid accumulates and propagates at a certain position to produce holes. When the water pressure increases to a certain extent, the fracturing fluid is punctured and unloaded in other directions at this position, and the fracturing fluid is continuously punctured and unloaded. The stress-concentration zone is formed on the wall of the swelling holes and puncture holes, resulting in serious compaction of the coal itself. The porosity of this compaction zone is low, which seriously affects the gas-drainage effect. Therefore, conventional hydraulic fracturing technology in soft coal cannot achieve the ideal effect of permeability enhancement.

The red circle in Figure 6(b) is the acoustic emission caused by tensile failure. It can be seen from Figure 6 that medium-sandstone fracturing is mainly tensile failure. Under the action of internal water pressure in the fracturing hole, an effective long fracture propagating along the maximum horizontal stress is formed, and the hydraulic fractures on both sides of the fracturing hole are symmetrical.

Table 1: Mechanical parameters of numerical simulation model [2].

Parameters	Medium sandstone	Sandy mudstone	Mudstone	Soft coal
Mean degree	3	3	3	3
Compressive strength (MPa)	90	72	15	2
Elastic modulus (GPa)	25	13	8	5
Poisson's ratio	0.22	0.31	0.31	0.33
Coefficient of residual strength	0.1	0.1	0.1	0.1
Coefficient of porosity pressure	1	1	1	1

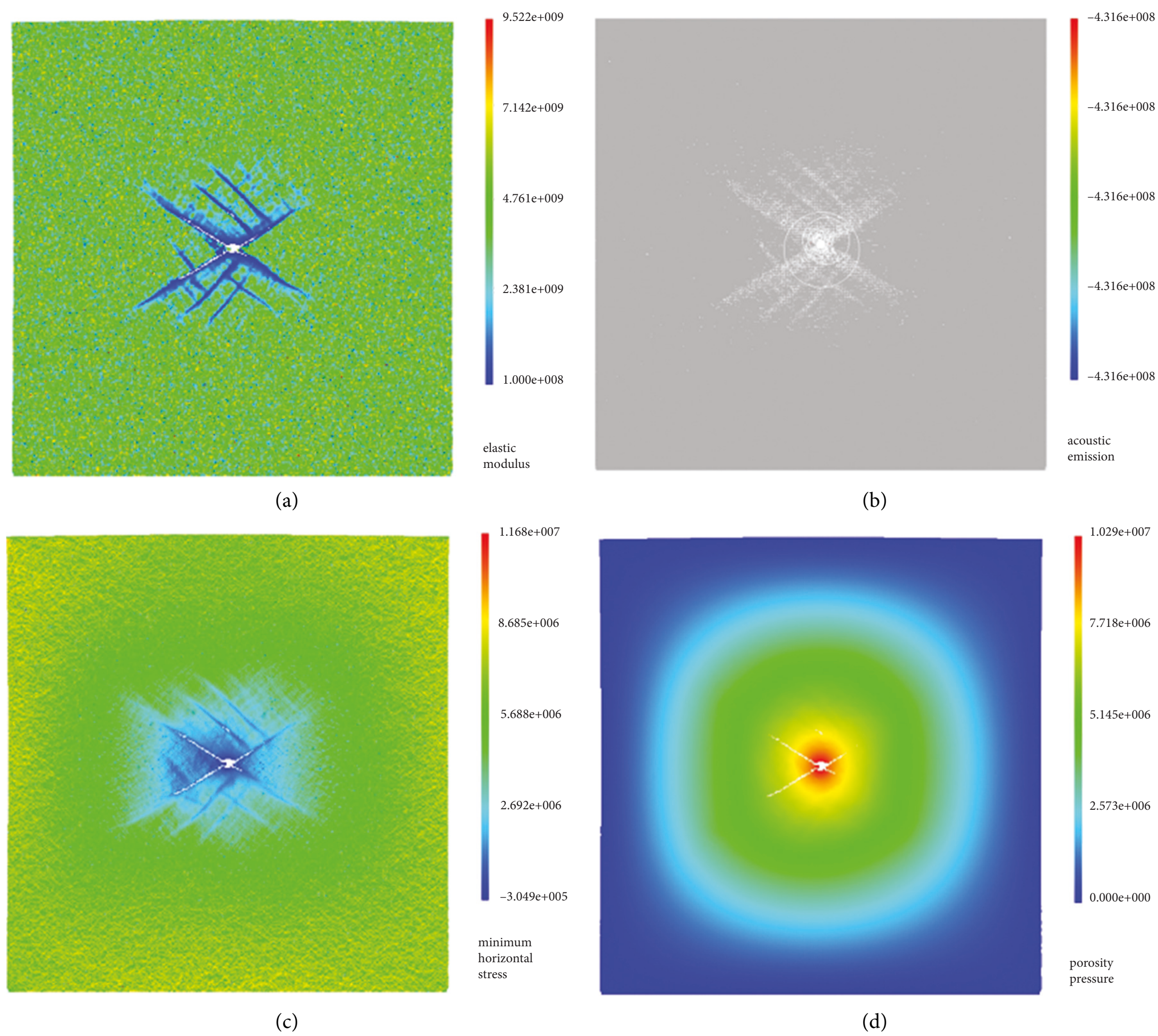


Figure 5: Fracture morphology of soft coal fracturing. (a) Elastic modulus. (b) Acoustic emission. (c) Minimum horizontal stress. (d) Porosity pressure.

Compared with Figures 5 and 6, the soft coal is still in shear failure at Step 2–47, and finally, no effective hydraulic fracture is formed; meanwhile, the hydraulic fractures of middle sandstone at Step 17–6 have been completely formed; hydraulic fractures on both sides of the fracturing hole are symmetrical and the fracturing range is large enough. This shows that the effect of medium-sandstone fracturing is better than that of soft-coal fracturing, which can provide a channel for gas migration by transforming adjacent strata of soft coal to form vertical fractures.

4.2. Effect of Different Injection Rates on Fracture Propagation. Injection rate is crucial to roof fracturing of outburst coal seams. In the present work, the hydraulic fracturing of composite coal rock under different injection rates was simulated, and the propagation characteristics of hydraulic fractures were compared and analyzed. Confining-pressure stress parameters were as follows: vertical loading stress (σ_v) 14 MPa and lateral loading stress (σ_H) 9 MPa. In accordance with the lithology characteristics of the adjacent rock strata of the outburst coal seam, the model was divided into seven

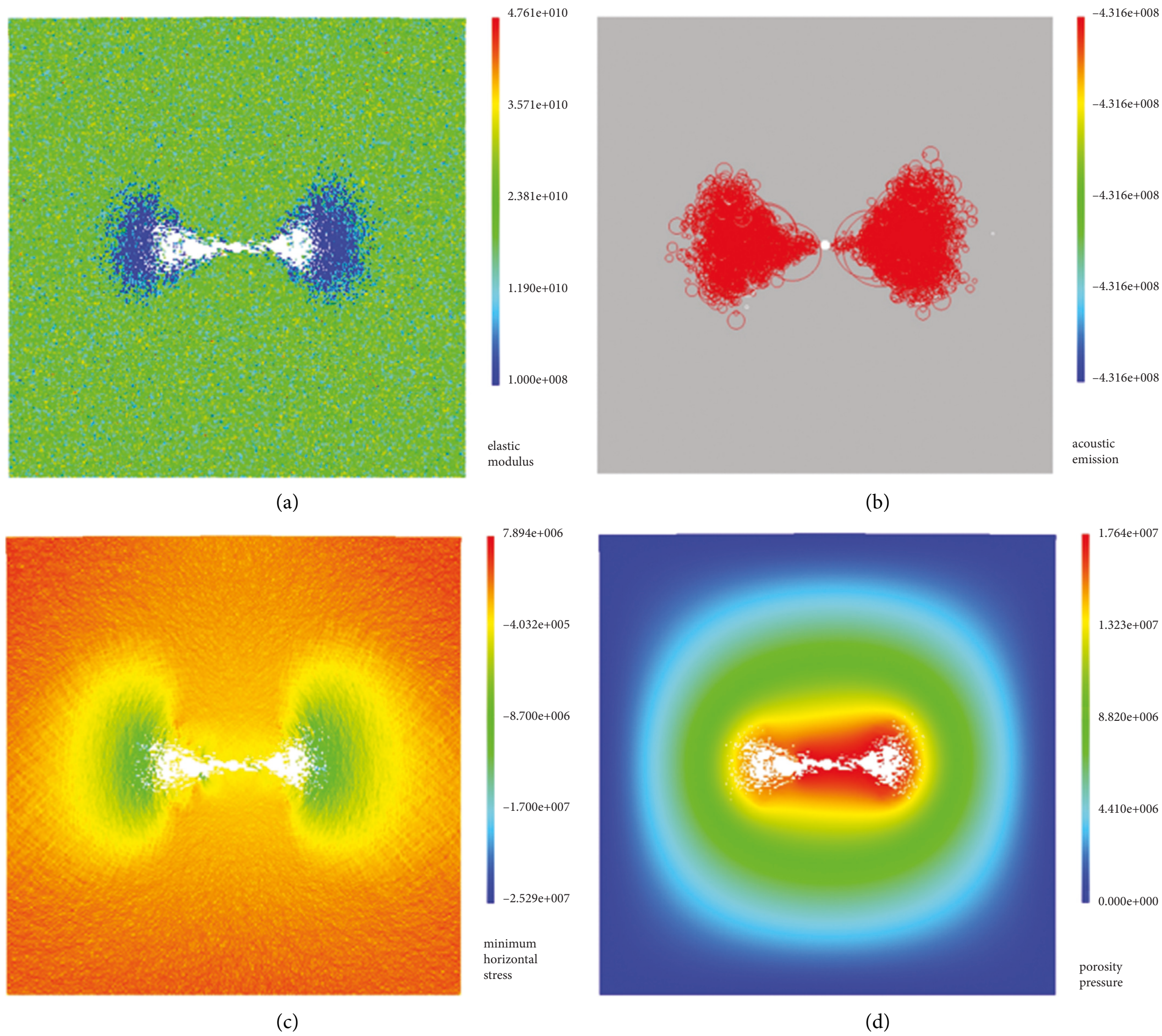
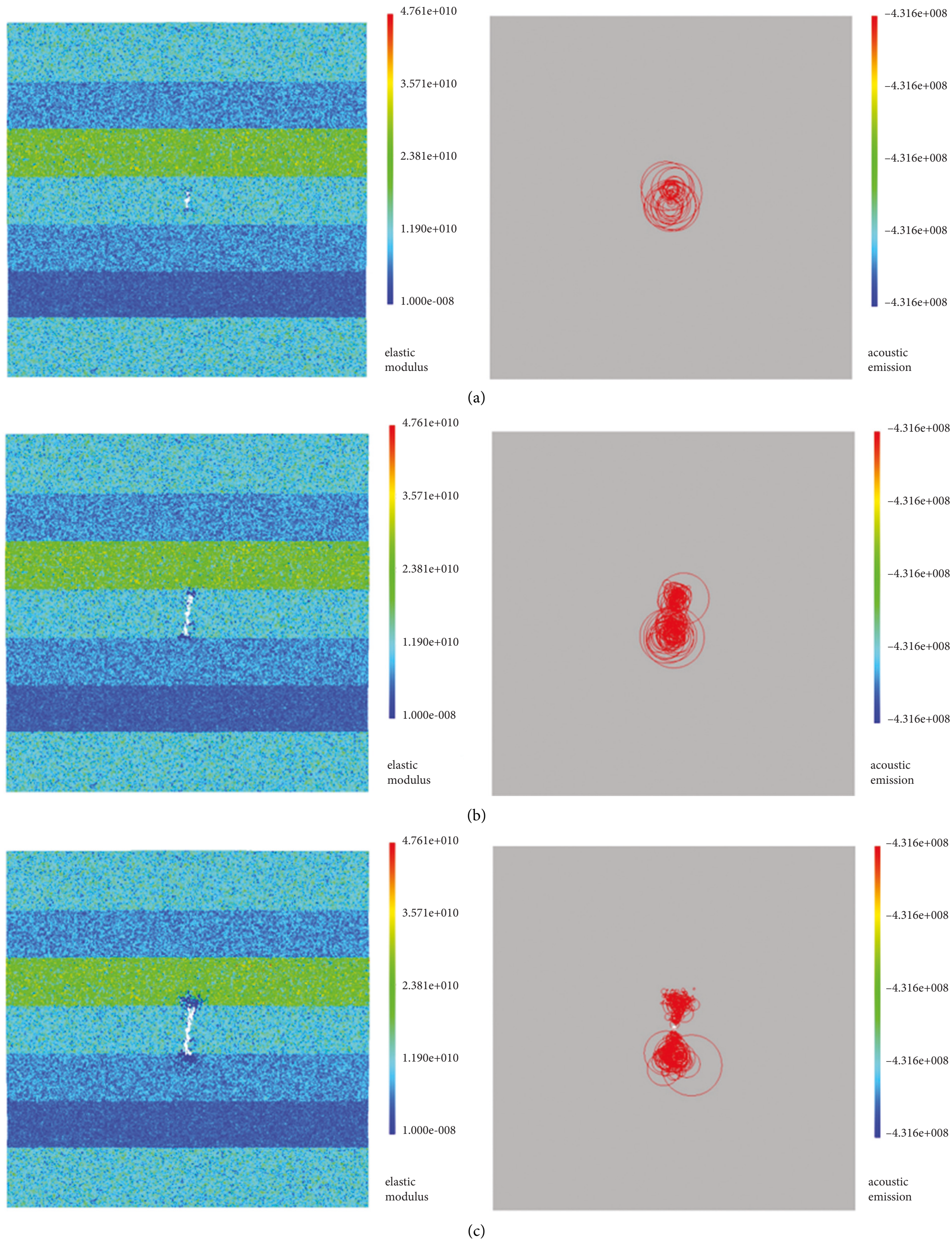


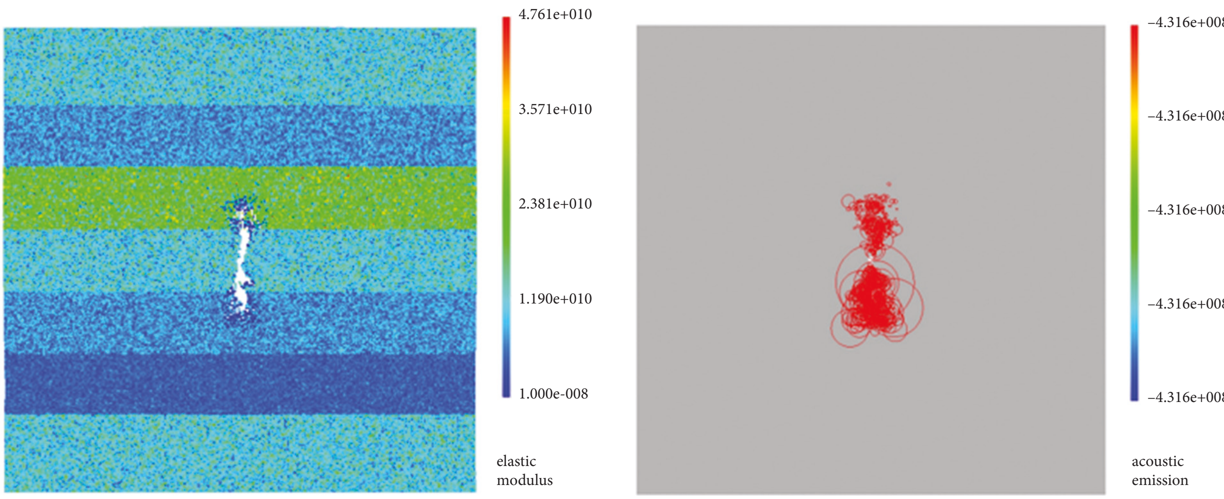
Figure 6: Fracture morphology of medium sandstone fracturing. (a) Elastic modulus. (b) Acoustic emission. (c) Minimum horizontal stress. (d) Porosity pressure.

layers, i.e., sandy mudstone, mudstone, medium sandstone, sandy mudstone, mudstone, soft coal, and sandy mudstone, from top to bottom, and the rock thicknesses are 5 meters, 4 meters, 4 meters, 4 meters, 4 meters, and 5 meters in turn. The radius of the fracturing hole at the center of the numerical model was 0.2 m, as was the distance between the fracturing hole and adjacent strata. The injection rates were as follows: initial water pressure in fracturing hole of Model No. 1, 10 MPa, and increasing in steps of 0.5 MPa; initial water pressure in fracturing hole of Model No. 2, 10 MPa, and increasing in steps of 0.2 MPa.

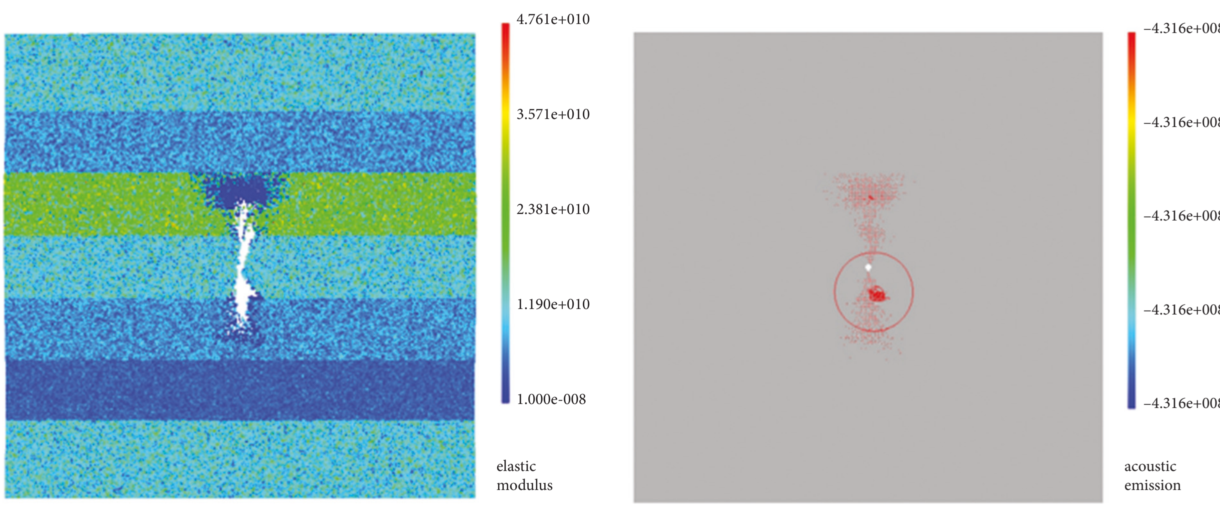
It can be seen from Figure 7(a) that, under the action of internal water pressure in the fracturing hole, Model No. 1 appears to incur tensile failure at Step 37–1. Under the continuous action of internal water pressure in the fracturing hole, the hydraulic fractures propagated in the vertical direction. It can be seen from Figures 7(b)–7(e) that the hydraulic fractures in sandy mudstone reached medium sandstone and mudstone at the same time, i.e., at Step 37–6, and branch fractures propagated right below those. The energy released by hydraulic fractures propagating downward is greater than that by hydraulic fractures propagating upward, and the hydraulic fractures first propagate to the interface between medium sandstone and mudstone. This phenomenon indicates that the hydraulic fractures are more likely to propagate in the strata with large elastic modulus, and the energy released by acoustic emission is small. From Steps 37–12 to 37–14, the model experienced the process of pressure holding, energy accumulation, and energy release, and finally, the fracture tended to propagate in the rock strata with a larger elastic modulus. At Step 37–16, the hydraulic fracture propagated downward to soft coal and upward to the mudstone-sandstone interface. Finally, the upper end of the numerical model was destroyed, and numerical calculation stopped at the same time.

Hydraulic fractures along maximum stress were generated and are shown in Figure 8(a); they reached the interface of the adjacent upper and lower strata at the same time at Step 87–2, and propagated into the adjacent strata at Step 87–3. This shows that, under the action of internal water pressure in the fracturing hole, hydraulic fractures tend to propagate upward in medium sandstone. In Figure 8(d), the

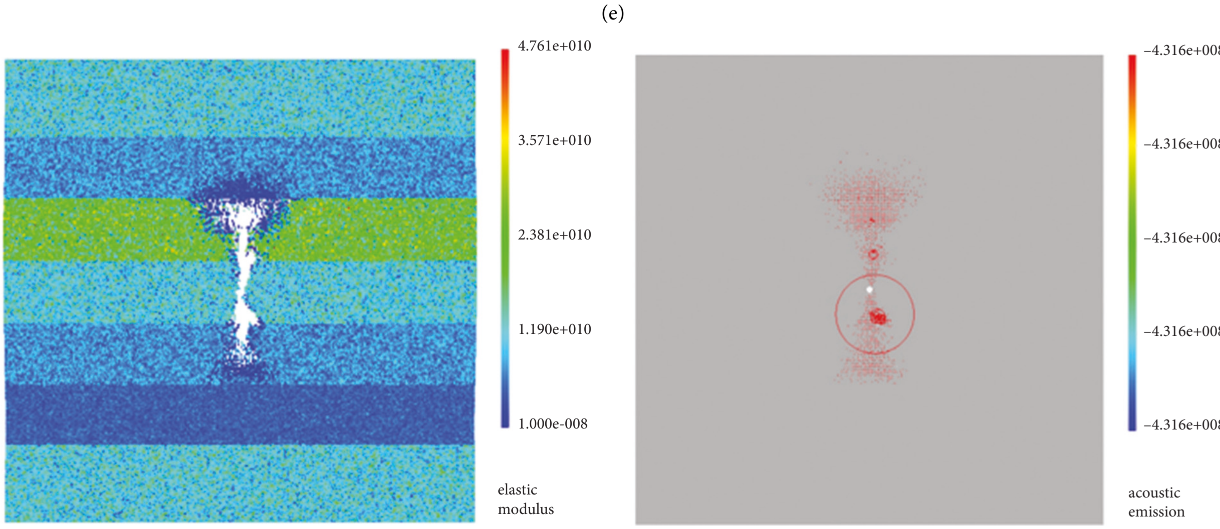

4.761e+010
3.571e+010
2.381e+010
1.190e+010
1.000e-008
elastic modulus
−4.316e+008
−4.316e+008
−4.316e+008
−4.316e+008
−4.316e+008
acoustic emission
(a)
4.761e+010
3.571e+010
2.381e+010
1.190e+010
1.000e-008
elastic modulus
−4.316e+008
−4.316e+008
−4.316e+008
−4.316e+008
−4.316e+008
acoustic emission
(b)
4.761e+010
3.571e+010
2.381e+010
1.190e+010
1.000e-008
elastic modulus
−4.316e+008
−4.316e+008
−4.316e+008
−4.316e+008
−4.316e+008
acoustic emission
(c)



(d)



(e)



(f)

Figure 7: Continued.

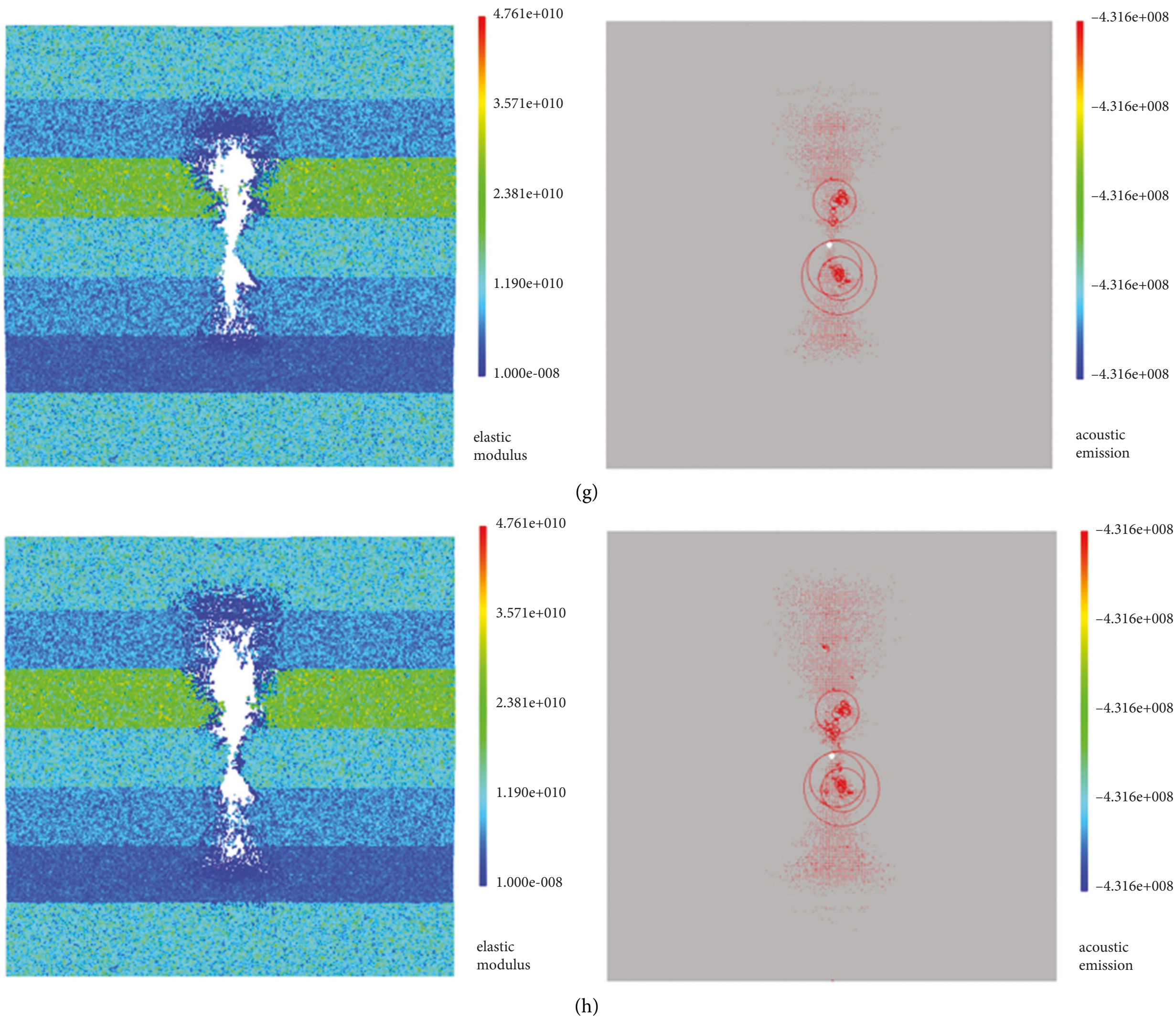
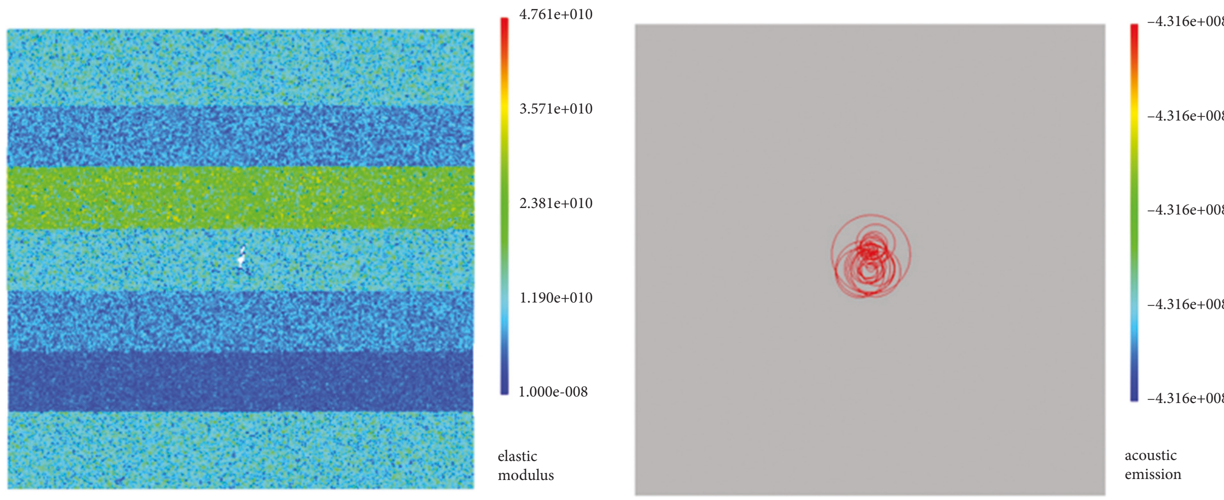


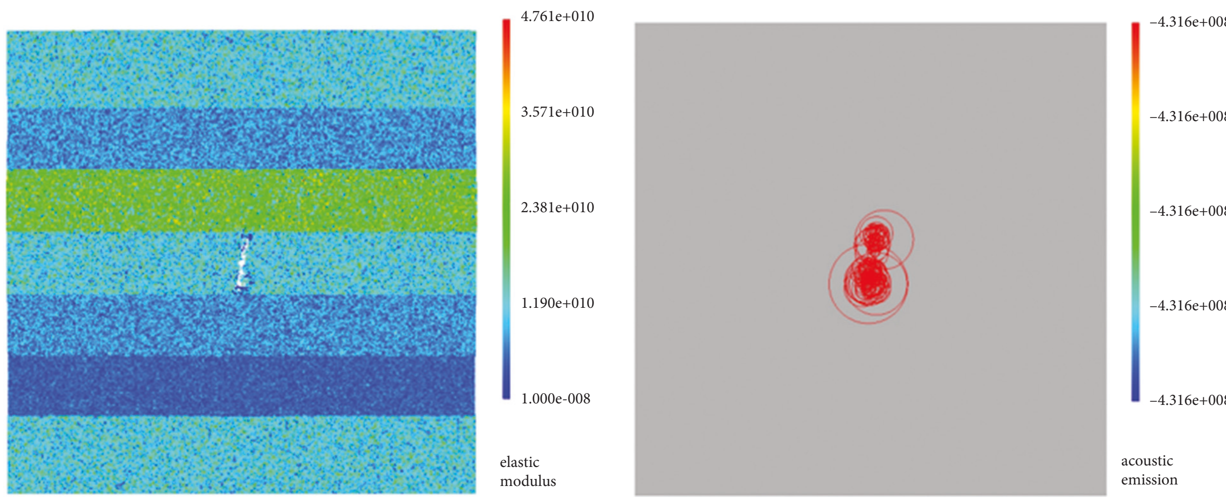
Figure 7: Elastic modulus and acoustic emission of numerical model No. 1. (a) Step 37–1. (b) Step 37–6. (c) Step 37–7. (d) Step 37–10. (e) Step 37–12. (f) Step 37–14. (g) Step 37–16. (h) Step 37–18.

hydraulic fractures reach the medium sandstone-mudstone interface first, and then separately enter the mudstone upward and soft coal downward at Step 88–9. From Figures 8(f)–8(h), under the action of water pressure in the fracturing hole, hydraulic fracture tends to propagate through the interface between soft coal and sandy mudstone and is finally destroyed at the lower end of the numerical model, at which time numerical calculation is stopped.

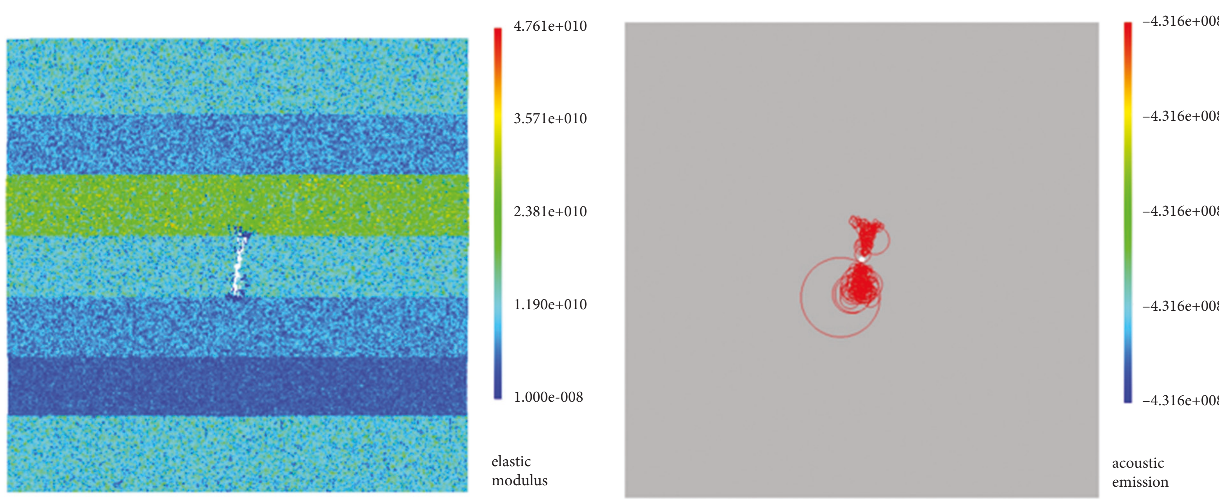
Comparing Figures 7 and 8, it can be concluded that when hydraulic fractures propagate in different strata, the water pressure at the fracture tip is larger, and the released energy is higher in the strata with smaller elastic modulus. With different injection rates, the failure location, width, and propagation path of the numerical model are different. When the fracturing fluid increment was 0.5 MPa, the model was damaged at the upper end. When the fracturing fluid increment was 0.2 MPa, the model was damaged at the lower end; in addition, the fracture width in Figure 8 is smaller than that in Figure 7. When the fracturing fluid increment was 0.2 MPa, the influence of the elastic modulus on the fracture propagation path is not significant, but an energy-storage process occurs at the interface. The above results show that the fracture-propagation path is not only related to the elastic modulus of fractured strata but also affected by fracturing fluid displacement, corresponding to theoretical analysis.



(a)



(b)



(c)

Figure 8: Continued.

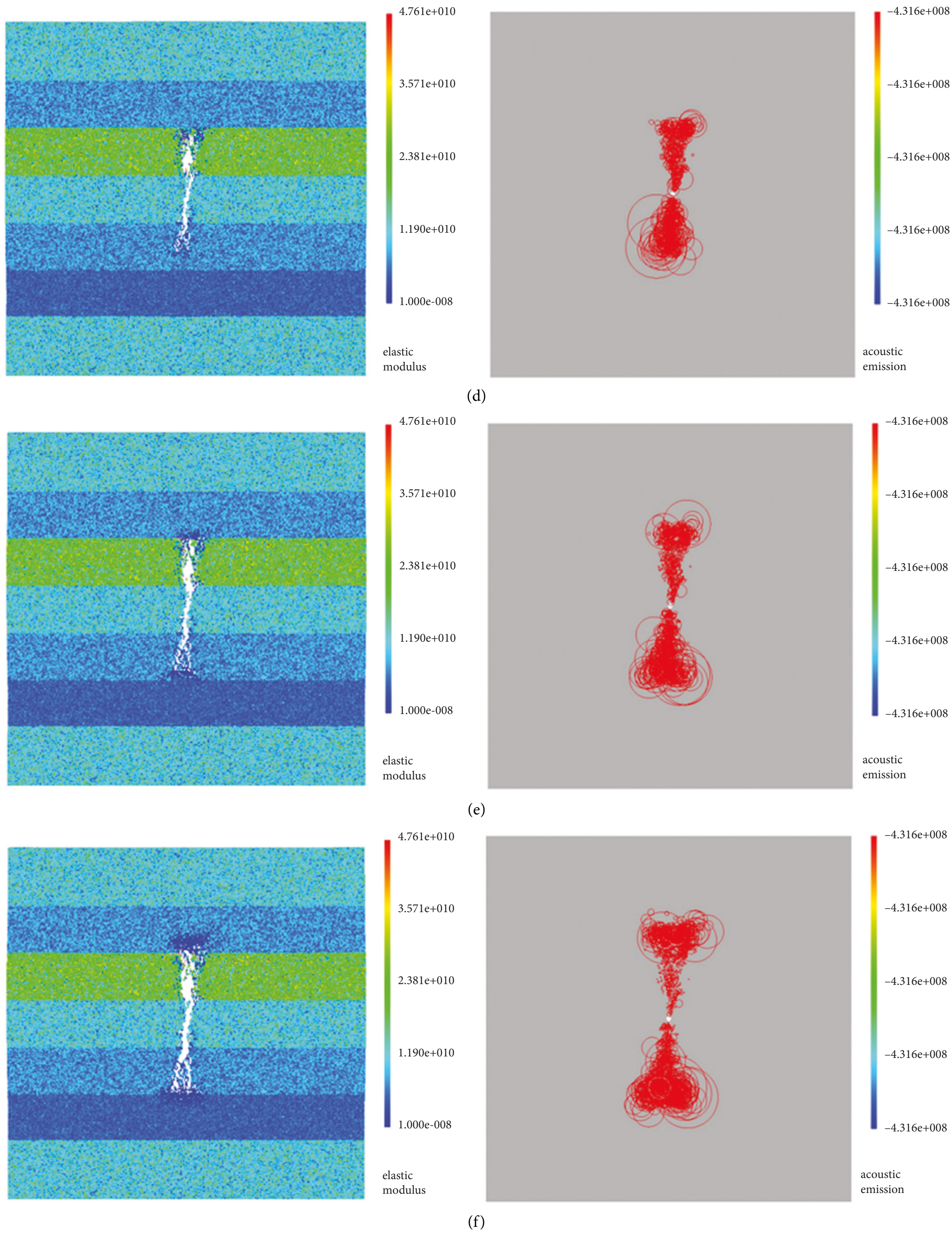


Figure 8: Continued.

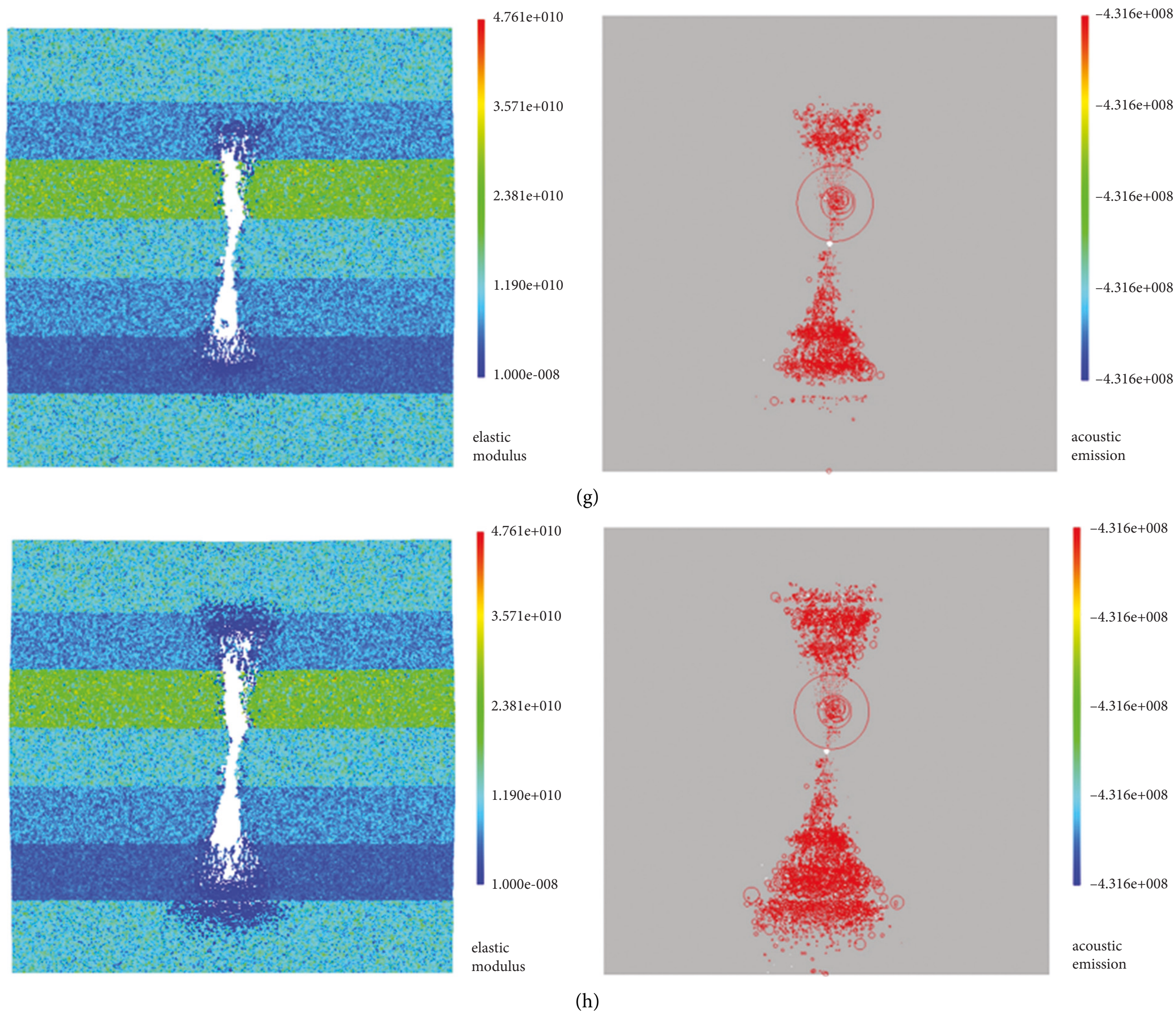


Figure 8: Elastic modulus and acoustic emission of numerical model No. 2. (a) Step 86–1. (b) Step 87–2. (c) Step 87–3. (d) Step 88–7. (e) Step 88–9. (f) Step 88–10. (g) Step 88–13. (h) Step 88–14.

5. Conclusion

To understand the vertical fracture propagation mechanism in the roof of an outburst coal seam, the effects of differences in physical parameters and in situ stress between an outburst coal seam and its roof strata on roof-fracturing fractures were revealed. The results are as follows.

(1) The elastic modulus of roof strata is greater than that of an outburst coal seam, and the horizontal stress of an outburst coal seam is less than that of roof strata. Therefore, fracture length in roof strata is longer than that of an outburst coal seam, and roof-fracturing fracture has the material conditions to communicate downward with a coal seam.

(2) The roof-fracturing fractures can enter an outburst coal seam vertically when the coal-rock interface is cemented well and does not slip. The lower fracture height is positively correlated with the minimum horizontal stress difference between the roof strata and outburst coal seam and is also related to fracturing fluid flow, natural fracture, and other factors.

(3) The effect of medium-sandstone fracturing is better than that of soft-coal fracturing. The latter is dominated by shear failure, while the former fracturing is dominated by tensile failure. Vertical fractures can be formed by reforming the adjacent strata of a soft-coal seam to communicate with the coal seam, providing a channel for gas migration.

(4) The energy released in rock strata with small elastic modulus is higher than that in rock strata with large elastic modulus, and the water pressure at the fracture tip is also larger. When the injection rate is different, the failure location, width, and propagation path are different. Therefore, the rock distribution and fracturing fluid displacement should be considered in field fracturing to ensure the fracturing effect.

Data Availability

The data used to support this study can be found in this manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Fan Zhang conceived the experiments. Fan Zhang, Hanjin Wan, and Yan Liu performed the experiments. Fan Zhang, Shuwei Li, and Zijiang Li analyzed the experimental results. Fan Zhang prepared the manuscript. All authors reviewed the manuscript.

Acknowledgments

The authors deeply appreciate the financial support provided by the Doctoral Program of Henan University of Engineering (DKJ2020005); National Innovation and Entrepreneurship Training Program for College Students (202111517008); Program for Innovative Research Team (in Science and Technology) in University of Henan Province (22IRTSTHN009).

References

[1] Y. Li, J. Chen, D. Elsworth, Z. Pan, and X Ma, "Nanoscale mechanical property variations concerning mineral composition and contact of marine shale," *Geoscience Frontiers*, vol. 13, no. 4, Article ID 101405, 2022.

[2] Y. Li, C. Zhang, D. Tang et al., "Coal pore size distributions controlled by the coalification process: an experimental study of coals from the Junggar, Ordos and Qinshui basins in China," *Fuel*, vol. 206, pp. 352–363, 2017.

[3] Y. Li, Y. Wang, J. Wang, and Z Pan, "Variation in permeability during CO2–CH4 displacement in coal seams: Part 1 – experimental insights," *Fuel*, vol. 263, Article ID 116666, 2020.

[4] H. Lin, P. Ji, and X. Kong, "Precise borehole placement model and engineering practice for pre-draining coal seam gas by drilling along seamJ," *Journal of China Coal Society*, vol. 47, no. 3, pp. 1220–1234, 2022.

[5] Y. Lu, L Rui, and X. Xian, "Discussion on the efficient exploitation method of deep coalbed methane with pressure relief by ground directional well+hydraulic slottingJ," *Journal of China Coal Society*, vol. 46, no. 3, pp. 876–884, 2021.

[6] E. Wang, G. Zhang, and C. Zhang, "Research progress and prospect on theory and technology for coal and gas outburst control and protection in ChinaJ," *Journal of China Coal Society*, vol. 47, no. 1, pp. 297–322, 2022.

[7] H. Li, W. Liang, and G. Li, "Ductile failure-seepage coupling constitutive equations of broken soft coal and its verification in indirect fracturing engineeringJ," *Journal of China Coal Society*, vol. 46, no. 3, pp. 924–936, 2021.

[8] Y. Xu, Y. Zhu, and P. Zhang, "Application of CBM horizontal well development technology in the roof strata close to broken-soft coal seamsJ," *Natural Gas Industry*, vol. 38, no. 9, pp. 70–75, 2018.

[9] Q. Zhang, C. Ge, and W. Li, "A new model and application of coalbed methane high efficiency production from broken soft and low permeable coal seam by roof strata-in horizontal well and staged hydraulic fractureJ," *Journal of China Coal Society*, vol. 43, no. 1, pp. 150–159, 2018.

[10] H. Li, Z. Jiang, and J. Shu, "Numerical simulation of layer-crossing propagation behavior of hydraulic fractures at coal-rock interfaceJ," *Coal Geology & Exploration*, vol. 48, no. 2, pp. 106–113, 2020.

[11] J. Gao, B. Hou, and M. Chen, "Effects of rock strength and interfacial property on fracture initiation and propagationJ," *Chinese Journal of Rock Mechanics and Engineering*, vol. 37, no. S2, pp. 4108–4114, 2018.

[12] Z. Jiang, H. Li, and L. Fang, "Fracture propagation mechanism of staged through-layer fracturing for horizontal well in roof adjacent to broken-soft coal seamsJ," *Journal of China Coal Society*, vol. 45, no. S2, pp. 922–931, 2020.

[13] Y. Li, J. Yang, Z. Pan, and W Tong, "Nanoscale pore structure and mechanical property analysis of coal: an insight combining AFM and SEM images," *Fuel*, vol. 260, Article ID 116352, 2020.

[14] K. Tian, W. Gong, and W. Erjian, "Gas pressure relief-permeability increase effect comparative analysis about hydraulic disturbance to soft coal seam and its sandstone roofJ," *Journal of China Coal Society*, vol. 46, no. 6, pp. 1888–1897, 2021.

[15] Y. Xu, "Layer-penetrating staged fracturing law of horizontal wells within roof of coal seams under stress interferenceJ," *Coal Geology & Exploration*, vol. 48, no. 4, pp. 11–18, 2020.

[16] Z. Meng, K Yin, and P. Zhang, "Calculation model of in-situ stress based on fault frictional strength and its applicationJ," *Coal Science and Technology*, vol. 46, no. 6, pp. 24–28, 2018.

[17] P. Wu, *Experimental Investigation on the Crack Propagation of Hydraulic Fracturing in Coal-Rock combinationD*, Taiyuan University of Technology, Taiyuan, 2017.

[18] T. K. Perkins and L. R. Kern, "Widths of hydraulic fractures," *Journal of Petroleum Technology*, vol. 13, no. 09, pp. 937–949, 1961.

[19] X. Wu, *Research on Control Mechanism of Fracture Propagation of Multi-Stage Hydraulic Fracturing Horizontal Well in Roof of Broken Soft and Low Permeability Coal seamD*, China Coal Research Institute, Beijing, 2017.

[20] T. Jiang, J. Zhang, and G. Huang, "Experimental study of fracture geometry during hydraulic fracturing in coalJ," *Rock and Soil Mechanics*, vol. 39, no. 10, pp. 3677–3684, 2018.

[21] J. Liu, C. Liu, Q. Yao, and G Si, "The position of hydraulic fracturing to initiate vertical fractures in hard hanging roof for stress relief," *International Journal of Rock Mechanics and Mining Sciences*, vol. 132, Article ID 104328, 2020.

[22] Y. Lu, T. Gong, B. Xia, B. Yu, and F Huang, "Target stratum determination of surface hydraulic fracturing for far-field hard roof control in underground extra-thick coal extraction: a case study," *Rock Mechanics and Rock Engineering*, vol. 52, no. 8, pp. 2725–2740, 2019.