International Journal of Advanced Engineering and Technology Research
ISSN: 3106-8677 (Print), ISSN: 3106-8685 (Online) | Vol. 3, No. 1, 2026

Numerical Analysis of Hydraulic Fracture Propagation Characteristics in Fractured Coal Rock Based on Digital Image Technology

Zhiheng Hou

School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454003, China

Abstract: China is rich in coalbed methane resources. However, due to the strong heterogeneity of coal and rock and the complexity of natural fracture system, the fracture propagation mechanism of hydraulic fracturing is not clear, which restricts the accurate prediction of reservoir reconstruction effect. Traditional numerical simulation methods mostly use statistical distribution function to describe the heterogeneity of materials, which is difficult to reflect the real morphology of coal-rock fractures. Therefore, based on the real fracture process analysis software RFPA2D, this paper introduces digital image technology (DIT) to construct a numerical model that can reflect the real spatial distribution of natural fractures in coal and rock, and systematically studies the influence of in-situ stress difference coefficient and natural fracture density on the propagation characteristics of hydraulic fractures. The results show that the existence of natural fractures is the basic condition for the formation of complex fracture network. Under the condition of low in-situ stress difference (ks=0.2), there is a significant positive correlation between the complexity of hydraulic fractures and the density of natural fractures. High-density natural fractures can effectively induce the diversion and branching of hydraulic fractures, thus forming a more developed fracture network. The final form of hydraulic fractures is the result of the competition and synergy between the in-situ stress field and the natural fracture network. When the local stress difference is small, the natural fracture plays a major role in the fracture propagation. When the local stress difference increases, the in-situ stress field gradually becomes the dominant factor controlling the direction and shape of fracture propagation. It is concluded that the coupling effect of in-situ stress difference coefficient and natural fracture density is the key factor to control the complexity of coal-rock hydraulic fracture network. The relevant understanding can provide theoretical basis for the optimization of hydraulic fracturing parameters and the evaluation of permeability enhancement effect in coal seams.

Keywords: Coalbed methane, hydraulic fracturing, fracture network, RFPA2D, digital image technology.

1. Introduction

At present, more than 40 % of China 's natural gas is dependent on imports, and it is expected to reach 600 billion cubic meters of natural gas consumption in 2035 [1], and more than 50 % of natural gas will be dependent on imports. It is of strategic significance to increase the exploration and development of coalbed methane to ensure national energy security. China 's coalbed methane is faced with the problems of low resource exploration rate and low average gas production per well. Establishing an exploration and development technology system suitable for geological characteristics is the top priority to solve these problems, and fracturing reservoir reconstruction technology is the key to this technology system. Hydraulic fracturing technology uses the high pressure of the ground to inject the fracturing fluid into the coal reservoir to induce the formation of a complex fracture system, so as to achieve the purpose of increasing production and permeability. It is an important means to improve the permeability of coal seam and the productivity of coalbed methane [2]. In the process of fracturing, the natural fractures in coalbed methane will cause the initiation and expansion of hydraulic fractures, thus affecting the fracturing effect of coal seams.

In recent years, domestic and foreign scholars have made remarkable achievements in rock mechanics characteristics [3-4], construction parameter optimization [5], in-situ stress field distribution and fluid migration. Compared with shale or sandstone, coalbed methane reservoirs have lower elastic modulus, higher Poisson 's ratio and more significant heterogeneity [6-7], resulting in changes in the local stress state around the wellbore. Because coal is more easily broken under strong stress, the formation and expansion of hydraulic fractures are more complicated.

The distribution characteristics of coal-rock fractures are different from those of sandstone and shale. It is more complicated. It is difficult to obtain the fracture characteristic information of coal-rock content by conventional hydraulic fracturing experiments. Ordinary numerical simulation cannot reflect the true morphology of coal-rock fractures. It is necessary to adopt numerical simulation methods that can reflect both the failure characteristics of coal-rock and the true morphology of coal-rock fractures.

2. A Brief Description of RFPA and the DIT

2.1. Introduction to RFPA Software

RFPA (Realistic Failure Process Analysis) is a software system for the whole process analysis of rock failure independently developed by Professor Tang Chun 'an 's team from the Rock Failure and Instability Research Center of Northeast University. The original version of the software RFPA2D was officially published in " Journal of Rock Mechanics and Engineering " in 1997 [8]. After nearly 30 years of continuous development, it has gradually expanded from the initial two-dimensional basic version to the three-dimensional version, parallel computing version and a series of versions covering multi-field coupling analysis such as seepage, temperature and gas. It has become a representative numerical simulation software with independent intellectual property rights in the field of rock mechanics in China [9].

The core principle of RFPA is based on finite element theory and statistical damage theory. It characterizes the inhomogeneity of material mechanical parameters (such as strength, elastic modulus) by introducing statistical distribution functions such as Weibull or normal, and uses the unit failure and weakening mechanism to simulate discontinuous deformation behavior. Therefore, it provides an effective way to solve the problem of discontinuous medium mechanics by using the method of continuous medium mechanics [9]. In terms of function and application, RFPA series software is divided into two types: 2D version and 3D version. Its core functions include: simulating the whole process of deformation and fracture of rock under various loading conditions, detecting the law of acoustic emission (AE) in the process of fracture, considering the non-uniform distribution characteristics of material mechanical parameters, and simulating the influence of macroscopic defects such as joint cracks. At the level of engineering application, RFPA can be widely used in geotechnical engineering problems such as roadway excavation and failure, pillar failure, roof caving, slope stability analysis, tunnel surrounding rock stability evaluation, and surface subsidence prediction in mining engineering. In addition, the software also developed extended functions such as seepage analysis, temperature analysis, gas migration analysis, and fluid-solid coupling [8].

In recent years, the RFPA method has also been extended to the field of earth science. Based on the RFPA method, Tang Chun an 's team developed the “Earth Simulator”, which regards the Earth 's lithosphere as a non-uniform brittle material system to simulate the fracture and evolution process of the lithosphere under thermal drive. International rock mechanics experts have evaluated this method as a “promising numerical calculation method” [9]. RFPA has become an indispensable numerical test tool in the field of rock mechanics and engineering.

2.2. Introduction of DIT

DIT (Digital Image Technology) refers to the collection, processing, analysis and understanding of digital images through computers. In the field of rock mechanics and geotechnical engineering, DIT usually involves digital image processing (DIP) methods such as image enhancement, image segmentation, edge detection, feature extraction, etc. Since the mid-1990s, digital image processing technology, as an accurate measurement and digital representation method of material mesoscopic spatial structure and geometric shape, has been rapidly applied to the quantitative analysis of mesoscopic structure of rock and other materials. The basic idea is to establish a computational grid that can truly reflect the meso-structure of rock by means of digital image processing technology, and to realize the leap from qualitative description to quantitative characterization of rock heterogeneity.

In specific applications, DIT is mainly used in the following aspects: First, the characterization of rock meso-structure, that is, the mineral particles, pores, cracks and other meso-characteristics of rock are extracted by digital image processing; second, numerical simulation of rock mechanics, the extracted digital image information is mapped to the finite element mesh, and a numerical model reflecting the real meso-structure of rock is established. Third, rock CT image analysis, extraction of rock internal cracks, holes and other important information characteristics; fourth, rock fracture information detection, using Canny and other algorithms to accurately and quickly obtain fracture information from rock mass images. In addition, DIT can also realize non-contact measurement of rock fracture width.

2.3. Implementation of DIT Technology in RFPA

The core of the realization of DIT in RFPA is to transform the real mesoscopic structure image of rock into a numerical calculation model, so as to break through the limitation of traditional methods using statistical theory (such as Weibull distribution) to describe the heterogeneity of materials. The basic idea is to extract the meso-structure information of rock by means of digital image processing technology, map it to the finite element mesh, and combine it with the RFPA system to establish a numerical model that can more accurately reflect the meso-structure of rock [10].

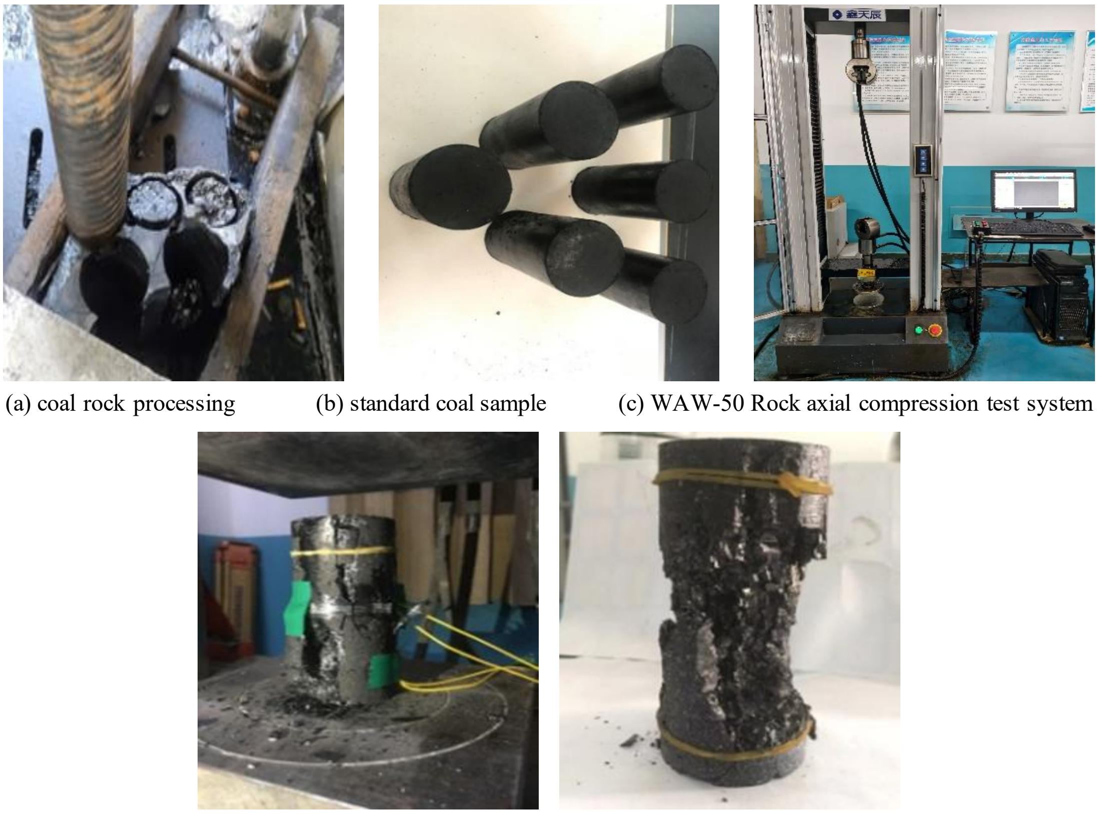
In the specific implementation, firstly, digital images such as rock surface photos or CT scans are obtained, and different mineral components (such as quartz, feldspar, mica, etc.) and microscopic characteristics such as pores and cracks are identified by image segmentation and other processing techniques. The digital image is composed of pixels. Each pixel is directly mapped to a unit in the finite element calculation. According to the color or gray value of the pixel, different mechanical parameters (such as elastic modulus, strength, etc.) are assigned to the corresponding unit. On this basis, stress solution and failure analysis are carried out [11]. Zhu Wancheng et al. implemented this technique into the RFPA program to simulate the whole process of fracture of heterogeneous rock under the coupling of external load and seepage [10].

3. Construction of Numerical Model for Hydraulic Fracturing of Fractured Coal-Rock Mass

3.1. Model Construction

3.1.1. Parameter Calibration

The coal rock of Yuxi Coal Mine was selected and taken back to carry out indoor experiments. The coal rock is processed into a standard cylindrical coal sample with a diameter of 50 mm and a height of 100 mm, as shown in Figure 1 (a) and (b). The uniaxial compression test of the coal sample is carried out. The test instrument adopts the WAW-600 rock axial compression test system, as shown in Figure 1 (c). The maximum applied load range of the test machine is 50 KN. The strain gauges are pasted on the side of the coal sample to calculate the Poisson 's ratio. Under the continuous external load applied by the testing machine, the specimen was finally destroyed.



(a) coal rock processing (b) standard coal sample (c) WAW-50 Rock axial compression test system

(d) coal sample loading (e) coal sample failure

Figure 1. Coal sample processing and uniaxial compression test

The stress-strain relationship curve of uniaxial compression in Yuxi Coal Mine is shown in Figure 2. The uniaxial compression curves of coal samples are not the same, reflecting the heterogeneity of coal rock.

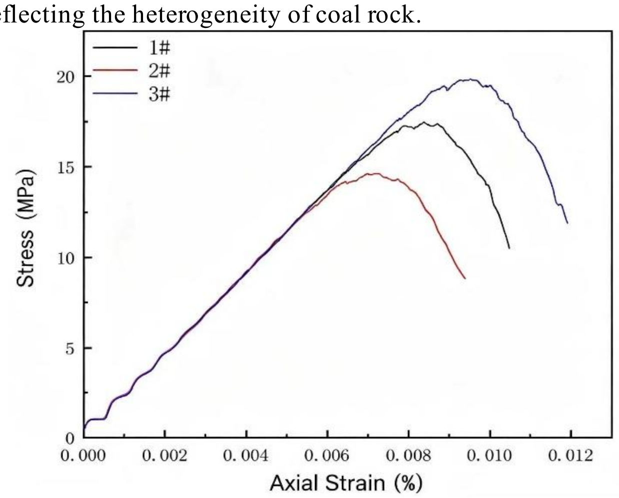


Figure 2. Uniaxial compression stress-strain curve of coal sample

3.1.2. Model Construction

According to the practice and research at home and abroad, the propagation characteristics of hydraulic fractures are affected by multiple factors, including in-situ stress state, natural fracture density, fracture spacing and so on. In-situ stress state is a key factor affecting the propagation direction of hydraulic fractures. Under different in-situ stress states, the initiation pressure and propagation path of hydraulic fractures will be different. Rock deformation and fracture lead to stress state and mechanical behavior between rock blocks on both sides of the fault. Under this stress mechanism, hydraulic fractures tend to expand along the direction of the maximum horizontal principal stress [12]. When natural fractures are more complex, hydraulic fractures may expand along weak structural surfaces (bedding planes, fissures, or secondary joints, etc.), making the extension extremely complex, and even forming a complex fracture grid. After the intersection of hydraulic fractures and natural fractures, the propagation direction may turn, and the turning angle is determined by the stress intensity factors of type I and type II fractures. Under the action of shear stress and tensile stress, cracks will produce type I and type II cracks, and expand according to the maximum circumferential stress criterion [13].

Based on the principle and simulation method of RFPA software, a two-dimensional plane strain model is established as shown in Figure 3. The digital model size is 200mm × 200mm, and the mechanical properties and parameters of coal and rock are shown in table 1. A borehole with a diameter of 8mm is set in the center of the model. The confining pressure load is applied to the model boundary to simulate the influence of different in-situ stress difference coefficients on crack propagation. The initial water pressure in the wellbore is set to 20MPa, the initial water head is 500m, that is, 5MPa, and the water head increment per step is 35m, that is, 0.0035m3·s-1, until the hydraulic fracture occurs, and the experiment is stopped when the model is destroyed. In the simulation, the strength, Poisson's ratio and Young 's modulus are Weibull distribution.

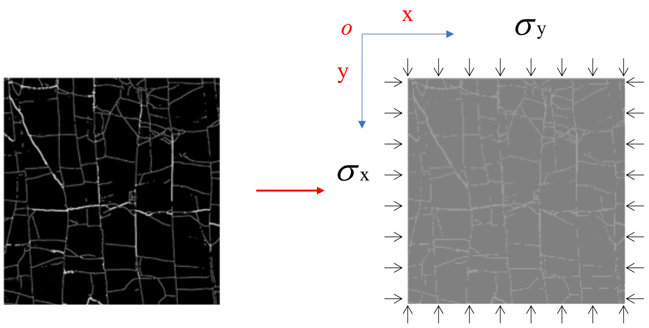


Figure 3. Two-dimensional digital image model of coal rock

Table 1. Mechanical parameters of coal rock

material	homogeneity coefficient m	Elastic modulus E_0/GPa	Compressive strength f_c/MPa	Poisson 's ratio μ	friction angle φ/°	permeability coefficient K m/s
coal	3.0	3.03	18.14	0.33	30	1×10-11
natural fractures	3.0	0.51	0.16	0.38	26	1×10-8

4. Analysis of Numerical Simulation Results

4.1. The Influence of Ground Stress Difference on the Complexity of Hydraulic Fracture

The propagation direction of hydraulic fractures is the result of the combined action of in-situ stress difference coefficient and natural fracture density. Especially in homogeneous media, ground stress is the main factor leading to fracture propagation. The influence of in-situ stress on hydraulic fracture propagation is reflected by the in-situ stress difference coefficient Ks, which is defined as:

$$k_s = \frac{\sigma_x - \sigma_y}{\sigma_y} \tag{1}$$

In the formula: σ_x is the maximum horizontal principal stress; σ_y is the minimum horizontal principal stress. Based on the model, the influence of in-situ stress difference coefficient on the complexity of hydraulic fractures is studied.

4.1.1. In-situ Stress Parameter Setting

In order to better simulate the formation conditions, the maximum horizontal in-situ stress value is fixed according to the requirements of coal-rock hydraulic fracturing test. By changing the minimum in-situ stress, the influence of different in-situ stress difference coefficients on the complexity of hydraulic fractures and the influence of natural fractures inside coal-rock on the propagation process of hydraulic fractures are simulated. The specific simulated in-situ stress parameters are set as shown in Table 2.

Table 2. In-situ stress parameters for hydraulic fracturing simulation

simulation program	Maximum horizontal stress σ_x/MPa	minimum horizontal principal stress σ_y/MPa	ground stress deviation /MPa	coefficient of difference in ground stress k_s
scheme 1	12	10	2	0.2
Scheme 2	12	8	4	0.5
Scheme 3	12	6	6	1.0
Scheme 4	12	4	8	2.0

4.1.2. Simulation Results of Different In-Situ Stress Difference Coefficients

The simulation test results show that the energy release generated during the crack initiation promotes the main crack to be parallel to the direction of the maximum horizontal principal stress. When the in-situ stress difference coefficient of coal rock specimen is small, the natural fracture has a great influence on the complexity of hydraulic fracture. Hydraulic fractures are more likely to propagate along weakly cemented natural fractures, and complex branch fractures are generated during the extension process. With the gradual increase of in-situ stress difference coefficient, the control effect of in-situ stress is gradually enhanced, and the complexity of hydraulic fractures is gradually weakened. As shown in Figure 4, the above fracture morphology can be seen that when Ks=0.2, the fracture complexity is higher, and the fracture network is easier to form near the wellbore. The larger the ground stress difference, the simpler the fracture morphology.

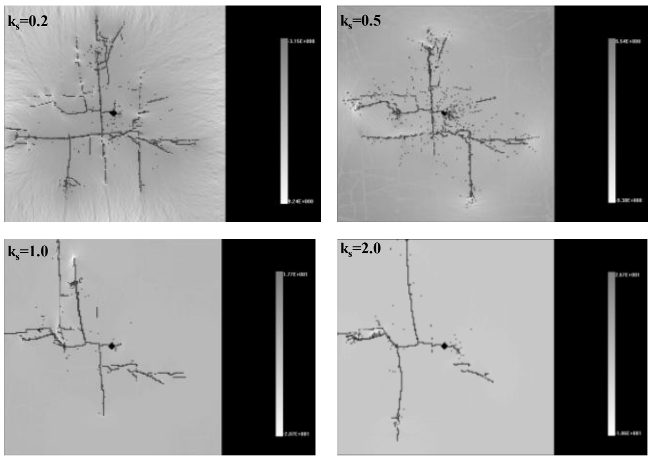


Figure 4. Characteristics of hydraulic fracture propagation in fractured coal rock with different geostresses

4.1.3. Fracture Complexity Index

Cipoll et al. [14] obtained the Fracture Complexity Index (F_{CI}) by dividing the total width and total length shown on the microseismic cloud map, which can evaluate the fracture complexity during hydraulic fracturing. The index can better understand the propagation characteristics of fractures.

$$F_{CI} = \frac{W}{L} \tag{2}$$

In the formula: F_{CI} is the fracture complexity index; W is half of the sweep range of fracturing fluid in the direction of vertical fracture length; L is the half length of the crack. It can be seen from the formula that the lowest fracture complexity index is 0 and the highest is 1. The fractures between the two are complex fractures, and the complexity is proportional to the index.

From Figure 5, it can be seen that the K_s=0.2 model forms a simple fracture network with the largest complexity, and its fracture complexity index FCI is 0.91. The K_s=0.5 model forms a simple fracture network with FCI of 0.66. When the model Ks increases to 1.0 and 2.0, only branch fractures are formed in the two models, and the fracture complexity index F_{CI} of both models is 0.27, which is due to the fact that the in-situ stress is the main controlling factor in the high in-situ stress difference model, and the influence of natural fractures is weakened.

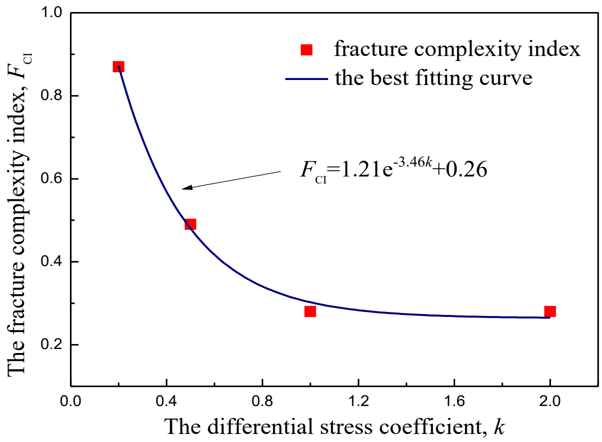


Figure 5. Relationship of the fracuture complixity index (F_{CI}) and the differential stress coefficient (K_s)

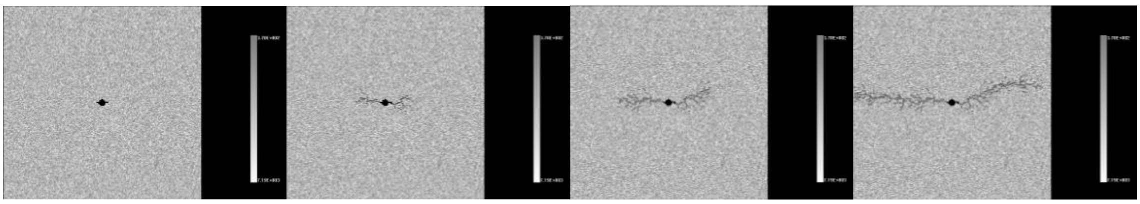
4.2. The Influence of Natural Fracture Density on the Complexity of Hydraulic Fracture

The existence of natural fractures has an inducing effect on the initiation and propagation of hydraulic fractures, which helps to increase the number of cracks, thereby affecting the transformation effect of coal-rock reservoirs [15]. Studies have shown that even if hydraulic fractures do not contact with natural fractures, natural fractures may open. With the shear slip of the natural fracture surface, the expansion of hydraulic fractures will produce stress concentration near the fracture surface, which will affect the stress distribution on both sides of the fracture surface, forming a stress shadow effect, resulting in an increase in local formation pore pressure and minimum horizontal stress [16]. The existence of natural fractures helps to form a complex fracture network and increase the porosity of coal in the fracture zone, thereby indirectly increasing the permeability of coal and increasing the permeability and yield. In coal-rock reservoirs with natural fractures, hydraulic fractures initially expand along the direction parallel to the maximum horizontal principal stress, and then are captured and opened by natural fractures and further extended.

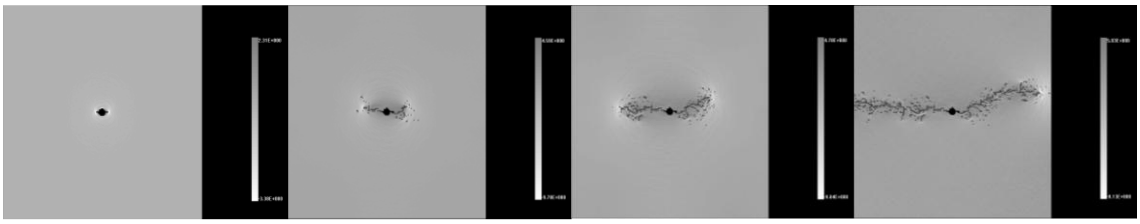
4.2.1. Numerical Simulation of Coal Rock Without Natural Fracture

From the above tests, it can be seen that the hydraulic fracture network is more complex under the condition of in-situ stress difference coefficient K_s=0.2. Therefore, in the case of different natural fracture density, we set the in-situ stress difference coefficient to K_s=0.2.

In the absence of natural fractures, the simulation results are shown in Figure 6. As the pressure of the water injection hole continues to increase, the stress concentration area on both sides of the wellbore begins to destroy and produce micro-cracks. For coal-rock reservoirs without natural fractures, the difference of in-situ stress is the main factor affecting the propagation of hydraulic fractures.



(a) Elastic diagram of tight coal rock



(b) Stress diagram of tight coal rock

Figure 6. Hydraulic fracturing simulation without natural fractures

4.2.2. Comparison of Fracture Propagation Under Different Natural Fracture Densities

The fracturing model with K_s=0.2 was used for numerical simulation under the same conditions of boundary conditions, loading methods and parameter properties. The simulation scheme is shown in Table 3. It can be seen from Figure 7 that 1 # natural fracture development density is the largest, followed by 2 # and 3 #.

Table 3. Simulation schemes with different natural fracture densities

specimen	Maximum horizontal stress σ_x/MPa	minimum horizontal principal stress σ_y/MPa	coefficient of difference in ground stress k_s	Natural fracture density
1#	12	10	0.2	big
2#	12	10	0.2	middle
3#	12	10	0.2	small

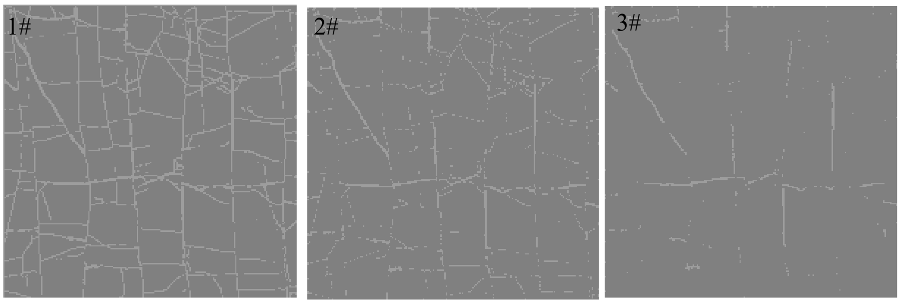
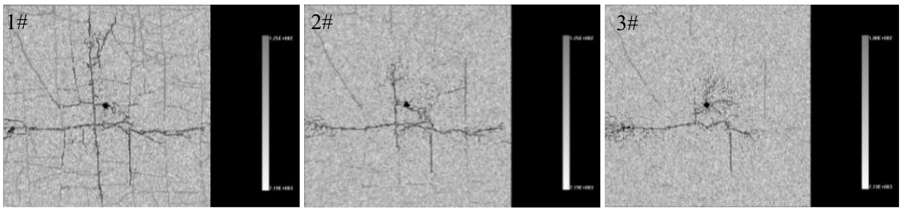


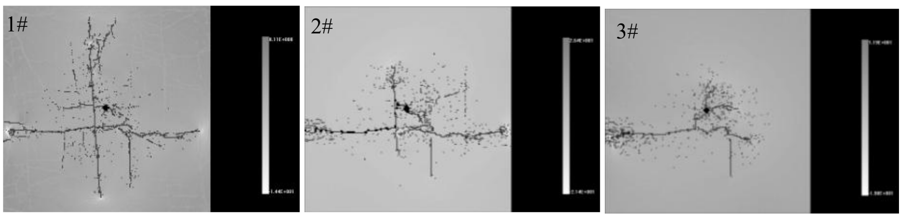
Figure 7. Specimens with different natural fracture densities

From the simulation results, as shown in Figure 8 when K_s=0.2, the greater the density of natural fracture development, the more weak cementation surfaces will appear. As the fluid pressure of the water injection well increases, a small range of complex fracture networks will be generated around the initiation point. At this time, the natural fracture surface is more prone to shear slip, which makes the hydraulic fracture more easily captured by the natural fracture. The extension direction of hydraulic fractures is dominated by natural fractures, the controlling factors of stress difference are gradually weakened, and the fracture network is more complex. The extension direction of the main fracture is parallel to the direction of the maximum principal stress, which satisfies the Anderson fault theory model [17].

When K_s=0.2, with the decrease of natural fracture density, the complexity of hydraulic fractures also decreases, and the stress difference becomes the main controlling factor of fracture propagation. However, hydraulic fractures may still interact with a few natural fractures and affect the fracture propagation path. However, when the fracture network is not K_s=2.0, the case of large natural fracture density is complex. It can be seen that the density of natural fracture development determines the complexity baseline of fracture network. Compared with the in-situ stress difference coefficient, the natural fracture density is the dominant factor affecting the development efficiency of coalbed methane.



(a) Elastic diagram of fractured coal rock



(b) Stress diagram of fractured coal rock

Figure 8. Hydraulic fracture propagation of coal rock under different natural fracture densities

5. Conclusion

(1) In this paper, the finite element software that can reflect the real failure characteristics of rock materials is used, and the digital image technology is embedded to construct a numerical model of hydraulic fracturing of fractured coal rock that can reflect the real morphology of fractures in coal rock.

(2) Numerical simulation reproduces the whole process of hydraulic fractures in fractured coal and rock from initiation, expansion, branching and formation of complex network fractures.

(3) The smaller the in-situ stress difference is, the easier the natural fractures are activated, and the more complex the hydraulic fractures are. Even when the in-situ stress difference is large, more complex multi-branch fractures can be formed. It can be seen that natural fractures have a strong control on the complexity of hydraulic fractures. The complexity of hydraulic fractures formed by models with different natural fracture structures is different. In general, the greater the density of natural fractures, the more complex the hydraulic fractures formed.

(4) Due to the existence of natural fractures, the hydraulic fractures formed are all multi-branch fracture structures and network fracture structures, and there is no single double-wing hydraulic fracture structure.

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