Research Article

Investigation of the Fracturing Effect Induced by the Disturbing Stress of Hydrofracturing Using the Bonded-Particle Model

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Hydraulic fracturing applications have shown a stress disturbance effect during hydraulic fracture propagation, which is often ignored. Using laboratory and discrete element numerical simulation tests, hydraulic fracture propagation under this stress disturbance is systematically studied. The results show that during hydraulic fracturing, the bedding plane is damaged by the stress disturbance, forming a bedding fracture zone (BFZ). The nonlinear fracture characteristics of the formation process of the disturbed fracture zone are revealed, and two indexes (the number of fractures in the disturbed fracture zone and the size of the disturbed fracture zone) are proposed to evaluate the fracturing effect of the stress disturbance. Based on these indexes, multifactor sensitivity tests are conducted under different geological conditions and operational factors. When the principal stress (σ_1) difference is large, the number of hydraulic fractures gradually decreases from many to one, and the direction of the hydraulic fractures gradually approaches the vertical direction of σ_3 , but the change in the in situ stress condition has no obvious effect on the stress disturbance effect. The weaker the bonding strength of the bedding plane, the more significant the stress disturbance effect is, and the easier it is for the fractures to expand along the bedding plane. With increasing injection rate, the stress disturbance effect first increases and then decreases, and the hydraulic fracture propagates from along the bedding plane to cross the bedding plane. With increasing relative distance between the injection hole and bedding plane, the stress disturbance effect presents a linearly increasing trend, and the hydraulic fractures along the bedding planes extend. Based on the experimental results, the relationship between the fracturing effect of the stress disturbance and the extension mode of the hydraulic fracture is determined, and an optimization method for hydraulic fracturing in composite rock reservoirs is given. The research results can provide a theoretical basis for controlling the formation of complex fracture networks in composite rock reservoirs.

1. Introduction

Since its successful application in Kansas in 1947, hydraulic fracturing has been widely used in oil-gas field development, mine roof control, and other related fields and has achieved good application results [1–4]. The key to hydraulic fracturing design is the morphology of hydraulic fractures [5]. Due to long-term geological movement, most rock masses in nature (including tight oil-gas reservoirs and deep coal rock masses) contain a large number of structural planes of different sizes, such as bedding planes, joints, and natural fractures [6, 7]. When hydraulic fracturing is carried out on reservoirs with bedding planes, hydraulic fractures extending to bed-

ding planes will exhibit behaviours such as penetration, steering, capture, and bifurcation [8]. The existence of bedding planes significantly affects the extension mode and expansion morphology of hydraulic fractures [9–11], which directly determines the final hydraulic fracturing effect of the reservoir [12]. Therefore, the key to improving the permeability of low permeability reservoirs and enhancing the weakening effect of hard roofs above coal seams is to study the propagation mechanism of the hydraulic fracture in composite rock materials with bedding planes.

In recent years, relevant scholars have carried out a large number of experiments on the interaction mechanism between hydraulic fractures and bedding planes. The results

show that the injection rate, in situ stress coefficient, bedding plane bonding strength, and fracturing fluid viscosity have an obvious influence on the interaction mode of hydraulic fractures at the bedding plane [13–20]. The above experiments provide good references for related mechanistic research. However, the above research focuses on the overall propagation response characteristics of the hydraulic fracture under different hydraulic macrofracturing conditions, ignoring the influence of the fracturing effect induced by the disturbing stress of hydrofracturing on the propagation path of the hydraulic fracture at the bedding plane, and the relationship between them is not clear. Therefore, there are limitations in the understanding of the hydraulic fracture propagation law of composite rock materials, which cannot overall describe the real hydraulic fracture propagation in the bedding plane. Related theories of rock fracture mechanics have shown that the disturbance stress produced in the process of crack propagation will lead to a continuous change in the surrounding rock stress field and then to a change in the rock mechanical properties. With the deepening of research studies, some scholars have carried out experiments on microcrack propagation mechanisms and found that [21, 22], when the fracture approaches the bedding plane, the disturbing stress field at the fracture tip will lead to the early failure of the bedding plane and form a microfracture zone on the bedding plane, which is referred to as the fracturing effect induced by the disturbing stress [23, 24]. The bedding plane fracture zone induced by the disturbance stress has a significant trapping effect on the fracture propagation. However, to date, research on this effect has been mainly focused on surface fracture propagation under a single stress loading state. In contrast, research on fracture propagation under the complex stress of hydraulic fracturing fluid-solid coupling has been minimal. Due to the “black box” environment of hydraulic fracturing experiments [25], this effect is difficult to monitor in hydraulic fracturing wells and laboratories, which explains why most studies ignore the influence of the fracturing effect induced by the disturbing stress on hydraulic fracture propagation. At present, the stress disturbance effect of hydraulic fracturing is still in the theoretical stage, and there is no systematic research on this influencing factor through relevant experiments or numerical simulations.

With the continuous progress of computer technology and numerical simulation algorithms, the combination of experimental research and numerical simulations provides a feasible solution to solve this problem [12, 26–29]. At present, there are four popular numerical simulation methods used to research hydraulic fracturing [30–32]: the finite element method (FEM), extended finite element method (XFEM), boundary element method (BEM), and discrete element method (DEM). The basic idea of the FEM is to discretize the elastic body into an equivalent system of small elements [33]. In this method, the crack boundary coincides with the mesh nodes, and a mesh reconstruction method is used to simulate the crack propagation. The hydraulic fracturing model established by this method requires less calculation and has a high efficiency. However, the hydraulic fracture can only extend along a preset path, and the FEM cannot simulate the deflection of hydraulic fractures or the

formation process of a complex fracture network [34, 35]. The XFEM is based on the FEM and introduces a shape function to represent the discontinuity of the displacement field [36–38], so the description of the discontinuous displacement field is completely independent of the mesh boundary. This method can simulate the fracture propagation along any path without grid reconstruction. This is advantageous in the analysis and calculation of fracture problems and greatly improves the calculation efficiency. The disadvantage of the XFEM is that the hydraulic fracturing simulation of a natural fractured reservoir needs further development. The BEM is a numerical method that divides the elements along the boundary of the domain and approximates the boundary conditions with functions satisfying the governing equations by interpolating at the boundary elements. Because the number of elements needed in the calculation model is small and the data preparation is simple, the solution efficiency and accuracy of the BEM are high. However, this method requires a known analytical solution to solve the problem, so it is only suitable for solving linear and homogeneous problems [39–42]. The main idea of the DEM is to use an explicit algorithm to calculate the motion of particles or blocks: that is, update the motion and contact state of particles in each calculation [43, 44]. When the contact force exceeds its bearing limit, the material will demonstrate shear dislocation, compression shear failure, tensile failure, and other rock fracture phenomena [45, 46]. The channel formed between particles can be used to simulate the fluid flow in a pipe. Because the DEM does not need to satisfy the continuity condition, it has significant advantages in dealing with discontinuous structures such as bedding planes and natural fractures. In addition, the DEM is very suitable for simulating the initiation and propagation of microcracks in rock. Considering that this paper mainly focuses on the micromechanism of the stress disturbance effect on the bedding plane damage in the process of hydraulic fracture propagation, the discrete element simulation method is more suitable.

According to the laboratory experimental results, a discrete element numerical simulation program is debugged and validated, to verify the validity of the numerical model, to truly reproduce the whole process of the dynamic propagation of hydraulic fractures, and to observe the stress field distribution inside the test block and the bedding plane fracture zone formed by the disturbance effect, which is an effective way to study the hydraulic fracture propagation law of composite rock materials considering the stress disturbance effect.

In conclusion, experimental research and a DEM numerical simulation using particle flow code (PFC) are combined in this paper, focusing on the stress disturbance fracturing effect of hydraulic fracturing and describing the formation characteristics of the bedding disturbance microfracture zone. The interaction mechanism between the hydraulic fracture and bedding disturbance fracture zone is studied, and a sensitivity analysis of geological conditions and hydraulic fracturing conditions affecting the fracturing effect of stress disturbance is carried out. The research results can provide a theoretical basis for controlling the formation of a complex fracture network of composite rock materials.

2. Particle Flow Method

2.1. Parallel Bond Model. The linear parallel bond model used in this paper is appropriate for simulating the micromechanical properties of composite rock material. The parallel bonding model (BPM) is similar to a group of springs, which are evenly arranged on the adjacent area of two contact particles centered on the contact point and consist of a linear element and a parallel bond element [47] (Figure 1). Among them, linear element can transmit elastic interactions between particles. Parallel bond element provides a bonded effect that can transfer forces and moments between particles [48]. If maximum stresses exceed the corresponding bond strength [49], the parallel bond will break. The bond material and its associated forces, moments, and stiffness will be removed from the model, and only the linear model will be available.

Force displacement laws for contact force and momentum in the BPM are, respectively, computed as follows [44]:

$$F_c = F_l + F_d + F_b, \quad (1)$$

$$M_c = M_b, \quad (2)$$

$$M_b = M_n^b n_i + M_s^b t_j, \quad (3)$$

where F_l refers to the linear force and F_d denotes the hysteretic damping force [47], which is applied to dissipate the energy of the system for each particle in each calculation step; F_b represents the parallel bond force; and M_b stands for the parallel bond moment.

The parallel bond force and moment of parallel bond element are computed as follows:

$$F_i = F^n n_i + F^s t_j, \quad (4)$$

$$M_i = M^n n_i + M^s t_j, \quad (5)$$

where F^n and F^s denote the normal and tangential bond forces, respectively, and M^n and M^s are the torques.

According to the beam bending theory, the maximum tensile stress σ_c and shear stress τ_c acting on the parallel bond can be obtained from

$$\sigma_{\max} = \frac{F^n}{A} + \frac{|M^s|R}{I}, \quad (6)$$

$$\tau_{\max} = \frac{|F^s|}{A}, \quad (7)$$

where A and I are the area and moment of inertia of parallel bonded cross section, respectively.

$$A = 2Rt, \quad t = 1, \quad (8)$$

$$I = \frac{2}{3}r^3t, \quad t = 1, \quad (9)$$

where R is the average radius of two contacting particles and t is the particle unit thickness (PFC^{2D}).

When tensile and shear strength of parallel bond element exceed $\sigma_{\max}$ or $\tau_{\max}$, the parallel bonds break [47].

FIGURE 1: Parallel bond model: (a) parallel bond; (b) bond failure (stiffness, damping, and friction).

2.2. Fluid-Solid Coupling Model. In the program, the fluid-solid coupling is realized by assuming the geometric space of particle-particle contact as the parallel plate channel of fluid flow (Figure 2(b)). The adjacent parallel plate fluid channels in the model are connected to form a closed “domain” model (Figure 2(a)). In the calculation process, the water pressure in the “domain” is continuously updated and acts on the particles. The seepage flow q between the connected domains is determined by the hydraulic gap a width of the connecting “pipe,” the water pressure p_1 and p_2 of the “domain” and the dynamic viscosity μ of the fluid [50], as shown in equation (10):

$$q = \frac{a^3}{12\mu} \frac{p_2 - p_1}{L}, \quad (10)$$

where $p_2 - p_1$ is the pressure difference between two adjacent areas, L is the length of the pipe and its value is the sum of the radius of particles connected with the calculated contact, and a is determined by the contact force between particles.

In the calculation time step Δt , the change of pore fluid pressure is calculated by the bulk modulus of fluid.

$$\Delta p = \frac{K_f}{V_d} \left(\sum q \Delta t - \Delta V_d \right), \quad (11)$$

where K_f is the bulk modulus, V_d is the apparent volume of the domain, and $\sum q$ is the total flow of the domain from the surrounding pipes.

$$F_i = p n_i s, \quad (12)$$

where n_i is the external average unit vector of the connecting line between adjacent particles and s is the distance from the center of the corresponding particle to the contact point.

In addition, because of the explicit algorithm, in order to ensure the stability of the numerical model, the pressure change caused by water flow must be less than the

FIGURE 2: Pipeline and domain in PFC^{2D}: (a) fluid grid—the solid green circle represents solid particles; the middle area of particles represents drainage basin; the solid red circle represents basin center; the green line segment represents pipeline; (b) domain and pipe—the width W and length L of pipelines are shown, respectively.

disturbance pressure:

$$\Delta t = \frac{2rV_d}{NK_fka^3}, \quad (13)$$

where N is the number of pipes connected to a domain and r is the average radius of particles around a domain. In addition, in order to ensure the stability of the whole computing domain, the global time step must be the minimum of all local time steps.

3. Basic Law of Hydraulic Fracture Propagation in Composite Rock considering the Stress Disturbance Effect

3.1. Test System and Scheme. A 500 mm × 500 mm × 500 mm true triaxial hydraulic fracturing experimental system, as shown in Figure 3, was used for the hydraulic fracture propagation test of composite rock. Three channels of the four-channel electrohydraulic servo loader accurately controlled the confining pressure loading, and the other channel controlled the oil-water loading converter to control the loading of the water pressure.

3.2. Preparation of the Test Block. Cement mortar test blocks were used in the experiments to simulate hydraulic fracturing on site. No. 32.5 cement, filtered fine sand, and fresh water with a mass ratio of 3.5:1:0.3 were mixed to cast the test blocks. The bedding plane pouring method was used to pour the sample into a particular steel mould of 300 × 300 × 300 mm. The air-dried composite rock material sample is shown in Figure 4. The mechanical strength of the test block was tested by sampling. The main experimental parameters were as follows: the compressive strength was 15.85 MPa, the average tensile strength was 1.65 MPa, the tensile strength was 0.28 MPa at bedding plane, Poisson's ratio was 0.18, the cohesion was 0.30 MPa at bedding plane and 2.94 MPa elsewhere, and the porosity of the test block was 0.14.

3.3. Calibration of Numerical Model Parameters. In this study, a numerical model of the composite rock material was established by using the particle flow code (PFC^{2D}). To make the mechanical properties and failure characteristics of the DEM simulation samples consistent with the laboratory test results, a numerical model with a length of 100 mm and a width of 50 mm was established to calibrate the mechanical parameters. The minimum particle radius $R_{\min}$ was 0.64 mm, the ratio of maximum particle radius to a minimum particle radius was 1.66, and the porosity was 0.14. The microparameters were adjusted repeatedly until the stress-strain curve, and the final fracture mode of the simulated specimen was consistent with the laboratory test. Table 1 shows the microscopic parameters of the simulated sample. Table 2 shows a comparison of the parameters of the laboratory test and numerical simulation. Figure 5 shows the contrast of the stress-strain curve and the final fracture mode of the complete specimen.

The simulated stress-strain curve is in good agreement with the test curve (Figure 5). To obtain the tensile strength of the bedding plane of the composite rock material test block, shear experiments were carried out on the sample. Figure 6 shows the failure morphology of the test blocks after the experiments. According to the Mohr-Coulomb criterion, the tensile strength of the bedding plane was calculated, and the value was 1/5.8 of the matrix rock mass. The mechanical properties of simulated bedding planes are similar to those of typical rock bedding planes [51]. Therefore, the test blocks can be used to simulate the bedding planes.

The rock parameters obtained above were used to model the composite rock mass materials. The model is shown in Figure 4. The modelling size of the square model is 300 mm in length and 300 mm in width, which contains approximately 12787 particles. The material is divided into three areas. To distinguish the bedding planes, the colour of the middle area is set to purple, and the outer two areas are green. The fluid injection point is located in the centre of the model. The distance between the two bedding planes and the centre of the injection point is 68 mm. The confining pressure

FIGURE 3: True triaxial hydraulic fracturing test system: (a) schematic diagram of test system; (b) laboratory test system diagram.

FIGURE 4: Three-dimensional diagram and simulation diagram of composite rock material test block with bedding (unit: mm) [51].

TABLE 1: Micromechanical parameters of simulated samples.

Particle parameters					Parallel bonding parameters				
E_c (GPa)	k_n/k_s	μ	$R_{\max}/R_{\max}$	ρ (g·cm ⁻³)	$\bar{E}_c$ (GPa)	$\bar{k}_n/k_s$	$\bar{\sigma}_c$ (MPa)	$\bar{\tau}$ (MPa)	$\bar{\lambda}$
1.51	1	0.1	1.66	2.65	1.51	1	5.4	12.7	1

TABLE 2: Comparison of parameters between laboratory test and numerical simulation test.

Value type	Density ρ (g·cm ⁻³)	Young's modulus E (GPa)	Uniaxial compressive strength σ_c (MPa)	Poisson's ratio	Porosity
Experimental value	2.65	0.92	15.85	0.18	0.14
Simulation value	2.65	0.90	15.94	0.18	0.14

FIGURE 5: Laboratory test and numerical simulation of the stress-strain curve and final fracture mode of the intact specimen.

FIGURE 6: Morphology of test blocks after damage [51].

loading of the test block was realized by applying a stress constraint on the boundary (wall) of the model. In addition, the fluid viscosity, fluid bulk modulus, and model permeability used in the model were consistent with the laboratory tests (Table 3).

3.4. Spatial Morphology of the Hydraulic Fracture in Composite Rock. According to the test scheme shown in Table 4, the dynamic hydraulic fracture propagation process was monitored, and the formation process of a bedding fracture zone (BFZ) was studied.

After the hydraulic fracturing test, the composite rock material test block was split, and the internal hydraulic fracture extends parallel to the maximum principal stress direction (Figure 7). The hydraulic fracture morphology of composite rock material is significantly different from that of the continuous symmetrical double-wing hydraulic frac-

ture in homogeneous rock. Figure 8(a) shows that the hydraulic fracture front on both sides of bedding planes is clearly discontinuous and staggered for a certain distance and the dyeing depth on both sides is different. This “unconformity” phenomenon indicates that when the hydraulic fracture extends to the bedding plane, the bedding plane is damaged. The hydraulic fracture first extends along the bedding plane and then extends through the bedding plane. Affected by the bedding plane, the direction and path of the hydraulic fracture expansion are changed to a certain extent, forming a “≠” shape of a cross fracture with the bedding planes.

In addition, compared with Figure 8(b), the simulation results of the hydraulic fracture morphology and hydraulic fracture propagation mode at the bedding plane are in good agreement with the laboratory test results. In the simulation test, after the hydraulic fractures of the two wings extended

TABLE 3: Parameters in the process of hydraulic fracturing.

Fracturing parameters		Particle flow model	Laboratory test
μ_v (Pa·s)	Viscosity coefficient of fracturing fluid	$135 \cdot 10^{-3}$	$135 \cdot 10^{-3}$
K_f (GPa)	Bulk modulus of fracturing fluid	10	10
K (mD)	Permeability	65.1762	65.1762

TABLE 4: Experimental scheme for hydraulic fracturing of composite rock materials.

Test name	Confining pressure (MPa)			In situ stress coefficient	Bedding plane cementation strength (MPa)	The injection rate of fracturing fluid (ml/min)
	σ_1	σ_2	σ_3			
1-1 (laboratory test)	6	4.5	3	0.5	0.28	50
1-2 (simulation test)	6		3	0.5	0.28	50

FIGURE 7: Real hydraulic fracture morphology: (a) homogeneous rock mass [39]; (b) composite rock mass with bedding plane.

to the bedding plane, all the hydraulic fractures extended along the bedding plane for a small distance and then extended through the bedding plane. The bedding plane was obviously damaged, and the microfracture zone of the bedding plane was formed. The propagation path of hydraulic fractures on both sides of the bedding plane is obviously discontinuous with a staggered distance. In addition, the hydraulic fracture opening was measured (Figure 8). The main hydraulic fracture opening is 0.54 mm, the bedding plane hydraulic fracture opening is 0.09 mm, and the fracture opening ratio is 6. In the simulation test, the opening degree of the main hydraulic fracture is 0.50 mm, the opening degree of the bedding plane hydraulic fracture is 0.08 mm, and the opening ratio is 6.25. The results of the model fracture opening are highly consistent with the laboratory test results, which proves the rationality of the simulation test.

In conclusion, the existence of the bedding plane has a significant impact on the propagation trajectory of the hydraulic fracture. By comparing the laboratory test results with the numerical simulation results, the effectiveness of the discrete element fluid structure coupling numerical model proposed in this paper is verified. Because of the closeness of the laboratory fracturing test, it is difficult to observe the dynamic propagation process of the hydraulic fracture and the fracturing effect induced by the disturbing stress of hydrofracturing. Therefore, based on verifying the rationality

of the simulation above, the next section analyses the simulation results in detail.

4. Discussion: The Principle of the Fracturing Effect Induced by Disturbing the Stress of Hydrofracturing

4.1. Damage Evolution Law of the Disturbed Fracture Zone of the Bedding Plane under the Stress Disturbance Effect. The simulation results are shown in Figure 9. The dynamic hydraulic fracture propagation process of composite rock can be divided into two stages (HF1 as an example): before the hydraulic fracture extends to the bedding plane and after the interaction between the hydraulic fracture and bedding plane. In the first stage (Figure 9: step-1, step-2, and step-3), after hydraulic fracture initiation, the main hydraulic fracture propagation gradually approaches the bedding plane until it just intersects with the bedding plane. Notably, in this stage, the main hydraulic fracture intersects with the bedding plane, but the fracturing fluid does not invade the bedding plane. In the second stage (Figure 9: step-4, step-5, and step-6), after the main hydraulic fracture intersects with the bedding plane, the fracturing fluid invades the formation, and the hydraulic fracture interacts with the bedding plane until hydraulic fracturing is completed. It can be seen from

FIGURE 8: Comparison of laboratory test and simulation test: (a) laboratory test hydraulic fracture propagation plane; (b) simulated test hydraulic fracture.

FIGURE 9: Dynamic propagation process of hydraulic fracture and the formation process of bedding plane fracture zone.

the first stage in the figure that when the HF1 fracture tip is 14.3 mm away from the II bedding plane, microcracks are initiated at the II bedding plane; that is, the fracture occurs ahead of time before the bedding plane intersects with the hydraulic fracture. The reason is that the disturbing stress field in front of the hydraulic fracture tip induces the failure of the bedding plane; that is, the fracturing effect is induced by the disturbing stress of hydrofracturing.

From the distribution of the model stress field shown in Figure 9, the particles in the test block are in a compression state (green zone) under the action of confining pressure before the failure of the test block. After injection hole crack, a tensile load area is formed at the hydraulic fracture tip, that is, the stress disturbance area (red zone). With hydraulic fracture expansion, the compressive stress field at the front end of the hydraulic fracture tip weakens, and the tensile stress field increases gradually. The range of the tensile stress field is far greater than the permeable range of the fracturing fluid. Because the range of the tensile disturbance stress field at the hydraulic fracture tip is much larger than the permeability range of the fracturing fluid, when HF1 is 14.3 mm away from the bedding plane, the disturbance stress on the bedding plane has broken through the tensile limit of the bedding plane. In addition, in the process of hydraulic fracture propagation, the red area at the front of the hydraulic fracture tip expands continuously, which shows that the disturbing tensile stress perpendicular to the hydraulic fracture propagation direction increases steadily. The black area on both sides of the hydraulic fracture deepens continuously, which shows that the disturbing compressive stress on both sides of the hydraulic fracture parallel to the propagation direction increases continuously. In the first stage, the fracture zones are all generated by the disturbance stress at the fracture tip. The fracture zone formed in this stage is called the bedding disturbance fracture zone (BFZ).

In the second stage of hydraulic fracture propagation, after HF1 extends to bedding plane II, the fracturing fluid directly invades the bedding plane, and the hydraulic fracture is fused with the disturbance fracture zone of the bedding plane. At this time, the failure of the bedding plane is no longer the disturbance effect but the water wedge effect of fracturing fluid on the bedding plane. By observing the propagation paths of HF1 and HF2, it can be found that the propagation path of hydraulic fractures on the bedding plane is consistent with the bedding plane disturbance fracture zone of the first stage. This finding shows that the propagation path of hydraulic fractures at the bedding plane is highly sensitive to the disturbance fracture zone formed in the first stage. The disturbed fracture zone forms the dominant flow path and leads to the capture of hydraulic fractures. There is a significant correlation between the two.

At present, the hydraulic fracturing experimental research mainly focuses on the second stage of hydraulic fracture propagation. The effect of the stress disturbance effect during the first stage of hydraulic fracture propagation on the propagation path of hydraulic fractures is ignored. Thus, the relevant mechanism research is not perfect, the theoretical results and experimental phenomena are difficult to match. The particle flow research method proposed in this

paper can effectively solve this problem. In Section 4.2, the correlation between the development characteristics of the disturbed fracture zone and the hydraulic fracture extension mode is revealed.

4.2. Relationship between the Stress Disturbance-Induced Cracking Effect and Hydraulic Fracture Propagation. According to the theory of nonlinear fracture mechanics [52, 53], the formation process and propagation behaviour of BFZs are highly consistent with those of the propagation fracture process zones (FPZs) [54, 55]. The formation process can be described as follows: under the influence of the stress disturbance effect, many microcracks are generated on the bedding plane, which dissipate energy and cause the fracture energy of the bedding plane rock material to decrease significantly. When the accumulated dissipated energy of microcracks reaches the fracture energy, a fracture surface of unit length is produced [56, 57]. If the stress disturbance effect is stronger in the process of hydraulic fracturing, then more microfractures accumulate in the disturbed fracture zone of the bedding plane. The larger the dissipated energy of the bedding rock material is, the smaller the energy required for fracture propagation per unit length of the bedding plane, the smaller the resistance of the hydraulic fracture extending along the bedding plane when the hydraulic fracture extends to the bedding plane, and the higher the tendency of hydraulic fracture propagation along the bedding plane (Figure 10).

In addition, Simpson et al. [58] showed that the density of microfractures is positively correlated with the rock permeability, and a large number of microfractures expand and penetrate each other in the bedding plane under the effect of a stress disturbance. With increasing microcracks in the bedding plane, the density of microcracks in the bedding plane area increases significantly, which leads to the enhancement of the local permeability of the bedding plane, that is, the formation of a high permeability area of the bedding plane. Additionally, the formation of the disturbed fracture zone intensifies the fragmentation and opening of the bedding plane, forms the dominant flow path, and significantly improves the tendency of hydraulic fractures to expand along the bedding plane.

5. Analysis of the Influencing Factors of the Hydraulic Fracture Propagation of Composite Rock Materials considering the Effect of a Stress Disturbance

5.1. Evaluation Index of the Fracturing Effect Induced by Disturbing Hydrofracturing Stress. Due to the influence of the hydraulic fracture tip disturbance stress, the rock material in the bedding plane area is damaged. In the area where the damage is concentrated, microfractures of different scales expand and connect with each other, and many small microfracture areas expand and fuse with each other. The superposition of microfracture areas at all levels constitutes the bedding plane fracture zone.

The formation of microcracks is accompanied by energy dissipation. With an increase in the number of microcracks, when the accumulated dissipation energy of microcracks

FIGURE 10: Formation mechanism of disturbed fracture zone in bedding plane during hydraulic fracturing: (a) cohesive fracture model of the disturbed fracture zone at the bedding plane (BFZ); (b) softening law of cohesive fracture.

reaches the fracture energy, a macrofracture surface per unit length is formed. Because the microfractures are multiscaled [59, 60], the formation of each microfracture is based on the formation and penetration of multiple secondary microfractures, so the total energy dissipated by forming a single microfracture is equal to the accumulated energy dissipated by forming multiple secondary microfractures. If the smallest level of the microcracks is S (Figure 11(f)), then N smallest level (S) of the microcracks needs to be activated to form a unit length of the macrofracture surface [61]. The energy (G_s) dissipated by the opening of the smallest level microcrack is constant (Figure 11(g)) [60], so the total number (N) of the smallest level microcracks activated by the formation of the unit length macrofracture surface is constant [62, 63]; that is, the smallest level microcracks are continuously formed until the accumulated dissipated energy reaches the fracture energy of the unit length macrofracture ($G = NG_s$) (Figure 11(d)).

In the numerical simulation of particle flow, the fracture between pairs of particles is the smallest level of the microfracture, and the energy required to fracture single particles is fixed. Then, the energy required to the fracture of a pair of particles can be regarded as the minimum energy level. Based on the excellent characteristics of numerical simulation software (PFC^{2D}) and the previous discussion on the relationship between the macrofracture surface and all levels of microcracks, the number of microcracks in the disturbed fracture zone of the bedding plane can be counted to quantitatively analyse the damage degree of the stress disturbance effect on the bedding plane to characterize the degree of the stress disturbance effect.

The size of the disturbed microfracture zone of the bedding plane is another important index to measure the effect of a stress disturbance. The density of microfractures is positively correlated with the rock permeability [58]. That is,

FIGURE 11: The mechanism and model assumption diagram of hydraulic fracture propagation considering stress disturbance effect: (a) simplification of hydraulic fracturing process; (b) formation of microfracture zone in front of real hydraulic fracture; (c) optical electron micrograph of microfracture generated by bedding plane under stress disturbance effect and schematic diagram of multiscale microfracture; (d) linear softening curve of a cohesive crack; (e) the diagram of the minimum-scale microcrack; (f) the sketch map of the secondary microfracture [62, 63].

compared with the area without fractures, the permeability of the disturbed fracture zone is significantly increased, which easily forms the dominant flow path of the fracturing fluid. Therefore, the larger the size of the disturbed fracture zone is, the longer the dominant flow path in the bedding plane, and the greater the tendency of the expansion along the bedding plane. Therefore, the size of the disturbed microfracture zone of the bedding plane is an important index to evaluate the stress disturbance effect.

5.2. Discussion: Sensitivity of Stress Disturbance-Induced Cracking under Different Conditions

5.2.1. Influence of In Situ Stress. According to the scheme shown in Table 5, three groups of different horizontal in situ stress differences are set, and the in situ stress differences are 1, 3, and 5 MPa. The final test results are shown in Figure 12. The stress disturbance fracturing effect occurs on the bedding plane of the three groups of test blocks, forming the disturbed fracture zone of the bedding plane. In groups 2-3 (difference = 1 MPa), hydraulic fractures initiate at 60°, 135°, and 270° of the injection hole. Among them, hydraulic fracture (HF3) extends in the middle rock (rock-2) throughout the whole process. The left wing (HF1) of the hydraulic fracture first extends along the bedding plane and then extends through the bedding plane. The right wing (HF2) of the hydraulic fracture extends along the bedding plane. In group 2-2 (difference = 3 MPa), hydraulic fractures initiate in the direction of 157° and 330° of the injection hole. The left side of the hydraulic fracture (HF1) propagates along and across the bedding plane. The right wing of the hydraulic fracture (HF2) extends along the bedding plane. Hydraulic fractures of group 2-1 (difference = 5 MPa) initiate in the direction of 15° and 190° of the injection hole. The propagation direction of the hydraulic fracture is parallel to the direc-

TABLE 5: Experimental scheme for hydraulic fracturing of composite rock materials.

Test name	Confining pressure (MPa)			In situ stress difference (MPa)	Bedding plane cementation strength (MPa)	The injection rate of fracturing fluid (ml/min)
	σ_1	σ_2	σ_3			
2-1	8	3	5		0.28	50
2-2	6	3	3		0.28	50
2-3	4	3	1		0.28	50

tion of maximum principal stress. The two wings of the hydraulic fracture propagate along and through the bedding plane. The propagation path of the hydraulic fracture deviates slightly at the bedding plane. Under different in situ stress conditions, the overall shape of hydraulic fractures is obviously different. With the increase in the main in situ stress difference, the number of hydraulic fractures will gradually decrease from many to one, the direction of hydraulic fractures will gradually approach the vertical direction of σ_3 , and the hydraulic fracture surface will gradually become flat.

To quantitatively analyse the damage degree of rock material in the bedding plane area under the stress disturbance effect, this paper provides statistics on the number of microcracks and the size of the bedding disturbance fracture zone under different in situ stress conditions (Table 6). Notably, the above characterization quantity statistics represent the large microfracture zone near the intersection point, and the distance away from the scattered microfracture zone is not included in the statistics. The reason is that the effect of long-distance discrete microfractures on the propagation path of hydraulic fractures is negligible. According to the results (Figure 13), the overall shape of hydraulic fractures is significantly different under different in situ stress

FIGURE 12: The shape of hydraulic fracture and the development of disturbed stress zone of bedding surface under different in situ stress conditions.

TABLE 6: The number of microcracks in the disturbed fracture zone and the size of microfracture zone.

Group	Stress difference (MPa)	I—bedding plane		II—bedding plane	
		The number of microcracks	The size of disturbed microfracture zone (mm)	The number of microcracks	The size of disturbed microfracture zone (mm)
2-1	5	9	15	8	18.428
2-2	3	7	15.875	9	18
2-3	1	11	16.714	9	19.714

conditions, but the number and size of microfractures in the disturbed fracture zone of the bedding plane are very close, and when microfractures occur in the bedding plane area of

the three groups of samples for the first time, the distance between hydraulic fractures and the bedding plane is almost equal. This shows that the damage difference of the stress

FIGURE 13: The number of microcracks and the size of the bedding disturbance fracture zone under different in situ stress conditions.

TABLE 7: Experimental scheme for hydraulic fracturing of composite rock materials.

Test name	Confining pressure (MPa)			In situ stress difference (MPa)	Bedding plane cementation strength (MPa)	The injection rate of fracturing fluid (ml/min)
	σ_1	σ_2	σ_3			
3-1	6	3	3	0.84	0.84	50
3-2	6	3	3	0.28	0.28	50
3-3	6	3	3	0.14	0.14	50

disturbance effect on the bedding plane is very small under different in situ stress conditions, and the stress disturbance fracturing effect is less sensitive to in situ stress conditions.

5.2.2. Influence of the Bond Strength of the Bedding Plane. In group 3-1 (Table 7), when the two wings of the main hydraulic fracture extend to the bedding plane, there is no disturbed fracture zone induced by the stress disturbance effect at the bedding plane. The hydraulic fracture extends directly through the bedding plane, with no change in the direction of the hydraulic fracture propagation. The hydraulic fracture trajectory is generally regular and flat, and the propagation trajectory is similar to the average rock. In group 3-2, the number of microfractures in the disturbed fracture zone of bedding plane I is 7, and the size of the disturbed fracture zone is 14.142 mm. The left wing (HF1) of the hydraulic fracture propagates along the bedding plane and across the bedding plane. The number of microfractures in the disturbed fracture zone of bedding plane II is 9, and the size of the disturbed fracture zone is 16.286 mm. The right wing (HF2) of the hydraulic fracture extends along the bedding plane. In the process of hydraulic fracturing, the test block of group 3-3 exhibits an obvious disturbance stress fracture phenomenon. The number of microfractures in the disturbance fracture zone at the interface of HF1 and bedding plane I is 11, and the range of the disturbance fracture zone is 30 mm.

The number of disturbance fracture zones at the interface of HF2 and bedding plane II is 15, and the range is 36.428 mm. After the two wings of the main hydraulic fracture extend to the bedding plane, they all extend along the bedding plane (Figure 14).

By comparing the development degrees of the three groups of bedded disturbed fracture zones (Figure 15), group 3-1 blocks did not appear in the disturbance fracture zone. Compared with group 3-2, the number and size of microfractures in group 3-3 increased by 162.5% and 170.3% (Table 8). The effect of the stress disturbance is highly sensitive to the bond strength of the bedding plane in the process of hydraulic fracturing. With a decrease in bedding plane cementation strength, the number and size of microfractures in the disturbed fracture zone increase linearly, and the stress disturbance effect also increases significantly. With a decrease in the development degree of the disturbed fracture zone, the extension mode of hydraulic fractures at the bedding plane changes from through bedding plane propagation to along bedding plane propagation.

The reason is that with the increase in the strength of the bedding plane, the ability of rock materials in the bedding plane to resist failure becomes increasingly stronger. When the hydraulic fracture extends to the bedding plane, the smaller the damage of the bedding plane caused by the stress disturbance effect is, the easier it is for the hydraulic fracture to maintain its self-similarity and continue to expand along the initial propagation direction.

5.2.3. Summary. Based on the two sets of test results in Section 4.1, it can be found that when the development degree of the disturbance fracture zone of the bedding plane is similar, the final hydraulic fracture propagation mode at the bedding plane is very close. Additionally, when the development degree of the disturbance fracture zone of the bedding plane is different, the final hydraulic fracture propagation mode is also significantly different. This phenomenon further shows

FIGURE 14: The shape of hydraulic fracture and the development of disturbed stress zone of bedding surface under different bond strength of the bedding plane.

that the development degree of the disturbed fracture zone and the extension mode of the hydraulic fracture have an obvious correlation and consistency. The stress disturbance effect has a significant impact on the propagation path and interactive breakthrough mode of hydraulic fractures. The stronger the stress disturbance effect is, the higher the development degree of the disturbance fracture zone of the bedding plane is. Moreover, the ability of the bedding plane to capture hydraulic fractures is improved, and the tendency of hydraulic fractures to expand along the bedding plane is improved. This experimental conclusion is consistent with the observations of the stress disturbance-induced fracture in Section 4. The theory of the mechanism has satisfactory consistency, and the experiment further verifies the reliability of the previous conclusion.

5.3. Operational Factors

5.3.1. Influence of Distance between the Injection Hole and Bedding Plane. According to the test scheme shown in Table 9, the different relative positions of the injection hole and bedding plane are set, and the relative distances are 58 mm, 80 mm, and 102 mm (Figure 16). In test group 4-1, the time step of the hydraulic fracture extending to the bedding plane is 17171, the bedding plane does not form an obvious disturbed fracture zone, the number of microfractures in the disturbed fracture zone on both sides is only 1 and 2, and the size of the disturbed fracture zone is 2.141 mm and 3.857 mm, respectively. The two wings of the hydraulic fracture spread through the bedding plane. In test group 4-2, the time step of the hydraulic fracture extending to the bedding

FIGURE 15: The number of microcracks and the size of the bedding disturbance fracture zone under different bond strength of the bedding plane.

TABLE 8: The number of microcracks in the disturbed fracture zone and the size of microfracture zone.

Group	Bedding plane cementation strength (MPa)	I-bedding plane		II-bedding plane	
		The number of microcracks	The size of disturbed microfracture zone (mm)	The number of microcracks	The size of disturbed microfracture zone (mm)
3-1	0.84	0	0	0	0
3-2	0.28	8	14.142	9	16.284
3-3	0.14	12	23.317	15	28.428

TABLE 9: Experimental scheme for hydraulic fracturing of composite rock materials.

Test name	Confining pressure (MPa)			Distance (mm)	Bedding plane cementation strength (MPa)	The injection rate of fracturing fluid (ml/min)
	σ_1	σ_2	σ_3			
4-1	6	3	58	0.28	50	
4-2	6	3	80	0.28	50	
4-3	6	3	102	0.28	50	

plane is 21316. The number and size of microfractures in the disturbed fracture zone formed by bedding plane I are 10 and 23.57 mm, respectively, and the number and size of microfractures in the disturbed fracture zone formed by bedding plane II are 14 and 28.142 mm, respectively. The two wings of the hydraulic fracture extend along the bedding plane. In test group 4-3, a large range of disturbed fracture zones was formed at the bedding plane, and the time step for the hydraulic fracture to expand to the bedding plane is 23093. The number of microfractures in the disturbed fracture zone formed by bedding plane I is 13, and the size of the disturbed fracture zone is 27.714 mm. The number of microfractures in the disturbed fracture zone formed by bedding plane II is 20, and the size of the disturbed fracture zone is 41.134 mm. The

two wings of the hydraulic fracture extend along the bedding plane.

By comparing the development degree of the three groups of bedded disturbed fracture zones (Table 10), compared with group 4-1, the relative distance between the injection hole and bedding plane of group 4-2 increases by 38%; the number and size of microfractures in disturbed fracture zone increase by 8 and 8.618 times. The relative position of group 4-3 increases by 76%, and the number and size of microfractures in the disturbed fracture zone increase by 11 and 11.474 times, respectively (Figure 17). With the increase in the relative position, the number and size of fractures in the disturbed fractures increase linearly, the stress disturbance effect increases significantly, and the propagation mode of hydraulic fractures at the bedding changes from through bedding plane propagation to along bedding plane propagation.

To reveal the action mechanism of the relative position of the injection hole and the bedding plane on the stress disturbance fracturing effect, the hydraulic pressure curves of different groups are derived (Figure 18). The breaking hydraulic pressure value and expanding hydraulic pressure value of the three groups of experiments are very close. After the hydraulic fracture extends to the bedding plane, the water pressure curve at the fracture tip undergoes a considerable

FIGURE 16: The shape of hydraulic fracture and the development of disturbed stress zone of bedding surface under different distances between the injection hole and bedding plane.

TABLE 10: The number of microcracks in the disturbed fracture zone and the size of microfracture zone.

Group	Distance (mm)	I—bedding plane		II—bedding plane	
		The number of microcracks	The size of disturbed microfracture zone (mm)	The number of microcracks	The size of disturbed microfracture zone (mm)
4-1	58	1	2.141	2	3.857
4-2	80	10	23.57	14	28.142
4-3	102	13	27.714	20	41.134

slip. When the hydraulic fracture extends to the bedding plane, the hydraulic pressure value of the hydraulic fracture tip is 10.26 MPa, 10.31 MPa, and 10.64 MPa (i.e., A, B, and C, respectively), and the hydraulic pressure is not very differ-

ent in this experiment. Therefore, the influence of the hydraulic pressure on the stress disturbance effect is small and can be ignored. However, different relative positions lead to significant differences in the time required for the

FIGURE 17: The number of microcracks and the size of the bedding disturbance fracture zone under different distances between the injection hole and bedding plane.

FIGURE 18: The water pressure curve under different distances between the injection hole and bedding plane.

TABLE 11: Experimental scheme for hydraulic fracturing of composite rock materials.

Test name	Confining pressure (MPa)			In situ stress difference (MPa)	Bedding plane cementation strength (MPa)	The injection rate of fracturing fluid (ml/min)
	σ_1	σ_2	σ_3			
5-1	6	3	3	3	0.28	50
5-2	6	3	3	3	0.28	100
5-3	6	3	3	3	0.28	200

hydraulic fractures to extend to the bedding plane. The farther the relative distance is, the longer the time required. The development time of group 4-2 is 25% higher than that of group 4-1, and the development time of group 4-3 is 35% higher than that of group 4-1. The development time is consistent with the growth of the bedding disturbance fracture zone, which indicates that the main factor affecting the stress disturbance fracturing effect is the duration of the stress disturbance effect. The longer the relative distance is, the longer the duration of the stress disturbance on the bedding plane, which leads to sufficient time for the development, expansion, and fusion of the microfractures on the

FIGURE 19: The shape of hydraulic fracture and the development of disturbed stress zone of bedding surface under different injection rate.

TABLE 12: The number of microcracks in the disturbed fracture zone and the size of microfracture zone.

Group	Injection rate (ml/min)	I-bedding plane		II-bedding plane	
		The number of microcracks	The size of disturbed microfracture zone (mm)	The number of microcracks	The size of disturbed microfracture zone (mm)
5-1	50	11	24.857	10	22.285
5-2	100	18	38.582	15	30.641
5-3	200	6	17.493	4	11.384

bedding plane, and the stronger the ability of the bedding plane to capture hydraulic fractures.

5.3.2. *Influence of Injection Rate.* According to the test scheme shown in Table 11, three groups of different injection

rates are set: 50 ml/min, 100 ml/min, and 200 ml/min. In group 5-1, the number of microfractures in the disturbed fracture zone of bedding planes I and II was 11 and 10, respectively, the size of the disturbed fracture zone is 24.857 mm and 22.285 mm, and the time step of the

FIGURE 20: The number of microcracks and the size of the bedding disturbance fracture zone under different injection rate.

FIGURE 21: The water pressure curve under different injection rate.

hydraulic fracture extending to the bedding plane is 15072. The two wings of the hydraulic fracture extend along and through the bedding plane. In group 5-2, the number of microfractures in the disturbed fracture zone is 18 and 15, and the size of the disturbed fracture zone is 38.572 mm and 30.641 mm. The time step of the hydraulic fracture extending to the bedding plane is 9205. The two wings of hydraulic fractures extend along and through the bedding plane. In group 5-3, the number of microfractures in the disturbed fracture zone of bedding planes I and II is 6 and 4, respectively, and the size of the disturbed fracture zone is

17.493 mm and 11.384 mm, respectively. The time step of hydraulic fracture extending to the bedding plane is 6062. The two wings of the hydraulic fracture extend through bedding planes (Figure 19).

By comparing the development degree of the three groups of disturbed fracture zones (Table 12), it can be found that compared with group 5-1, the number and size of microfractures in group 5-2 are increased by 57.1% and 62.6%, respectively, and the number and size of microfractures in group 5-3 are decreased by 52.4% and 38.5%, respectively (Figure 20). With increasing injection rate, the development

FIGURE 22: Experimental working face of hydraulic fracturing and permeability enhancement in composite coal seam.

degree of disturbed fracture zone increases first and then decreases. The stress disturbance effect is bilinear with increasing injection rate.

Existing studies have shown that the change in the pumping capacity will significantly affect the value of the hydraulic pressure and the velocity of hydraulic fracture propagation. With the increase in the injection rate, the value of the hydraulic pressure and the velocity of the hydraulic fracture propagation will increase significantly. The influence of the injection rate on the stress disturbance effect is mainly realized by the joint action of the hydraulic pressure and hydraulic fracture propagation velocity. The increase in the hydraulic fracture tip pressure is conducive to the effect of a stress disturbance, while the shortening of development time is not conducive to the effect of a stress disturbance.

In Figure 21, due to the increase in the injection rate, the hydraulic pressure at the fracture tip of group 5-2 is increased by 1.11 MPa compared with that of group 5-1, and the duration of the stress disturbance is reduced by 38.9% due to the increase in the hydraulic fracture propagation velocity. Finally, the development degree of the disturbed fracture zone is improved. The reason is that the hydraulic pressure of the fracture tip will clearly increase with increasing injection rate in a certain range. Although the expansion velocity of the hydraulic fracture is also increased, the amplitude is not large, so the disturbed fracture zone still has enough time to develop. At this time, the increase in hydraulic pressure is the main factor affecting the stress disturbance effect and the damage degree of the bedding plane. Therefore, with increasing injection rate in a certain range, the development degree of the disturbed fracture zone is improved. That is, the effect of high stress promoting the development of the disturbed fracture zone is stronger than that of an insufficient duration hindering the development of the disturbed fracture zone.

With a further increase in the injection rate, the hydraulic pressure at the fracture tip of group 5-3 is further increased by 2.04 MPa compared with that of group 5-1, and the duration of the stress disturbance is further reduced by 59.8%. Finally, the effect of the stress disturbance is reduced. The reason is that when the injection rate increases too much, although the hydraulic pressure at the fracture tip is higher, the hydraulic fracture propagation velocity is faster, and

there is not enough time for the development of microfractures in the disturbed fracture zone of the bedding plane. At this time, the development time is the dominant factor affecting the stress disturbance effect and the damage degree of the bedding plane. That is, the effect of high stress promoting the development of the disturbed fracture zone is stronger than that of an insufficient duration hindering the development of the disturbed fracture zone.

6. Field Application Example

Based on the hydraulic fracturing test results in Section 5, an industrial field test of hydraulic fracturing permeability enhancement was carried out. The hydraulic fracturing working face is shown in Figure 22. The stratum is a typical composite rock material, the upper part of the coal seam is dark grey clay, and some sections are light grey siltstone, which has a transitional contact relationship with the coal seam, and the bedding planes are weakly cemented, with poor continuity.

In the initial stage of the field test, the injection rate was set at 82 l/min. After the completion of the test, the gas drainage concentration, flow rate and purity of the working face were determined. The gas drainage concentration of the single hole after hydraulic fracturing was 18%, the average mixed flow rate of the single hole was 0.56 m³/min, and the purity was 0.075 m³/min·100 m. The reason for the low efficiency of gas drainage is that the hydraulic fracture did not extend easily across the bedding plane under a low injection rate, the pressure water was leaked along the bedding plane, and the expansion range of the hydraulic fracture was very limited. In addition, the coal seam was thin, the borehole was easily drilled into the rock, and the effective fracturing section was short, which seriously affected the extraction effect. Therefore, in the following test, the injection rate was increased to 128 l/min, and the single hole gas drainage concentration was increased to 54.4%. The average mixed flow rate was increased to 0.721 m³/min, which was an increase of approximately 28.7%. The purity was 0.559 m³/min·100 m, which was a 7.45-fold increase, and the gas drainage efficiency was significantly improved.

The improvement in gas drainage efficiency shows that under the high injection rate, the stress disturbance effect results in less damage to the bedding plane, the hydraulic fractures are less likely to turn along the bedding planes, the hydraulic fracture easily expands through the bedding plane, the fracture connectivity of the hydraulic macrofracture network in the reservoir is strong, and the distribution range is wide, forming a more complex fracture network. For the composite rock reservoirs with a poor continuity and low cementation strength, the injection rate can be appropriately increased, which is helpful to improve the effect of hydraulic fracturing. The research results of this section are consistent with the experimental results in Section 5.3.2, and the reliability of the model is verified. The research results can provide a theoretical basis for controlling the formation of complex hydraulic fracture network in oil and gas reservoirs and mine surrounding rock.

7. Conclusion

- (1) Based on the experimental study on the hydraulic fracture propagation law of composite rock material, the existence of a bedding plane can capture the hydraulic fracture and the hydraulic fracture will exhibit the phenomenon of discontinuous propagation at the bedding plane. In addition, the validity of the proposed numerical model is verified by comparing the results of indoor physical experiments and discrete element numerical simulations
- (2) Based on the numerical simulation of the hydraulic fracturing of composite rock material, the whole-stage dynamic propagation behaviour of the hydraulic fracture is obtained. There is a stress disturbance effect in the process of hydraulic fracturing. According to the formation mechanism of the bedding plane fracture zone, the whole process of hydraulic fracturing can be divided into two stages. The first stage is that the microfracture in the bedding plane is caused by the stress disturbance of the hydraulic fracture tip. The second stage is when the fracturing fluid enters the bedding plane and a water wedge occurs, resulting in the failure of the bedding plane
- (3) The fracturing effect of the stress disturbance significantly affects the extension mode of the hydraulic fracture of the bedding plane. It is found that the influence is mainly reflected in the following two points: (1) the formation of microfractures is accompanied by energy dissipation. The resistance of hydraulic fracture propagation along the bedding plane is greatly reduced. (2) The formation of the disturbance fracture zone in the first stage improves the degree of fragmentation of the bedding plane, greatly improves the permeability of the bedding plane, and forms the dominant flow path. The propagation path of the hydraulic fracture along the bedding plane is highly coincident with the path of the disturbed fracture zone
- (4) Based on the mechanism of the effect of the stress disturbance on rock hydraulic fracture propagation, combined with the relevant theoretical knowledge of nonlinear fracture mechanics, two important indexes for evaluating the effect of stress disturbance are proposed
- (5) The stress disturbance effect of the composite rock material is less sensitive to the in situ stress but has a higher sensitivity to the bond strength of the bedding plane. There is a negative correlation between the bond strength of the bedding plane and the effect of stress disturbance. With the increase in the stress disturbance effect, the propagation mode of hydraulic fractures at the bedding plane changes from propagation through the bedding plane to propagation along the bedding plane
- (6) The stress disturbance effect of the composite rock material is highly sensitive to the relative position of

the injection hole and bedding plane and the injection rate. With the increase in the relative distance between the injection hole and the bedding plane, the stress disturbance effect increases linearly, and the propagation mode of hydraulic fractures at the bedding plane changes from propagation through the bedding plane to propagation along the bedding plane. With increasing injection rate, the stress disturbance effect first increases and then decreases bilinearly, and the propagation mode of hydraulic fractures at the bedding plane changes from propagation along the bedding plane to propagation through the bedding plane

Nomenclature

E_c :	Elastic modulus (GPa)
ν :	Poisson's ratio
k_n :	Normal stiffness of particle element (N/m)
k_s :	Tangential stiffness of particle element (N/m)
μ :	Friction coefficient between particle elements
ρ :	Particle unit density (kg/m^3)
σ_1 :	Maximum horizontal geostress (MPa)
σ_3 :	Minimum horizontal geostress (MPa)
p :	Water pressure (MPa)
c_0 :	Cohesion of rock (MPa)
Φ :	Friction angle of rock ($^\circ$)
G_F :	The initial fracture energy (N/m)
G_f :	The dissipation energy (N/m)
$R_{\max}$:	Maximum particle radius (mm)
$R_{\min}$:	Minimum particle radius (mm)
$\bar{E}_c$:	Elastic modulus of particle element (GPa)
$\bar{k}_n$:	Normal stiffness of parallel bond (N/m)
$\bar{k}_s$:	Tangential stiffness of parallel bond (N/m)
$\bar{\sigma}$:	Normal strength of parallel bond (MPa)
$\bar{\tau}$:	Shear strength of parallel bond (MPa)
q :	Fluid volume rate (m^3/s)
w :	Pipe width (mm)
L :	Length of pipe (m)
N :	Number of pipelines connecting the domain
K_f :	Bulk modulus of fracturing fluid (GPa)
ν :	Injection rate of fracturing fluid (ml/min)
A :	Cross sectional area of fluid flow (m^2)
ΔP :	Change of liquid pressure in river domain (MPa)
ΔV_d :	Volume change of domain caused by volume force (m^3)
V_d :	Apparent volume of river domain (m^3)
w_0 :	Residual width of pipe (mm)
F_i :	Normal contact force under current load (N)
g_s :	Spacing between particles (mm)
μ :	Dynamic viscosity (Pa·s)
k :	Macropermeability of sample (mD)
BFZ:	Bedding fracture zone (definition of this paper)
FPZ:	Fracture process zone.

Data Availability

All the data have been included in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

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