

Research Article

Criterion for Hydraulic Fracture Propagation Behavior at the Interface of a Coal Measure Composite Reservoir

Yifeng Guo,¹ Runxu Zhang ,¹ Xinghua Zhang,¹ Kangkang Han,² Fazhi Yan ,¹ Cunbao Deng,¹ and Zhixin Jin¹

¹College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China

²Shanxi Blue Flame Holding Company Limited, Jincheng 048000, China

Correspondence should be addressed to Runxu Zhang; zhangrunxu@tyut.edu.cn

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Regarding the three expansion modes of hydraulic fractures at the interface of a coal measure composite reservoir (arrested, deflection, and penetration), based on the coupling theory of fluid flow and solid elastic deformation, a criterion that considers the influences of the injection parameters (fracturing fluid injection rate and viscosity) is established to predict the propagation path of hydraulic fractures at the interface of a composite reservoir. The criterion judges the propagation behavior of the fractures by comparing the water pressure in the wellbore and the critical seam pressure of the penetration and deflection. The controlled variable method is used to analyze the influences of the various factors on the propagation behavior of hydraulic fractures at the interface between layers. The results show that the differences in in situ stress, the interface cohesion, and the included angle mainly affect the critical seam pressure of the fracture deflection. The differences in elastic modulus, fluid injection rate, and fracturing fluid viscosity directly affect the water pressure in the wellbore. The difference in the fracture toughness mainly affects the crack propagation path by affecting the critical seam pressure of the deflection. The smaller the difference in the in situ stress is, the more likely it is that the hydraulic fractures will penetrate the layer. Larger differences in the fracture toughness between layers, interfacial cohesion, fluid injection rate, and fracturing fluid viscosity are more conducive to the hydraulic fractures penetrating the layer. When the angle between the hydraulic fractures and the interface is 25–55°, the hydraulic fracture is more likely to expand along the interface. This criterion takes into account the influences of the injection parameters and is of great significance to gaining a better understanding of the propagation behavior of hydraulic fractures at an interlayer interface.

1. Introduction

Coal measure gas, which is characterized by the coexistence of coalbed methane, tight sandstone gas, and shale gas, is an important type of unconventional natural gas resource [1, 2]. In the combined fracturing of a coal measure composite reservoir, the vertical expansion range of the hydraulic fractures determines the sharing degree of the stimulation measures, which is the key factor determining the success or failure of the fracturing operation [3]. Therefore, before combined fracturing of a coal measure composite reservoir is conducted, it is necessary to predict the vertical expansion range and shape of the hydraulic fractures and to predict whether the hydraulic fractures will penetrate the layers.

The corresponding criterion is the basis for determining whether a hydraulic fracture can penetrate through a layer, and understanding the factors influencing the fracture's ability to penetrate the layer is the premise.

The propagation behavior of hydraulic fractures at the interface of a composite reservoir is mainly controlled by geological factors, including the differences in the physical properties (e.g., the elasticity modulus, Poisson's ratio, fracture toughness, and in situ stress) and the characteristics of the interface between the different types of reservoirs (i.e., the interfacial bond strength and inclination angle). Through theoretical derivation and numerical simulation, Fung et al., Gu and Siebrits, and Li et al. [4–6] determined that the difference in the elastic moduli of the layers has little effect on the

fracture height, and even if the elastic modulus of the crack initiation layer differs by a factor of 10 from that of the adjacent layer, the hydraulic fracture will penetrate the interface and extend into the layer with the higher modulus. Laboratory and field tests also revealed that the difference in the elastic moduli of the layers does not substantially affect the penetration of the cracks. However, the elastic modulus may affect the intrafracture pressure. In a reservoir with a large elastic modulus, the intrafracture pressure of the hydraulic fractures will also be relatively large, so the fracture is more likely to enter the layer with the lower elastic modulus from the layer with the higher elastic modulus [7]. Thiercelin et al. and Wu et al. [8, 9] studied the effects of the differences in the interlaminar fracture toughness and Poisson's ratio on vertical crack propagation. They found that when the fracture toughness or Poisson's ratio of the crack initiation layer is greater than that of the adjacent layer, this can promote the propagation of the crack through the layer; otherwise, it will inhibit the crack penetration. However, the ranges of the fracture toughnesses and Poisson's ratios of different lithologic reservoirs are very small, so the influences of the fracture toughness and Poisson's ratio on fracture penetration are very limited. The difference in the minimum horizontal in situ stress of different reservoirs is the most critical factor inhibiting fracture penetration [10]. Tan et al. [11] conducted fracturing tests on layered rock samples and found that when the difference in the minimum horizontal in situ stress of the layers is greater than 2 MPa, the penetration range of the hydraulic fractures is significantly reduced; and when the difference in the minimum horizontal in situ stress of the layers is greater than 4 MPa, the hydraulic fractures are basically confined within the initiation layer. Warpinski et al. also reported that when the difference in the minimum horizontal in situ stress of the layers is greater than 10 MPa, the cracks will not be able to propagate through the interface into the adjacent layers [12]. The properties of the interface are also an important factor affecting the propagation behavior of hydraulic fractures at an interface in a composite reservoir. Daneshy [13] studied the effect of the interfacial strength on the vertical expansion of a fracture through fracturing tests on layered rock combination samples and concluded that when the bonding strength of the interlayer interface is high enough, the interface basically does not undergo slip failure, and the fracture can easily penetrate the interface and propagate into the other layers. Later, this conclusion was also confirmed by Teufel and Clark, Wang et al., and Gao et al. [14–17]. The inclination angle of the interface is also an important factor affecting the vertical penetration of the fracture. Tan et al. [18] concluded through numerical simulation that the greater the inclination angle, the more likely the interface is to slip and fail, and the more difficult it is for the fractures to penetrate the layer.

When hydraulic fractures encounter natural weak surfaces such as natural fractures, bedding planes, and weakly bonded interfaces in order to predict the propagation behavior of the hydraulic fractures, scholars in China and abroad have successively proposed various criteria, such as the Warpinski criterion [19], R&P criterion [20], e-R&P criterion [21], and Llanos criterion [22]. These criteria are mainly

used to discriminate the intersection behavior of hydraulic fractures and natural fractures. There are few criteria for discriminating the propagation behavior of hydraulic fractures when they encounter an interlayer interface. Zhao and Chen [23] adopted the method of rock fracture mechanics and fully considered the influence of the layered in situ stress, layered rock mechanical parameters, formation interface properties, and reservoir thickness to calculate the critical seam pressure for hydraulic fracture cessation, deflection, and penetration. The fracture propagation behavior is determined by comparing the water pressure in the wellbore with the two critical fracture pressures. However, this criterion only considers the case in which the hydraulic fracture is perpendicular to the interlayer interface. Due to the arbitrary distribution of the interfaces in a coal measure composite reservoir, it is necessary to extend this criterion to cases where the hydraulic fracture and the interface are not orthogonal. Moreover, this criterion does not consider the effects of the injection parameters on the crack propagation behavior at the interface.

In view of this, based on the research of Zhao et al. and the theories of fluid flow and solid elastic deformation, a criterion for fracture propagation through an interface in a coal measure composite reservoir for any interface dip angle was developed in this study. The criterion focuses on the influences of the fracturing fluid parameters on the pressure in the fracture. The propagation behavior of the hydraulic fracture at the interface between layers is determined by comparing the critical seam pressure for deflection, the critical seam pressure for penetration, and the water pressure in the wellbore. Based on the experimental data obtained in previous studies, the accuracy of the discriminant results of this criterion was compared under the same conditions. Finally, the control variable method was used to analyze the sensitivities of the influencing parameters.

2. Establishing the Judgment Criterion

2.1. Physical Model and Basic Assumptions. The expansion form of hydraulic fractures in a formation is shown in Figure 1. Figure 1(a) is a schematic diagram of the fracture propagation shape during the hydraulic fracturing process, and Figure 1(b) is a schematic diagram of the relative positions of the hydraulic fractures when they meet an interface in a coal measure composite reservoir. In Figure 1, σ_h is the horizontal minimum in situ stress of the composite reservoir; σ_v is the vertical in situ stress of the composite reservoir; h is the height of the hydraulic fracture; α is the angle between the hydraulic fracture and the interface between the layers; O is the crack initiation position; and A and B are the upper and lower ends of the hydraulic fracture in the height direction, respectively.

To simplify the calculations, the following basic assumptions were made in the model. (1) The hydraulic fracture is a quasi-three-dimensional elliptical fracture when a single formation expands, and the fracture surface is perpendicular to the direction of the minimum in situ stress and extends statically. (2) In the fracture expansion process, there is a tiny fracture process zone at the tip. (3) Each reservoir of the

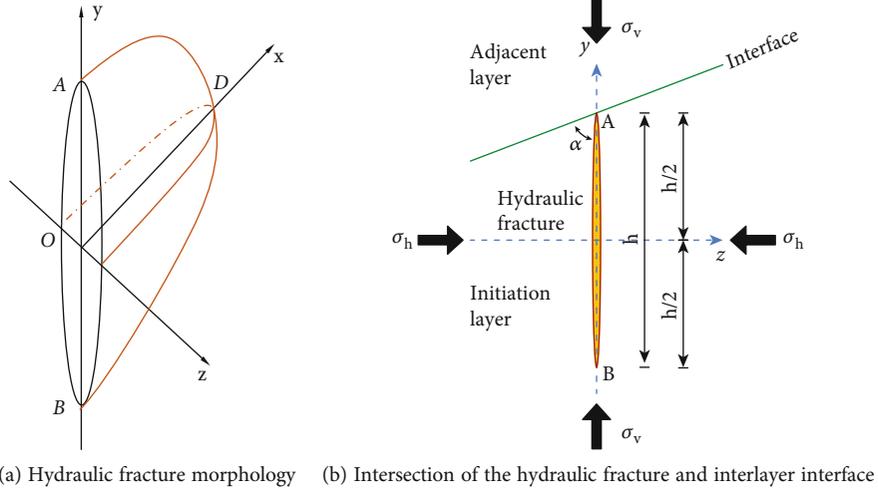


FIGURE 1: Schematic diagrams of the physical model.

composite coal measure reservoir is an ideal homogeneous and isotropic body, the interlayer interface is well cemented, and the rock fracture obeys the theory of elastic fracture mechanics. (4) The flow of the fracturing fluid is one-dimensional laminar flow along the fracture length, the fluid is incompressible, and the filtration of the fracturing fluid is not considered.

2.2. Model of Water Pressure Distribution in Fractures. There is a pressure drop in the fracturing fluid in both the fracture length and fracture height directions. The longitudinal pressure drop of the fracturing fluid affects the extension of the hydraulic fractures at the interface between layers. Neglecting the longitudinal pressure drop will lead to a larger deviation. To be more consistent with the actual situation, after introducing the pressure drop gradient in the fracture height direction, the water pressure $P_F(y)$ in the center of the fracture along the fracture height direction y can be obtained as follows:

$$P_F(y) = P_0 - g_v y, \quad (1)$$

where y is the coordinate of a point in the direction of the fracture height (m), P_0 is the water pressure in the wellbore (MPa), and g_v is the pressure drop gradient in the direction of the slit height (MPa/m).

Based on the basic assumptions, it can be concluded that the flow of the fracturing fluid in the fracture is simple one-dimensional laminar flow along the length of the fracture, and the fluid is incompressible. The flow rate at different locations within the fracture is not constant, and it is a complex function that changes as the fracture grows. Based on the first-order linear partial differential equation for fluid pressure in elliptical pipes, the continuous equation for one-dimensional laminar flow of the fracturing fluid along the fracture length direction, and the expression for the fracture width, the integral terms that cannot be simply analytically expressed can be properly approximated. The simple analytical solution of P_0 is as follows [24, 25]:

$$P_0 = \frac{3.3\pi\sqrt{\pi}\gamma E^3 q}{16\sqrt{lh}K_{IC}^3} + \frac{107\rho q^2 E^2}{432\pi h^2 K_{IC}^2}, \quad (2)$$

where q is the displacement of the fracturing fluid (m^3/s), ρ is the fluid density (kg/m^3), h is the height of the fracture (m), γ is the fracturing fluid's viscosity (mPa·s), E is the elastic modulus of the reservoir (GPa), K_{IC} is the type-I fracture toughness of the reservoir ($\text{MPa}\cdot\text{m}^{1/2}$), and l is the half-length of the fracture (m).

2.3. Critical Fracture Pressure for Different Propagation Behaviors of Fractures

2.3.1. The Cracks Directly Pass through the Interlayer Interface. If the interlayer interface is well consolidated, when the hydraulic fracture reaches the interlayer interface, it will directly pass through the interface and enter the adjacent layer. According to the basic assumptions, when the hydraulic fracture intersects the interlayer interface,

$$2l = h. \quad (3)$$

At this time, the critical condition for the crack to pass through the interface into the adjacent layer and continue to expand is

$$K_A = K_{AC}, \quad (4)$$

where K_{AC} is the fracture toughness of the adjacent layer ($\text{MPa}\cdot\text{m}^{1/2}$) and K_A is the stress intensity factor of the fracture tip when the hydraulic fracture reaches the interlayer interface ($\text{MPa}\cdot\text{m}^{1/2}$). Under plane strain conditions, the stress intensity factor of a hydraulic fracture with height h is [26]

$$K_A = \frac{1}{\sqrt{\pi h}} \int_{-h/2}^{h/2} P(y) \sqrt{\frac{h+2y}{h-2y}} dy, \quad (5)$$

where $P(y)$ is the distribution function of the net pressure within the fracture. When the hydraulic fracture reaches the interlayer interface, assuming that the critical pressure in the center of the fracture required for the critical seam pressure of penetration is P_1 , the stress decomposition diagram of the fracture profile is shown in Figure 2.

Based on the stress decomposition of the fracture profile, the distribution function $P(y)$ of the net pressure in the fracture can be obtained as follows:

$$P(y) = P_1 - g_v y - \sigma_{23} \left(\frac{-h}{2} < y < \frac{h}{2} \right). \quad (6)$$

By simultaneously solving Equations (3)–(6), the critical fracture pressure P_1 at which the hydraulic fracture directly penetrates the interface and enters the adjacent layer can be obtained.

2.3.2. The Fractures Propagate along the Interlayer Interface. The bond strength and dip angle of the interlayer interface play important roles in the crack propagation. When the strength of the interlayer interface is weak or the dip angle is large, the hydraulic fracture may expand along the interface after intersecting with the interface. At this time, shear slip failure mainly occurs at the interlayer interface, and the critical condition for the hydraulic fractures to propagate along the interface is [27]

$$|\tau_{r\theta}| = \tau_I = \mu \sigma_n + C, \quad (7)$$

where $\tau_{r\theta}$ is the shear stress acting on the interface (MPa), τ_I is the shear strength of the interface (MPa), μ is the friction factor of the interface, σ_n is the normal stress acting on the interface (MPa), and C is the cohesive force of the interface (MPa). When the hydraulic fracture reaches the interlayer interface, based on elastic-plastic theory, the stress

field at the tip of the hydraulic fracture can be expressed as follows [28]:

$$\begin{cases} \sigma_z = \sigma_v + \frac{K_A}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right), \\ \sigma_y = \sigma_h + \frac{K_A}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right), \\ \tau_{zy} = \frac{K_A}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2}, \end{cases} \quad (8)$$

where σ_z , σ_y , and τ_{zy} are the stress components at the tip of the hydraulic fracture (MPa), r and θ are the polar coordinates of the tip of the hydraulic fracture, σ_v is the vertical in situ stress (MPa), and σ_h is the minimum horizontal in situ stress (MPa). When the dip angle of the interlayer interface is α , the stress component of the stress field at the tip of the hydraulic fracture at the interface is

$$\begin{cases} \sigma_r = \frac{\sigma_z + \sigma_y}{2} + \frac{\sigma_z - \sigma_y}{2} \cos 2\alpha + \tau_{zy} \sin 2\alpha, \\ \sigma_\theta = \frac{\sigma_z + \sigma_y}{2} - \frac{\sigma_z - \sigma_y}{2} \cos 2\alpha - \tau_{zy} \sin 2\alpha, \\ \tau_{r\theta} = \tau_{zy} \cos 2\alpha - \frac{\sigma_z - \sigma_y}{2} \sin 2\alpha, \end{cases} \quad (9)$$

where σ_r , σ_θ , and $\tau_{r\theta}$ are the axial stress, normal stress, and tangential stress at any point on the interlayer interface, respectively (MPa). By substituting Equation (9) into Equation (10), we can obtain the stress component of the stress field at the tip of the hydraulic fracture at the formation interface under the combined action of the in situ stress and the water pressure in the fracture:

$$\begin{cases} \sigma_r = \frac{K_A}{\sqrt{2\pi r}} \cos \frac{\alpha}{2} \left(1 - \sin \frac{\alpha}{2} \sin \frac{3\alpha}{2} \cos 2\alpha + \sin \frac{\alpha}{2} \cos \frac{3\alpha}{2} \sin 2\alpha \right) + \frac{\sigma_v + \sigma_h}{2} + \frac{\sigma_v - \sigma_h}{2} \cos 2\alpha, \\ \sigma_\theta = \frac{K_A}{\sqrt{2\pi r}} \cos \frac{\alpha}{2} \left(1 + \sin \frac{\alpha}{2} \sin \frac{3\alpha}{2} \cos 2\alpha - \sin \frac{\alpha}{2} \cos \frac{3\alpha}{2} \sin 2\alpha \right) + \frac{\sigma_v + \sigma_h}{2} - \frac{\sigma_v - \sigma_h}{2} \cos 2\alpha, \\ \tau_{r\theta} = \frac{K_A}{\sqrt{2\pi r}} \cos \frac{\alpha}{2} \left(\sin \frac{\alpha}{2} \cos \frac{3\alpha}{2} \cos 2\alpha + \sin \frac{\alpha}{2} \sin \frac{3\alpha}{2} \sin 2\alpha \right) - \frac{\sigma_v - \sigma_h}{2} \sin 2\alpha. \end{cases} \quad (10)$$

According to fracture mechanics, there is a fracture process zone at the tip of a hydraulic fracture, in which the material undergoes plastic deformation. It is generally considered that the stress in the fracture process zone is less than or equal to the stress at its edges; that is, the stress in the fracture process zone does not exceed the stress when $r = r_c$. r_c is the radius of the fracture process zone at the tip of the hydraulic fracture (m). Assuming that the critical pressure at the center of the fracture required for the hydraulic fracture to expand along the interface is P_2 , the

distribution function $P(y)$ of the net pressure in the fracture can be obtained as follows:

$$P(y) = P_2 - g_v y - \sigma_{23} \left(\frac{-h}{2} < y < \frac{h}{2} \right). \quad (11)$$

When the hydraulic fracture spreads along the interface, the following relationship is satisfied:

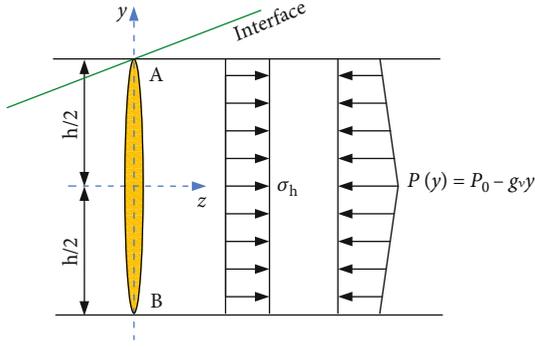


FIGURE 2: Stress distribution of the fracture profile.

$$\begin{cases} \sigma_n = \sigma_\theta, \\ r = r_c. \end{cases} \quad (12)$$

By combining Equations (5), (7), (10), (11), and (12), the critical fracture pressure P_2 can be obtained when the hydraulic fractures expand along the interlayer interface.

2.4. Criterion

- (1) If $P_0 < \min(P_1, P_2)$, the hydraulic fracture stops spreading after it intersects with the interlayer interface
- (2) If $\min(P_1, P_2) = P_2$ and $P_0 > P_2$, then the hydraulic fracture will spread along the interlayer interface after intersecting with the interlayer interface
- (3) If $\min(P_1, P_2) = P_1$ and $P_0 > P_1$, then the hydraulic fracture intersects with the interlayer interface and passes directly through the interface into the adjacent layer

3. Verification of Discriminant Criteria

To test the accuracy of the criterion, the accuracy of the criterion was verified by comparing the results of the criterion under the same conditions with the experimental data of Zhou et al. [29] and the laboratory data of Jiang et al. [28]. The initial experimental parameters of Zhou et al. and Jiang et al. are presented in Table 1.

Table 2 presents the results obtained in Zhou et al.'s experiments and the judgment results of the discriminant criteria developed in this study, and it compares the two sets of results. The symbol ✓ in the table indicates that the judgment results are consistent with the experimental results, and the symbol ✗ indicates that the judgment results are inconsistent with the experimental results. Comparison of the results revealed that except for the last set of experiments, the judgment results of the criterion developed in this study are in good agreement with the experimental results of Zhou et al., which verifies the accuracy of the criterion.

Jiang et al.'s experimental results were used to further verify the judgment method developed in this study. Table 3 presents Jiang et al.'s experimental results and the

calculation results of the discriminant criteria developed in this study, and it compares the two sets of results. It can be seen from Table 3 that the results obtained using the judgment criterion developed in this study are consistent with Jiang et al.'s test results, which further verifies the accuracy of the criterion. It can be seen from the comparison of the results that only the last set of experimental comparison results is inconsistent. This is because the criterion established in this paper is based on the assumption that each coal measure is homogeneous and isotropic. Furthermore, the rock materials used in the actual fracturing tests were not uniform. There were obvious dents near the interface of the rock layer in the eighth group of tests (Table 2), and the heterogeneity near the interface was stronger than that of the previous seven groups, which in turn affected the propagation path of the hydraulic fractures in this set of experiments. Overall, the judgment results of the criterion developed in this study are in good agreement with Zhou et al.'s experimental results, which verifies the accuracy of the criterion.

4. Parametric Analysis

Taking the sand-mudstone composite reservoir of the Shihezi Formation in the Linxing Block in the Ordos Basin as the geological background, the effects of the differences in the in situ stress, rock mechanical properties (elastic modulus and fracture toughness), fluid injection parameters (injection rate and viscosity of fracturing fluid), and interface properties (interface dip angle and cohesion) on the propagation behavior of the hydraulic fractures at the interface in the coal measure composite reservoir were studied. The hydraulic fracture propagation behavior at the interface in the coal measure composite reservoir under the influences of the different parameters was analyzed based on the critical seam pressure for the fracture deflection P_1 , the critical seam pressure for the fracture penetration P_2 , and the water pressure in the wellbore P_0 . Table 4 presents the basic parameters of the sand-mudstone composite reservoir.

4.1. Difference in In Situ Stress. The main parameters of the model were set according to Table 4. The angle between the hydraulic fracture and the interface was set as 45° , and the vertical in situ stress of the reservoir was gradually changed. The difference between the ground stress and the horizontal minimum principal stress was set as 0, 2.5, 5, 7.5, 10, 12.5, and 15 MPa in sequence. The influence of the difference in the in situ stress on the propagation behavior of the hydraulic fractures at the interface in the coal measure composite reservoir was analyzed by studying the variations in the critical seam pressure for fracture deflection P_1 , the critical seam pressure for fracture penetration P_2 , and the water pressure in the wellbore P_0 under different in situ stress differences. The results are shown in Figure 3.

It can be seen from Figure 3 that the water pressure in the wellbore P_0 and the critical seam pressure for deflection P_1 basically do not change under the different in situ stress differences. The critical seam pressure for penetration P_2 decreases linearly as the in situ stress difference increases,

TABLE 1: Initial experimental parameters of Zhou et al. and Jiang et al.

Experimental group		E (GPa)	ν	K_{IC} (MPa·m ^{1/2})	C (MPa)	μ	γ (mPa·s)	q (m ³ /min)
Zhou et al.	Initiation layer	8.402	0.23	0.59				
	Adjacent layer	8.402	0.23	0.59			135	2.52×10^{-7}
	Interface				3.2	0.89		
Jiang et al.	Initiation layer	3.63	0.19	0.52				
	Adjacent layer	2.75	0.23	0.20			1	2×10^{-5}
	Interface				0	0.32		

TABLE 2: Comparison of Zhou et al.'s experimental results and the results of the proposed criterion.

No.	α (°)	σ_h (MPa)	σ_v (MPa)	$\Delta\sigma$ (MPa)	r_c (m)	Experimental results	Criterion results	Uniformity
1	90	5	10	5	0.0011	Penetration	Penetration	✓
2	90	3	10	7	0.0019	Penetration	Penetration	✓
3	60	3	13	10	0.0026	Penetration	Penetration	✓
4	60	5	8	3	0.0026	Penetration	Penetration	✓
5	60	3	10	7	0.0026	Deflection	Deflection	✓
6	30	5	8	3	0.0012	Deflection	Deflection	✓
7	30	5	10	5	0.0012	Deflection	Deflection	✓
8	30	3	13	10	0.0021	Arrested	Deflection	✗

TABLE 3: Comparison of Jiang et al.'s experimental results and the results of the proposed criterion.

No.	α (°)	σ_h (MPa)	σ_v (MPa)	$\Delta\sigma$ (MPa)	r_c (m)	Experimental results	Criterion results	Uniformity
1	90	6	3	3	0.0011	No penetration	Deflection	✓
2	90	7	3	4	0.0019	No penetration	Deflection	✓
3	90	8	3	5	0.0026	No penetration	Deflection	✓
4	90	9	3	6	0.0026	Penetration	Penetration	✓

and it intersects the line where the critical seam pressure for deflection P_1 is located at point (7.9, 25.11). Since the water pressure in the wellbore P_0 is always greater than the critical seam pressure for deflection P_1 under these parameter values, the established criterion shows that when P_1 is less than P_2 , the fracture spreads through the layer. Thus, when the in situ stress difference is less than 7.9 MPa (light blue area in Figure 3), the hydraulic fractures propagate through the layers at the interlayer interface; and when the in situ stress difference is greater than 7.9 MPa (light gray area in Figure 3), the hydraulic fractures propagate along the interface at the interlayer interface. It can be seen that the in situ stress difference is the main factor affecting the propagation path of the hydraulic fractures at the interlayer interface. When the other conditions remain unchanged, the in situ stress difference mainly changes the relationship between the three pressures by affecting the critical seam pressure for fracture deflection P_2 , thereby affecting the propagation path of the hydraulic fractures.

4.2. Rock Mechanical Properties

4.2.1. Difference in Elastic Moduli. The main parameters of the model were set according to Table 4, the angle between

the hydraulic fracture and the interface was set as 45°, and the elastic modulus of the reservoir was gradually changed (24, 24.5, 25, 25.5, and 26 GPa). The difference in the elastic moduli was set as 4, 4.5, 5, 5.5, and 6 GPa. The effect of the difference in the elastic moduli of the reservoir layers on the propagation behavior of the hydraulic fractures at the interface in the coal measure composite reservoir was analyzed by studying the variations in the critical seam pressure for fracture deflection P_1 , the critical seam pressure for fracture penetration P_2 , and the water pressure in the wellbore P_0 under different elastic moduli differences. The results are shown in Figure 4.

It can be seen from Figure 4 that the critical seam pressure for deflection P_1 and the critical seam pressure for penetration P_2 under the different elastic moduli differences basically do not change. The water pressure in the wellbore P_0 increases linearly as the difference in the elastic moduli increases, and it intersects the line where the critical seam pressure for deflection P_1 is located at point (7.9, 25.11). Because the critical seam pressure for penetration P_1 is always smaller than the critical seam pressure for deflection P_2 under these parameter settings, according to the established criterion, when P_0 is less than P_1 , the fracture stops expanding after intersecting with the interlayer interface.

TABLE 4: Basic parameters.

Type	Parameter	Number
Mudstone	Elastic modulus (GPa)	20
	Poisson's ratio	0.25
	Density (g/mm ³)	1.94
	Tensile strength (MPa)	4.1
	Fracture toughness (MPa·m ^{1/2})	0.416
	Horizontal minimum ground stress (MPa)	25
	Horizontal maximum ground stress (MPa)	30
	Overburden pressure (MPa)	40
	Layer thickness (m)	10
	Elastic modulus (GPa)	25
Sandstone	Poisson's ratio	0.2
	Density (g/mm ³)	2.45
	Tensile strength (MPa)	6.7
	Fracture toughness (MPa·m ^{1/2})	0.995
	Horizontal minimum ground stress (MPa)	25
	Horizontal maximum ground stress (MPa)	30
	Overburden pressure (MPa)	40
	Layer thickness (m)	20
Interface	Tensile strength (MPa)	1.78
	Cohesion (MPa)	1.15
	Friction factor	0.15

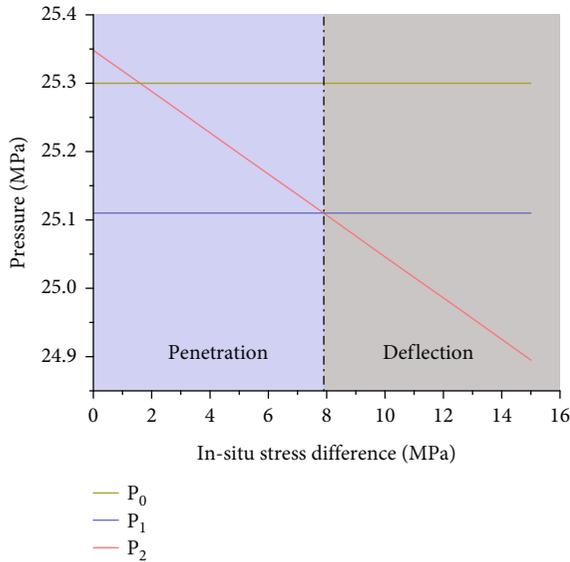


FIGURE 3: Changes in P_0 , P_1 , and P_2 under different in situ stress differences.

Therefore, when the difference in the elastic moduli is less than 4.9 GPa (light orange area in Figure 4), and the fracture stops spreading after it intersects with the interlayer interface. When the difference in the elastic moduli is greater than 4.9 GPa (light blue area in Figure 4), the hydraulic fracture propagates through the layer at the interlayer interface. Thus, the difference in the elastic moduli of the reservoir

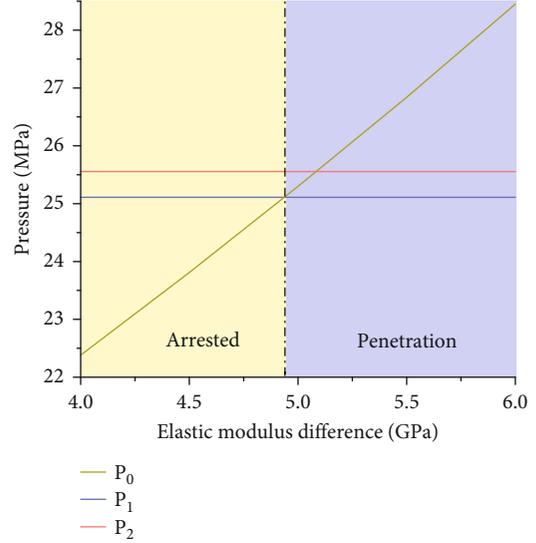


FIGURE 4: Changes in P_0 , P_1 , and P_2 under different elastic moduli differences.

layers affects the propagation path of the hydraulic fractures at the interface between layers. When the other conditions remain unchanged, the difference in the elastic moduli of the layers mainly changes the relationship between the three pressures by affecting the water pressure in the wellbore P_0 , thereby affecting the propagation path of the hydraulic fractures.

4.2.2. *Difference in Fracture Toughness.* The main parameters of the model were set according to Table 4. The angle between the hydraulic fracture and the interface was set as 75°, and the fracture toughness of the interlayer was gradually changed (0.395, 0.595, 0.795, 0.995, 1.195, 1.395, and 1.595 MPa·m^{1/2}). The difference in the fracture toughness between the reservoir and the interlayer was set as 0.6, 0.4, 0.2, 0, -0.2, -0.4, and 0.6 MPa·m^{1/2}. The effect of the difference in the fracture toughness on the propagation behavior of the hydraulic fractures at the interface in the coal measure composite reservoir was analyzed by studying the variations in the critical seam pressure for fracture deflection P_1 , the critical seam pressure for fracture penetration P_2 , and the water pressure in the wellbore P_0 under different fracture toughness differences. The results are shown in Figure 5.

It can be seen from Figure 5 that the water pressure in the wellbore P_0 and the critical seam pressure for penetration P_2 basically do not change with the differences in the fracture toughness. The critical seam pressure for penetration P_1 decreases linearly as the difference in the fracture toughness increases, and it intersects the line where the deflection critical fracture pressure P_2 is located at point (0.1, 25.223). Since the water pressure in the wellbore P_0 is always greater than the critical seam pressure for deflection P_2 under these parameter settings, according to the established criterion, the fracture expands along the interface when P_1 is greater than P_2 . Thus, when the fracture toughness difference is less than 0.1 MPa·m^{1/2} (light gray area in

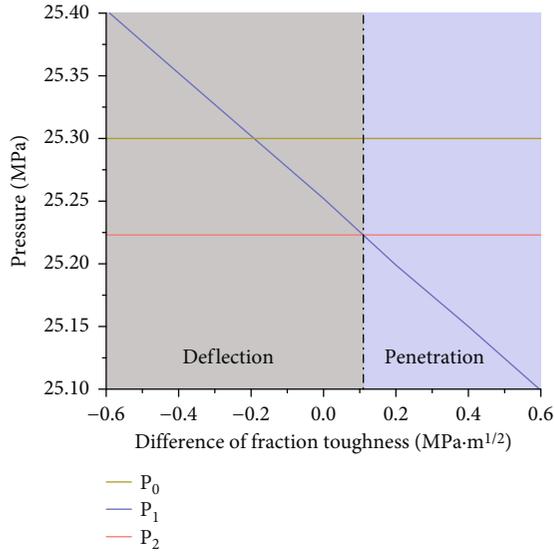


FIGURE 5: Changes in P_0 , P_1 , and P_2 under different fracture toughness differences.

Figure 5), the hydraulic fractures propagate along the interface at the interlayer interface; and when the fracture toughness difference is greater than $0.1 \text{ MPa} \cdot \text{m}^{1/2}$ (light blue area in Figure 5), the hydraulic fractures propagate through the layers at the interlayer interface. It can be seen that the difference in the fracture toughness affects the propagation path of the hydraulic fractures at the interlayer interface. When the other conditions remain unchanged, the difference in the fracture toughness mainly changes the distance between the three pressures by affecting the critical seam pressure for fracture penetration P_1 , which in turn affects the propagation path of the hydraulic fractures.

4.3. Fracturing Parameters

4.3.1. Fracturing Fluid Injection Rate. The fracturing fluid injection rate is easy to control in engineering. Studying the effect of the fracturing fluid injection rate on the hydraulic fracture propagation behavior is helpful in determining whether the hydraulic fracture propagation mode can be directly controlled by controlling the fracturing fluid injection rate. The main parameters of the model were set according to Table 4. The angle between the hydraulic fracture and the interface was set as 90° . The fracturing fluid injection rate was gradually changed (3.444, 3.456, 3.468, 3.48, 3.492, 3.504, 3.516, 3.528, 3.54, 3.552, 3.564, and $3.576 \text{ m}^3/\text{min}$). The effect of the liquid injection rate on the propagation behavior of the hydraulic fractures at the interface in the coal measure composite reservoir was analyzed by studying the variations in the critical seam pressure for fracture deflection P_1 , the critical seam pressure for fracture penetration P_2 , and the water pressure in the wellbore P_0 under different fracturing fluid injection rates. The results are shown in Figure 6.

It can be seen from Figure 6 that the critical seam pressure for deflection P_1 and the critical seam pressure for

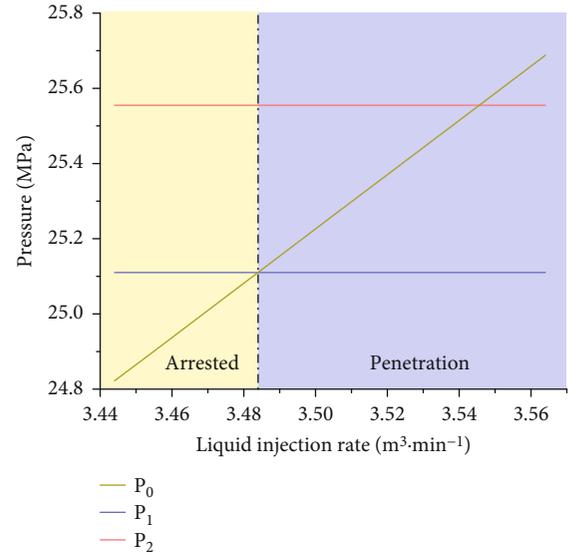


FIGURE 6: Changes in P_0 , P_1 , and P_2 with injection rate.

deflection P_2 do not change substantially with the injection rate. The water pressure in the wellbore P_0 increases linearly with increasing injection rate, and it intersects the line where the critical seam pressure of deflection P_1 is located at point (3.484, 25.11). Since the critical seam pressure for deflection P_1 is always lower than the critical seam pressure for deflection P_2 under these parameter settings, according to the established criterion, the fracture stops expanding when P_0 is less than P_1 . Thus, when the injection rate is less than $3.484 \text{ m}^3/\text{min}$ (light gray area in Figure 6), after the hydraulic fracture intersects with the interlayer interface, the expansion stops. When the injection rate is greater than $3.484 \text{ m}^3/\text{min}$ (light blue area in Figure 6), the hydraulic fracture propagates through the layer at the interlayer interface. It can be seen that the injection rate directly affects the propagation path of the hydraulic fractures at the interlayer interface. When the other conditions remain unchanged, the injection rate mainly changes the relationship between the three pressures by affecting the water pressure in the wellbore P_0 , which in turn affects the propagation path of the hydraulic fractures.

4.3.2. Fracturing Fluid Viscosity. The main parameters of the model were set according to Table 4. The angle between the hydraulic fracture and the interface was set as 90° , and the viscosity of the fracturing fluid was gradually changed (1.4, 1.45, 1.5, 1.55, and $1.6 \text{ mPa} \cdot \text{s}$). The effect of the fracturing fluid's viscosity on the propagation behavior of the hydraulic fractures at the interface in the coal measure composite reservoir was analyzed by studying the variations in the critical seam pressure for fracture deflection P_1 , the critical seam pressure for fracture penetration P_2 , and the water pressure in the wellbore P_0 under different fracturing fluid viscosities. The results are shown in Figure 7.

It can be seen from Figure 7 that the critical seam pressure for deflection P_1 and the critical seam pressure for penetration P_2 do not change substantially with the fracturing

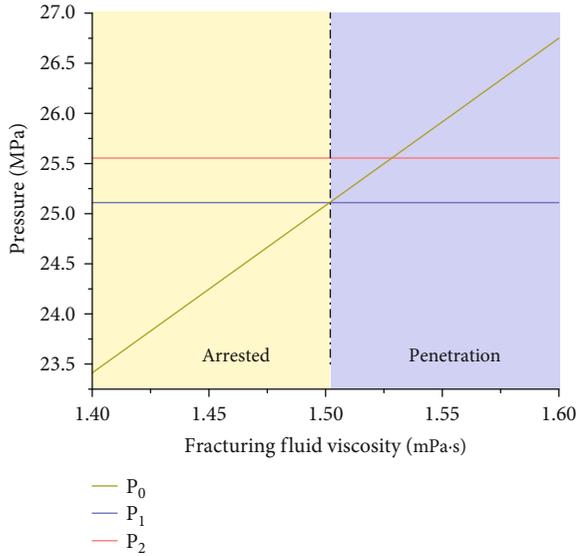


FIGURE 7: Changes in P_0 , P_1 , and P_2 with fracturing fluid viscosity.

fluid viscosity. The water pressure in the wellbore P_0 gradually increases with increasing fracturing fluid viscosity, and it intersects with the line where the critical seam pressure for deflection P_1 is located at point (1.5, 25.11). Since the critical seam pressure for deflection P_1 is always lower than the critical seam pressure for penetration P_2 under these parameter settings, according to the established criterion, the fracture stops expanding when P_0 is less than P_1 . Therefore, when the viscosity of the fracturing fluid is less than 1.5 mPa•s (light gray area in Figure 7), the hydraulic fracture stops spreading after it intersects with the interface; and when the viscosity of the fracturing fluid is greater than 1.5 mPa•s (light blue area in Figure 7), the hydraulic fractures propagate through the layers at the interlayer interface. It can be seen that changing the viscosity of the fracturing fluid affects the propagation path of the hydraulic fractures at the interface between the layers. When the other conditions remain unchanged, the viscosity of the fracturing fluid mainly changes the relationship between the three pressures by affecting the water pressure in the wellbore P_0 , which in turn affects the propagation path of the hydraulic fractures.

4.4. Interface Properties

4.4.1. *Interface Dip Angle.* The main parameters of the model were set according to Table 4. The angle between the hydraulic fracture and the interlayer interface was gradually changed (10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°). The influence of the interface dip angle on the propagation behavior of the hydraulic fractures at the interface in the coal measure composite reservoir was analyzed by studying the variations in the critical seam pressure for fracture deflection P_1 , the critical seam pressure for fracture penetration P_2 , and the water pressure in the wellbore P_0 under different interface dip angles. The results are shown in Figure 8.

It can be seen from Figure 8 that the water pressure in the wellbore P_0 and the critical seam pressure for penetra-

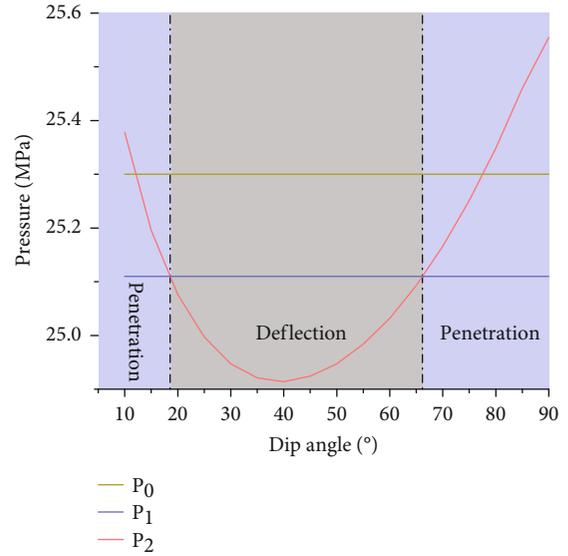


FIGURE 8: Changes in P_0 , P_1 , and P_2 with the interface inclination angle.

tion P_1 basically do not change with the interface dip angle. The critical seam pressure for deflection P_2 initially decreases and then increases with increasing interface inclination angle, and it intersects the line where the critical seam pressure for penetration P_1 is located at points (18.6, 25.11) and (66.16, 25.11). Under these parameter settings, the water pressure P_0 in the wellbore is always greater than the critical seam pressure for penetration P_1 , while the critical seam pressure for deflection P_2 changes from greater than the critical seam pressure for penetration P_1 to less than the critical seam pressure for penetration P_1 with increasing interface dip angle. According to the established criterion, when P_1 is less than P_2 , the fracture propagates through the layer; and when P_1 is greater than P_2 , the fracture expands along the interface. Thus, when the interface dip angle is less than 18.6° (light blue area in Figure 8), the hydraulic fractures spread through the layers at the interlayer interface. When the interface dip angle is 18.6–66.16° (light gray area in Figure 8), the hydraulic fractures spread along the interface at the interlayer interface. When the interface dip angle is greater than 66.16° (light blue area in Figure 8), the hydraulic fractures propagate through the layers at the interlayer interface. It can be seen that the interface dip angle affects the propagation path of the hydraulic fractures at the interlayer interface. When the other conditions remain unchanged, the interface dip angle mainly changes the relationship between the three pressures by affecting the critical seam pressure for fracture deflection P_2 , thereby affecting the propagation path of the hydraulic fractures.

4.4.2. *Interfacial Cohesion.* The main parameters of the model were set according to Table 4. The angle between the hydraulic fracture and the interface was set as 60°, and the interfacial cohesion between the reservoir layers was gradually changed (0, 1, 2, 3, 4, 5, and 6 MPa). The effect of the interfacial cohesion on the propagation behavior of

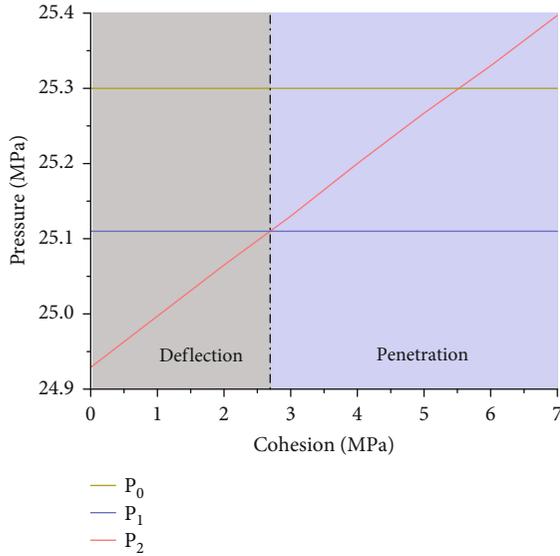


FIGURE 9: Changes in P_0 , P_1 , and P_2 with interfacial cohesion.

the hydraulic fractures at the interface in the coal measure composite reservoir was analyzed by studying the variations in the critical seam pressure for fracture penetration P_1 , the critical seam pressure for fracture deflection P_2 , and the water pressure in the wellbore P_0 under different interfacial cohesion values between the reservoir layers. The results are shown in Figure 9.

It can be seen from Figure 9 that the water pressure in the wellbore P_0 and the critical seam pressure for penetration P_1 basically do not change with the interfacial cohesion. The critical seam pressure for deflection P_2 increases linearly with increasing interfacial cohesion, and it intersects the line where the critical seam pressure for penetration P_1 is located at point (2.7, 25.11). Since the water pressure in the wellbore P_0 is always greater than the critical seam pressure for penetration P_1 , under these parameter settings, according to the established criterion, the fracture expands along the interface when P_2 is less than P_1 . Thus, when the interfacial cohesion is less than 2.7 MPa (light gray area in Figure 9), the hydraulic fracture spreads along the interface at the interlayer interface; and when the interfacial cohesion is greater than 2.7 MPa (light blue area in Figure 9), the hydraulic fracture spreads through the layer at the interlayer interface. It can be seen that changing the interfacial cohesion affects the propagation mode of the hydraulic fractures at the interlayer interface. When the other conditions remain unchanged, the interfacial cohesion mainly changes the relationship between the three pressures by affecting the critical seam pressure for fracture deflection P_2 , thereby affecting the propagation mode of the hydraulic fractures.

5. Conclusions

Based on the theories of fluid flow in fractures and elastic deformation of solids, in this study, the influences of the injection parameters on the fracture propagation path were investigated, and a criterion for judging the propagation of

hydraulic fractures through an interface in a coal measure composite reservoir with any interface dip angle was developed. The criterion was used to judge the propagation behavior of cracks at an interlayer interface by comparing three pressures (the water pressure in the wellbore and the critical seam pressures for penetration and deflection). The results obtained using the proposed criterion were found to be in good agreement with previous experimental data. The other interesting conclusions obtained from the parametric sensitivity analysis of this criterion are as follows.

- (1) The difference in the in situ stress, the interface dip angle, and the interfacial cohesion directly affect the critical seam pressure for deflection P_2 when the fracture propagates along the interface. The critical seam pressure for deflection P_2 decreases linearly as the in situ stress difference increases. When the in situ stress difference is less than 7.9 MPa, the hydraulic fracture spreads through the layer. The critical seam pressure for deflection P_2 increases linearly with increasing interfacial cohesion. When the interfacial cohesion is greater than 2.7 MPa, the hydraulic fracture propagates through the layer. As the interface dip angle increases, the critical seam pressure for deflection P_2 initially decreases and then increases, and the hydraulic fracture expands when the interface dip angle is 25–55°. This means that the smaller the in situ stress difference is, the greater the interfacial cohesion is, and the easier it is for the hydraulic fracture to spread through the layer. When the interface dip angle is 25–55°, the hydraulic fracture is more likely to expand along the interface
- (2) The difference in the elastic moduli, the fluid injection rate, and the fracturing fluid's viscosity directly affect the water pressure in the wellbore P_0 . As the difference in the elastic moduli, the injection rate, and the fracturing fluid's viscosity increase, the water pressure in the wellbore P_0 increases linearly. When the difference in the elastic moduli is greater than 4.9 GPa, the hydraulic fractures propagate through the layer; when the injection rate is greater than 3.484 m³/min, the hydraulic fractures propagate through the layer; and when the fracture fluid viscosity is greater than 1.5 mPa•s, the hydraulic fractures propagate through the layer. The larger the difference in the interlayer elastic modulus, the faster the fluid injection rate, the greater the viscosity of the fracturing fluid, and the more likely it is that the hydraulic fractures will propagate through the layers
- (3) The difference in the fracture toughness mainly changes the relationship between the three pressures by affecting the critical seam pressure for penetration P_1 , thereby changing the propagation mode of the hydraulic fractures. The critical seam pressure for propagation P_1 decreases linearly as the difference in the fracture toughness increases. When the fracture toughness difference is greater than 0.1 MPa•m^{1/2},

the hydraulic fracture propagates through the layer at the interlayer interface, indicating that the larger the interlayer fracture toughness difference is, the more likely it is that the hydraulic fracture will penetrate the layer

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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