Study on fracture propagation and interaction mechanism during hydraulic fracturing

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Abstract. With the widespread application of hydraulic fracturing technology, the corresponding numerical simulation methods have been rapidly developed, and we have a deep understanding about the fracture propagation trajectory during hydraulic fracturing at the same time. However, the fracture interference mechanism during hydraulic fracturing is still insufficiently understood. Based on linear elastic fracture mechanics and relevant fracture criterion, a simulation model was established to simulate the fracture propagation by using boundary element method. The interaction mechanisms between fractures are studied. Results show that hydraulic fractures will change distribution direction of formation stresses during propagation process, and asymmetric fractures tend to merge together during propagation. The reverse propagation phenomenon between two fractures in numerical simulation rarely exists in the actual formation. The analysis and research on the mechanism of crack propagation and interaction can provide a theoretical basis for the trajectory control of hydraulic cracks in the later period.

1. Introduction

With the rapid development of science and technology, our country's demand for oil and gas resources is increasing seriously. At present, hydraulic fracturing technology is an important way to improve oil and gas well recovery.

In recent years, scholars at home and abroad have carried out a lot of research on hydraulic fracturing. When hydraulic fractures and hydraulic fractures or hydraulic fractures and natural fractures are in contact with each other, with the continuous injection of fracturing fluid, there are three types of interactions between hydraulic fractures and natural fractures: stop propagation near natural fractures, penetrate natural fractures and extend along natural fractures. The greater the crack approach angle and horizontal stress difference, and the higher the strength of the natural crack and parent rock bond, the easier the hydraulic crack penetrates the natural crack and vice versa [3,4]. At the same time, scholars have introduced fracture criteria into the determination of intersecting fractures, such as fracture shear strength theory [5,6], stress intensity factor theory [7], Griffith energy principle [8]. Based on these criteria, different numerical simulation models were established, some of which considered the distribution of random natural fractures [9], some extended their simulation models to three-dimensional conditions [10]. When there is no contact between fractures, such as simultaneous fracturing and multi-cluster fracturing, the fracture tip will depart or approach each other[11]. In the actual hydraulic fracturing process, especially when there are other fractures near the
hydraulic fracture, it is still unknown that the tip of hydraulic fracture will tend to be closer to other fractures or deviate from other fractures. At present, the analysis of this problem and the study of the internal interaction mechanism are still relatively lacking.

In this paper, the basic mechanical model is established based on the theory of elastic mechanics and fracture mechanics. After the boundary element calculation method is used to discretize the boundary and fracture, a simulation calculation model that can simulate the fracture propagation of hydraulic fracturing was established. The remainder of this paper is organized as follows. The construction of the computational model and relevant validation are described in Section 2. The interaction mechanism between fractures been analysed in Section 3. The paper ends with some conclusions in Section 4. In this paper, for simplicity, our numerical model incorporates some assumptions in the calculation process: (1) isothermal conditions, (2) two dimensions, and (3) homogeneous rock, with isotropy of the rock porosity and mechanical properties.

2. Simulation model

2.1 Fracture criterion

During the hydraulic fracturing, the damage of rock under complex stress fields mainly performs as shear failure and tension failure, which is respectively denoted by $K_I$ and $K_{II}$. In this place, we put the maximum circumferential stress criterion as the fracture criterion which is proposed by Erdogan and Sih[12] in 1963. As is shown in Figure 1, the stress distribution at the tip of fracture in the polar coordinate can be expressed as the equations below:

\[
\begin{align*}
\sigma_r &= \frac{1}{2\sqrt{\pi r}} \left[ K_I (3 - \cos \theta) \cos \frac{\theta}{2} + K_{II} (3 \cos \theta - 1) \sin \frac{\theta}{2} \right] \\
\sigma_\theta &= \frac{1}{2\sqrt{\pi r}} \cos \frac{\theta}{2} \left[ K_I (1 + \cos \theta) - 3K_{II} \sin \theta \right] \\
\tau_{r\theta} &= \frac{1}{2\sqrt{\pi r}} \cos \frac{\theta}{2} \left[ K_I \sin \theta + K_{II} (3 \cos \theta - 1) \right]
\end{align*}
\]

Where $\sigma_r$ is the radial stress near the fracture tip, $\sigma_\theta$ is the circumferential stress near the fracture tip, $\tau_{r\theta}$ is the shear stress near the fracture tip, MPa, $r$ is the distance between any unit to fracture tip, $m$, and $\theta$ is the fracture opening angle, °.

By calculating the derivative of $\theta$ from Equation (1), we can obtain the relationship between the I-II mixed stress intensity factor and the opening angle (Equation (2)), the relationship is as follow:

\[
K_I \sin \theta + K_{II} (3 \cos \theta - 1) = 0
\]

Based on the maximum circumferential stress criterion, the opening angle must satisfy two conditions:

\[
\frac{\partial \sigma_\theta}{\partial \theta} = 0 \quad \text{and} \quad \frac{\partial^2 \sigma_\theta}{\partial \theta^2} < 0
\]
2.2 Boundary element method

Boundary element method was first proposed by Crouch [13] in 1976. And now this method is divided in two aspects: displacement discontinuity method and stress discontinuity method. According to displacement discontinuity method, a fracture can be divided into small elements with two discontinuity planes. In the x-y coordinate system shown in Figure 2, the planes can be expressed as y=0+ and y=0-.

The displacements of the two sides are symbolized by \( u(x, 0+) \) and \( u(x, 0-) \), respectively. D is defined as the tangential and perpendicular difference in displacement between two sides of the element. \( D_x \) and \( D_y \) are the definition of D in x- and y-direction.

\[
\begin{align*}
D_x &= u_x(x, 0+) - u_x(x, 0+) \\
D_y &= u_y(y, 0+) - u_y(y, 0+)
\end{align*}
\]

(4)

The solution for displacements and stresses caused by the fracture-relative movement \((D_x, D_y)\) can expressed as [14]:

\[
\begin{align*}
u_x &= D_x [2(1-\nu) f_{rx} - y f_{rx}x] + D_y [(1-2\nu) f_{rx} - y f_{ry}y] \\
u_y &= D_x [2(1-\nu) f_{rx} - y f_{rx}y] + D_y [2(1-\nu) f_{ry} - y f_{ry}y] \\
\sigma_{xx} &= 2GD_x (2f_{rxy} + y f_{rxy}) + 2GD_y (f_{rr} + y f_{rry}) \\
\sigma_{yy} &= 2GD_x (y f_{rxy}) + 2GD_y (f_{rr} + y f_{rry}) \\
\sigma_{xy} &= 2GD_x (f_{rr} + y f_{rxy}) + 2GD_y (y f_{rry})
\end{align*}
\]

(5)

(6)

2.3 Simulated flowchart

During simulation process, the fracture tip propagation and in-situ stress variation are obtained. The detailed calculation flow chart is shown in Figure 3.

Figure 3. Computer program flow chart. Using the maximum circumferential stress criterion, the opening angle and propagation path of the fracture were calculated. If the tip of the fracture does not satisfy the opening requirement, the calculation stops, otherwise, the fracture extends in the direction of the opening angle and repeat the aforementioned calculation until get a planned fracture length.
3. Simulation results
Before numerical simulation, it is necessary to confirm in-situ stress parameters, rock mechanics parameters and construction parameters, these parameters are determined from field and laboratory tests performed on samples [15-16] and is shown in Table 1. The Model size is about 100m×100m. In this chapter, we will conduct numerical simulation on multi-cluster fracturing and synchronous fracturing. Therefore, physical model diagrams under different fracturing methods are established, as shown in Figure 4 and Figure 5. $\sigma_H$ and $\sigma_h$ are respectively the maximum and minimum horizontal stress.

| Reservoir geologic data                      | Fracturing design parameters |
|---------------------------------------------|-------------------------------|
| Young’s modulus /MPa                       | Fracturing pressure /MPa      |
| 32860.38                                    | 35                            |
| Poisson’s ratio                             | Perforation depth /m          |
| 0.221                                       | 5                             |
| Maximum horizontal stress /MPa              | Fracture spacing /m           |
| 35                                          | 10                            |
| Minimum horizontal stress /MPa              |                               |
| 30                                          |                               |
| Fracture toughness /MPa•m^{1/2}             |                               |
| 2.5                                         |                               |
| Rock density /kg•m^{-3}                     |                               |
| 2600                                        |                               |

Figure 4. Multiple clusters fracturing

The physical model diagram shown in Figure 4 is a single well in which two clusters of fractures are fracturing. In order to observe the change of the stress field between clusters during multi-cluster fracturing, the fracturing simulation was conducted between the previous two fractures. Compare above two simulation results(Figure 6 and Figure 7) show that when two symmetrical fractures are fracturing at the same time, due to the slippage of the fracture surface and cracking at the tip, compressive stress zones will be generated on both sides of the fracture, which will cause the two fractures to extend away from each other. After fracturing, perforating fracturing is performed in the middle of the two clusters of fractures. Under normal circumstances, the fracture propagate in the direction of the maximum horizontal principal stress (vertical direction), but the stress between the two clusters of fractures has reversed at this time, causing the fracture pressure of the post-fracturing to extend in the direction of the maximum horizontal principal stress. It can be seen that during the multi-cluster fracturing, as the fracture surface expands, the induced stress will reverse between the two fractures as propagation. This flipping helps to induce natural micro-fractures to communicate with hydraulic fractures to form a fracture network and improve oil and gas seepage.

In order to study the mutual interference of hydraulic fractures at an asymmetric position, numerical simulation of simultaneous fracturing was carried out under the same geological parameters. As is shown in figure 8. During propagation, hydraulic fracture tend to connect with each other instead of mutual repulsion. It can been seen that crack tip always tends to expand to the weak surface during fracture propagation, because the energy required for crack tip cracking in this propagation way is the lowest. Furthermore, in order to verify the conjecture, the horizontal well is set to have a certain angle with the minimum horizontal principal stress direction, so that in a single well multi-cluster fracturing, the stress field between fractures is asymmetric. As shown in figure 9, Similar to synchronous
fracturing, when the stress of multiple fractures in the reservoir is not completely symmetrical, the fractures tend to be close to each other. It can be seen that although the fractures extend backwards in multiple clusters fracturing in simulation, in actual reservoirs, due to the difference in rock properties and inhomogeneity of the in-situ stress, hydraulic fractures will tend to be close to each other in most cases.

Figure 6. Multiple clusters fracturing (simulation result)

Figure 7. Synchronous fracturing (simulation result)

Figure 8. Direction reversal of stress

Figure 9. Fracture propagation under asymmetric stress

4. Conclusion

Based on the theory of elastic mechanics and fracture mechanics, a simulation model was established to study the propagation of multi-fractures and induced stress during hydraulic fracturing, which led to the following conclusions:

(1) For simultaneous fracturing, two fractures attract and approach each other, which extends the fracture length. While for aligned fracture distribution, two fractures coalesce into one in the end. Thus
it is more suitable to choose unsymmetrical fracture distribution to form a more complex fracture network in formation.

(2) Although in the numerical simulation, the crack tip may have the phenomenon of exclusion each other, in the actual situation of the reservoir, fractures are more likely have a tendency to connect with each other during the expansion process.

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