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Analysis the hydraulic fracturing in the unconventional shale reservoir based on Finite Discrete Element Method

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Abstract. Hydraulic fracturing of horizontal well is the key technology to develop unconventional resources. Simultaneous fracturing in horizontal well is the prevalent method applied in the field practice. To achieve successful and desired stimulated rock volumes and fracture networks, it is necessary to understand the influence of stress on fracture geometry. This paper proposed a 2D model to simulate the fracture propagation in simultaneous hydraulic fracture operation based on Finite Discrete Element Method (FDEM). In this model, the fracturing fluid leak-off and natural fractures are coupled. The simulation results demonstrated that the induced stress field can not only affect the fracture extended length, but also the width of fracture. The outer fractures dominate the inner fractures in growth. And the central fractures stop propagating after they reached a certain length due to the induced stress field. These simulations are meaningful for stimulation design and required spacing conditions to acquire the desired fracture lengths, proppant placement, and production rates.

1. Introduction

Hydraulic fracturing is a commonly used technique in shale gas development to enhance reservoir permeability and well efficiency [1]. Many fracturing models have been presented during the last several decades. Hydraulic fracturing is a complicated and difficult process to model because it involves the coupling of at least three processes [2, 3]: (1) mechanical deformation induced by fluid pressure on the fracture surface; (2) the fracture fluid flows within the fracture; (3) the fracture propagation under the fluid pressure. To meet the requirement of complicated hydraulic fracturing processes with branches, some multi-fractures propagation models were developed [4].

In order to determine the optimum spacing and optimum staging between fractures, a 2D model to simulate the fracture propagation in simultaneous hydraulic fracture operation based on Finite Discrete Element Method [5]. In this method, fluid flow is assumed to occur through a network generated from the same triangular mesh used for the mechanical calculations, and the flow channels are created at the interfaces between adjoining triangular finite elements [6]. The initiation and propagation of fractures in this model described by non-linear fracture mechanics. According to this theory, as the tensile strength of a material is exceeded at the tip of an opening fracture, a zone characterized by non-linear behavior, called the fracture process zone.

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2. Theory and Method

FDEM is a numerical method that combines continuum mechanics principles with discrete element method to simulate interaction, deformation, and fracturing. FDEM has the ability to explicitly capture the entire deformation and fracturing process. It is a hybrid technique that combines the advantages of the FEM and DEM approaches. While the medium is undergoing elastic deformation, the behavior of intact material is explicitly modelled by FEM. As the strength of the material is exceeded fractures are initiated, giving rise to discontinuous blocks where the interaction between these blocks is captured by DEM. The FDEM approach is capable of tracking fracture initiation and propagation by applying the principles of non–linear elastic fracture mechanics. In this study, three interconnecting modules were used to simulate fracturing, namely (1) a mechanical solver which calculates the deformation of the intact rock mass as well as the initiation, propagation and interaction of fractures; (2) a cavity volume calculator then captures the changes of the cavity volume due to fracture propagation, the elastic deformation, and fluid compressibility. It also tracks the newly created wet boundaries by checking their connection with the initial source of fluid; (3) a pump model then interacts with the previous two modules to calculate fluid pressure while considering the pumping conditions.

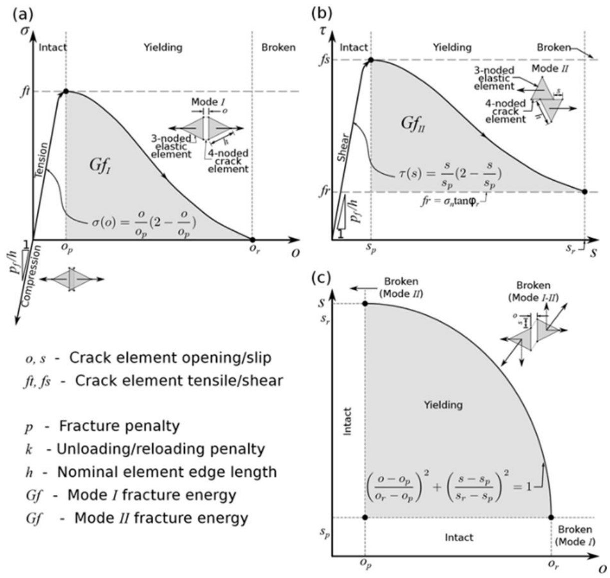

Figure 1. Fracture model implemented in FDEM: (a) cohesive model for Mode I, (b) slip weakening model for Mode II, and (c) criterion for Mixed-Mode fracture initiation.

In the FDEM, the load and element mass are treated as nodes to build the dynamic equation of a system according to Newton's second law.

$$\mathrm{M}\ddot{x}+\mathrm{C}\ddot{x} = F(x) \tag{1}$$

Where M and C are the mass matrix and damping matrix of all nodes, respectively, and F(x) represents the total nodal force vector which includes the node force vector $F_c(x)$ assigned by the contact force between tetrahedral elements, the node force vector F_d induced by the deformation of tetrahedral elements, the node force vector $F_j(x)$ caused by the deformation of joint elements, and the node force vector F_e (x) assigned by the external load.

The introduction of the damping matrix C consumes the kinetic energy of the system; by which we use dynamic relaxation to solve the static problem. The damping matrix is given by

$$\mathrm{C} = \mu\mathrm{I} \tag{2}$$

where μ is the damping coefficient, and I is a unit matrix. For a mass spring system with single degree of freedom, the critical damping coefficient is given by

$$\mu = 2h\sqrt{\rho E} \tag{3}$$

Where h is the edge length of an element, ρ is the element density, and E is the elastic modulus of the element. The system kinetic energy will be consumed at the fastest rate if the critical damping is used.

3. Results and Discussion

3.1. Model Description

A multistage fracture propagation model based on FDEM was established. The model was 180 m in the X direction (along the wellbore and parallel to the minimum horizontal principal stress), 180 m in the Y direction (perpendicular to the minimum horizontal principal stress). The target formation is a sand-rich formation, so the model was treated as pure sand, and no interlayer was built in the model. The target formation is a shale-rich formation, so the model was treated as pure shale, and no interlayer was built in the model. The input parameters in the model are listed in table 1.

Table 1. Input parameters for the fracture propagation model.

Parameter	Unit	Value
Young's modulus	$\times 10^3$ MPa	40.49
Poisson's ratio	Dimensionless	0.20
Porosity	%	2.7
Permeability	10^{-3} μm^2	0.014
Initial pore pressure	MPa	61
Vertical stress	MPa	75.55
Minimum Horizontal Principle stress	MPa	86.14
Maximum Horizontal Principle stress	MPa	95.14

3.2. Results Analysis

In this simulation, simultaneous propagation of four hydraulic fractures was considered. From the results, outer fractures tend to longer than the rest of the fractures. This is because the stress shadow on the outer fractures will be less than the fractures inside. With the propagation of outer fractures, the induced stress field would restrict the extension of inner fractures. This effect is seen when the outer fractures start to propagate more rapidly than the remaining fractures in the fracture network. The larger outer fractures exert more stress shadow on the fracture near to them, which will inhibit the growth of these fractures more than the center fracture. As the outer fractures grows large enough the stress shadow over the remaining fractures increase and completely suppress their growth after sometime. In addition, the fracture width of outer fractures is larger than that of inner fractures. The main reason account for this phenomenon was the diversion of the minimum horizontal principle stress. From the figure 2(a), when the time was 70 s, the four fractures began to initiate and propagate, and the inner two fractures did not show an obvious damage. There existed an obvious diversion of the minimum horizontal principle stress in outer fractures, while the minimum horizontal principle stress of inner fractures did not show an obvious change. When the time was 90 s (figure 2(b)), the four fractures had a clear damage. It should be noticed that the diversion of the minimum horizontal principle stress in outer fractures was much severer than that in inner fractures. What' more, the natural fractures in the model began to initiate and propagate. When the hydraulic fracture interacted with the natural fractures, the trajectory of the hydraulic fractures began to change. The main reason was that the strength of natural fracture surface was lower than that of rock matrix. When the time was 110 s and 130 s, the damage degree of inner fracture was more serious than that the time was 90 s. There was an apparent inconsistency in the propagation of fractures. The length and width of outer fractures were larger than that of inner fractures. The main reason accounted for this phenomenon was that with the propagation of fractures, the diversion of minimum horizontal principle stress was more severe. Affected by the diversion of minimum horizontal principle stress, the extension pressure of the inner fractures was much higher than the outer fractures. Under the same injection ratio and injection pressure, the net pressure in inner fractures were lower than the outer fractures, which caused the shorter fractures. In addition, the aperture of the inner fractures was also a function of net pressure. Lower net pressure contributes to a narrow fracture in the model. So an obvious “enwrapped” phenomenon occurred in this model.

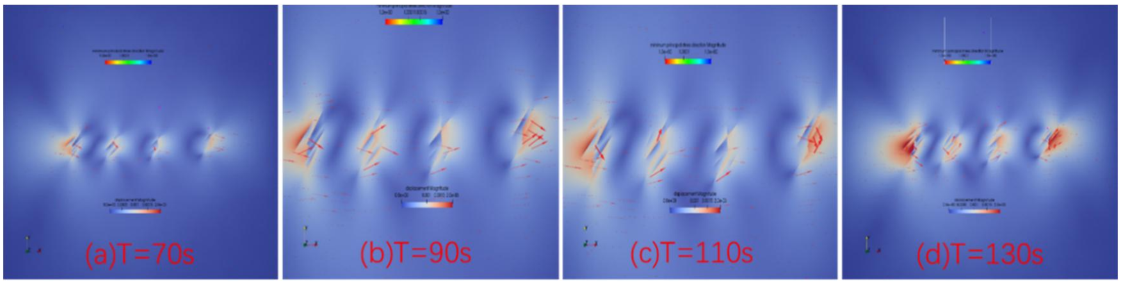

Figure 2. Fracture geometry of four fractures.

In the following discussion, fracture 1, 2, 3 and 4 represent the fractures which propagate from the left to right. As can be seen, the maximum width of fracture 1 is 0.0051m, and the average width is 0.003 m. The maximum width of fracture 2 is 0.0141m, and the average width is 0.007 m. When the width of fracture 1 decreases dramatically at x = 50 m, the width of fracture 2 and 3 rises very rapidly, and then decreased to zero when the fracture length exceeded to 80 m. Combined with figure 2, the tighter the cluster space was, the more severe the minimum horizontal principal stress diversion was. In the model, affected by fracture 1 and fracture 4, so the length of fracture 2 and fracture 3 was shorter than fracture 1 and fracture 4.

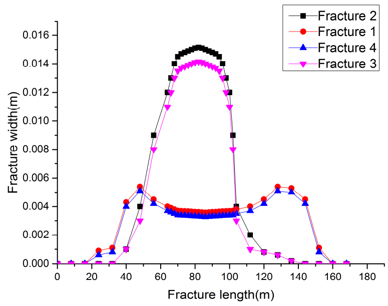

Figure 3. Fracture length versus fracture width of the four fractures.

4. Conclusion

This research was based on the 2D seepage-stress-damage coupled multi-fracture simultaneous propagation model to study the fracture propagation based on finite discrete element method with DFN. In this model, the fracture geometry, stress field redistribution was analyzed. From the simulation, the multi fracture simultaneous propagation model demonstrated that tight cluster space will insufficiently extend the middle fracture in height and length. Because of the diversion of the maximum horizontal principal stress, the induced stress field will increase the extending resistance of the middle fracture. The tighter the cluster space is, the higher the induced stress. The induced stress field can reduce the fracture propagation velocity and can even make the extension stop. Additionally, the induced stress field can also contribute to a complicated fracture network.

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