Computers and Geotechnics 91 (2017) 58–70

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research paper

Modeling hydraulic fracture propagation using cohesive zone model equipped with frictional contact capability

Y. Li [a,b], J.G. Deng [a,b], W. Liu [a,b,*], Y. Feng [c]

[a] State Key Laboratory of Petroleum Resource & Engineering, China University of Petroleum (Beijing), Beijing 102249, China
[b] College of Petroleum Engineering, China University of Petroleum (Beijing), Beijing 102249, China
[c] Department of Petroleum and Geosystems Engineering, University of Texas at Austin, Austin, TX 78712, USA

ARTICLE INFO

Article history:
Received 18 January 2017
Received in revised form 1 July 2017
Accepted 2 July 2017

Keywords:
Hydraulic fracturing
Cohesive zone model
Natural fracture
Frictional contact

ABSTRACT

We present a new pore pressure cohesive element for modeling the propagation of hydraulically induced fracture. The Park-Paulino-Roesler cohesive zone model has been employed to characterize the fracturing behavior. Coulomb's frictional contact model has been incorporated into the element to model the possible shear reactivation of pre-existing natural fractures. The developed element has been validated through a series of single-element tests and an available analytical solution. Furthermore, intersection behaviors between the hydraulic fracture and the natural fracture under various conditions have been predicted using the present element, which shows good agreement with experimental results.

1. Introduction

Hydraulic fracturing has been widely used in the petroleum industry to extract hydrocarbons from reservoirs with ultra-low permeability which were previously economically unviable. During hydraulic stimulation, pressurized fluid is injected into the rock formations to create fractures and/or reactivate pre-existing natural fractures [1]. Other applications of hydraulic fracturing include the measurement of in situ stress [2,3], preconditioning ore bodies for caving [4], and stimulation of geothermal reservoirs [5,6]. With the rapid development of unconventional resources, the initiation and propagation of hydraulic fractures in tight rocks have been extensively investigated from an analytical perspective [2,7–11] and a numerical point of view [12–17]. However, modeling of hydraulic fracturing remains a challenging task due to the involved complicated coupled processes [13,14]: (i) rock deformation caused by the fluid pressure on the fracture faces, (ii) flow of fracturing fluid within the fracture, (iii) fracture propagation, and (iv) leak-off of fluid from the fracture into the formation. In addition, friction between fracture surfaces also plays a significant role in shear reactivation of natural fractures. Generally, the rock deformation can be described by the theory of elasticity which relates the fracture width with the fluid pressure in the fracture. The fluid flow in the fracture can be modeled by the cubic law which relates the flow rate in the fracture to the fracture width and the fluid pressure gradient. Usually, linear elastic fracture mechanics (LEFM) theory (i.e. fracture propagation occurs if the stress intensity factor equals to the fracture toughness) is used as a criterion for fracture propagation.

Analytical solutions of fluid-driven fracturing played an important role in the design of fracturing treatments in the early time. KGD [18,19] and PKN [20,21] models are the two well-known fracturing models, which can predict the behaviors of plane strain bi-wing fractures with constant height. In recent years, the scaling law and asymptotic framework [7,8,22,23] have been used to understand the different propagation regimes of hydraulic fractures. Analytical methods mentioned above are widely used and adequate for engineering purposes in the early time. However, their applications are limited to simple situations such as constant injection rate, simple fracture geometries, and linearly elastic and homogeneous medium. For hydraulic fracturing treatments in unconventional reservoirs featuring low-permeability and pre-existing natural fractures, complex fracture networks may be created which cannot be adequately described by the simple analytical methods.

In order to investigate the hydraulic fracturing in unconventional reservoirs with complex fracture geometry and boundary conditions, numerical methods are a viable alternative since the complex practical conditions can be conveniently considered in a numerical model. Various numerical methods have been proposed

* Corresponding author at: College of Petroleum Engineering, China University of Petroleum (Beijing), Beijing 102249, China.
E-mail address: liuwei@cup.edu.cn (W. Liu).

http://dx.doi.org/10.1016/j.compgeo.2017.07.001
0266-352X/

for the simulation of hydraulic fracturing. These methods can be roughly classified into two categories: (1) continuum-based methods and (2) discontinuum-based methods.

A representative in the continuum-based methods is the displacement discontinuity method (DDM). Kresse [24], Zhang [25,26] and Wu [27,28] used DDM to simulate the propagation of hydraulic fracture and its interaction with pre-existing natural fractures. McClure [29] used DDM to investigate the diagnostic fracture injection tests with complex fracture networks. Later, DDM was extended to three dimensions by Wu [30] and McClure [31]. In the context of finite element methods, Carrier [32], Chen [14], and Li [33] used pore pressure cohesive element to model the fluid-driven fracture. Dahi-Talegahani [16] and Chen [34] simulated hydraulic fracturing using extended finite element method (XFEM). The above mentioned DDM and XFEM can simulate the propagation of hydraulic fracture with arbitrary paths. In addition to the conventional continuum approaches summarized above, some new continuum approaches have been introduced in recent year. Wang [35] used the RFPA software to investigate the shear stimulation in naturally fractured reservoirs. Miehe [36], Wick [37] and Liu [38] used a Phase-Field model to simulate the fluid-driven fractures and the interaction between multiple fractures. Ouchi [39] developed a Peridynamics model to simulate the propagation of hydraulic fractures in heterogeneous, and naturally fractured reservoirs. However, until now, large-scale simulation is still a problem for these new methods.

For typical discontinuum-based methods, continuum domain is discretized into a series of separate blocks or particles and fracture propagation is characterized by the separation of these blocks or particles. The discontinuum-based approach is represented by the universal distinct element code (UDEC) and 3 dimensional distinct element code (3DEC). Nagel [40] used the UDEC software to model the shear reactivation of pre-existing natural fractures around the hydraulic fracture. The results show that changes of stress field due to hydraulic fracture propagation have a dramatic influence on the shear reactivations of the pre-existing natural fractures, which, in turn, significantly affect the growth of the hydraulic fracture. Farzin [41] investigated the initiation and propagation of hydraulically induced fractures by 3DEC. Another major type of discontinuum-based method is discontinuous deformation analysis (DDA). Choo [42] and Morgan [43] present a new hydraulic fracturing model based on DDA. In addition to the continuum- and discontinuum-based methods, hybrid method, such as the finite-discrete element method (FDEM) is also an important method for hydraulic fracturing simulation [44–46].

In general, the continuum-based methods have some difficulties in modeling the intersection between hydraulic fracture and natural fracture while most of the discontinuum methods need a small time increment due to the explicit integration scheme. Therefore, we try to develop a new model, which is similar to the discontinuum-based methods but uses an implicit integration scheme to obtain a relatively larger time increment.

In this paper, we developed a 2D, fully coupled finite element model to simulate the propagation of hydraulic fractures in tight rocks. Two types of elements are involved in the finite element mesh, i.e. bulk elements and pore-pressure cohesive zone (PPCZ) elements. Zero-thickness PPCZ elements are inserted into any two neighboring triangular elements. The propagation, branching, merging, and intersection of fractures can be captured by the PPCZ elements and the deformation of surrounding matrix is model by bulk elements. For the reason that the bulk element has been extensively implemented in many commercial or open source FEM codes, we restrict our attention to the development and implementation of the PPCZ element in this study. The mechanical behaviors of the PPCZ element are characterized by Park-Paulino-Roesler (PPR) cohesive zone model proposed by Park [47]. Interfacial friction plays an important role in the shear reactivation of pre-existing natural fractures, which is one of the main purposes of fracturing treatment in unconventional reservoirs [29,35,48]. However, the original PPR model can be only used to simulate the fracturing behaviors of frictionless material. To simulate the shear reactivation of pre-existing natural fractures, Coulomb's friction law is also incorporated into the cohesive element.

In Section 2, governing equations of the PPCZ element are provided. Detailed finite element formulations for this new element are discussed in Section 3. In Section 4, our model is validated through a series of single-element tests and an available analytical solution. Furthermore, the intersection behaviors between the hydraulic fracture and the natural fracture have been predicted by the PPCZ element and compared to the existing experimental results. In Section 5, some advantages and limitations of this new method are discussed briefly. Finally, some conclusions are given in Section 6.

2. Governing equations

2.1. Fluid flow in the fracture

The fluid flow in the fracture (Fig. 1) is controlled by the mass conservation equation:

$$\frac{\partial \rho w}{\partial t} + \frac{\partial \rho q}{\partial s} = 0 \tag{1}$$

where w is the fracture width; ρ is the fluid density; q is the volume flow rate; and s is the coordinate along the fracture.

For a Newtonian fluid, the flow inside the fracture can be described by the cubic law derived from the Poiseuille equation between two parallel plates:

$$q(s,t) = -\frac{w(s,t)^3}{12\mu}\frac{\partial p}{\partial s} \tag{2}$$

where μ is the fluid viscosity.

Assuming the fluid is incompressible, combining Eqs. (1) and (2), the following lubrication equation can be obtained:

$$\frac{\partial w}{\partial t} - \frac{\partial}{\partial s}\left(\frac{w^3}{12\mu}\frac{\partial p}{\partial s}\right) = 0 \tag{3}$$

The above equations can be solved with appropriate initial and boundary conditions. Usually, the conditions at the crack mouth and tip of the fracture can be expressed as:

$$q(s=0,t) = q_0(t) \tag{4}$$

$$w(s=l,t) = 0, \quad q(s=l,t) = 0 \tag{5}$$

where l is the fracture length. In fact, when the first condition in Eq. (5) is satisfied, the second one is fulfilled naturally.

2.2. Fracture propagation

Fracture propagation is assumed to be governed by a cohesive zone model. This model was first proposed by Barenblatt [49] to overcome some limitations of the LEFM. It avoids the stress singularity at the fracture tip and characterizes the nonlinear fracture process zone ahead of the tip. Generally, this process zone may experience three stages: elastic, softening, and complete failure. The cohesive zone model has been successfully applied to simulate fracture propagation in various materials from brittle to ductile, such as rocks, cement, and metals [14,15,32,34,50–57].

The behaviors of a cohesive element are governed by a traction-separation law. In this study, the PPR potential-based cohesive law