Computers and Geotechnics 81 (2017) 59–76

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Impact of water and nitrogen fracturing fluids on fracturing initiation pressure and flow pattern in anisotropic shale reservoirs

Xiangxiang Zhang [a], J.G. Wang [a,b,*], Feng Gao [a,b], Yang Ju [a,c], Jia Liu [b]

[a] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China
[b] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China
[c] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology at Beijing, Beijing 100083, China

ARTICLE INFO

Article history:
Received 28 January 2016
Received in revised form 24 June 2016
Accepted 28 July 2016

Keywords:
Anisotropic shale
Hydrofracturing
Moving mesh
Fracturing initiation pressure
Seepage area

ABSTRACT

A numerical model is proposed to investigate the impact of water and nitrogen fracturing fluids on the fracturing initiation pressure and the flow pattern in anisotropic shale reservoirs. This model considers the anisotropy of shale deformation and permeability, the compressibility of fracturing fluid, and the fluid moving front. A crack initiation criterion is established with the stress intensity factor of mode I crack. Both crack initiation pressure and seepage area are verified and analyzed. These results show that shale deformation and permeability anisotropy, fracturing fluid compressibility, viscosity, and pressurization rate have significant impacts on fracturing initiation pressure and seepage area.

1. Introduction

Shale anisotropy is one of the most distinct features. This feature contains mechanical anisotropy and permeability anisotropy and generally originates from the mineral foliation, stratification, and discontinuities in the rock mass [9,68]. In the bedding shale, the deformation properties, the fracture toughness and the pattern of fracture initiation and propagation are significantly impacted by the weak cementation force and high compressibility of bedding planes [10,5,49,71]. Niandou et al. [42] observed that the elastic property (Young's modulus, Poisson's ratio and shear modulus) of the shale is non-linear and anisotropic. The plastic deformation and the failure behavior of shale strongly depend on confining pressure and loading orientation. Therefore, shale demonstrates strongly anisotropic behaviors in tensile strength, compression wave velocity, and shear wave velocity [19]. For example, Cho et al. [9] found that the extents of deformation and strength anisotropy in the Boryeong shale were significant and substantial errors were expected if this anisotropy was not considered. Anisotropy also impacts the fracturing properties of shale. The fracture toughness of anisotropic rocks depends on the rock properties and the initial crack orientation [5]. With a weak bonding, fracture containment is possible and associated with slippage at the interface. The pattern of fracture propagation depends on the relative mechanical properties of fractured formations [13]. In addition, the permeability of shale varies with flow direction because the bedding planes have much higher permeability and compressibility than the orthogonal planes [7]. Several models have been recently proposed to describe the inducing evolution of anisotropic permeability [36,65,6,59]. However, these previous works only partially considered the anisotropy of shale because it is a challenge to take the effect of anisotropy into full accounts.

Hydraulic fracturing (HF) is a technique where fluids are pumped into wellbore under high pressure in order to fracture the geologic formations and enhance formation permeability [3,53]. As one of main approaches to enhance the production rate of an unconventional gas reservoir, hydraulic fracturing with water fluid has been widely studied [40,70,26,63,64]. Pogacnik et al. [44] explored the use of a mixed crack mode to simulate the damage and permeability enhancement during hydraulic fracturing/shearing within the reservoir. Due to the existing of nature fractures, Taleghani et al. [55] discussed the interactions between hydraulic fractures and natural fractures. But the impact of type and property of fracturing fluid on fracture initiation and permeation area is still not clear.

During hydraulic fracturing, the fracturing fluids of different viscosity are used. The fracturing fluid permeation affects the fracturing mechanism of the rock around the wellbore [51,48,40].

* Corresponding author at: School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China.
E-mail address: nuswjg@yahoo.com (J.G. Wang).

http://dx.doi.org/10.1016/j.compgeo.2016.07.011
0266-352X/

Therefore, the viscosity of fracturing fluid may have an important effect on the hydraulic fracturing. Based on experimental results [21], breakdown pressures and fracture complexity in shale increase with the increase of fluid viscosity. The pressurization rate of fracturing fluid also impacts the fracture initiation and breakdown pressure [24,25,72]. However, it is still not clear how these parameters impact the permeation and fracturing behaviors.

Water injection may cause serious environmental problems. For example, some chemicals are essential to the injected HF fluids. This may produce a great volume of waste water and thus induce serious environment problems [53]. In order to solve the problems associated with water fluid, some new fracturing fluids such as nitrogen and CO_2 have been proposed [8,73,57,22,52,54,58,69]. Water and nitrogen are significantly different in their compressibility and viscosity. These differences may induce different permeations and eventually impact the fracturing behaviors. For example, Gomaa et al. [21] experimentally found that nitrogen reduces the breakdown pressure and maximizes the fracture complexity. Alpern et al. [2] observed the hydraulic rupture under zero triaxial far-field stresses by different types of fracturing fluids. Li et al. [34] performed the fracturing experiments by using N_2, H_2O and CO_2 as fracturing fluid under conventional triaxial compression conditions. They examined the breakdown pressure and the resulting morphology of the fracture networks. However, the fracturing mechanisms by using different types of fracturing fluid have not been well investigated through theoretical analysis or numerical simulation.

The impact of seepage zone on the fracturing mechanics has been studied [24,25,72,41,29,40], but its quantitative analysis has not been well conducted. During hydraulic fracturing, the boundary of fracturing fluid moves forward and the seepage zone expands with the volume of injection fluid. At this time, the computational domain for fluid dynamics, heat transfer, and other disciplines or the front is moving forwards. This poses a challenge to computational technology. The computational domain, or boundary shape, must be determined, together with any field variables internal to the domain [47]. It is essential to solve these problems accurately due to the effect of the moving interfaces on the physics of the problems [32]. Thus, the permeation of fracturing fluid is a moving boundary problem. Generally, main approaches for the prediction of moving boundary have three classes: Euler method, Lagrange method, and Arbitrary-Lagrange-Euler method [12,18,35,39]. These approaches are helpful to capture the front movement of injection fluid. Wang et al. [62] proposed a simple approach to predict the moving boundary in one-dimensional space. Due to rock anisotropy, the movement of the fluid front should be anisotropic. Therefore, this paper will extend it to two-dimensional space.

In this work, a numerical model is proposed to comparatively investigate the impact of water and nitrogen fracturing fluids on fracturing initiation pressure and flow pattern before fracture initiation. This model considers the anisotropy of shale deformation and permeability, the compressibility of fracturing fluid and the moving boundary during the injection of fracturing fluid. A crack initiation criterion is established based on the stress intensity factor of a mode I crack and incorporated into this numerical model. This model is then verified through the comparison with our shale fracturing experiments under laboratory conditions and those experimental data or numerical simulation results by other researchers. Finally, the fracturing processes by injecting water and nitrogen are simulated by this numerical model. The impacts of fracturing fluid type, viscosity, shale permeability, permeability anisotropy and pressurization rate are analyzed. A new complex parameter is proposed to investigate the combined effect of viscosity, shale permeability and pressurization rate. The outline of this paper is as follows: Section 2 gives the governing equations for the anisotropic deformation, fluid flow and the constitutive laws for directional permeability as well as the treatment of moving boundary. Section 3 proposes a crack initiation criterion. Section 4 discusses the verification of the numerical model. Section 5 conducts parametric study to explore the key parameters in hydraulic fracturing. Section 6 summarizes the understanding and draws the conclusions.

2. Governing equations for each physical process

Shale is of typical bedding structures, thus being of anisotropy in both deformation and permeability properties. This paper makes the following assumptions: (1) shale is continuous and anisotropic. Its strain is infinitesimal; (2) the sorption of shale matrix is not considered due to the short time of injection process and gas viscosity does not change with pressure; (3) the fluid flow in the shale satisfies the Darcy's law; (4) the chemical effect of methane and water within the shale is ignored; (5) all processes involved are isothermal.

2.1. Governing equation for the deformation of orthotropic porous media

The strain-displacement relationship is expressed by

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{1}$$

Constitutive model for linear elastic rocks can be expressed by

$$\varepsilon = \boldsymbol{S}\sigma \tag{2}$$

where ε, $\boldsymbol{S}$ and σ denote strain, elastic compliance, and stress tensors, respectively.

For orthotropic rocks, Eq. (2) can be expressed in a matrix form as

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_y} & -\frac{\nu_{xz}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{yx}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{yz}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{zy}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix} \tag{3}$$

in which

$$\frac{\nu_{ij}}{E_j} = \frac{\nu_{ji}}{E_i} \quad i,j = x,y,z;\ i \neq j \tag{4}$$

The stiffness matrix has nine independent elastic constants. The term E_i is the elastic modulus in the ith direction. The term ν_{ij} is the Poisson's ratio that characterizes the strain response in the ith direction to the strain acting to the jth direction. The term G_{ij} is the shear modulus in the jth direction whose normal is in the ith direction.

For a pseudo-static deformation process, the equation of motion for a saturated porous medium is expressed as

$$\sigma_{ij,j} + f_i = 0 \tag{5}$$

where σ_{ij} is the total stress component of a shale element, and f_i is the body force per unit volume in the ith direction.

The effective stress is expressed as

$$\sigma_{ij}^e = \sigma_{ij} + \alpha p \delta_{ij} \tag{6}$$

where the Biot's coefficient is $\alpha = 1 - K/K_s$; K is the bulk modulus of the shale; K_s is the bulk modulus of grains and δ_{ij} is Kronecker delta.