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A three-dimensional poroelastic analysis of rock failure around a hydraulic fracture

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ABSTRACT

Three-dimensional stress and pore pressure distributions around a hydraulic fracture are numerically calculated to analyze the potential for formation failure resulting from pressurization of the hydraulic fracture. The three-dimensional numerical model used combines the finite element method and the poroelastic displacement discontinuity method. Elements of the model formulation and solution procedures are first presented. Then, the problem of water injection into a rectangular fracture in Barnett Shale is presented and the potential for rock failure is assessed using Mohr–Coulomb failure criterion with a tension cut-off. Simulation results show that rock failure can occur in the vicinity of the fracture especially near the fracture tips. The dominant failure mode is tension in the close vicinity of the fracture where the pore pressure attains its highest values. Shear failure potential exists away from the fracture walls where shear stresses are sufficiently high to overcome the strength of the rock. Analysis for various injection rates shows that the extent of the potential failure zone increases with increasing injection rate. The failure zone is larger when the formation has a higher modulus of elasticity. Injecting a less viscous fluid enhances pore pressure diffusion into the rock and increases the size of the failure zone.
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1. Introduction

Hydraulic fracturing by water injection is extensively used to stimulate unconventional gas and geothermal reservoirs. The water is pumped at a high pressure into a selected section of the wellbore to create and extend a fracture(s) into the formation. The applied pressure in the fracture(s) re-distributes the pore pressure and stresses around the main fracture causing rock deformation and failure by fracture initiation, and/or activation of discontinuities such as joints and bedding planes. The net result is often enhancement of the formation permeability. The rock failure process is often accompanied by micro-seismicity that can provide useful information regarding the stimulated volume.

The formation response to injection has been the subject of many studies (Ge and Ghassemi, 2008; Koning, 1985; Palmer et al., 2007; Perkins and Gonzalez, 1985; Warpinski et al., 2001); however, the literature pertaining to the subject of rock failure around a hydraulic fracture is not extensive. Warpinski et al. (2001) presented a semi-analytical method to calculate the stress and pore pressure variations induced by a hydraulic fracture, and evaluated the likelihood and potential causes of micro-seismic activity in the vicinity of a major fracture. The semi-analytical method was based on simple crack geometry and approximation of the pore pressure in the reservoir without flow considerations in the fracture. In their study, it was concluded that pore pressure plays the most important role in development of the micro-seismic activities.

Palmer et al. (2007) adopted a 2D model to study the impact of stimulation of Barnett Shale permeability enhancement. They matched the failed reservoir volume with known volume of micro-seismic cloud by using injection permeability as the matching parameter, which was interpreted as an enhanced permeability due to shear or tensile failure away from the fracture plane.

Ge and Ghassemi (2008) also used a 2D approach and studied the impact of the in-situ stress, pore pressure, as well as poroelastic and thermoelastic phenomena on the rock failure around a hydraulic fracture. The resulting stresses were also used to calculate the stimulated volume and the permeability enhancement.

In this paper, we present a 3D poroelastic numerical model for analysis of stress distribution around an irregularly-shaped fracture. The model is applied to study the potential for rock failure in the vicinity of the fracture. The model couples fluid flow in the fracture with poroelastic deformation of the reservoir matrix to calculate the pore pressure and stresses in the rock. Numerical examples are presented to highlight the characteristics of stress distributions, and the effect of injection rate on the extent of the potential rock failure zone for a large fracture.

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Nomenclature

A	fracture plane (m^2)
B	Skempton's pore pressure coefficient
C	fluid diffusivity (m^2/s)
D_n	displacement discontinuity (m)
D_f	fluid flux discontinuity (m/s)
G	shear modulus (MPa)
k	rock matrix permeability (m^2)
l	total number of element nodes
m	total number of elements
M	Biot's modulus
$\mathbf{N}^{(m)}$	element shape function
n	outward normal to surface
p	pore pressure (MPa)
p_0	ambient reservoir pore pressure (MPa)
p_n^{cd}	pore pressure caused by a continuous displacement discontinuity (MPa)
p^{cf}	pore pressure caused by a continuous fluid source (MPa)
p_n^{id}	pore pressure caused by an instantaneous displacement discontinuity (MPa)
p^{if}	pore pressure caused by an instantaneous fluid source (MPa)
q	fluid discharge in the fracture (m^2/s)
Q	pumping rate (m^3/s)
v_l	fluid leak-off velocity (m/s)
t	time (s)
u_i	solid displacement components (m)
w	fracture aperture (m)
w_0	initial fracture aperture (m)
$\mathbf{x}$	vector of influence point coordinates (m)
$\mathbf{x}'$	vector of influencing point coordinates (m)

Greek symbols

α	Biot's effective stress coefficient
ε	volumetric strain
μ	viscosity of the fluid (Pa s)
υ	drained Poisson's ratio
ρ_F	density of the fluid (kg/m^3)
σ_{nn}^{cd}	stress components caused by a continuous displacement discontinuity (MPa)
σ_n^{cf}	stress components caused by a continuous fluid source (MPa)
σ_{nn}^{id}	stress components caused by an instantaneous displacement discontinuity (MPa)
σ_n^{if}	stress components caused by an instantaneous fluid source (MPa)
σ_{n0}	initial stress components (MPa)
σ_n	normal stress component to fracture (MPa)
σ_v	vertical in-situ stress (MPa)
σ_{hmin}	minimum horizontal in-situ stress (MPa)
σ_{hmax}	maximum horizontal in-situ stress (MPa)

2. Theory and governing equations

The problem consists of flow in the fracture and coupled diffusion/deformation in the reservoir matrix. As water is the most commonly used fluid in Shale and geothermal stimulation, it is assumed the fluid in the fracture is incompressible and Newtonian. Also, the rock matrix is assumed to be poroelastic with constant properties. We use a combination of the finite element and displacement discontinuity methods to solve the coupled fracture flow and rock deformation problem. The former is used for fluid flow in fracture while the latter is used for the solid mechanics part of the problem. Once the stresses and pore pressures at field points around the main fracture are calculated, the results can be used in a failure criterion to assess the potential for rock failure.

2.1. Fluid flow in the fracture

The flow of an incompressible fluid in the fracture with smoothly varying aperture is laminar and governed by the cubic law (Zimmerman and Bodvarsson, 1996):

$$\nabla_2 p(x,y,0,t) = -\frac{12\mu}{w^3(x,y,t)}\mathbf{q}(x,y,t) \tag{1}$$

where ∇_2 is the 2D gradient operator (in the fracture plane, A), $p(x,y,0,t)$ is the fluid pressure in the fracture, μ is the fluid viscosity, $w(x,y,t)$ is the fracture aperture, $\mathbf{q}(x,y,t)$ is the fluid discharge. For the incompressible fluid and variable fracture apertures, the fluid continuity equation is

$$-\nabla_2\cdot\mathbf{q}(x,y,t) - 2v_l(x,y,t) = \frac{\partial w(x,y,t)}{\partial t} \tag{2}$$

where $\nabla_2\cdot$ is the two-dimensional divergence operator, v_l the fluid leak-off from one side of the fracture wall into reservoir matrix, $\partial w/\partial t$ is the rate of volume increase. Substitution of Eq. (1) into Eq. (2) yields the following governing equation for fluid flow inside the fracture:

$$\nabla_2\cdot\left[\frac{w^3(x,y,t)}{12\mu}\nabla_2 p(x,y,0,t)\right] - 2v_l(x,y,t) = \frac{\partial w(x,y,t)}{\partial t} \tag{3}$$

The boundary conditions for Eq. (3) can be written as follows: (i) the fluid is pumped into the fracture through a section ∂A_p, so that:

$$-\frac{w^3}{12\mu}\left(\frac{\partial p}{\partial n}\right) = Q \tag{4}$$

for that section and (ii) the flux at crack front ∂A_f is zero:

$$-\frac{w^3}{12\mu}\left(\frac{\partial p}{\partial n}\right) = 0 \tag{5}$$

Note that Q is the pumping rate per unit length of the section ∂A_p and n is the outward normal vector of the fracture line. The global mass balance is used to ensure a unique solution to the problem (Yew, 1997):

$$-\int_A 2v_l dxdy - \int_A \frac{\partial w}{\partial t}dxdy + \int_{\partial A_p} Q ds = 0 \tag{6}$$

in which v_l is leak-off into the rock matrix and is expressed using Darcy's law:

$$v_l(x,y,t) = -\kappa\frac{\partial p(x,y,z,t)}{\partial n}\Big|_{z=0} \tag{7}$$

where $\kappa = (k/\mu)$ is the rock permeability coefficient, in which k is the intrinsic permeability and n is the outward normal of the fracture surface, $z=0$ denotes the fracture surface.

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