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Three-dimensional poroelastic modeling of injection induced permeability enhancement and microseismicity

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ABSTRACT

A combined boundary element/finite element numerical method is employed to investigate the response of a hydraulic fracture/natural fracture network to injection. The model is three-dimensional and poroelastic. It considers the effects of fracture interactions, fluid diffusion into the matrix and the natural fractures, fracture opening and shear dilation. The natural fractures behavior is modeled using non-linear deformation in both shear and normal directions. For the shear mode, the slip-weakening model is used to simulate the post-shear failure behavior of the fractures. An example simulation is carried out to study the response of a fracture network to injection. The calculated injection pressure profile is used to ascertain the deformation response of the fracture network and its permeability enhancement. The simulation results clearly illustrate the potential for induced microseismicity due to permanent shear slip on natural fractures surrounding a hydraulically driven major fracture. Although the slip on the natural fractures can potentially contribute to seismic activity, its contribution to permeability enhancement depends on whether or not they propagate to connect to form a "hydraulically" connected network with the main fracture. When the natural fracture system is not connected to the main flow path, the MEQ information may overestimate the so-called stimulated reservoir volume.

1. Introduction

Enhanced Geothermal Systems (EGS)[1] and the extraction of hydrocarbons from low permeability reservoirs rely on generating a permeable fracture network.[2] Numerical modeling is a suitable tool to design and analyze the stimulation processes of the fracture network. It is extremely essential to utilize a modeling technique that encompasses the major affective mechanisms accurately. Early models of fracture analyses[3,4] relied on elastic two-dimensional analytical models of single fractures and ignored the poroelastic effects. Later on, the generation of a fracture network during the injection into unconventional reservoirs has been recognized.[5–9] However, these models underscored the need to fully coupled fracture network behavior to injection/extraction processes. Recent models, explicitly consider the effect of fracture network in the two dimensional fully coupled analysis.[10–11] In this paper a three dimensional (3D) fully coupled poroelastic model is presented and used to simulate injection into a network of fractures. The model uses the poroelastic displacement discontinuity (DD) to simulate fractures and the finite element method to model fluid flow inside fractures. The DD is based on improving the development of Zhou and Ghassemi[12] to consider multiple nonlinear elastic rock joints, slip-weakening behavior after permanent slippage, shear dilation and its effect on the fracture permeability enhancement, and transition of joint fractures (i.e. crack surfaces are in" contact condition) to hydraulic fractures (i.e. crack surfaces are separated from each other).

2. Governing equations

2.1. Constitutive relations for rock matrix

The constitutive behavior of fluid-saturated rocks is described by the linear theory of poroelasticity.[13,14] The coupled

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equations for deformation and fluid diffusion in porous rock under isothermal conditions can be found in Rice and Cleary.[14] The equations present the relationship among the volumetric response of porous rock, pore pressure variations, and changes in the pore pressure in response to an applied mean stress. Besides, pore-fluid diffusion relationship can be presented by Darcy's law.[13,14] By combining these relations and the equilibrium and compatibility conditions, three-dimensional field equations (Navier's equations with pore pressure coupling) can be presented as follow:

$$G\nabla^2 u_i + \frac{G}{1-2\nu}u_{k,ki} - \alpha\,\nabla p = 0$$

$$\frac{\partial p}{\partial t} - \frac{2k\,G\,B^2(1-2\nu)(1+\nu_u)^2}{9\mu(\nu_u-\nu)(1-2\nu_u)}\nabla^2 p = -\frac{2G\,B(1+\nu_u)}{3(1-2\nu_u)}\frac{\partial \varepsilon}{\partial t} \tag{1}$$

where G is the rock shear modulus, u_i is the rock displacement component in "i" direction, ν is drained Poisson's ratio, ν_u is un-drained Poisson's ratio, α is Biot's coefficient, p is pore pressure, t is time, k is rock permeability, B is Skempton's coefficient, μ is pore fluid viscosity, and ε is the volumetric strain. Eq. (1) should be solved with the appropriate boundary and initial conditions.

2.2. Fluid flow inside fractures

A fracture is represented as a parallel plate model. The separation (W) between the plates is assumed constant for a representative element of the fracture. This particular fracture geometry is amenable to an exact solution of the Stokes equation.[15] The solution for steady state, laminar incompressible flow is known as the Cubic law, $Q = W^3/12\mu\nabla p$, where Q is the volumetric flow rate and $\nabla\mathbf{p}$ is the pressure gradient applied to the fluid. Using Darcy's Law, an expression for parallel plate permeability (k_f), in units of length^2, is obtained: $k_f = W^2/12\mu$.

Assuming isothermal conditions, mass transfer in fracture system includes fluid flow within the fracture and leak-off into the reservoir matrix. It is also assumed that the cubic law is valid in the fracture. By taking into account that the fracture aperture is variable over time, mass continuity equation can be presented as follows:

$$\nabla(W\times\mathbf{v}) = -\,2\,\upsilon_l + Q_{inj}(t)\delta(\mathbf{x}_{inj}) - Q_{ext}(t)\delta(\mathbf{x}_{ext}) - \frac{\partial W}{\partial t} \tag{2}$$

where W is fracture opening, $\mathbf{v}$ is the fracturing fluid velocity vector, υ_l is leak-off from one surface of fracture into rock matrix, $Q_{inj}(t)$ is the injection rate, $Q_{ext}(t)$ is the production rate, $\delta(\mathbf{x}_{inj})$ and $\delta(\mathbf{x}_{ext})$ are the functions that are zero everywhere except at $\mathbf{x}_{inj}$ and $\mathbf{x}_{ext}$ which are the location of injection and extraction wells accordingly. The governing equation for fluid flow inside fracture system is derived by substituting the fluid mass continuity Eq. (2) into the Cubic law:

$$\nabla\left(\frac{W^3}{12\mu}\nabla p\right) = \left\{\frac{\partial W}{\partial t} - Q_{inj}(t)\ \delta(\mathbf{x}_{inj}) + Q_{ext}(t)\ \delta(\mathbf{x}_{ext}) + 2\upsilon_l\right\} \tag{3}$$

in which the fluid pressure on the fracture surface, the fracture aperture, and leakoff from the fracture surface into the rock matrix are unknown. These unknowns should to be calculated during solution procedure for a given history of injection and extraction rates.

3. Numerical implementation

3.1. Discretization of principal relations

To analyze a fracture system during an arbitrary injection or extraction period, partial differential Eqs. (1) and (3) should be solved simultaneously with corresponding boundary and initial conditions. These two equations are coupled via the fluid pressure inside fracture and fracture aperture.

Governing Eq. (1) with an infinite boundary, fracture surface boundary, and initial in-situ condition is solved numerically using a discontinuity technique. In the discontinuity method, fractures are considered as surfaces across which normal and two shear displacement components and fluid flux are discontinuous. Hence, the stresses and pore pressure distributions in the field depend on the quantity of discontinuities on the fracture surface as well as the corresponding in-situ stresses and pore pressure. By invoking the poroelastic displacement discontinuity technique,[16,17] the stresses and pressure at any point can be evaluated using the strengths of the DDs, fluid flux discontinuities, and in-situ stresses and pressure:

$$\sigma_{ij}(\mathbf{x},t_n) = \int_0^{t_n}\int_A \{\sigma^{id}_{ijkn}(\mathbf{x}-\boldsymbol{\chi},t-t')\times D_{kn}(\boldsymbol{\chi},t') + \sigma^{is}_{ij}(\mathbf{x}-\boldsymbol{\chi},t-t')\times D_f(\boldsymbol{\chi},t')\}dA(\boldsymbol{\chi})dt' + \sigma_{is}(\mathbf{x},0)$$

$$p(\mathbf{x},t_n) = \int_0^{t_n}\int_A \{p^{id}_{ij}(\mathbf{x}-\boldsymbol{\chi},t-t')\times D_{ij}(\boldsymbol{\chi},t') + p^{is}(\mathbf{x}-\boldsymbol{\chi},t-t')\times D_f(\boldsymbol{\chi},t')\}dA(\boldsymbol{\chi})dt' + p(\mathbf{x},0) \tag{4}$$

where $\sigma_{ij}(\mathbf{x},t_n)$ is the "ij" component of stress tensor at point $\mathbf{x}$ and time t_n, $p(\mathbf{x},t_n)$ is the pore pressure at point $\mathbf{x}$ and time t_n, A is cracks surface, $\sigma^{id}_{ijkn}(\mathbf{x}-\boldsymbol{\chi},t-t')$ represents induced instantaneous "ij" stress components at time t and location $\mathbf{x}$ due to unit instantaneous DD in "kn" directions occurring at time t' and location $\boldsymbol{\chi}$, $D_{kn}(\boldsymbol{\chi},t')$ is the strength of instantaneous DD in "kn" directions at time t' and location $\boldsymbol{\chi}$, $\sigma^{is}_{ij}(\mathbf{x}-\boldsymbol{\chi},t-t')$ is induced instantaneous "ij" stress components at time t and location $\mathbf{x}$ due to unit instantaneous fluid source at time t' and location $\boldsymbol{\chi}$, $D_f(\boldsymbol{\chi},t')$ represents the strength of instantaneous fluid source (equal to $2\upsilon_l$) at time t' and location $\boldsymbol{\chi}$, $p^{id}_{ij}(\mathbf{x}-\boldsymbol{\chi},t-t')$ denotes induced pore pressure at time t and location $\mathbf{x}$ due to unit instantaneous DD in "kn" direction occurring at time t' and location $\boldsymbol{\chi}$, $p^{is}(\mathbf{x}-\boldsymbol{\chi},t-t')$ is the induced pore pressure at time t location $\mathbf{x}$ due to unit instantaneous fluid source occurring at time t' at location $\boldsymbol{\chi}$, $\sigma_{ij}(\mathbf{x},0)$ is 'ij' component of in-situ stress tensor at location $\mathbf{x}$, $p(\mathbf{x},0)$ is in-situ pore pressure at location $\mathbf{x}$.

To calculate the strength of DDs and the fluid source discontinuity (leakoff), Eq. (4) is considered on the fracture surface (i.e. $\mathbf{x}$ is located on A) and the temporal integrals of the instantaneous fundamental solutions are expressed in terms of continuous fundamental solutions.[18,19] In this manner, temporal integration is circumvented. Moreover, by discretizing t_n into "s" increments of Δt, representing the boundaries of all fractures by "N" quadrilateral four node elements, assuming constant DDs and linear variation of fluid source intensities across each element, the boundary integral Eq. (4) can be re-written as: