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# Three-Dimensional Poroelastic Modeling of Multiple Hydraulic Fracture Propagation from Horizontal Wells

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ABSTRACT

Numerical simulations of multistage hydraulic fracturing usually neglect poroelastic effects. However, in case of low permeability reservoirs, where hydraulic fracturing is usually carried-out using relatively low viscosity fluids and high injection rates, coupled poroelastic mechanisms need be included for better understanding of the fracturing process, which can involve rock failure and/or reactivation of natural fractures. In this paper, we present a fully coupled three-dimensional poroelastic analysis of multiple fracture propagation from horizontal wells. The numerical model uses the indirect boundary element method of displacement discontinuity for poroelastic response of the rock, the finite element method for fracture fluid flow, and the linear elastic fracture mechanics approach for fracture propagation. The model accounts for the mechanical interactions among multiple fractures, mixed-mode propagation, fluid diffusion into the reservoir matrix, and the effects of fluid diffusion on the rock mechanical response. The model is verified with analytical solutions, and numerical examples of simultaneous and sequential fracturing of single and multiple horizontal wells in the Niobrara Chalk formation are presented. The results show the created fracture network geometries are strongly influenced by the mechanical interactions among the fractures. It is also demonstrated that the poroelastic effect increases the net fracture pressure and causes a reduction in fracture volume. The poroelastic model illustrates the transient character of stress shadow, and is particularly useful for re-fracturing analysis since it readily calculates the stress variations due to reservoir depletion.

## 1. Introduction

Multistage hydraulic fracturing of horizontal wells is a commonly used technique for enhancing the permeability of unconventional reservoirs. Horizontal well stimulation usually involves creating cluster of multiple fractures in stages along the wellbore using different well completion techniques. These multiple fracture stages generate large contact surface area with the reservoir and increase of reservoir permeability. In fracturing low permeability reservoir, it is important to optimize the spacing between fractures to achieve economical production rates and an optimum depletion of the reservoir. Designing closely-spaced fractures would tend to use excessive energy and the mechanical interaction between fractures may result in undesirable stimulation outcome e.g., termination of fracture propagation. The mechanical interaction between multiple fractures arises from a fracture's "stress shadowing" effect[1] which varies with the net applied fluid pressure. In homogeneous rocks, the mechanical interaction between fractures is a function of spacing among them, and the in-situ stress contrast, However, in heterogeneous systems, rock properties and poroelastic processes[2] become important. The effect of stress shadowing when multiple hydraulic fractures are created parallel to each other is of major interest in numerical simulations and have been studied using multiple fracture models (e.g.,).[1–5]

Several numerical studies of 3D hydraulic fracture simulation have been carried out. [6] presented a 3D coupled model based on the displacement discontinuity method and demonstrated multiple fracture propagation from the vertical wells and[7] developed a 3D non-planar fracture propagation using the extended finite element method. 3D non-planar mixed-mode propagation was simulated in[8] using the VMIB, and[9] extended the work to include thermal stress effects. Other modeling efforts include planar 3D and non-interacting, or with simplified interactions among fractures such as.[10–12] These earlier numerical models have been based on the theory of elasticity, and many of them do not consider out-of-plane propagation of fractures due to mechanical interaction or in-situ stress anisotropy.

In case of unconventional reservoirs (e.g., tight oil and shale gas reservoirs), where hydraulic fracturing is carried-out using relatively low viscosity fluids and high fluid injection rates, the coupled

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poroelastic phenomena such as changes in the rock deformation due to diffusion of the pore pressure and the pore pressure induced by the mechanical deformation of the solid rock need to be incorporated for better understanding of hydraulic fracturing which often involves rock failure and/or reactivation of natural fractures. The coupled fluid diffusion/rock deformation processes can be accounted following Biot's linear poroelastic theory.[13,14] Often, the poroelastic effects on the hydraulic fracturing process are included using the "backstress" concept.[15–19] Recently, a few studies have been presented for 3D hydraulic and natural fracture simulation using coupled poroelasticity e.g.,[20] and[21] presented 3D poroelastic analysis of pressurized natural fractures. Kumar and Ghassemi[22–25] studied multiple 3D fracture propagation from the horizontal wells in poroelastic reservoirs using the DD method. Salimzadeh et al.[26] also have presented a poroelastic finite element based 3D model to study mechanical interaction among multiple fractures.

In this paper, we present a fully coupled 3D poroelastic hydraulic fracture model with capabilities to simulate multistage fracturing from a multiple well system and refracturing of multiple horizontal wells (see.[24,25,27] The study is motived by the need to evaluate the impact of pore pressure and poroelastic effects on stress shadowing during multistage fracturing of a horizontal well and the multiple horizontal wells. The model uses a combination of the poroelastic displacement discontinuity (DD) method to simulate solid rock deformation and fluid diffusion in rock matrix, and the Galerkin's finite element approach is used to model fluid flow inside the fractures. The major details of 3D poroelastic DD formulation for the case of a stationary fracture can be found in.[20,21,28] A brief description of the governing equations and implementation methodologies are included in this paper. The verifications of model are presented first using the asymptotic analytical solution for impermeable rock. Finally, the model is applied for analysis of simultaneous propagation of multistage fractures from multiple horizontal wells.

## 2. Theory and governing equations

### 2.1. Poroelastic deformation of the rock matrix

The poroelastic deformation of the rock matrix is governed by linear theory of poroelasticity The Biot's theory was reformulated by several authors such as.[29,30] Under isothermal conditions, the coupled constitutive equations for the poroelastic rock mass are givens as[31]:

$$\varepsilon_{ij} = \frac{1}{2G}\left[\sigma_{ij} - \frac{\nu}{(1+\nu)}\delta_{ij}\sigma_{kk}\right] + \frac{\alpha(1-2\nu)}{2G(1+\nu)}\delta_{ij}p \tag{1}$$

$$\zeta = \frac{\alpha(1-2\nu)}{2G(1+\nu)}\sigma_{kk} + \frac{\alpha^2(1-2\nu)^2(1+\nu_u)}{2G(1+\nu)(\nu_u-\nu)}p \tag{2}$$

where $\sigma_{ij}$ is the total stress tensor, $\varepsilon_{ij}$ is the strain tensor, $p$ is the pore pressure, ζ is the fluid content variation per unit volume of porous material, $\alpha$ is the Biot's effective stress coefficient, $G$ is the shear modulus, $\nu$ and $\nu_u$ are the drained and undrained Poisson's ratio, respectively, $\delta_{ij}$ is the Kronecker delta function, and the indices "$i$" and "$j$" varies from 1 to 3 for 3D analysis, the repeated indices "$kk$" represents summation of the corresponding variable. The above equations present fundamental phenomenon of deformation of fluid saturated porous rocks which are the volumetric response of the rock mass, pore pressure variation, and change in the pore pressure due to applied stresses. For complete description of the governing equations of the poroelasticity along with constitutive equations (Eqs. 1 and 2), the equilibrium condition, fluid diffusion, and the fluid mass balance equation should be included. The pore fluid diffusion is governed by Darcy's law as:

$$q_i = -\frac{k}{\mu}\nabla p \tag{3}$$

where $q_i$ is the fluid flux in $i^{\text{th}}$ direction, $k$ is the rock permeability, $\mu$ is the pore fluid viscosity, and ∇ is the gradient operator In absence of the body force and fluid source, by combining the constitutive equations, diffusion equation, and the equilibrium conditions, the field equations for the poroelastic rock matrix are given using the Navier's equations with coupling terms as[31]:

$$G\nabla^2 u_i + \frac{G}{(1-2\nu)}u_{k,ki} - \alpha\nabla p = 0 \tag{4}$$

and the pore-fluid diffusion equation is given as:

$$\frac{\partial p}{\partial t} - \frac{2\kappa G B^2(1-2\nu)(1+\nu_u)^2}{9(\nu_u-\nu)(1-2\nu_u)}\cdot\nabla^2 p = -\frac{2GB(1+\nu_u)}{3(1-2\nu_u)}\frac{\partial\varepsilon}{\partial t} \tag{5}$$

where $\mu_i$ represents the solid displacement in $i^{\text{th}}$ direction, $B$ is the Skempton's pore pressure coefficient, and $\kappa = k/\mu$ is the reservoir permeability coefficient. The above equations establish basis for the linear poroelastic analysis and need to be solved numerically using appropriate initial and boundary and conditions for a given problem.

#### *2.1.1. Boundary integral equations for rock matric and fracture deformation*

The indirect boundary integral equations for the displacement discontinuity (DD) method are used for numerical implementation of Eqs. (4) and (5). The development and application of the DD started with attempts to simulate mining problems involving silt-like openings with one dimension much smaller compared with the other dimensions.[32–36] Crouch[35] developed the fundamental solutions for a DD line segment in infinite and semi-infinite media. Other investigators developed the point load DD formulation based on the Green's fundamental solution for a point source.[37–39] These fundamental solutions can be integrated over arbitrarily shaped element to generalize the DD method. The point load DD solution represents discrete analogs of Kupradze's type equations (e.g.,[40–44] for the double layer potential for elasticity. The point source DD concept have been extended for the 2D and 3D hydraulic fracture simulations in the poroelastic media in several works.[15,16,18,20,45,46] For completeness, a brief description of the 3D poroelastic DD formulation and its numerical implementations are included in this paper.

A fracture in a poroelastic media can be simulated by distributing displacements and the fluid flux discontinuities on its surface and applying the principle of superposition to sum their effects such that the boundary conditions are satisfied. Using the corresponding singular solution, boundary integral equations for the resultant displacements, fluid fluxes, stresses, and reservoir pore pressure can be derived. The boundary integral representations for the stresses and pore pressure at any point in the reservoir or on the fracture surface can be expressed as[20,21,28,47]:

$$\sigma_{ij}(\mathbf{x},t) = \int_0^t\int_\Gamma \left\{\begin{matrix}\sigma_{ijkn}^{id}(\mathbf{x}-\boldsymbol{\chi};t-\tau)D_{kn}(\boldsymbol{\chi},\tau)\\ +\sigma_{ij}^{is}(\mathbf{x}-\boldsymbol{\chi};t-\tau)D_f(\boldsymbol{\chi},\tau)\end{matrix}\right\} d\Gamma(\boldsymbol{\chi})d\tau + \sigma_{ij}^0(\mathbf{x}) \tag{6}$$

$$p(\mathbf{x},t) = \int_0^t\int_\Gamma \left\{\begin{matrix}p_{ij}^{id}(\mathbf{x}-\boldsymbol{\chi};t-\tau)D_{ij}(\boldsymbol{\chi},\tau)\\ +p^{is}(\mathbf{x}-\boldsymbol{\chi};t-\tau)D_f(\boldsymbol{\chi},\tau)\end{matrix}\right\} d\Gamma(\boldsymbol{\chi})d\tau + p_0(\mathbf{x}) \tag{7}$$

where $\mathbf{x}$ and $\boldsymbol{\chi}$ represents the local coordinates of the source and field points, respectively, $t$ is the current time and $\tau$ is the time when the location $\boldsymbol{\chi}$ receives the fluid first time, $D_{kn}$ represent the DD vector, $D_f$ is the fluid source intensity vector, $\sigma_{ijkn}^{id}$, $\sigma_{ij}^{is}$, $p_{ij}^{id}$, and $p^{is}$ are the instantaneous fundamental solutions for the stresses and pore pressure due to a unit impulse of the displacement discontinuity ("$id$") in the "$kn$" direction and a unit impulse of the fluid source intensity ("$is$"), $\sigma_{ij}^0(\mathbf{x})$ are the in-situ stress components, and $p_0(\mathbf{x})$ is the in-situ reservoir pore pressure. These fundamental solutions are functions of the poroelastic properties of rock mass and spatial distance and time interval between field and source points. A physical representation of displacement discontinuities and fluid source intensity are shown in Fig. 1.