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A damage mechanics approach to the simulation of hydraulic fracturing/shearing around a geothermal injection well

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ABSTRACT

Enhanced geothermal energy production requires the stimulation of natural fracture pathways to increase fluid flow within a reservoir while still effectively recovering the heat. During injection/production, reservoir permeability exhibits various degrees of enhancement or degradation with time. These changes are generally attributed to various multiphysics processes that act both during short-term stimulation and during production over the longer term. Important mechanisms of stimulation include tensile failure by hydraulic fracturing or shear failure by hydraulic shearing. A wide range of methods have been used to numerically simulate permeability enhancement in porous and fractured media including models based on damage mechanics, discrete fracture mechanics, critical shear strain criteria, effective stress, and even empirical permeability multipliers. We explore the use of damage mechanics to represent hydraulic fracturing/shearing within the reservoir. The model incorporates an energy release rate micro-crack model in mixed modes (opening – I and shear – II) to simulate damage and permeability enhancement. The model is calibrated against compression tests to determine interrelationships between damage and both deformation and permeability. It is then applied to contrast both isothermal and thermal quenching effects during stimulation of hot reservoirs with cold fluid injection. The results illustrate that when fluid pressures are sub-failure, the damage zone is limited to the near wellbore region. As fluid pressure is increased, near wellbore mode II failure transitions to mode I hydraulic fracturing and rapidly increasing damage. A method of simulating cold water injection induced damage due to both shear and tensile failures is needed in the geothermal industry. This work offers a step forward in that direction.

1. Introduction and background

Permeability is one of the most crucial hydrologic parameters and can vary over 16 orders of magnitude [19]. Permeability often determines the feasibility of projects involving geologic processes and their economic potential. This is especially true in geothermal energy production. Enhanced geothermal energy production requires the stimulation of natural fracture pathways to increase fluid flow without creating "short circuits" that allow cold fluid to quickly pass through a system without gaining sufficient heat energy. Changes in permeability are generally attributed to various multiphysics processes that act both during short-term stimulation and during production over the longer term. Important mechanisms of stimulation include tensile failure by hydrofracking or shear failure by hydroshearing; there is a growing interest in the latter as it potentially contributes to a large stimulated volume of self-propped fractures that is advantageous to heat transfer. In addition, the long term response is modulated by processes of chemical alteration (dissolution and precipitation), thermal and poroelastic deformation of fractures or of the rock matrix, or inelastic failure. All of these processes contribute to the evolution of permeability within the reservoir. A wide range of methods has been used to numerically simulate permeability evolution in porous and fractured media. Models based on damage mechanics, discrete element methods, critical shear strain criteria, cohesive zone finite elements, the eXtended Finite Element Method (XFEM), effective stress, and even empirical permeability multipliers have been proposed.

Clark [9] published perhaps the first paper on hydraulic fracturing (hydrofracking), then termed "pressure parting," which was targeted toward increasing oil well productivity. Hydrofracking is understood to occur when injection pressure exceeds the minimum principal stress. It is characterized by fractures opening in tension and results in the development of highly permeable fracture pathways. An alternative stimulation technique is termed

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"hydroshearing." The term was coined to indicate that existing fractures can dilate and slip in shear at lower pressures than are required by hydrofracking [8]. A benefit of this work's mixed mode approach is that both hydroshearing and hydrofracking and the transition between the two stimulation techniques can be simulated with this approach.

A common fracture modeling approach in finite element analyses involves representing a fracture as a discontinuity and using cohesive zone elements to control the failure energy. The concept of a cohesive zone in fracture mechanics can be traced back to the work of Barenblatt [2] and Dugdale [12] and are often referred to as "Plastic Strip Yield Models". The cohesive zone acts as a fracture process zone where a resisting force or traction acts on each crack surface as a function of the displacement jump across the surfaces. Hillerborg et al. [18] were the first to apply a cohesive zone model in finite element analysis to investigate crack formation and growth in concrete. Cohesive zone models have been used to simulate hydraulic fracturing in hydro-mechanical models [7,40,6]. In those works (and traditionally), the crack path was specified *a priori*, so the locations of the cohesive elements were known. However, there are formulations that allow for the dynamic insertion of cohesive elements between any elements of the finite element mesh (e.g., [47]). One of the main difficulties in traditional cohesive zone modeling is overcoming mesh dependencies, as fractures propagate along element edges.

The XFEM allows for discontinuities to cut directly through elements of a mesh [33]. This technique largely overcomes the problems with mesh dependencies in fracture discontinuity techniques. Cohesive zone models have also been applied to the XFEM [32]. The XFEM technique has been used to model the behavior of single fractures in THM modeling by Khoei et al. [25] and for modeling hydraulic fracturing in a poroelastic medium [34]. Recently, Gupta and Duarte [16] have developed a technique using the XFEM in 3D hydraulic fracture simulations allowing for non-planar crack propagation. The main strength of the XFEM is its ability to represent large-scale discontinuities without remeshing. However, in reservoir rock, micro-scale discontinuities exist and can affect permeability and other material behaviors. These defects can perhaps be much smaller than the size of the finite elements.

Damage mechanics is a branch of continuum mechanics that incorporates micro-scale effects into the continuum scale model through the damage variable [10]. Early damage mechanics work was focused on expressing failure in metallic materials. Lemaitre [27] provided an early treatise on the theory and usage of damage mechanics for explaining the behavior of metals under high loads. Mazars and Pijauder-Cabot [31] extended damage mechanics theory for applications related to brittle materials such as concrete and implemented it into finite element simulations. Halm and Dragon [17] developed a thermodynamically consistent, easy-to-use, and anisotropic implementation of damage mechanics into the solid mechanics constitutive theory. Damage mechanics approaches have now been used to study hydraulic fracturing in reservoir rock [48,30]. These papers present a coupled hydro-mechanical framework to test damage-induced permeability enhancement models for application to shale oil plays. A noticeable shortcoming in these approaches (for geothermal) is a lack of consideration of thermal effects as well as non-tensile fracture scenarios such as hydroshearing.

More recent examples of shear stimulation simulations with geothermal applications can be seen in the works of Kelkar et al. [24], Rutqvist et al. [39], and Dempsey et al. [11]. Rutqvist et al. [39] used a simplified Coulomb criterion to determine the volume that would be enhanced by shear failure near an injection site. The initiation criterion was simplified so that it effectively became a maximum principal stress criterion. Their work targeted pre-stimulation behavior and permeability evolution was not taken into account. Kelkar et al. [24] and Dempsey et al. [11] used a Mohr–Coulomb initiation criterion to determine where shear slip occurred near an injection site. Permeability was then altered by either a multiplier [24] or by a sigmoidal function [11], both designed to approximate the measured permeability data obtained by Lee and Cho [26]. These works offer several attractive features, however, the effects of fracture evolution on properties of the solid constitutive theory were not accounted for in these works.

There are also a number of models that use an approach for simulating permeability enhancement by specifying permeability as a function of effective stress [35,36]. In Nathenson [35] stress was simplified to a scalar value and four different effective stress/permeability evolution relationships were tested against geothermal well data. Pogacnik et al. [36] extended Nathenson's "inverse power" relationship to include the full stress tensor. These works do not employ an initiation criterion, so permeability continuously evolved with the stress state. The effective stress relationships of Nathenson [35] can trace their roots back to the cubic law of planar fracture flow popularized by Gangi [14]. While the law theoretically describes flow through a single channel, it often breaks down in complex flow regimes with multiple nonlinear fracture pathways.

In this work, we employ a damage mechanics approach by extending previous work [30,37] to account for a mixed mode fracture criterion that accounts for both shear and tensile failure regimes using microcrack fracture mechanics inside the finite elements. Both shear and tensile failure modes are of interest in Enhanced/Engineered Geothermal Systems (EGS) and a unified model that can account for both modes in a THM simulator has not been previously investigated. THM simulation results of a cold water injection scenario in a uniform 2D medium are shown in the results section. Also, we account for permeability evolution as a result of micromechanical damage that is incurred during loading.

2. Balance equations

2.1. Linear momentum balance for the rock matrix

In this work, inertial forces in the solid rock matrix are ignored. The linear momentum balance (from [4]) is written as:

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{f} = \mathbf{0} \tag{1}$$

where the vector $\nabla \cdot \boldsymbol{\sigma}$ is the spatial divergence of the Cauchy stress tensor (to be formally defined in the next section) and $\mathbf{f}$ a vector of body forces (both external and density related). Note that bold-face fonts are used to express matrix and vector quantities. The Cauchy stress can be split into two components to represent the effect of pore fluid pressure on the solid matrix [29,19]:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}'' - \alpha p \mathbf{I} \tag{2}$$

where $\boldsymbol{\sigma}''$ is Biot's effective stress tensor, α is a constant between 0 and 1, p is the pore fluid pressure, and $\mathbf{I}$ is the identity tensor. The effective stress is defined by

$$\boldsymbol{\sigma}'' = \mathbf{C}^D : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_T) \tag{3}$$

where $\mathbf{C}^D$ is the fourth-order material constitutive tensor (that includes damage), $\boldsymbol{\varepsilon}$ is the strain tensor, ":" represents the double contraction of two tensors, and $\boldsymbol{\varepsilon}_T$ is the thermal strain tensor given by

$$\boldsymbol{\varepsilon}_T = \left(\frac{\beta_s}{3}\right) \Delta T \; \mathbf{I} \tag{4}$$

where β_s is the volumetric coefficient of thermal expansion of the solid and ΔT is the change in temperature from the reference state.