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A sequential implicit discrete fracture model for three-dimensional coupled flow-geomechanics problems in naturally fractured porous media

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ABSTRACT

A sequential implicit numerical method based on discrete-fracture model and the Galerkin Finite Element method, for time-dependent coupled fluid flow and geomechanics problems in fractured subsurface formations is presented. Discrete-fracture model has been used to explicitly represent the fracture network inside porous media. The Galerkin Finite Element method with adaptive unstructured gridding is implemented to numerically solve the spatially three-dimensional and time-dependent problem. The presented method is validated with previously obtained solutions. Two problems are numerically solved by applying the presented methodology in a three-dimensional fractured petroleum reservoir under different production and injection conditions. The modeling results demonstrate that changes in fracture aperture and permeability due to geomechanical stress, have a significant impact on well performance and production rate in fractured reservoirs.

1. Introduction

The stress dependent fluid flow is one of the challenging problems in many fields of geosciences. Interactions between solid media and the fluid which is stored in it, lead to an inherently time-dependent coupled fluid flow and geomechanics problem. These interactions are due to changes in fluid pore pressure (via injection or removal of the fluid), which in turn cause the solid media to deform. As a result of this deformation, the characteristics of the solid media such as permeability (i.e. the ability of the media to conduct fluid) change. The changes in solid media's characteristics alters the way that the fluid flows within it. This chain of events inside the porous media demonstrates the nature of the coupled fluid flow and geomechanics problem (Rutqvist and Stephansson, 2003).

Disregarding the effects of geomechanical parameters on fluid flow in petroleum reservoirs can lead to significant economic and environmental damages. For instance, excessive water flooding for oil recovery enhancement, without considering the geomechanical factors and how they activate or deactivate fluid pathways has caused massive oil leaks in the past (Gu et al., 2014). Therefore it is important to pay careful attention to geomechanical effects in fractured formations.

Many previous studies exist in the literature, concerning the stress-sensitivity effects in conventional porous media (Pedrosa, 1986; Kilmer et al., 1987; Zhang and Ambastha, 1994; Chin et al., 2000; Wang et al., 2010; Qanbari and Clarkson, 2012, 2014; Shaoul et al., 2015). However, coupled fluid flow and geomechanics study in fractured formations is a relatively new field of study in reservoir simulation.

Different approaches have been taken by several researchers to present a method for solving the stress dependent fluid flow problem in fractured porous media. In one-way coupled method, the changes in fluid properties affect the geomechanics, but geomechanical information is not shared with the fluid flow. On the other hand, two-way coupled methods allow fluid flow and geomechanics to interact with each other. Numerical simulation of two-way coupled problems can be carried out using two distinct approaches: one is the fully implicit scheme, in which the flow and geomechanics equations are solved simultaneously, and the second approach is called the sequential method. Fully implicit methods offer a more accurate solution, but have large computational costs. However, sequential methods are more flexible from a computational perspective, but might suffer from convergence and stability limitations (Castelletto et al., 2015; Gutierrez et al., 2001; Kim et al., 2012; Jalali and Dusseault, 2012; Settari and Mourits, 1998). Another approach which is called loose coupling, is a middle ground between one-way and two-way coupling method. In loose coupling, two sets of equations, one for fluid flow and the other for geomechanics are solved independently, but information is shared between the two at specified time intervals (Minkoff et al., 2003).

There are different numerical methods to solve the fluid flow and the geomechanics problem in porous media. For the fluid flow problem,

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finite element based methods have been widely used to simulate the coupled problem (Karimi-Fard and Firoozabadi, 2003; Monteagudo and Firoozabadi, 2004; Martin et al., 2005). Many other works based on the finite volume method have also been published (Karimi-Fard, 2004). For the solid mechanics part, finite element based methods have also been used extensively (Zienkiewicz and Taylor, 2005). Finite element based methods and hybrid finite element-finite volume methods have been employed in solving the coupled fluid flow and geomechanics problems (Gu et al., 2014; Garipov et al., 2016). Integral finite difference method is another approach that has been used in such problems (Hu et al., 2013). Another relatively new scheme, is the extended finite element method (XFEM) which is suitable for problems with local features that cannot be fixed by mesh refinement (Khoei et al., 2006; Lamb et al., 2013; Shamloo et al., 2005).

Many researchers have investigated the coupled problem in fractured media. Some of these works have utilized the dual-porosity model (Chen and Tuefel, 2000; Segura et al., 2016). Discrete fracture model has been more widely used recently in coupled fluid flow and geomechanics problems (Garipov et al., 2016; McClure et al., 2016; Norbeck et al., 2014; Philip et al., 2005). Instead of solving the coupled system of equations, Moinfar et al. (2013) used in-situ stress conditions to estimate the stress field within the reservoir, and utilized an experimental relation to compute the fracture aperture deformation due to the stress field (Moinfar et al., 2013). Rutqvist et al. (2014) implemented a linked multicontinuum and crack tensor approach to simulate coupled fluid flow, geomechanics and solute transport in fractured rock (Rutqvist et al., 2014). Garipov et al. (2016) presented a fully implicit coupled fluid flow and geomechanics formulation for fractured formations. In their work, contact problem has been included to study the effects of geomechanical stress on fracture aperture and hydrocarbon production rate (Garipov et al., 2016).

In the present work, we aim to implement the discrete fracture model along with the Galerkin finite element model to present a sequential implicit time-dependent numerical method to solve the coupled fluid flow and geomechanics problem in subsurface naturally fractured formations. The presented method is sequential implicit, which means that first, the fluid flow equation is solved implicitly. After obtaining the unknown fluid flow variable, i.e. pore pressure, geomechanical equations are explicitly solved based on the values acquired for pore pressure. We use the discrete fracture model (Karimi-Fard and Firoozabadi, 2003; Monteagudo and Firoozabadi, 2004) to represent the fracture system inside the porous media. In this work, an experimental relation is used to correlate the fracture aperture deformation with the calculated stress field.

Firstly, the theory and governing equations for fluid flow and geomechanical stress, fracture modeling and fracture aperture relation with stress field are presented. In the third section, the numerical method and computational grid structure are explained. The method is then validated with the results obtained from similar research in section four. After model validation, some examples of the application of the presented method are offered.

2. Mathematical formulation

In this section, the underlying theory and equations governing the coupled fluid flow and geomechanics problem are presented. The assumptions made in the method are also presented.

2.1. Assumptions

- The fluid is single-phase and slightly compressible and has constant properties.
- The solid media is linearly elastic and its properties also remain constant.
- The fractures are two dimensional rectangular planes that have variable apertures that are functions of the applied stress field.

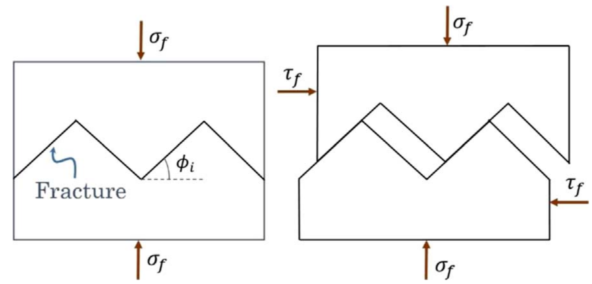

Fig. 1. Shear dilation.

- In-situ stress field is constant at all times.
- Gravity effects are neglected.

2.2. Governing equations

The mechanical behavior of Porous media is described by the poroelasticity theory. According to this theory, the total stress is the sum of stress caused by fluid pore pressure and the stress inside the rock skeleton (Biot, 1941; Chen et al., 1995).[1]

$$\sigma_{ij}=\sigma'_{ij}+\alpha P\delta_{ij}$$

$$\delta_{ij}=\begin{cases} 1,\& \ i=j \\ 0, \ \& \ i \neq j \end{cases} \tag{1}$$

Where σ is the total stress tensor, σ' is the biot effective stress, P is fluid pore pressure and α is the biot coefficient. Fluid flow equation is governed by the law of conservation of mass:

$$\alpha\frac{\partial\epsilon}{\partial t}+S\frac{\partial P}{\partial t}=-\nabla.\boldsymbol{v} \tag{2}$$

Where ϵ is strain, v is fluid velocity and S is storativity which is equal to:

$$S=\phi C_f+(\alpha-\phi)C_r \tag{3}$$

Where, ϕ is the porosity of porous media, C_f is fluid compressibility and C_r is rock skeleton compressibility. In Eq. (2), there are two unknown variables, P and v. However according to Darcy's law, fluid velocity is related to pore pressure:

$$v=-\frac{k}{\mu}\nabla P \tag{4}$$

Where k is the permeability of porous media and μ is the viscosity of fluid. Combining, Eqs. (3) and (4), results in Eq. (5).

$$\alpha\frac{\partial\epsilon}{\partial t}+S\frac{\partial P}{\partial t}=\nabla.(\frac{k}{\mu}\nabla P) \tag{5}$$

The stress which acts on a representative volume of the porous media is the total stress. The conservation of momentum in rock skeleton can be written as:

$$\nabla.\sigma-f=0 \tag{6}$$

Where f is the vector of external forces. Assuming that deformations are small and porous media is linearly elastic, effective stress can be written in terms of strain:

$$\sigma'_{ij}=-\left(K-\frac{2}{3}G\right)\epsilon_v-2G\epsilon_{ij}i=j\sigma'_{ij}=-2G\epsilon_{ij}i=j \tag{7}$$

In Eq. (7), K is the bulk modulus and G is the shear modulus of rock skeleton, ϵ_v is the volumetric strain and is equal to:

$$\epsilon_v=\epsilon_{xx}+\epsilon_{yy}+\epsilon_{zz} \tag{8}$$

[1] Tensile stress is positive.