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Faults simulations for three-dimensional reservoir-geomechanical models with the extended finite element method

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ABSTRACT

Faults are geological entities with thicknesses several orders of magnitude smaller than the grid blocks typically used to discretize reservoir and/or over-under-burden geological formations. Introducing faults in a complex reservoir and/or geomechanical mesh therefore poses significant meshing difficulties. In this paper, we consider the strong-coupling of solid displacement and fluid pressure in a three-dimensional poro-mechanical (reservoir-geomechanical) model. We introduce faults in the mesh without meshing them explicitly, by using the extended finite element method (X-FEM) in which the nodes whose basis function support intersects the fault are enriched within the framework of partition of unity. For the geomechanics, the fault is treated as an internal displacement discontinuity that allows slipping to occur using a Mohr–Coulomb type criterion. For the reservoir, the fault is either an internal fluid flow conduit that allows fluid flow in the fault as well as to enter/leave the fault or is a barrier to flow (sealing fault). For internal fluid flow conduits, the continuous fluid pressure approximation admits a discontinuity in its normal derivative across the fault, whereas for an impermeable fault, the pressure approximation is discontinuous across the fault. Equal-order displacement and pressure approximations are used. Two- and three-dimensional benchmark computations are presented to verify the accuracy of the approach, and simulations are presented that reveal the influence of the rate of loading on the activation of faults.

1. Introduction

Faults are geological fractures of rock in which there has been relative displacement in the plane of fracture. Fault slip reactivation may be triggered by changes in hydraulic pressures and deformations of the rock matrix, which occur during injection and/or extraction of resident fluids as a result of disposal of waste water or CO_2, or as a result of hydrocarbon extraction. The motion of faults due to the injection or removal of fluids is known to induce seismicity (National Research Council, 2012), and for potentially generating leaks in containment scenarios. The potential for fault reactivation associated with industrial activities is an important problem not just from a safety viewpoint, but also from a public acceptance perspective. It is becoming increasingly apparent that accurate and reliable simulation techniques are needed that can

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capture the solid displacement, pressure, and thermal and saturation effects in reservoir-geomechanical models. In this paper, we consider the strong coupling between solid displacement and fluid pressure in a three-dimensional reservoir-geomechanical model, and present extended finite element simulations that reveal the influence of loading rates on the activation of faults.

Mechanical and hydraulic characterization of faults have been the subject of many experimental studies (Barton, 2013; Evans et al., 1997; Faulkner et al., 2003; Jaeger and Cook, 1969; Mizoguchi et al., 2008; Wibberley and Shimamoto, 2003). The concept of a Mohr–Coulomb shear strength description in terms of a cohesion and friction angle is widely accepted, albeit with some caveats (Barton, 2013). Hydraulic description in terms of permeability is more controversial. As discussed in Rubin (2015), fault zones most often act as barriers to a cross-fault (impermeable fault) flow, and some that are usually active, act as conduits for along-fault flow. Permeability numbers from the fault zone that hosted the Kobe earthquake in Japan have been reported to be 10^{-2} m^2 for the very fine-grained core of the fault zone; and 10^{-16} m^2 for the surrounding zone of damaged rock. A nearly impermeable fault core surrounded by a fractured host rock is a prescription for a fault-normal permeability that is much less than that of the host rock, and for an along-fault permeability that is much higher. As reported by Rubin (2015), of all the rock properties that are commonly measured, permeability is among the most wildly varying. Permeability depends on the confining pressure, amount of fault slip, etc. Note that the very low permeability of 10^{-20} m^2 applies to regions only millimeters across.

Faults are geological entities with thicknesses several orders of magnitude smaller than the grid blocks typically used to discretize reservoir and/or over-under-burden geological formations. Coates and Schoenberg (1995) used finite-difference to model faults with a displacement discontinuity across it. Since this initial work, finite elements have been adopted for faults modeling. However, introducing faults in a complex reservoir and/or geomechanical finite element mesh presents significant difficulties due to the need to generate very refined meshes in the vicinity of the faults. Several researchers have recently focused on fault modeling in geomaterials (see, e.g. Cappa and Rutqvist, 2011; Rinaldi et al., 2014), but most of the studies are limited to two dimensions and only approximately account for the coupling between fluid flow and solid deformation that occurs in fluid-saturated porous media (so-called poro-mechanical effects). Furthermore, these implementations are restricted to sealing faults, and do not fully address the challenge of inserting a fault within a mesh. A recent study (Jha and Juanes, 2014) addresses this challenge in both 2D and 3D by modeling faults as surfaces of discontinuity using interface elements (fault must lie along element boundaries) and Lagrange multipliers, but it is also restricted to sealing faults. Early theoretical work on issues related to embedding strong discontinuities in saturated porous materials can be found in Armero and Callari (1999). In the present paper, we use the extended finite element method (X-FEM) to introduce faults without the need to mesh them explicitly. Numerical results using the X-FEM have been presented in 2D for fractured porous media (de Borst et al., 2006; Fumagalli and Scotti, 2014; Lamb et al., 2013; Réthoré et al., 2007; Talebian et al., 2013), and for 3D hydraulic fracture simulations (Gupta and Duarte, 2014; Secchi and Schrefler, 2012). The implementation of the X-FEM in 3D (Sukumar et al., 2000) is significantly more complex than in 2D (Moës et al., 1999).

In the three-dimensional model for the geomechanics, we treat the fault as an internal displacement discontinuity that allows slipping to occur using a Mohr–Coulomb type criterion. For the reservoir, the fault is either an internal fluid flow conduit that permits fluid flow to occur within the fault as well as to enter or leave the fault, or is a barrier to flow. In the X-FEM, the faults are represented by enriching the displacement approximation with a discontinuous function via the framework of partition-of-unity (Melenk and Babuška, 1996). For sealing/impermeable faults, a pressure discontinuity must occur across the fault, and a discontinuous function is used to model the pressure discontinuity across the fault. For fault as a fluid flow conduit, the transverse permeability is typically several orders of magnitude smaller than the host. Conversely, the longitudinal permeability can be larger than the host. For this case, one must use a continuous pressure function that permits a discontinuous normal pressure gradient across the fault. For internal fluid flow conduits, a C^0 continuous function is used for the fluid pressure approximation that admits a discontinuity in its normal derivative across the fault (Moës et al., 2003; Sukumar et al., 2001). For the standard finite element contribution, equal-order solid displacement and pressure approximations are used. As shown and discussed in detail in Prevost (2013), two-way coupling of pressure and stress equations is required if poro-mechanical effects are to be accurately captured. Also, as shown in Prevost (2013), one-way *inexpensive* iterative (sequential) integration of reservoir-geomechanical equations can work, but requires a very large number of iterations for accurate integration of such strongly-coupled equations. This is not surprising since it is well-known that fixed-point iterations, if they converge at all, require a large number of iterations to converge.

This paper is organized as follows. Section 2 outlines the poro-mechanical field equations, and the essentials of the weak formulation are described in Section 3. The displacement and pressure approximations in the modeling of faults using the X-FEM are presented in Section 4, with details on the residual contributions from the stress and pressure equations. Central to the success of the fully coupled implementation is the computation of the Jacobian matrix, which is discussed in Section 5. The elemental contributions to the coupling Jacobian matrix are computed through numerical finite-differencing of the residuals (Preisig and Prevost, 2011a, 2012; Prevost, 1981, 2013, 2014). In Section 6, numerical results in 2D and 3D are presented that affirm the versatility and sound accuracy of the method.

2. Field equations

Detailed derivations of the poro-mechanical equations can be found in Coussy (2004). For an isothermal fully saturated