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Research Paper

A fully coupled three-dimensional hydro-mechanical finite discrete element approach with real porous seepage for simulating 3D hydraulic fracturing

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ABSTRACT

A fully coupled 3D hydro-mechanical model with real porous seepage is presented for simulating hydraulic fracturing. In this model, fluid flow in a fracture is expressed by 2D fracture seepage in the broken joint elements based on the Cubic law, while fluid flow in the rock matrix is represented by 3D porous seepage in the tetrahedral elements based on Darcy's law. Several problems that have closed-form solutions and a 3D fracturing problem are given to verify the model. The simulation results show that the model can capture crack initiation and propagation, and the fluid pressure evolution during hydraulic fracturing.

1. Introduction

Hydraulic fracturing is the key technology in petroleum, shale gas and enhanced geothermal systems. It involves not only the deformation of a solid under the effect of fluid pressure but also the fracturing of the solid. Many researchers have studied hydraulic fracturing and put forward several theoretical models, such as the PKN model [1,2], the KGD model [3,4], the radial or penny-shaped model [5], and some pseudo-3D models and planar-3D models [6–8]. Later, rather than developing new analytical models for hydraulic fracturing with complex fracture networks, researchers have been focused on the properties of classical hydraulic fracturing models. For example, a scaling and asymptotic framework was developed by Detournay et al. [9,10], who recognized that the hydraulic fracture is governed by two competing energy (i.e., viscous flow and the creation of surface area in the solid) and fluid storage mechanisms (i.e., the storage of fluid in the fracture and fluid leak-off into the permeable solid). Later, many fruitful semi-analytical and numerical solutions have been obtained for different asymptotic regimes [11–18], such as zero toughness impermeable, small toughness impermeable, finite toughness impermeable, large toughness impermeable, zero toughness permeable regime, and finite toughness permeable regime solutions [19]. Although these theoretical models or solutions are only applicable to simple geometries that are very different from an actual fracturing scenario with complex natural fracture networks, they are important in understanding hydraulic fracturing and provide benchmarks for numerical simulations.

Many numerical models have been also used to study hydraulic fracturing, such as the finite element method (FEM), the extended finite element method (XFEM), the displacement discontinuity method (DDM), the discontinuous deformation analysis method (DDA), the discrete element method (DEM), and the finite discrete element method (FDEM).

For example, Fu et al. [20] and Settgast et al. [21] built an explicit 2D/3D hydraulic coupling model to simulate hydraulic fracturing with arbitrary fracture networks based on FEM. Hunsweck et al. [22] presented a finite element approach to simulate plane-strain hydraulic fractures with lag. Gupta and Duarte [23] presented simulations of non-planar three-dimensional hydraulic fracture propagation. Chen [24] proposed a 3D finite element model based on existing pore pressure cohesive finite elements to simulate the propagation of viscosity-dominated hydraulic fracture in an infinite, impermeable elastic medium. Wangen [25] suggested a finite element approach for the modeling of hydraulic fracturing in 3D. Yao et al. [26] developed a 3D pore pressure cohesive zone model for simulation of hydraulic fracturing in quasi-brittle rocks. However, FEM needs remeshing (with high computation cost) as fractures continually propagate [27–29].

In order to overcome the limitations of the finite element method, some researchers have used XFEM to simulate hydraulic fracturing. For example, Salimzadeh and Khalili [36] proposed a fully coupled three-phase model for simulating hydraulic fracturing in porous media, where XFEM is used to handle discontinuities and a cohesive crack model is used as a fracturing criterion. Faivre et al. [37] proposed a 2D coupled HM-XFEM with cohesive zone model and applied it to a fluid-driven fracture. Mohammadnejad and Khoei [38] developed a fully coupled

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numerical model for the modeling of hydraulic fracture propagation in porous media using XFEM in conjunction with the cohesive crack model. XFEM can avoid the remeshing, but it needs to discretize the solution domain into a fine mesh if the crack propagation path is unknown in advance, which will lead to a very large computational load, and cannot effectively simulate complex multiple-crack propagation and intersection.

Some researchers have used DDM to simulate hydraulic fracturing [39,40]. For example, Kresse et al. [41] used DDM to study fluid-driven ruptures in natural reservoirs, but the rock matrix was assumed to be impermeable. Norbeck [42] introduced an efficient numerical modeling framework that integrated the embedded fracture modeling (EFM) strategy into a DDM to simulate hydraulic fracturing. Ganis et al. [43] proposed an algorithm for modeling saturated fractures in a poroelastic domain in which the reservoir simulator is coupled with DDM. The simulation of hydraulic fracturing with DDM usually assumes that the rock matrix is impermeable and cannot consider fluid infiltration into the rock matrix from the fracture. In addition, these simulations are usually limited to two-dimensional cases.

When dealing with discontinuous problems, especially with a large number of natural fractures, those continuum numerical methods have some inherent flaws. For this reason, some researchers have used discontinuous numerical methods (e.g., DDA, DEM) to study hydraulic fracturing. For example, DDA was used to simulate hydraulic fracturing by taking the hydro-mechanical coupling and the fragmentation of the block into account [44–47]. Some researchers used the discrete element method to study hydraulic fracturing. For example, Nasehi and Mortazavi [48] and Hamidi and Mortazavi [49] introduced virtual joint technology in UDEC/3DEC to simulate crack initiation and propagation of a typical reservoir driven by fluid. Although these methods can simulate crack initiation and propagation, the fluid flow in fractures and the interactions between fluids and solids, they do not take into account fluid leakage into the surrounding rock matrix from fractures, i.e., the permeability of the rock matrix is assumed to be zero. The particle flow method [50] is another method that can be used to simulate hydraulic fracturing [51–57]. However, the microscopic parameters of the method are difficult to calibrate, and the fracture characterization is not intuitive. In addition, the concept of stress and strain in continuum mechanics no longer directly exists in this method.

To overcome the shortcomings of the above methods in simulating hydraulic fracturing, we construct a fully coupled 3D hydro-mechanical model with real porous seepage in 3D FDEM in this paper. In this model, the porous seepage in the rock matrix is represented by a real three-dimensional flow, rather than the equivalent approach that the porous seepage in the rock matrix is represented by the fracture seepage in the unbroken joint elements. For an equivalent approach, it is necessary to calibrate the initial aperture of the unbroken joint element to characterize the macroscopic permeability of the rock sample. In addition, the equivalent approach has the lag phenomenon in fluid flow when dealing with unsteady porous seepage and cannot consider the pores in rock. Thus, the equivalent method cannot deal well with the unsteady problem of hydraulic fracturing [69]. However, the fully coupled 3D model described in this paper does not contain these shortcomings; it can consider the permeability anisotropy of the rock matrix and the fluid loss from the fracture into the rock matrix. Furthermore, the fully coupled 3D model can simulate crack initiation and propagation, and the interaction between fluid and solid. Since cracks extend along the tetrahedral element boundary, remeshing is not needed. The cracks consist of triangular faces, and the characterization of the cracks is very intuitive. FEM is used to calculate the stress and strain of the tetrahedral elements, and thus the concept of stress and strain in continuum mechanics is well preserved in FDEM. In addition, the discrete element method is used to process contacts between elements in FDEM; the contacts can be easily handled when the crack is closed.

This article is organized as follows. First, the fundamentals of 3D FDEM are briefly introduced, including the governing equation, contact detection, contact force and the joint element constitutive model. Next, the basic assumptions of the three dimensional fully coupled model are introduced. The 3D real porous seepage model and fracture seepage model is presented in Section 4. Then, the fracture-stress-seepage coupling process is introduced in Section 5. Finally, the fully coupled model is thoroughly verified using two examples that have analytical solutions. The third example is a hydraulic fracturing problem with complex fracture networks in which the interaction between hydraulic fracturing and pre-existing fractures is studied. Moreover, the effect of in situ stress on hydraulic fracturing is investigated in the last example and compared with experimental result.

2. Fundamentals of the 3D finite discrete element method

The finite discrete element method (FDEM) [58,59] is an excellent method for simulating fracture of solid material. In recent years, FDEM has been widely used in the field of rock mechanics, especially for problems related to rock fracture [60–63]. Some of the literature based on FDEM and related to this paper can be found in Latham et al. [64], Lei et al. [65,66], Grasselli et al. [67], Yan et al. [30,31,33,35,68], and Lisjak et al. [69].

In 3D FDEM, each individual block is discretized into a finite element mesh with tetrahedral elements, and a 6-node joint element with zero initial thickness is inserted on the common surface between the adjacent tetrahedral elements, as shown in Fig. 1. The finite element method is used to determine the stress and strain of the constant strain tetrahedral element, while the discrete element method is used to deal with the contact between the tetrahedral elements so that the method can simulate the sliding and rotation of the block. In addition, the breakage and fragmentation of the block can be modeled by the joint element breaking. The deformation of the block can be simulated by a deformable tetrahedral element and the unbroken joint element with a bonding effect. Next, we describe the governing equations, contact detection and contact force, and the joint element constitutive model.

2.1. Governing equations

The governing equations of FDEM are essentially the same as those of DEM, that is, according to Newton's second law, the dynamic equations of the nodes are given by

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}), \tag{1}$$

where $\mathbf{M}$ and $\mathbf{C}$ are the mass and damping diagonal matrices of all of the nodes in the system, $\mathbf{F}(\mathbf{x})$ denotes the unbalanced nodal force vector. It includes the nodal force $\mathbf{F}_c$ caused by the contact force, the nodal force $\mathbf{F}_d$ caused by the deformation of the tetrahedral elements, the nodal force $\mathbf{F}_e$ caused by the external load, and the nodal force $\mathbf{F}_j$ caused by the bonding stress of the joint elements. The damping matrix $\mathbf{C}$ is used to dissipate the kinetic energy of the system when solving the static problems by dynamic relaxation. The damping matrix $\mathbf{C}$ is given by

$$\mathbf{C} = \mu\mathbf{I}, \tag{2}$$

where μ is the damping coefficient and $\mathbf{I}$ is the unit matrix. According to the single-degree-of-freedom mass spring system, the critical damping coefficient is given by [59]

$$\mu = 2h\sqrt{\rho E}, \tag{3}$$

where h is the length of the element, ρ is the density of the solid, and E is the elastic modulus. When critical damping is used, the kinetic energy of the system can be consumed with the fastest speed.

The nodal force $\mathbf{F}_d$ caused by the deformation of tetrahedral elements can be obtained directly from the linear elastic constitutive law, while the nodal force $\mathbf{F}_c$ caused by the contact force and the nodal force $\mathbf{F}_j$ caused by the bonding stress of joint elements will be presented in