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A 2D fully coupled hydro-mechanical finite-discrete element model with real pore seepage for simulating the deformation and fracture of porous medium driven by fluid

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A B S T R A C T

Based on the finite-discrete element method (FDEM), a 2D fully coupled model with real pore seepage is proposed. This model can solve the problem of the deformation and fracture of porous medium driven by fluid. In this model, the fluid flow in the fracture is expressed by the cubic law, while the fluid flow in the rock matrix is characterized by Darcy's law and solved by the finite volume method. The interaction between pore seepage and fracture seepage is realized at the fracture. Three analytical solutions are presented to verify the correctness of the proposed model. The results show that the numerical solutions agree well with the analytical solutions. In addition, a hydraulic fracturing problem with a complex fracture network is studied using this model. The simulation results show that the model can capture the fracture initiation, propagation, and intersection, the interaction of natural fractures and newly generated fractures, and the evolution of fluid pressure during hydraulic fracturing. The model can be used not only to simulate hydraulic fracturing in shale gas and geothermal mining but also to solve a series of geomechanical problems related to the effect of fluid. Thus, this model has broad application prospects.

1. Introduction

Hydro-mechanical coupling refers to the interaction of seepage and mechanics. Many geomechanical problems are related to hydro-mechanical coupling, such as landslide or slope failure, dam foundation damage, stability of excavation, design and safety assessment of nuclear waste underground disposal, oil and gas exploration and geothermal mining, hydraulic fracturing, compression and settlement of reservoirs, hydraulic fracturing, coal mining, coalbed methane extraction, underground storage of fluids, oil and gas geological storage, and toxic liquid waste disposal.

1.1. Analytical methods for hydro-mechanical coupling

Classic models of hydro-mechanical coupling of porous media such as soil can be traced to the effective stress principle and the one-dimensional theory of consolidation proposed by Terzaghi [1]. Extending the work of Terzaghi, Biot [2,3] used the theory of elasticity and Darcy's law to describe solid behavior and interstitial fluid flow, respectively, denoted Biot consolidation theory. Based on this theory, several enhanced hydro-mechanical coupling formulations have subsequently been proposed to study the pore mechanical response of fractured-porous rock masses [4–6].

Another important driving force for the study of hydro-mechanical coupling in rock is the extensive application of hydraulic fracturing technology in oil and shale gas exploitation. A series of analytical models of hydraulic fracturing have been established, such as the PKN model [7,8], KGD model [9,10], the radial or penny-shaped model [11], and some pseudo-three dimensional (P3D) and three-dimensional (PL3D) models [12]. Recent progress in the analytical modeling of hydraulic fracturing has been reviewed elsewhere [13].

1.2. Numerical methods of hydro-mechanical

Analytical methods of hydro-mechanical coupling are often oversimplified and generally consider a homogenous elastic medium or simple geometry. Experimental methods are not only expensive but also extremely tedious and time consuming. Thus, experimental methods are not efficient, especially for routine industry application. Therefore, numerical methods have been established for hydro-mechanical coupling. For example, some continuum numerical methods have been adopted for the simulation of hydraulic fracturing, of which the most representative are

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the displacement discontinuity method (DDM) [14–16], the finite element method (FEM) [17–22], and the extended finite element method (XFEM) [23,24]. However, these methods have some limitations in simulating hydraulic fracturing. For example, in DDM, fluid can flow through closed natural fractures, but the rock itself is still impermeable. Thus, DDM cannot consider fluid loss into the rock matrix. A drawback of FEM in the simulation of hydraulic fracturing is that the modeling of crack growth requires grid remeshing, which is computationally burdensome and involves the transfer of data between different meshes. Although XFEM avoids mesh regeneration, it requires a very fine mesh in the solution domain, which leads to a huge computational load when the crack propagation path is unknown in advance. Thus, it is difficult to simulate the propagation and intersection of complex multiple cracks using XFEM. Moreover, a common problem of the continuum numerical methods is that they cannot adequately handle the contact when the crack is closed.

Discontinuous numerical methods are another tool for simulating hydraulic fracturing that have been used widely in recent years. For example, discrete element methods (such as UDEC/3DEC) [25,26] can simulate crack initiation and propagation by introducing a virtual joint between the divided sub-blocks. Thus, combined with hydro-mechanical, discrete element method can be used to simulate hydraulic fracturing [27–29]. Similarly, the discontinuous deformation analysis method can also be used for simulating hydraulic fracturing by introducing the same technology [30–34]. The numerical manifold method is another potential method. The coupled hydro-mechanical model in Ref. [42] is also used in the numerical manifold method [62], which makes it possible to simulate hydraulic fracturing. However, these discontinuous numerical methods all consider the fluid flow in fractures but do not take into account fluid leakage from fractures into the surrounding rock matrix; i.e., the pore seepage into the rock matrix is neglected. The particle discrete elements method (PFC) [35] bonds a series of balls together to characterize the continuum. By breaking inter-spherical bonds, the method simulates the fracture and fragmentation of the solid, which can be used to simulate hydraulic fracturing combined with a hydro-mechanical coupling module [36–40]. 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 defects of the above methods in simulating hydraulic fracturing, this paper proposes a two-dimensional fully coupled model for simulating the deformation and fracture driven by fluid is proposed based on the finite discrete element method (FDEM). The model is presently implemented in the Y-flow code [41,42]. The advantage of this model is that it takes into account both the fracture seepage in the fracture and the real pore seepage in the rock matrix, in contrast to the equivalent method [43–45]. Thus, the model considers the permeability anisotropy of the rock matrix and the fluid loss from the fracture into the rock matrix. Furthermore, the model can simulate the crack initiation and propagation, the interaction of complex fractures, and the interaction between fluid and solid. Since cracks extend along the element boundary, remeshing is not needed. The cracks consist of line segments, and the characterization of the cracks is very intuitive. FEM is used to calculate the stress and strain of a triangular element, 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.

The paper is organized as follows. First, the fundamentals of FDEM are briefly introduced. In Section 3, the basic assumptions of the fully coupled hydro-mechanical model are introduced. The 2D coupled model with real pore seepage and fracture seepage is introduced in detail in Section 4, which introduces the basic idea of hydro-mechanical coupling, the fracture seepage flow model, the two-dimensional pore seepage model, the coordination process between fracture seepage and pore seepage at the fissure, the application of fluid pressure in fractures and pore pressure in the rock matrix, and the fracture-stress-seepage coupling process. In Section 5, the model is verified thoroughly using three examples with analytical solutions to test the effectiveness of the model in addressing unsteady saturated seepage, unsteady unsaturated seepage and hydro-mechanical coupling in porous media. The fifth example is a hydraulic fracturing problem with complex fracture networks. The interaction of hydraulic fractures and natural fractures is studied.

2. The fundamentals of the finite discrete element method (FDEM)

FDEM is a general numerical method for simulating the fracturing of solid materials [41,46–48]. It combines the advantages of FEM for the simulation of solid deformation and the advantages of the discrete element method to address contacts between blocks. In addition, non-linear fracture mechanics are introduced in the joint element. This method has become widely used in the field of rock mechanics, especially for problems related to rock fracture [42,49–54].

The fundamental basis of two-dimensional FDEM is that the continuum is divided into a triangular finite element mesh, and a 4-node joint element with bonding effect is inserted on the common edge of adjacent triangular elements. Thus, the triangular elements do not share nodes, as shown in Fig. 1. FEM is used to solve the stress and strain of the triangular element, while the discrete element method is used to address the contact between triangular elements. Thus, the sliding and rotation of the block can be simulated. In addition, the fragmentation and fracture of the continuum can be modeled through joint element breaking. The fracture criterion of the joint element in FDEM is shown in Fig. 2. The deformation of the continuum can be simulated by the deformable triangular element and the unbroken joint element with a bonding effect. Next, we introduce the dynamic equations for the system, contact detection, and contact force calculation.

2.1. Dynamic equations

After the continuum is discretized, it is composed of triangular elements, joint elements and nodes. The displacement calculation of the continuum is attributed to the calculation of nodal displacement. The contact force, the reaction force induced by deformation of triangular element, and the bonding force of joint element are all assigned to the nodes. Finally, the motion equation with node displacement as unknown is constituted as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} = \mathbf{F}_c(\mathbf{x}) + \mathbf{F}_e(\mathbf{x}) + \mathbf{F}_j(\mathbf{x}) + \mathbf{F}_{ext}(\mathbf{x}), \tag{1}$$

where $\mathbf{M}$ is the mass matrix and $\mathbf{C}$ is the damping matrix, both of which are diagonal matrices, $\mathbf{x}$ is the displacement vector of nodes. The kinetic energy of the system is consumed by the damping, by which the static problem can be solved using dynamic relaxation. The damping matrix is given by

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

where I is a unit matrix, μ is the damping coefficient. According to the single-degree-of-freedom point spring system, the critical damping coefficient is given by [2]

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

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