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Application of distinct element methods to simulation of hydraulic fracturing in naturally fractured reservoirs

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ABSTRACT

The Distinct Element Method (DEM) represents a rock mass as an assembly of blocks (polygonal or polyhedral). Contacts between blocks correspond to discontinuities (i.e., fractures or joints) that can exhibit non-linear mechanical behavior, including slip and opening. If flow in rock fracture is approximated using the lubrication equation, coupled hydro-mechanical DEM models can be used for simulation of rock mass treatment by fluid injection. However, this approach has a limited capability for simulating fracture propagation. The synthetic rock mass (SRM) concept overcomes this limitation. In SRM, the bonded particle model (BPM), which is an assembly of circular or spherical particles bonded to each other, represents deformation and damage of intact rock. If pre-existing discontinuities are represented in the BPM, the resulting model, referred to as SRM, has the capability of simulating hydraulic fracturing in naturally fractured reservoirs. The model delivers a pattern of hydraulic fractures that evolves in response to both intact rock fracturing and sliding and opening of pre-existing joints.

1. Introduction

Extraction of the abundant reserves of shale gas and oil around the world has been made economical over the last 15 years because of advances in two technologies: horizontal drilling and multi-stage hydraulic fracturing [1]. Multi-stage fracturing from a horizontal section of a wellbore, commonly 700–3000 m in length, allows effective stimulation of the production horizon. Although hydraulic fracturing has been used in successful commercial applications in conventional reservoirs since 1949, there is still a lack of understanding of the hydraulic fracturing effects in these very low permeability, “unconventional” reservoirs. This often leads to unreliable well completion designs.

The main difficulties in achieving reliable completion design arise from: (1) complexity of the physical processes involved, (2) geological complexity, uncertainty and spatial variability, and (3) relatively limited access (typically a single wellbore) to the treated formation. Even hydraulic fracturing of a formation that can be idealized as homogeneous, isotropic, and continuous involves complex, non-linear, hydro-mechanical processes occurring on different length scales. Shale gas and oil reservoirs, on the length and time scales of interest during hydraulic fracturing stimulations, cannot be approximated properly as homogeneous or continuous. Hydraulic fracturing and stimulation of shale formations are critically affected by the interaction between the hydraulic fracture and the discrete fracture network (DFN). This interaction affects not only the speed of hydraulic fracture propagation, but also the stimulation of the reservoir characterized by the extent to which the DFN undergoes inelastic deformation (i.e., slip and opening). Thus, in order to be able to analyze and design a hydraulic fracturing treatment, it is necessary to have analytical tools capable of simulating propagation of fluid-driven fractures in discontinuous (already fractured) rock masses.

Limited access to the simulated formation is an additional challenge to modeling hydraulic fracturing. There is considerable uncertainty in the characterization of the rock mass and particularly of the DFN. Also, due to relative inaccessibility, interpretation of the model results and model calibration to the response of a particular reservoir is difficult and uncertain. The injection pressure and microseismic data are usually the only information available to assess the response of deep reservoirs to fluid injection. Thus, it is essential that the numerical models (besides capabilities to explicitly represent a DFN and to predict injection pressures) can also generate synthetic microseismicity. Such models can be used as components of fracture network engineering (FNE), discussed briefly in Section 2. FNE is a methodology that promises to provide a robust approach for designing fractured rock mass stimulation by fluid injection.

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For years, the distinct element method (DEM), originally developed by Cundall [2], has been used in different industries (e.g., mining, civil and nuclear waste disposal) to solve problems involving stability of fractured rock masses. Some of the initial applications of DEM to problems of hydraulic treatment of the rock mass were conducted by Pine and Cundall [3]. These models were fully coupled hydro-mechanically and flow in rock joints was approximated by the lubrication equation [4]. They were best suited for problems of fluid flow through a DFN coupled with deformation of fractured rock mass. Typically it was assumed that pre-existing fractures did not propagate.

3DEC [5] is a three-dimensional (3D) distinct element code for simulation of a general mechanical interaction of polyhedral solid blocks. The blocks can be assumed to be rigid or fully deformable. An assembly of tightly packed blocks approximates fractured rock mass with the contacts between blocks representing the rock joints. The contacts can deform elastically or inelastically, resulting in opening or slip, typically governed by Coulomb slip law. The formulation of a numerical scheme for resolution of general block interaction and contact detection in 3D was described by Cundall [6]; the formulation of mechanical calculations for motion and interaction between deformable polyhedral blocks as implemented in *3DEC* was described by Hart et al. [7]. A fully coupled 3D numerical model of fluid flow in deformable fractured rock masses was originally implemented in *3DEC* by Damjanac [8]. In recent years, *3DEC* has been used successfully for investigation of the response of fractured rock mass to fluid injection and hydraulic fracturing (e.g., [9]) and prediction of induced microseismicity [10]. These applications demonstrate its suitability as an analytical tool for FNE. An example that illustrates application of the DEM (as implemented in *3DEC*) to simulation of hydraulic fracturing, and the effect and importance of DFN for fracture propagation are presented in Section 3. In the beginning of the same section, *3DEC* results are compared with semi-analytical solution (PKN) in verification of the code and the DEM for simulation of hydraulic fracturing.

Applicability of coupled DEM models to hydraulic fracture propagation is limited to the cases in which the fracture trajectory is known. To overcome the limitation of the original DEM models in which the fracture trajectory needs to be predefined, a new generation tool has been developed. This tool uses the bonded particle model (BPM) [11] and the synthetic rock mass (SRM) concept [12]. It has been developed specifically to model hydraulic fracture propagation in naturally fractured reservoirs. The SRM concept is realized as a bonded-particle assembly containing multiple joints. Each joint consists of a planar array of bonds that obey a special model, namely the smooth joint model (SJM). The SJM allows slip and separation at particle contacts, while respecting the given joint orientation rather than local contact orientations. Overall fracture of a synthetic rock mass depends on both fracture of intact material (bond breaks), as well as yield of joint segments.

Previous SRM models have used the general purpose codes *PFC2D* [13] and *PFC3D* [14], which employ assemblies of circular/spherical particles bonded together. Much greater efficiency can be realized if a "lattice," consisting of point masses (nodes) connected by springs, replaces the balls and contacts (respectively) of *PFC*. The lattice model still allows fracture through the breakage of springs along with joint slip, using a modified version of the SJM. The new 3D program, *HF Simulator*, described in this paper, is based on such a lattice representation of brittle rock. *HF Simulator* overcomes all of the main limitations of the conventional (including the original DEM) methods for simulation of hydraulic fracturing in jointed rock masses. It is computationally more efficient than *PFC*-based implementations of the SRM method. A description of this novel methodology, its verification, and one example application are presented in Section 4.

2. Fracture Network Engineering (FNE)

In order to understand the rock mass response to fluid injection, we must rely on "indirect" data. These include injection pressure and flow rate as functions of time, microseismic signals (now being monitored and processed more often) and tracer tests during injection/production.

The microseismic data provide information on location, time, magnitude and source mechanisms of local instabilities (events) caused by fluid injection in the rock mass. Although microseismic events may result from either fracturing of the intact rock or seismic slip on pre-existing fractures, the magnitudes of events associated with intact rock fracturing are typically below the threshold of recording equipment, and therefore are not included in the recorded microseismic data [15]. The extent of microseismic activity very often is assumed to correspond to the stimulated rock volume (SRV). Although there should be a correlation, it is not clear that these two volumes are the same [15]. For example, if a microseismic event is caused by change in the total stress, it might not be connected to the wellbore by a continuous high-permeability (i.e., stimulated) region. Microseismic data do not allow a clear distinction to be drawn between events that are caused by total stress change ("dry events") and events caused by fluid pressure change ("wet events").

Proper interpretation of the microseismic signals requires a numerical model that is capable of generating synthetic microseismicity. Such numerical models can be calibrated by comparing the model results with the observed field microseismicity (and the injection-pressure data) until the predicted and observed data are in close agreement. This is the essence of the FNE [16] method. The calibrated model can be used for interpretation of the field microseismicity. Also, forward-looking analysis then can be carried out to simulate how an assumed fracture network will behave for different stimulations with the goal of establishing design criteria for a field project and engineering the most effective fracture network (Fig. 1). Both DEM and the lattice models have the capability of generating synthetic microseismicity, following a similar approach to Hazzard et al. [17].

3. DEM as a component of fracture network engineering

Numerical models based on the DEM can serve as the analytical component in FNE. In the DEM, an assembly of blocks (polygonal or polyhedral) or particles can be used to represent the mechanical behavior of the fractured rock mass. Contacts between the blocks can open or slide to approximate the behavior of pre-existing or newly created fractures. Although the DEM typically does not represent partially fractured blocks or allow fracture propagation through a block, both effects can be achieved by gluing (i.e., assigning certain bond strength in normal and shear directions) some parts of the interfaces between the blocks and allowing progressive failure of the interfaces, as dictated by evolution of the contact stresses during simulation. Detailed formulation of DEM and coupled hydro-mechanical model for simulation of flow in fractured rock mass can be found in *3DEC* technical documentation [5]. A verification test and application example using DEM, as implemented in the *3DEC* numerical code, are presented to demonstrate solution of hydraulic fracturing problems and suitability of the DEM-based models as an analytical tools for FNE.

3.1. Verification test: PKN fracture

In the verification problem, the propagation of a planar vertical hydraulic fracture constrained within a 20-m thick horizontal layer was simulated. Newtonian fluid with 1 cP (10^{-3} Pa s) viscosity was

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