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Fully 3D simulation of fluid-pressure-driven fracturing using a novel continuum-discontinuum approach: Preliminary results

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Summary

The goal of this paper is to present recent advances in the field of hydraulic fracturing modelling. In particular, a novel, fully 3D, hybrid finite-discrete element method (FDEM) approach was developed to numerically simulate fluid-pressure-driven fracturing. The effectiveness of the new approach is illustrated by simulating fracture nucleation and growth around a pressurized cylindrical cavity in a homogeneous and isotropic medium. Realistic emergent pressure response and fracture patterns are obtained, thus providing a first verification of the implementation. The simulated fracture network highlights a distinctive 3D interaction of individual fractures around the location of injection.

Introduction

The economical development of unconventional reservoirs relies heavily on hydraulic fracturing (HF), a stimulation technique that enhances the effective drainage from low-permeability rock formations through the creation of an interconnected fracture network. While the overall process of fluid-pressure-driven fracturing is well understood, a quantitative description of the process is still an open research problem due to physical complexities and geological uncertainties. In particular, the mechanics of HF involves complex, non-linear, hydro-mechanical processes occurring on different length scales in a three-dimensional space. Therefore, in recent years there has been a growing interest in the development of advanced geomechanical models that aim to realistically simulate HF treatments in unconventional reservoirs. Among the different approaches, fully (or true) 3D models are essential to capture important “out-of-plane” effects during HF, including the interaction between multiple fractures, the role of in-situ and induced stress fields, and complex structural-geological conditions (e.g., bedding and natural discontinuities). In this study, a fully 3D numerical method based on a continuum-discontinuum approach, namely the hybrid finite-discrete element method (FDEM) (Munjiza, 2004, Munjiza et al., 2011, Mahabadi et al., 2012), is developed and preliminary simulation results are illustrated.

Methodology

In a 3D FDEM model, solid rock is discretized by a tetrahedral mesh with embedded cohesive crack elements (Figure 1a). During elastic loading, stresses and strains are assumed to be distributed over finite elements (i.e., the continuum portion of the model). Upon exceeding the peak strength of the rock, the strains are assumed to localize within a narrow zone, commonly known as the fracture process zone (FPZ). The mechanical non-linearities developing in the FPZ are lumped into a stress-displacement relationship implemented at the crack element level (Figure 1b). The progressive mechanical breakdown associated with fracture nucleation and growth within the continuum is therefore captured by the softening and breakage of the crack elements. The strength of the rock can be overcome due to (i) a tensile stress acting normal to the crack element plane (i.e., Mode I), (ii) a shear stress acting parallel to the crack element plane (i.e., Mode II or Mode III), or (iii) a combination of the previous modes (Mixed Mode). Since adaptive re-meshing is not performed, fracture trajectories are restricted to the initial element topology. As the simulation progresses through explicit time stepping, displacements, rotations and interactions of newly-created discrete bodies occur and new contacts are automatically recognized.

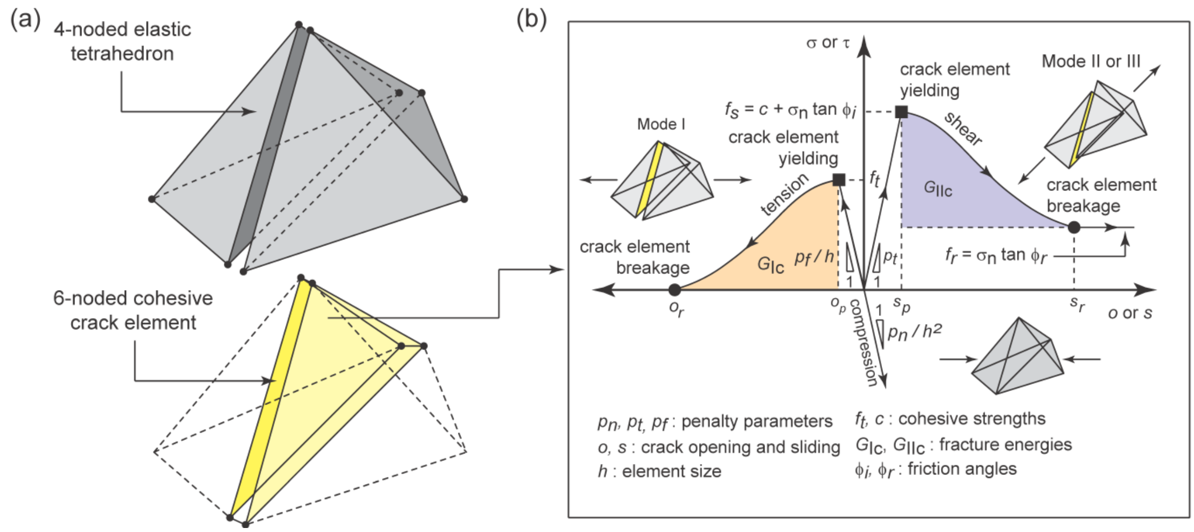

Figure 1 (a) Representation of 3D FDEM elastic tetrahedral finite elements with embedded cohesive crack elements. (b) Constitutive behaviour of the cohesive crack elements defined in terms of normal and tangential bonding stress versus crack relative displacement (i.e., opening and sliding). Notice that the crack bonding stresses are assessed at seven different integration points on the element surface.

Fluid-pressure-induced fracturing is captured by a simplified approach based on the principle of mass conservation for a compressible fluid pumped into a deformable solid. The model is hydro-mechanically coupled in the sense that variations in fluid volume, due to elastic deformation or fracturing affect the pressure of the fluid, which, in turn, affects rock deformation and failure. The solid matrix is assumed to be impermeable, and viscous dissipations, due to the flow of fluid in the fracture network, are neglected. In other words, the intra-crack fluid pressure is assumed to be uniform along the fractures and the fracturing process is captured as a temporal sequence of hydraulic equilibrium states. As such, the approach is restricted to the toughness-dominated regime of hydraulic fracture propagation (Detournay, 2004).

At each simulation time step, the numerical solver evaluates the rock deformation, updates the fracture topology and hydraulic interconnectivity, determines the fluid volume, V, and computes the intra-crack fluid pressure, P. In particular, the fluid pressure is calculated by assuming a linear elastic compressible fluid:

$$P = P_0 + K \log [m/(V\rho_0)], \quad (1)$$

where ρ_0 and P_0 are the fluid reference density and pressure values, respectively, K is the fluid bulk modulus, and m is the fluid mass computed from the injection flow rate (prescribed as a pumping boundary condition).

Demonstrative example

The newly-developed numerical approach was used to simulate the fluid-pressure-induced failure of a cylindrical cavity subjected to a constant injection flow rate. The model geometry consisted of a 20-mm-diameter, 50-mm-long cylindrical cavity placed at the center of a 300x300x300-mm cube (Figure 2a). To maximize the model resolution in the cavity near field, while keeping the run times within practical limits, a mesh refinement zone, with an average finite element size of 3 mm was adopted around the cavity boundary. The element size was then graded towards the external boundaries, where an element size equal to 12 mm was used. The rock material was assumed to be homogeneous and isotropic. The assigned input parameters are reported in Table 1. The two end surfaces of the cylinder were assigned a zero-displacement boundary condition, thus mimicking the presence of a stiff packer sealing off the injection section of borehole.

Table 1 Rock input parameters for the numerical model

Parameter	Value
Bulk density, ρ (kg/m^3)	2,300
Young's modulus, E (GPa)	10
Poisson's ratio, ν	0.27
Damping coefficient, μ (kg/m·s)	4.3×10^6
Tensile strength, f_t (MPa)	0.5
Cohesion, c (MPa)	10
Mode I fracture energy, G_{Ic} (J/m^2)	0.1
Mode II fracture energy, G_{IIc} (J/m^2)	10
Friction angle, ϕ (°)	23
Normal contact penalty, p_n (GPa·m)	200
Tangential contact penalty, p_t (GPa/m)	200
Fracture penalty, p_f (GPa)	100

As shown in Figure 2b, the model captures the expected injection pressure response. Initially, a linear increase of fluid pressure is reproduced due to the coupled elastic deformation of the fluid inside the cavity and the surrounding solid rock. The appearance of the first fluid-pressure-induced tension crack is approximately associated with a maximum in the injection pressure curve (i.e., breakdown pressure, P_b). Subsequently, a drop in pressure is recorded in response to an increase of cavity volume induced by further crack nucleation and growth. Due to the unconfined conditions in this particular model, the injection pressure eventually reaches a low steady-state value (0.6 MPa) with continued fracture propagation.

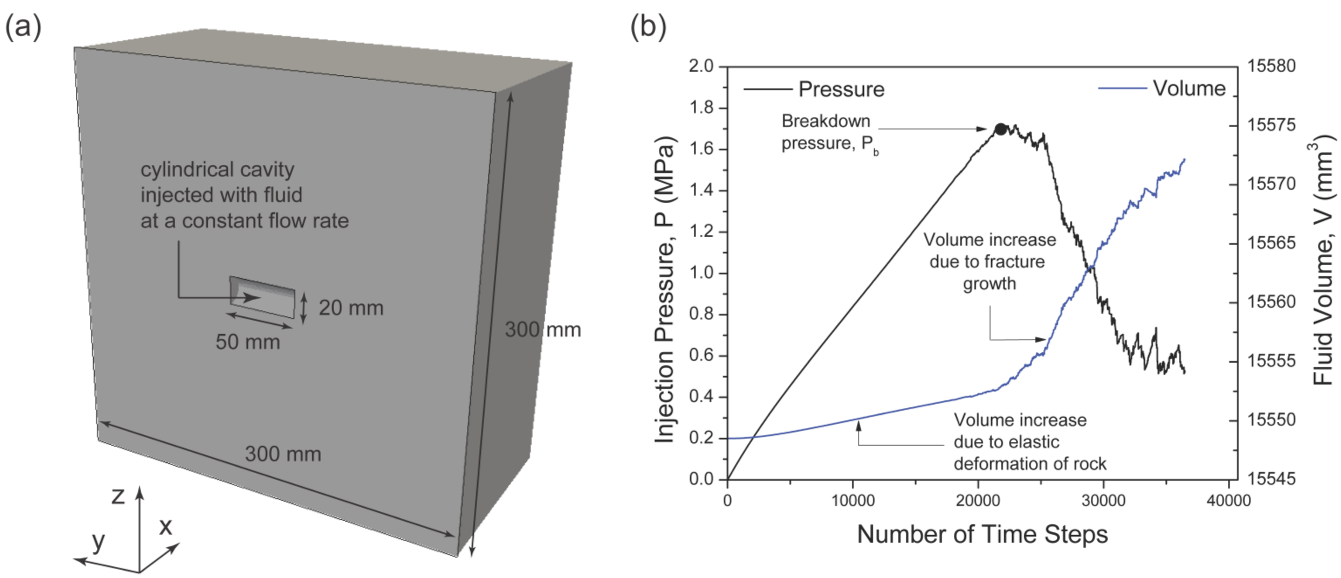

Figure 2 (a) Model geometry (clipped along the yz plane). (b) Emergent injection pressure and fluid volume responses.

Examination of the simulated crack patterns in the cavity near field indicates that hydraulic fractures first nucleate around the cavity circumference due to the tensile hoop stress induced by the pressurized fluid (Figure 3b), thereby forming a radial pattern of cracks. As the fluid injection continues, these hydraulic fractures tend to propagate towards the external boundary of the model. Thus, their length (in the direction perpendicular to the cavity axis) and width (in the direction parallel to the cavity axis) increase (Figure 3cd). In proximity to the circular ends of the cavity, initially separated fractures tend to interact to form a distinctive three dimensional feature (Figure 3e-f).

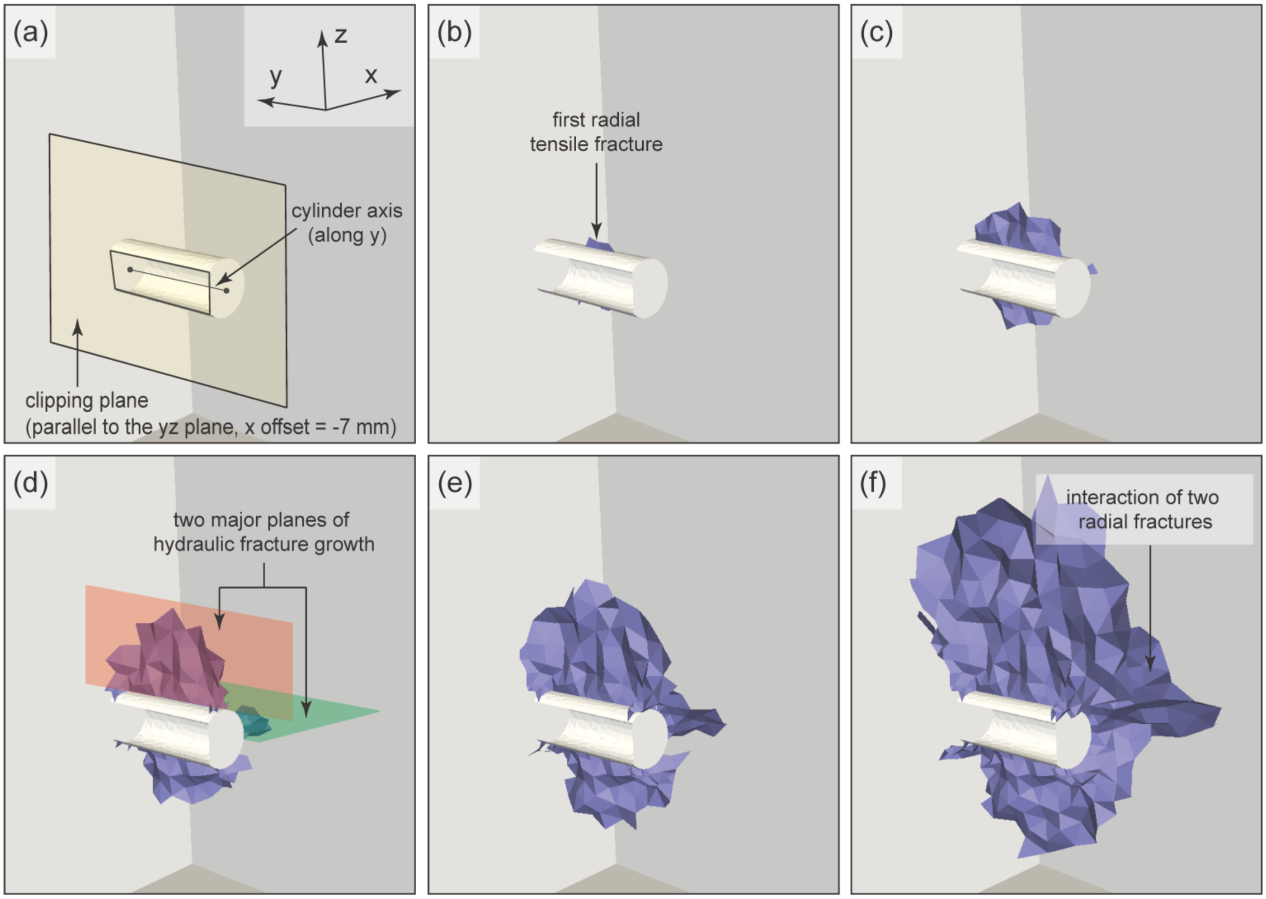

Figure 3 (a) – (f) Simulated temporal evolution of fracture nucleation and growth around a pressurized cavity in a homogeneous and isotropic medium. All fractures nucleate in Mode I (i.e., tensile mode).

Conclusions

The preliminary results illustrated in this paper are part of an ongoing research and development effort to create and validate a 3D numerical code that could aid in the design and optimization process of HF operations in unconventional reservoirs. The presented FDEM approach appears to be a promising tool to obtain unique geomechanical insights into HF under realistic rock mass conditions. Furthermore, the inherent ability of FDEM to generate synthetic seismic events (Zhao et al., 2014) is being further investigated, with the ultimate goal of improving the current understanding and interpretation of microseismic data, through the explicit evaluation of their geomechanical causes (i.e., forward modeling). In future studies, a more accurate hydro-mechanical coupling will be introduced to account for viscous dissipations within the fracture network as well as for matrix leak-off effects. Also, rock mass fabric features, such as bedding planes and joints, will be explicitly incorporated into the model.

References

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