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Research Paper

Lattice simulation of laboratory hydraulic fracture containment in layered reservoirs

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ABSTRACT

Hydraulic fracture containment in layered reservoirs is simulated using a numerical model that couples fluid flow with a lattice representation of the solid with quasi-random distributed nodes connected by springs. We consider the influence of horizontal stress contrasts between layers, vertical stress, material fracture toughness, and the presence of horizontal weak interfaces. Observed results define distinct regions in a parametric space characterized by height growth, containment, and growth along the horizontal weak interface (T-shape growth). These numerical results match well to laboratory experimental benchmarks, and they extend the parametric study beyond what can be considered in the laboratory.

1. Introduction

Hydraulic fracturing has been widely used for enhancing gas and oil recovery. Accurate prediction of fracture height growth/containment is important for successful design and therefore it has been studied for decades. The previous studies include laboratory experiments (e.g. [11,29,17,32]) and model predictions (e.g. [27,31,10,3,1,18]). Although stress contrasts between reservoir and adjacent layers may often determine the leading behavior of the height growth, other parameters, such as interlayer contrasts in fracture toughness [27], permeability [20], and stiffness [30], can also influence height growth.

In addition to these better-studied factors, weak interfaces (e.g. bedding planes) above and/or below the reservoir can substantially limit height growth. The affect of weak interfaces on height growth has long been recognized through model predictions [10], field observations [31], and in laboratory experiments [11,29]. Xing et al. [32] carried out an experimental study that considers both the stress contrasts and the presence of the horizontal weak interfaces. They observed four geometric cases: containment, height growth, T-shape growth, and the combination of height growth and T-shape. The differentiation among these cases was shown to depend on the combination of fluid pressure, vertical in-situ stress, horizontal minimum stress in each layer, and the fracture toughness of the layers.

Numerical models that fully couple mechanical deformation, crack growth, fluid flow, and the presence of pre-existing joints (horizontal interfaces) are essential in the exploration of this problem. Numerical analysis can expand the applicability of the parametric study conducted in the laboratory by Xing et al. [32]. In turn, the laboratory experiments can be used to validate the numerical solution. This laboratory benchmarking of numerical simulations, and subsequent use of numerical simulations to further explore hydraulic fracture containment, comprises the main focus of this paper.

The distinct element method (DEM), introduced by Cundall [6], can reproduce many of the behaviors of soil and rock including the impact of pre-existing discontinuities [4]. DEM treats the material as an assembly of discrete particles that may or may not be bonded together. Pine and Cundall [22] conducted the initial application of DEM to hydraulic fracturing of rock masses, fully coupling a hydro-mechanical model that includes the fluid flow in rock joints as approximated by the lubrication equation. However, the original coupled DEM models can only be used when the fracture path is known. To overcome this limitation, the synthetic rock mass (SRM) approach has been developed [21]. The SRM includes a bonded particle model (BPM) representing brittle rock matrix and a smooth joint model (SJM) representing the pre-existing joints. The BPM can represent crack growth including matching the fracture toughness and reproducing the scale effect [23].

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The SJM allows slip and separation at particle contacts while respecting the given joint orientation. The original implementations of the SRM models employ assemblies of circular/spherical particles bonded together, realized in the general-purpose codes PFC2D [15] and PFC3D [16].

The most recent implementation of the SRM concept uses a lattice representation of the rock matrix. Here the balls and contacts of PFC3D are replaced by point masses (nodes) and connecting springs [9]. The lattice representation has precedent for the simulation of fracture in concrete (see [26,2,13]), including the deformation and fracture of concrete coupled with fluid flow (see e.g. [12,14]). There exists also a lattice model base on Biot's theory with statistically heterogeneous mechanical properties [19]. Lattice models for simulation of jointed rock masses offer advantages over both continuum models and full DEM models in terms of both computational efficiency and flexibility [5]. Thus motivated, a three dimensional lattice-based hydraulic fracture simulator, XSite, has been developed [9].

The current study focuses on numerical simulation of hydraulic fracture growth in layered reservoirs using XSite considering different horizontal and vertical confining stress, different fracture toughness, and the presence of horizontal weak interfaces. Specifically, we focus on benchmarking XSite with respect to the experimental data presented by Xing et al. [32], after which we expand the parametric study originally carried out in these experiments. First we will briefly describe the setup of the experiments, and the lattice model used by XSite, after which we present the results of the numerical simulations including comparison with experimental results.

2. Experimental methods

The experiments carried out by Xing et al. [32] provide the benchmark for the numerical study in this paper. They were run with a three-layered medium constructed from transparent polyurethane (PU) that enables real-time monitoring of the evolution of the hydraulic fracture geometry. In order to enable control of the strength of the material associated with both vertical and horizontal hydraulic fracture growth, each layer was subdivided into two sub-blocks, as shown in Fig. 1. The length and width of the specimen are both 152.4 mm. The height of the top and bottom barriers is 50.8 mm. The reservoir height was varied, with specimens using a 50.8 mm, 25.4 mm, or 12.7 mm reservoir layer. Thus, the ratio of final crack length L over reservoir height H_R varies from 1.5 to 6. The experiments are detailed in Xing et al. [32].

The loads were applied with hydraulic actuators using two axes of a true tri-axial loading frame. Transparent polymethyl methacrylate (PMMA) blocks were used to evenly spread the load from the smaller actuators to the PU specimens (Fig. 1). The reservoir layer and the bounding layers are made of PU materials with different Young's moduli to generate the stress contrasts upon application of the loading via platens that are much stiffer than the specimen (see [32]).

One of the key elements in these experiment is that the horizontal interfaces between the reservoir and adjacent layers were left unbonded so as to comprise the weak interfaces. In contrast, the strength of the vertical interfaces was varied, providing an analogue for the strength of the reservoir and barrier rocks. The vertical interfaces ranged from the limiting unbonded case to three bonded cases corresponding to different toughnesses, obtained by using different adhesives. After the loading, glycerin mixed with food dye was injected into the reservoir layer through a 3.175 mm injection hole by a syringe pump. The hydraulic fracture initiated in the interface between two blocks of the reservoir layer. The fracture paths in the experiments are prescribed; the fracture could only propagate along the interfaces between different blocks. Hydraulic fracture geometry, fluid pressure, pump rate, confining stresses, and fracture geometries were recorded during the whole procedure. In the experiments, the videos were recorded 30 frames per second. By varying the stress conditions, four different geometries were obtained (see Fig. 2). Containment occurred when the vertical and barrier stresses were both sufficiently large compared to the reservoir stress and fluid pressure. Height growth occurred for smaller barrier stress, and T-shaped growth occurred for smaller vertical stress. Combination cases were observed over narrow ranges of parameters at transitions among the basic geometries. A parametric space defining the stress conditions associated with these geometries is presented later along with results of the numerical simulations.

3. Lattice model description

3.1. Geometry and mechanical formulation

The model is based upon a lattice formulation for simulation of deformation and fracturing of the solid. The lattice is a set of nodes connected by 1D springs. In this model, the nodes (point masses) are placed in a quasi-random arrangement with the mean nodal spacing set by a user-defined model resolution [7]. There are two methods of generating the springs that connect the nodes: regular and Voronoi. In the regular lattice the springs are based on contact relations between imagined spherical particles (i.e., the model created in PFC3D). In the Voronoi lattice, the springs are placed based on Voronoi tessellation in 3D space, where the springs are created at common faces of the discretization domains [9].

Once the nodes are placed and connected by springs, the law of motion for each node can be expressed according to linear momentum balance and an explicit time stepping expressing the displacement in terms of the nodal velocity, that is

$$\dot{u}_i^{(t+\Delta t/2)} = \dot{u}_i^{(t-\Delta t/2)} + \Sigma F_i^{(t)} \Delta t/m$$
$$u_i^{(t+\Delta t)} = u_i^{(t)} + \dot{u}_i^{(t+\Delta t/2)} \Delta t \quad (1)$$

where $\dot{u}_i^{(t)}$ and $u_i^{(t)}$ are the velocity and position (respectively) of component i (i = 1,3) at time t, m is the mass of node, and $\Sigma F_i^{(t)}$ is the sum of all force components i acting on the nodes with time step Δt. Then, the force changes in the springs can be calculated using the relative displacements of the nodes according to

$$F^N \leftarrow F^N + \dot{u}_i^N k^N \Delta t$$
$$F_i^S \leftarrow F_i^S + \dot{u}_i^S k^S \Delta t \quad (2)$$

where N denotes "normal", S denotes "shear", k is the spring stiffness, and F is the spring force. If the force exceeds the calibrated spring strength (either in tension or shear), the spring breaks and a microcrack is formed.

3.2. Fluid flow formulation

A fluid flow model is an essential part of any hydraulic fracture simulator. Fluid flow in hydraulic fracture(s) is solved using a network of pipe-like fluid elements located at the centers of springs that are either broken or that were initially designated represent pre-existing joints. Pipes are thus formed between the fluid elements within a certain distance between each other, a function of the resolution. The pipe network evolves with the development of damage in the mechanical model and is updated automatically by connecting newly formed microcracks to the existing ones. Using the lubrication equation, the flow rate q along a pipe from fluid node A to node B, is calculated as [9]:

$$q = \beta \frac{w^3}{12\mu} [p^A - p^B + \rho_w g (z^A - z^B)] \quad (3)$$

where w is hydraulic aperture, μ is the viscosity of the fluid, p^A and p^B are the fluid pressures at nodes A and B, respectively, z^A and z^B are the elevations of nodes A and B, respectively, and ρ_w is fluid density. A fluid reservoir in node A or B is regarded as a penny-shaped crack with the aperture w that depends on its fluid content. The dimensionless number β is a built-in calibration parameter, a function of resolution that is

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