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Simulation of shale–proppant interaction in hydraulic fracturing by the discrete element method

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ABSTRACT

In this paper, a three dimensional discrete element method (3D DEM) was proposed and deployed to simulate shale–proppant interaction in hydraulic fracturing. Shale is represented by particles with cement bond, and proppant is represented by particles without a cement layer. The velocity Verlet method is implemented to substitute the traditional central time integration scheme. The proposed DEM is used to investigate the shale–proppant interactions and evaluate the fracture aperture under different proppant sizes, Young's moduli and pressure levels. The results reveal that, the more soft shale particle, the higher pressure and the larger proppant size imply smaller crack aperture and larger plastic zone for other given conditions.

1. Introduction

Hydraulic fracturing [1–10] is the process of initiation, propagation and branching of cracks by pumping fluids at relatively high flow rate and pressure. As an important technique for creating cracks in rocks, hydraulic fracturing has been widely used for oil and gas recovery for more than five decades [10], and it is also one of the most important techniques for oil and gas production from the oil/gas shale [11]. Hydraulic fracturing is a typical multi-physics (thermal, hydraulics, mechanics, chemistry, etc.) interaction process and it involves the coupling of at least three processes [12] (the mechanical deformation induced by the fluid pressure on the fracture surfaces, the flow of fluid within the fracture and the fracture propagation). The formation of hydraulic fractures includes nucleation, growth, coalescence, propagation, branching and termination in a variety of rock types and stress regimes at scales ranging from microns to many kilometers, and its result is heavily affected by some conditions [12] as the presence of layers of different types of rock, the in situ confining stresses, the leak-off of fracturing fluid from the fracture to the surrounding rock, the effects of shear and temperature on the fracturing fluid rheology, the transport of suspended proppant particles within the fracture, the presence of a nearby free surface, modeling of fracture recession and closure, etc.

Actually, hydraulic fracturing is very difficult to model but it is practically of great importance for maximizing its effectiveness, especially consider that the cost for hydraulic fracturing is often a significant portion of the total development cost [6,10,11,13]. Usually, in numerical simulation of hydraulic fracturing, the rock deformation is modeled using the theory of linear elasticity, which is used to determine the relationship between the fracture width and the fluid pressure; the famous models include PKN [14–16], KGD [17–19], pseudo-three-dimensional (P3D) [20], planar 3D (PL3D) [21,22] and fully 3D models [23]; the fluid flow is modeled using the lubrication theory, which is a non-linear partial differential equation and relates the fluid flow velocity, the fracture width and the pressure gradient [3,4,10,24–30], fracture propagation or not, which is usually determined by the linear elastic fracture mechanics (LEFM) and elasto-plastic fracture mechanics (EPFM). Meanwhile, the transport and placement of proppant within the fracture [12,25,31,32] is modeled by the mixture of proppant and fluid, which means that proppant-carrying fracturing fluid is treated as a two-component, interpenetrating continuum.

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The main purpose of hydraulic fracturing is to enlarge the reservoir's permeability as much as possible (hydraulic fracturing may have other purposes as changing the rock's physical and chemical properties), but the permeability of the fractured reservoir is strongly affected by the apertures of the fractures, thus the determination of the residual opening [33–36], fracture channel permeability filled with proppants [37] and the optimization of proppants are of great practical interest [38]. It means that hydraulic fracturing should generate intensive distribution of cracks during hydraulic fracturing and keep cracks open after hydraulic fracturing operation. For this purpose, during hydraulic fracturing process, carefully selected proppants are blended with fracturing fluid in a certain ratio and flow into fractures, and the main role of the proppants is to keep fractures open after fluid injection [10]. Therefore, the choice of proppants including size, properties and shape is crucial for hydraulic fracturing success which should consider the complicated geometry of fractures and oil shale's properties. Consequently, the shale–proppant interaction and sensitive analysis of some parameters e.g. shale's Young's Modulus, proppant's size and stress level are the main research contents of the current paper. It should be stressed here, Neto and Kotousov [34,35] have utilized distributed dislocation techniques (DDT) to analyze the residual opening of hydraulic fractures filled with granular proppants, but our work is based on discrete element method (DEM) [39–46]. Considering our ultimate goal is to develop an integrated tool to investigate some important aspects of hydraulic fracturing (not only the residual opening) as the prediction of permeability (permeability is a parameter in traditional hydraulic fracturing simulation and need to be priorly determined), each proppant within fractures during hydraulic fracturing process (traditional hydraulic fracturing simulation treats proppant-carrying fracturing fluid as a two-component, interpenetrating continuum and cannot track proppants) and even a fully small-scale hydraulic fracturing simulation is tracked, so DEM and computational fluid dynamics (CFD) [47–57] techniques are adopted and coupled in our work, in which, DEM implies: (i) DEM does not need to treat (mathematical) crack specially, (ii) DEM can handle multi-crack interaction easily, (iii) DEM treats proppant and shale rock uniformly, and (iv) DEM has the ability to track proppants during hydraulic fracturing simulation though the computational cost will increase significantly (traditional hydraulic fracturing simulation just gives volume concentration); our CFD is based on volume-of-fluid form of Navier–Stokes equations (Eulerian description for fluid and Lagrangian description for proppants) [50,51] rather than lubrication theory as Reynolds' equation. We focus on shale–proppant interaction and the residual opening and sensitivity analysis in this paper, and we will introduce our other works (e.g. the evaluation of permeability, the track of proppants and the microscopic hydraulic fracturing simulation) in the future.

The DEMs are proposed and continuously developed by Cundall and others [39–46], and they can directly mimic rocks and thus exhibit a rich set of emergent behaviors that correspond very well with real rock. They also provide a tool to investigate the micro-mechanisms that combine to produce complex macroscopic behaviors or to predict these macroscopic behaviors. In our developed DEM program, rock is viewed as a circular/spherical particle cluster with finite mass, and its mechanical performance is represented by the stiffness and strength of particles or cement bonds (also known as cement interactions) between particles. Different materials have different properties, specifically, for shale and proppant, it is reasonable that the shale particle is treated as a particle with a cement layer (cement interaction) and (larger) proppant particle is a particle without cement. In addition, unlike some commercial softwares e.g. PFC3D [55] and 3DEC [56], velocity Verlet method [58] is implemented for time integration. Furthermore, we extended grain's interaction and cement bond from elasticity to elasto-plasticity, it means that our DEM code can directly apply to high stress and high temperature cases as deep well.

In this paper, by utilizing our developed DEM code, we investigate shale–proppant interactions and evaluate the openings of fracture under different stress levels, the influence of shale's Young's modulus and spherical proppant's mean size. In the following sections, a brief introduction to the DEM theory will be presented, followed by the numerical algorithm of DEM algorithm issues. One numerical case is used to calibrate DEM's parameters by comparing it with an experimental stress–strain curve of oil shale. The next part discusses the influence of shale's Young's modulus and proppant's size distribution. Finally, we will discuss the merits and limitations of the proposed method, and point out the future work.

2. Theory of DEM

The solid rock is treated as a cemented granular material of complex-shaped grains in which both the grains and the cements are deformable and may break [46]. For simplicity, the following assumptions are posed (Fig. 1 illustrates its physical basis): (1) the particles are circular or spherical rigid bodies with a finite mass for 2-dimensional or 3-dimensional cases, respectively, (2) the particles move independently and can both translate and rotate, (3) the particles interact only at contacts, (4) the particles are allowed to overlap one another, and all overlaps are small relative to particle size and (5) bonds of finite stiffness can exist at contacts, and these bonds carry load and can break.

Because the DEM is formulated in a fully dynamical fashion, damping is necessary to dissipate kinetic energy, and the damping force F^d applied to each particle is given by

$$F^d = -\alpha\left|\vec{F}\right| sign(\vec{V}), \tag{1}$$

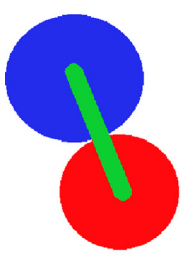
where α is dynamical damping, and $|\vec{F}|$ and $\vec{V}$ are the total external force and velocity, respectively.

For the interaction of two particles (grains), there are two types of force – normal and shear. The total normal force and the increment of shear force are calculated by,

$$F^n = K^n U^n, \quad -\Delta F^s = -K^s \Delta U^s \tag{2}$$

here U^n is the amount of overlap between the two particles (always positive), ΔU^s is the relative displacement at contact center between 2 particles A and B. K^n and K^s denote the normal and shear stiffness between two grains, and are given by

$$K^n = \frac{k_n^{(A)} k_n^{(B)}}{k_n^{(A)} + k_n^{(B)}} \tag{3}$$



Grain Interaction:

$$\begin{cases} F^n = K^n U^n \\ \Delta F^s = -K^s \Delta U^s \end{cases}$$

Cement Bond:

$$\begin{cases} \text{Incremental Normal Force}: \Delta\bar{F}^n = \bar{K}^n A \bullet \Delta U^n \\ \text{Incremental Shear Force}: \Delta\bar{F}^s = -\bar{K}^s A \bullet \Delta U^s \\ \text{Incremental Tortional Moment}: \Delta\bar{M}^n = -\bar{K}^s J \bullet \Delta\theta^n \\ \text{Incremental Bending Moment}: \Delta\bar{M}^s = -\bar{K}^n I \bullet \Delta\theta^s \end{cases}$$

Fig. 1. Physical model of implemented DEM.