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Numerical investigation of initiation and propagation of hydraulic fracture using the coupled Bonded Particle–Lattice Boltzmann Method

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A B S T R A C T

This paper presents a coupled Bonded Particle and Lattice Boltzmann Method (BPLBM) for modelling fluid–solid interactions in engineering, e.g. geomechanics. In this novel technique, the Bonded Particle model is employed to describe the inter-particle interactions, and the bonds between contacted particles are assumed to be broken when the tensional force and/or tangential force reach a certain critical value; while the Lattice Boltzmann method is used to model the fluid phase, and the Immersed Moving Boundary (IMB) scheme is utilised to resolve the fluid–solid interactions. Based on this novel technique, the investigation of hydraulic fracturing is carried out. The onset and propagation of hydraulic fracture are successfully captured and reproduced. Numerical results show that the coupled BPLBM is promising and efficient in handling complicated fluid–solid interactions at the grain level in hydraulic fracturing.

1. Introduction

Hydraulic fracturing is nowadays widely used to represent a process by which a fracture initiates and propagates due to hydraulic loading applied by a fluid inside the fracture. The application of hydraulic fracturing is abundant in geomechanics. Hydraulic fracturing began as a reservoir stimulation technique for oil exploitation in petroleum engineering. It was then used for hydrocarbon reservoir, shale oil production and geothermal energy extraction. The success of fracture stimulation is largely dependent on the size, shape and propagation behaviour of the created hydraulic fracture. Due to its complexity, the simulation of hydraulic fracturing has been a challenging research topic.

A good hydraulic fracturing model should include the mechanical deformation and fracturing propagation of the solid, the flow of the fluid within the fracture and the fluid pressure applied to the solid. Over the last decade, effort has been made and a number of numerical models have been proposed for the study of hydraulic fracturing. The computational fluid dynamics is the commonly used fluid solver. From the solid point of view, the Boundary Element Method [27], based on a weakly-singular, weak-form traction boundary integral equation, is the most popular approach [3,19]. An alternative is the combined Finite-Discrete Element Method [34,36]. This method treats the solid domain of interest as continuum at the beginning. When the simulation progresses, typically through explicit integration of the equations of motion, new discontinuities are allowed to form upon satisfying some fracture criterion, thus leading to the formation of new discrete bodies [14]. The Extended Finite Element Method (XFEM) [30], based on the generalized finite element method (GFEM) and the partition of unity method (PUM), is another approach. It extends the classical finite element method (FEM) approach by enriching the solution space for solutions to differential equations with discontinuous functions [31,6]. The latest technique for hydraulic fracturing is based on the numerical manifold method [28]; there are two kinds of covers, namely mathematical cover and physical cover. With these two kinds of cover, the method is quite suitable for modelling discontinuous problems [44].

In this work, a coupled Bonded Particle and Lattice Boltzmann Method (BPLBM) is proposed for the investigation of hydraulic fracturing. This novel technique, combining the Bonded Particle Method and the Lattice Boltzmann Method, is an extension of the Discrete Element–Lattice Boltzmann Method (DEM–LBM) [12,15,41]. Not only can it better simulate the mechanical response of geomaterials where cohesion forces exist between the bonded particles, but also tackle interactions between the granular particles and the fluid with high accuracy. It addresses fluid–particle issues at the grain-level commonly ranging from hundreds of microns to several centimetres.

The paper is organised as follows. In the next section a brief introduction of the Bonded Particle Method (BPM) is given, followed by the elaboration of the Lattice Boltzmann Method and the coupling of BPM and LBM. Then, validation of this coupling

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technique is performed and a hydraulic fracturing case in underground excavation is simulated using this coupled method and the initiation and propagation of fracture are captured at the microscale. Finally, it ends with conclusions and future work on how to improve this coupling method.

2. Computational methodology

In this section, we shall introduce the framework of the coupled BPLBM. In this method, the solid comprising bonded particles or granular particles is modelled by BPM in which the cohesion forces between bonded particles are considered by the contact bond model [38] and the fluid flow is solved using LBM with incorporation of the turbulence model [12].

In addition, the fluid–solid interactions are achieved through the Immersed Moving Boundary (IMB) scheme [35] which is commonly used in DEM–LBM.

2.1. Bonded Particle Method

It has been noted that the bonds existing between adjacent particles can resist both traction and shear forces and will break due to excessive traction and/or shear forces [11,22]. Therefore, the bonds play a vital role in determining the critical strength and force–displacement behaviour of geomaterials. Nowadays BPM is being extensively used for simulating brittle materials i.e. soil, rock and concrete. The concept of BPM is firstly proposed for rock by Potyondy and Cundall [38]. It originates from the Discrete Element Method (DEM) which has been proved to be an effective numerical tool for modelling problems consisting of granular particles. In BPM, the bond model mimicking cementation can be implemented between the particles in contact, and the bonds are able to carry normal forces, tangential forces and moment. When the bond force exceeds a critical value, the contact bond will break. In this case, only the particle–particle contact forces (independent of the bond) need to be considered.

The treatment of interactions between particles in this method is similar to that in the Discrete Element Method [7,8] in which particle–particle interactions are treated as a transient problem where an equilibrium state is reached when the internal forces are balanced. Newton's second law is utilised to determine the translation and rotation of each particle arising from the contact forces, e.g., externally applied forces and body forces as well as cohesive forces, while the force–displacement law is used to update the contact forces that keep changing due to the relative motion of particles at each contact. The dynamic behaviour is represented numerically by a time-stepping algorithm in which the velocities and accelerations are assumed to be constant within each time step. Because the propagation speed of disturbances is a function of the physical properties of the discrete medium, a sufficiently small time step should be chosen so that, in one time step, disturbances cannot propagate from a particle farther than its neighbouring particles. Therefore, at all times the resultant forces on any particle are determined exclusively by the neighbouring particles in contact.

Newton's second law governing the motion of a particle is given by

$$ma + cv = F_c + F_f + mg \tag{1}$$

$$I\ddot{\theta} = T_c + T_f \tag{2}$$

where m and I are respectively the mass and the moment of inertia of the particle; c is a damping coefficient; a and $\ddot{\theta}$ are respectively the acceleration and angular acceleration; F_c and T_c are respectively the contact forces and corresponding torques; F_f and T_f are the hydrodynamic force and torques. It should be emphasised that F_c can be either particle–particle contact forces for granular particles or cohesion forces F_b existing between bonded particles.

2.1.1. The particle–particle contact model

The particle–particle contact force F_c has two components, the normal contact force and tangential contact force, which are, respectively, given by

$$\text{Normal interaction laws}: \; F_n = K_n \delta^m \tag{3}$$

$$\text{Coulomb friction model}: \; F_t = -\frac{\dot{\delta}_t}{|\dot{\delta}_t|}\begin{cases} K_t|\delta_t|; & |K_t\delta_t| \leqslant \mu F_n \\ \mu F_n; & |K_t\delta_t| > \mu F_n \end{cases} \tag{4}$$

where K_n and K_t are respectively the normal stiffness and tangential stiffness; δ_t and $\dot{\delta}_t$ correspond to accumulated tangential sliding and sliding velocity; δ is the overlap of two particles. The coefficient m can be 1 or 3/2; the former is for the linear contact and the latter is for the Hertz contact model.

2.1.2. The contact bond model

The bond model used in this work is referred to as the contact bond model [21,38]. It approximates the physical behaviour of a vanishingly small cemented-like substance joining the two bonded particles. It can be envisioned as a pair of elastic springs (or a point of glue) with constant normal and shear stiffness acting at the contact point. These two springs have specified shear and tensile strength. The existence of a contact bond precludes the possibility of slip. This widely accepted bond model accounts for forces acting at the contact point, but it is unable to undertake moment. Thus more advanced bond models are required to simulate more complicated mechanical behaviours [38,37,22,23].

The contact bond is characterised by two parameters: normal bond strength (F_{bn}) and shear bond strength (F_{bs}). If the tensile contact force equals or exceeds the normal contact bond strength, the bond breaks, and both the normal and shear contact forces are set to be zero. However, when the shear contact force is equal or greater than the shear contact bond strength, the bond breaks, but the contact forces do not change. The contact bond model can be described by

$$\text{Normal component}: \; F_n^b = \begin{cases} K_n^b\delta; & F_n^b \leqslant F_{\max} \\ 0; & F_n^b > F_{\max} \end{cases} \tag{5}$$

$$\text{Tangential component}: \; F_t^b = -\frac{\dot{\delta}_t}{|\dot{\delta}_t|}\begin{cases} K_t^b|\delta_t|; & |K_t^b\delta_t| \leqslant \mu F_n^b \\ \mu F_n^b; & |K_t^b\delta_t| > \mu F_n^b \end{cases} \tag{6}$$

where K_n^b and K_t^b are respectively the normal stiffness and tangential stiffness for the cement; and $F_{\max}$ is the critical tensile force.

2.1.3. The general algorithm of BPM

The computational procedure of the Bonded Particle Method is briefly summarised as follows:

(1) A particle packing with a specified size distribution will be generated first. Then, the first contact detection will be performed to build up a contact list for particles in contact. At the meantime, the overlaps between these contacting particle pairs are recorded. Then, bond models will be introduced to the particles according to the first contact detection;

(2) When bond models are introduced, relaxation of the particle sample to a balanced state is required. Here a reduced-overlap method is proposed to secure a fast relaxation of a sample. At each time step, the deformation of the bond will be subtracted by the initial overlap record in the first step;

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