Three-dimensional multi-scale hydraulic fracturing simulation in heterogeneous material using Dual Lattice Model

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Hydraulic fracturing is a multi-physics and multi-scale problem related to natural processes such as the formation of dikes. It also has wide engineering applications such as extraction of unconventional resources, enhanced geothermal energy and carbon capture and storage. Current simulators are highly simplified because of the assumption of homogeneous reservoir. Unconventional reservoirs are heterogeneous owing to the presence of natural fracture network. Simulators that considered heterogeneous reservoirs are needed.

Different numerical methods have been suggested for hydraulic fracture simulations. They focus on the multi-physics nature of the problem. Because of high computational effort, three-dimensional multi-scale simulations are uncommon, in particular, modelling material as a heterogeneous medium. Lattice Element Method (LEM) is therefore proposed for multi-scale simulation of heterogeneous material.

In LEM, material is discretised into Voronoi cells and their interactions are modelled by lattices, hence a three-dimensional model is simplified to a network of one-dimensional lattice. Normal, shear and rotational springs are used to define the constitutive laws of a lattice. Lattice models are solved implicitly, giving high computational performance that enables desktop computers for simulation of a lattice model that consists of millions of lattices.

From simulations, normal springs govern the macroscopic bulk deformation while shear springs govern the macroscopic distortion. Rotational springs have negligible effects on both the macroscopic and the microscopic behaviour. There is fluctuation of stresses even under uniform loading which is one of the characteristics of a lattice model. The magnitude increases with the stiffness ratio of shear spring to normal spring. Additional heterogeneity can be applied by introducing statistical distributions on lattice parameters.

Fracturing process can be modelled by LEM by introducing a microscopic tensile strength and a microscopic shear strength to the lattice properties. The strength parameters can be related to the fracture toughness with the length scales of cells. From simulations, the relationships between model parameters and macroscopic parameters that are measurable in experiments are identified.

From the simulations of uni-axial tension tests, both the spring stiffness ratio and the applied heterogeneity govern the fracturing process. The heterogeneity increases the ductility

of a lattice model at the expense of the reduction on the macroscopic strengths. Different stages of fracturing are identified which are characterised by the model heterogeneity. Heterogeneous models go through the stages of the spatially distributed microscrack formation, the growth of multiple fracture clusters to the dominant fracture propagation. For homogeneous models, one of the microcracks rapidly propagates and becomes a dominant fracture with the absence of intermediate stages. From the uni-axial compression test simulations, a linear relationship is established between the macroscopic compressive strength to the microscopic strength ratio of shear spring to tensile spring. The peak compressive stress is reached at the onset of the microscopic shear crack formation. Ductility is mainly governed by the stiffness reduction ratio of a lattice in closed fractured stage to its unfractured stage.

A novel Dual Lattice Model (DLM) is proposed for hydraulic fracture simulation by coupling a solid lattice model with a fluid lattice model. From DLM simulations of hydraulic fracturing of the classical penny shape crack problem under hydrostatic condition, the heterogeneities from both the fracture asperity and the applied heterogeneity increase the apparent fracture toughness. A semi-analytical solution is derived to consider the effect of fluid viscosity in the elastic deformation regime. Two asymptotes are identified that give steep pressure gradients near the injection point and near the fracture tip. These two asymptotes are also identified in the DLM simulations. The DLM simulations also show three evolving regimes on energy dissipation/transfer mechanisms of hydraulic fracturing: from the viscosity dominant, the elastic deformation dominant and the mixture of elastic deformation and toughness.