Discrete Element Simulation of Hydraulic Fracturing and Induced Seismicity in Engineered Geothermal Systems

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ABSTRACT

In this paper the Discrete Element Model (DEM) 'ESyS_Particle', previously used to model fracture of brittle rocks and earthquake processes, is further developed to be able to be applied to the hydraulic fracturing process in Engineered Geothermal Systems (EGS). The advantage of DEM is that large deformations and dynamic process can be modelled easily. ESyS_Particle has been used to successfully model fracture of brittle rocks and earthquake processes in the past 15 years. Currently it incorporates thermal-hydro-mechanical coupling based on Darcy's Law and Biot theory. A simple simulation of a hydraulic fracture is provided, which reproduces the most basic features of hydraulic fracture. I hope to model induced seismicity in the future.

INTRODUCTION

Australia has a unique hot rock geothermal resource which can provide clean, reliable and cost-effective energy for centuries to come. A type of geothermal energy extraction process involves the injection of high pressure fluid to exchange heat from granite situated at depths near 5 km and temperatures up to 250 °C. Although hydraulic fracturing is a mature technique in the oil industry, there remain some issues which are not fully understood. The challenge in this process is how to stimulate and sustain the flow of fluid through the geothermal field and how to generate an efficient hydraulic subsurface heat exchanger system. Great effort is required to offer some explanations of types of fracturing and flow rates that occur under different conditions such as the fluid viscosity, propellants used, pump rates etc. This is a crucial step in understanding and quantifying the flow aspects of the heat exchanger, and can then be used to give some confidence to the viability and sustainability for such a system.

Another concern is the risk of fluid injection generating induced seismicity. One example is injection-induced earthquakes in Basel, Switzerland which occurred between December, 2006 and January, 2007. Although no severe damage was reported, the pumping operation was terminated and the project remains in suspension. The possible societal and economic impact of induced earthquakes associated with geothermal pumping can not be ignored in Australia. While monitoring seismic events provides valuable information with respect to spatial and temporal reservoir growth, a numerical model which has the capability of simulating the process is also helpful. Such a numerical model should include full coupling between thermal-, hydro- and mechanical- processes. A DEM is a good candidate because it is suitable for modelling brittle fractures and seismic events thanks to its discrete nature.

In this study, ESyS_Particle is developed to include thermal-hydro-mechanical coupling based on Darcy's Law and Biot poroelastic theory. The model is introduced briefly below, followed by an example of a hydraulic fracture simulation. It is intended that ESyS_Particle is further developed to be able to model induced seismicity in the future.

INTRODUCTION TO THE ESYS_PARTICLE MODEL

ESyS_Particle is a Discrete Element Model (DEM) developed by ESSCC, University of Queensland. It has been applied to the study of physical processes such as rock fracture, stick-slip friction behavior, earthquake processes and frictional behaviour of granular materials (Mora et al. 1993, 1994; Place et al. 2002). At its current state, ESyS_Particle is able to conduct simulations in parallel utilising the Message Passing Interface (MPI).

ESyS_Particle has been recently extended to include single particle rotation and a full set of interactions between particles. Some of the more important features that distinguishes ESyS_Particle from existing DEM's are the explicit representation of particle orientations using unit quaternion. Complete interactions (six kinds of independent relative movements are transmitted between two 3-D interacting particles) and a way of decomposing the relative rotations between two rigid bodies in such a way that the torques and forces caused by such relative rotations can be uniquely determined (Wang et al. 2006; Wang et al. 2008a). In most existing DEM codes, the incremental method is used to update the interactions between particles. However, results show that when dealing with finite rotations of particles, the incremental method is not as stable and accurate as the method used in ESyS-Particle (Wang et al. 2008a).

Figure 1 shows two examples of the ESyS_Particle Model. On the left is a simulation of a 2-D wing crack extension. Wing cracks are frequently observed in uniaxial compression of brittle materials with a pre-existing crack. It is found that tensile cracks nucleate at the tips of the flaw, grow in a stable manner with increasing compression, then tend to align with the direction of axial loads. It can be shown that these observations are well reproduced using our model (Wang et al. 2008b).

The right side of Figure 1 shows the 3D fracture pattern of a brittle rock-like material. In this example, the sample is subjected to slow uniaxial compression in the vertical direction. The colours represent vertical displacements. Discontinuities in colours show the formation of fractures which are difficult to capture in laboratory experiments because of the rapid nature of this process. When the main faults are formed, two intact blocks can be observed with more fragile parts shattering

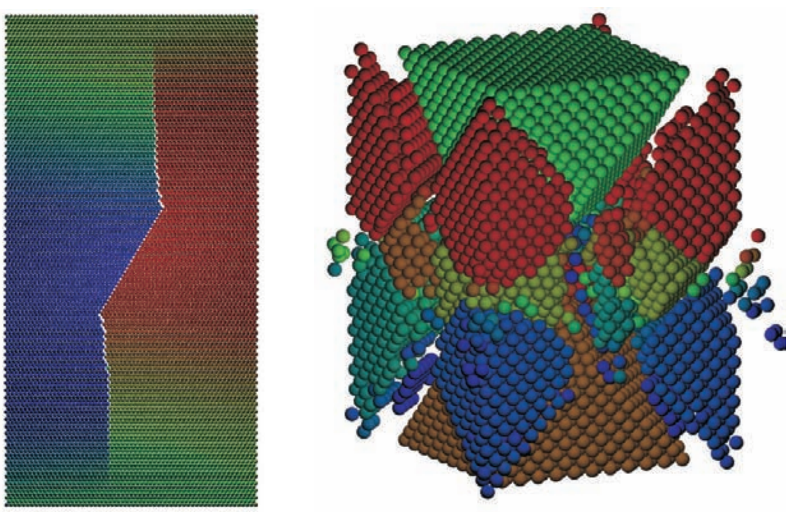

Figure 1. Simulation of 2-D wing crack extensions(left) and of the fracture pattern of a 3-D brittle rock-like material under uniaxial compression (right).

away from the four sides. This kind of pattern can be shown to occur in rock fracture experiments (Andreev, 1995).

Currently ESys_Particle has included thermal effects (which include heat transfer, thermal expansion and friction generated heat) and Darcy flow. The algorithm for hydro- and mechanical-coupling is outlined below.

Incorporation of pore flow within ESyS_Particle

Generally, movement of particles, or change of mechanical pressures will cause a change in pore pressure. On the other hand, Fluid pressure gives rise to extra forces on the particles, which in turn affects the movement of the particles. In the model presented, a two-way coupling between hydro- and mechanical- processes is realised using Darcy's Law and Biot poroelasticity theory.

Darcy's Law

Unlike the similar DEMs, volume space between particles is not viewed as pore voids in this study. Instead, the assumption is made that the voids inside rock are much smaller than the particle sizes; therefore the porosity is just an average concept for each particle. There is an average and uniform pore pressure p_i for each particle *i*. For two contacted particles *i* and *j*, the fluid exchange is

$$\Delta V_f = C(p_i - p_j)\Delta t \qquad (1)$$

where *C* is the conductance of the link, which is related to local permeability and geometry of the material.

Biot linear poroelastic theory

According to Biot's linear poro-elastic theory, the constitutive equations of a porous medium can be written as (Detournay and Cheng, 1993)

$$\varepsilon = -(P-\alpha p)/K_m \qquad (2a)$$

$$\zeta = -\alpha(P-p/B)/K_m \qquad (2b)$$

where p is pore pressure, $P=-\sigma_{kk}/3$ is the mean or total mechanical pressure (isotropic compressive stress), $\varepsilon = \varepsilon_{kk} = \Delta V/V$ is the volumetric strain (positive for extension), $\zeta = V_f/V$ is the variation of fluid content (positive corresponds to a "gain" fluid), α is Biot coefficient, B is the Skempton pore pressure coefficient and K_m is the drained bulk modulus of the material. V and V_f are the volume of the material and fluid respectively. From Equation 2a and 2b, the following equation is obtained

$$p = BP + K'\zeta \qquad (3)$$

where $K' = BK_m/\alpha$.

The pore pressure for particle *i* is updated according to:

$$p_i(t+\Delta t) = p_i(t) + B\Delta P_i + K'\Delta\zeta_i \qquad (4)$$

where $\Delta P_i = P_i(t+\Delta t) - P_i(t)$ and $\Delta\zeta_i(t+\Delta t) - \zeta_i(t) = C\Delta t\Sigma_j(p_j-p_i)/V$. The summation j goes though all the neighbouring particles of particle *i*.

Tunnel interaction

When a crack develops, the bond between two particles will break, and there exists a small separation of the particles. This increases the local permeability and fluid is allowed to flow into the crack, thereby increasing pore pressure and causing the crack to open wider.

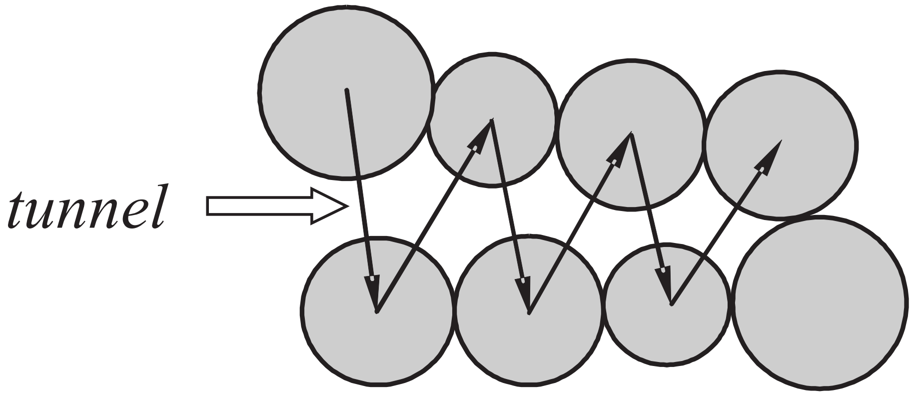

Figure 2. Schematic illustration of an zigzag simulation of fluid along a crack.

In the model presented, this process is taken into account. Besides the bonded interaction and elastic (or frictional) interaction, another kind of interaction, tunnel interaction, is introduced. In case of the tunnel interaction, particles do not come in contact with each other, but remain in close proximity from one another. Fluid flow between particles occurs in a zigzag route (Figure 2). This route is a good representation of the flow along the crack. In this case, the tunnel conductance is empirically set 20 to 100 times larger than normal. However this has the effect of slowing down calculations as smaller time steps are required to compute the problem.

Forces caused by pore pressure

Fluid pressure will give rise to forces acting on the particles. This mechanism has been included through the use of equation 2a which implies that when there is no volume change (ε=0) a mechanical pressure P=αp is required to balance the pore pressure, otherwise the volume will increase. This also suggest that a repulsive force $F_{ij} = \lambda A(p_i+p_j)/2$ is needed between the particles i and j, where A represents the contact area, and λ is a factor which depends on the geometry of particle packing and dimension of the problem. In 2-D regular packing is used.

Preliminary simulation of hydraulic fracture

Figure 3 shows snapshots from a 2-D simulation of hydraulic fracture. The model consists of 5301 particles of different sizes ranging from 0.1 to 1. A small and constant confining pressure is applied on the four boundaries. The image on the left shows the initial state of the simulation, the hole in the middle of the sample represents the location of where liquid is to be injected through increasing pressure. The middle image of Figure 3 shows the appearance of some cracks, once fluid flows into the cracks it will cause them to propagate as shown on the right hand side of Figure 3. Although the simulation remains predominantly un-calibrated against laboratory and *in-situ* testing, it can be shown to reproduce the basic features of hydraulic fracture. It is believed that a more realistic boundary conditions will be able to produce better results.

Simulation of induced seismicity by geothermal reservoir

Fluid extraction and injection can induce seismicity (Majer, 2006). Both fluid extraction and injection are undertaken in geothermal operations. In the case of water injection, pore pressure near the well increases.

The role of pore pressure in earthquake generation is that it can push apart the fault surfaces, reducing the "effective strength" of the fault. It is known that several factors control the

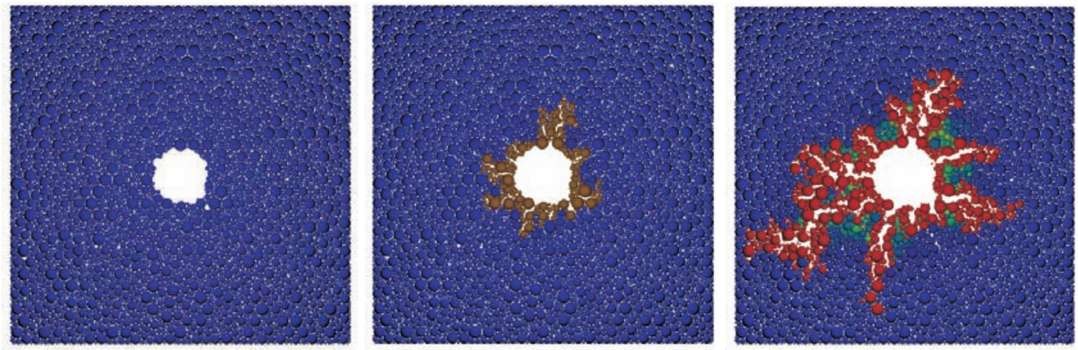

Figure 3. 2-D simulation of hydraulic fractures. The colours represent pore pressure (blue for low and red for high).

magnitudes, spatial and temporal distribution of induced seismicity. Using the model mentioned above, it is a future goal to investigate numerically the following aspects:

1) The impact of rate of fluid injection on induced seismicity.

2) The effect of permeability, strength of rocks.

3) The effect of sizes, orientations and distances of faults.

4) What controls the time lag (or delay) observed between induced events and the injection.

It is hoped this study will be helpful in understanding the dynamics of the physical processes of geothermal energy extraction and the mechanisms causing the seismicity.

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