Laboratory experiments and numerical simulations of hydraulic fracturing for enhanced geothermal systems

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ABSTRACT

Hydraulic fracturing experiments are performed on large igneous and metamorphic rock samples of size 300 mm × 300 mm × 450 mm at controlled conditions in the laboratory. The fractures are created by injecting high-pressure fluid into the rock. The growth and propagation of fractures and the associated micro-fractures are monitored via acoustic emission data recorded by transducers attached to the samples. These data sets then serve as benchmark data for verifying existing or new hydraulic stimulation codes which are used for field-scale stimulation design.

1. INTRODUCTION

Economic extraction of geothermal energy from deep, hot, and dry rock formations with extremely low porosity and permeability require techniques for enhancing existing weak or creating new permeable fracture zones. If successful, this hydraulic stimulation allows to exploit the heat stored in these dense formations by creating interconnected fracture networks facilitating the movement and heating of injected cold water. Apart from creating these fractures, the main challenge lies in predicting their propagation and final geometry.

We generate hydraulic fracturing data sets under controlled conditions in the laboratory. The boundary conditions and physical parameters are then used for simulating the fracturing experiment. The simulation is performed using a robust finite element model [1, 2].

2. EXPERIMENTAL SET UP

We designed and constructed a triaxial set-up to perform hydraulic fracturing experiments [1]. Large blocks of granite and marble, sized 300 mm × 300 mm × 450 mm, are fractured by injecting a glycerol-ink mixture at high pressure into a 20 mm diameter borehole. The borehole is drilled at the centre of the block, parallel to the long axis (Figure 1). In order to make the crack initiation and its location reproducible, a circumferential notch of radius 17±1 mm is cut into the borehole wall at a height of z = 225 mm (Figure 1). Prior to injection, the specimen is initially stressed by applying 5 MPa in vertical and 15 MPa in horizontal directions. The fracture propagation is monitored by recording the accompanying acoustic emissions by 32 transducers mounted on loading plates attached to the rock sample (Figure 1). Under controlled conditions, we repeat these fracking experiments for a number of injection protocols and stress boundary conditions. For each of these, a series of repeated experiments ensure the reproducibility and accuracy of the measurements. A detailed description of the experimental set up can be found in [3, 4]. Figure 2 shows the schematic of the experimental set up.

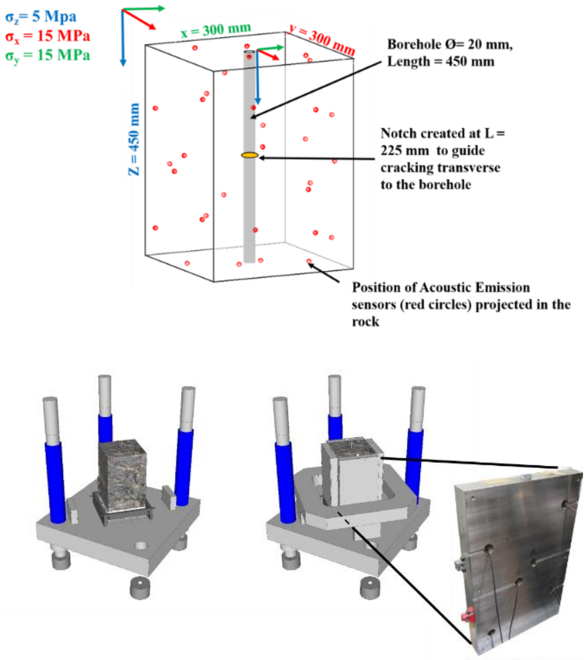

Figure 1: Top: configuration of the acoustic sensors (red open circles) on the different sides of the samples, bottom: schematic of the triaxial press with the sample loaded on it; the slots for acoustic emission sensors are shown in the steel loading plates [3].

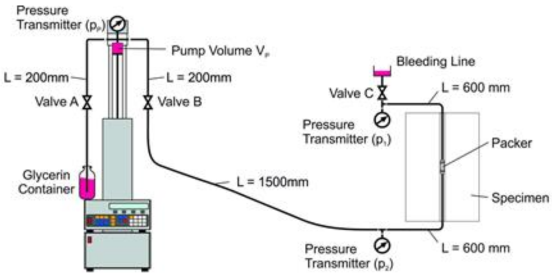

Figure 2: Schematic diagram of the experimental set up [3].

3. EXPERIMENTAL PROTOCOL

The experiment begins by applying the initial stresses (σ_x, σ_y, σ_z) on the sample. Fluid is pumped through the injection system to evacuate the system first and the fill it with injection fluid. A leakage test is done ensures that the injection system is tight. This is followed by active transmission experiments to determine the rock's seismic velocities.

Once the velocities are measured under the initial conditions, the injection cycle for the fracturing begins. The starting time of the pump is used as the reference time (t = 0 s) for all recorded data. The duration of injection is controlled by injecting a defined volume ΔV_p after the peak pressure. This defined volume and injection rate is restricted for ensuring a controlled fracture growth. The pump is stopped at ~1800 s after having injected a volume of ΔV_p. This is referred to as "shut-in". When the pressure in the injection system drops below the minimum confining stress (σ_z), the pressure in the injection system is released and the sample is unloaded from the set up.

A second hole is drilled after removing the packer in order to split the sample along the fracture plane. The extent of the created fracture is outlined by the spread of the red ink used in the injection fluid. Then we use photogrammetry for creating a 3D model of the delineated fracture surface.

4. EXPERIMENTAL RESULTS:

As an example, we present results of one of our latest experiments performed in a granite sample (GEMex03). This sample is characterised by very low porosity and permeability on the order of 1 % – 2 % and 10^{-19} m^2, respectively. Figure 3 presents the pressure P, the injection rate Q_0, and the acoustic emission events recorded during the test.

The pressure reaches a certain maximum at which the fractures initiates. This is followed by a decrease in pressure as a result of the fracture propagation within the rock. High density of acoustic emission events are observed during the growth of the fracture which decreases during the shut-in phase until the injection finally stops. In Figure 3, the filled coloured circles representing the acoustic emission events overly the pressure curves for better viewing. Their color, varying from dark blue to yellow corresponds to the time when the event occurred.

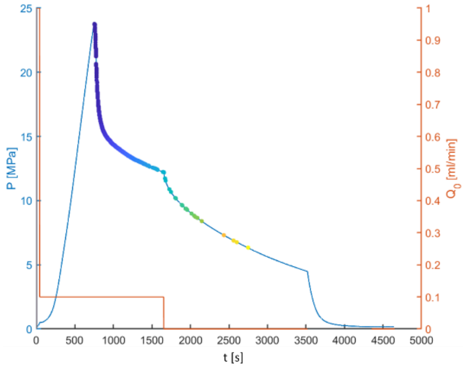

Figure 3: Plot of pressure P (MPa) and Injection rate Q_0 (ml/min) vs. time t (s) for GEMex03 experiment.

The split sample with the delineated fracture radii is shown in Figure 4. The fracture radius obtained from visual inspection (Figure 4-right) and later by photogrammetry (dashed outline in Figure 4-left) is on the order of ~ 90 mm – 100 mm.

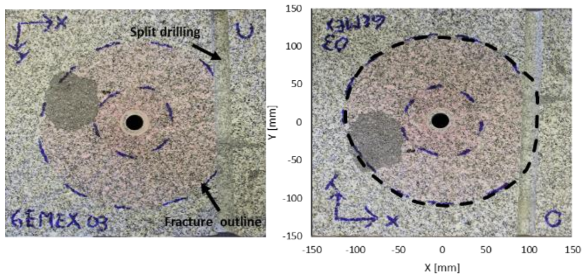

Figure 4: Split plane with coloured fracture zone showing the fracture radius (GEMex03)

The localised points of acoustic emission events detected during the crack propagation are shown in Figure 5. The spread of the acoustic emission events corroborates well with the fracture radii obtained by means of photogrammetry. The color bar on the right indicates the time (in seconds) during which the maximum events occurred.

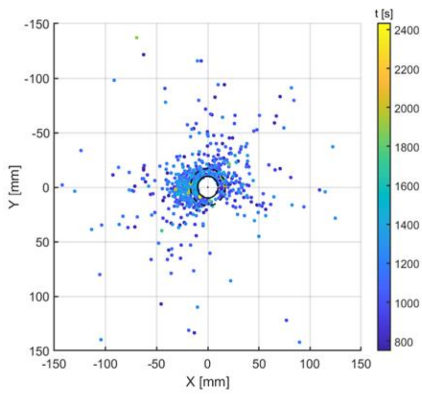

Figure 5: Acoustic emission events for GEMex 03 projected onto the X-Y plane

5. SIMULATION RESULTS:

A 3D model of the granite block is created with an initial fracture of radius 17 mm in the centre of the block. Table 1 shows the injection rate as well as other material parameters used in the simulations. Since the injection system (pump, tubes, etc.) is not included in the numerical model, the simulation results are presented for the time period after the start of the fracture propagation. The simulations are performed based on the Linear Elastic Fracture Mechanics approach. Fifty locations around the fracture tip are used to define the tip of the fracture. The stress intensity factors K_I, K_{II}, and K_{III} are evaluated at these locations, and used to evaluate the onset and direction of propagation vectors [5]. However, in the hydraulic fracturing process, the mode I stress intensity factor K_I is the main factor.

Since the size of the fracture in the experiment is relatively small (< 10 cm) compared to the size of the process zone (~ 1 cm - 2 cm), it is expected that the rock shows some ductile behaviour. Ductile materials are more difficult to frack because they yield before they crack [6]. Yao et al. [7] has suggested the effective fracture toughness as

$$K_{eff} = c \cdot K_{ic}, \qquad [1]$$

where the coefficient c varies from 1.414 to 2.236. The fracture toughness measured for our granite sample is $K_{ic} = 1.66 \pm 0.23$ MPa $m^{1/2}$. Thus, the effective fracture toughness using equation (1) varies between 2.35 to 3.71 MPa $m^{1/2}$. In the simulations, three values for fracture toughness are considered: 1.66, 2.5 and 3.0 MPa $m^{1/2}$. All other values reflect the property of the sample and parameters of the experiment.

Figures 6 and 7 show the simulation results for both injection pressure and fracture radius, respectively, versus time for different fracture toughness values.

Table 1: Data used for simulating the hydraulic fracturing experiment

Injection rate	0.1	ml/min
Fluid viscosity	0.6	Pa s
Young's modulus	36.9	GPa
Poisson's ratio	0.3	
Fracture toughness	1.6, 2.5, 3.0	MPa $m^{1/2}$
Minimum stress	5.0	MPa

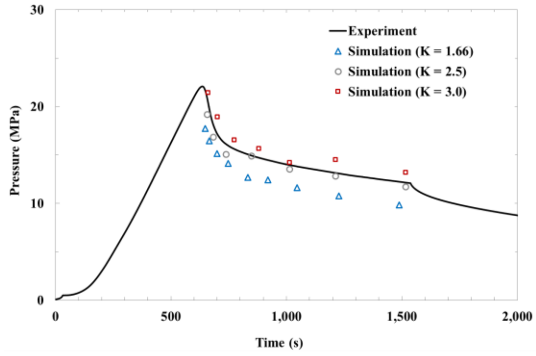

Figure 6: Injection pressure versus time for different fracture toughness.

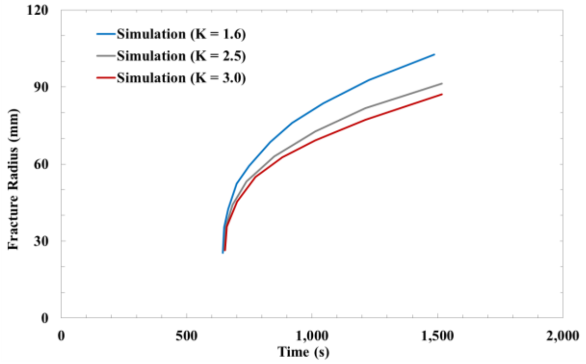

Figure 7: Simulated fracture radius versus time for different fracture toughness.

6. DISCUSSION AND CONCLUSION

The simulation results for different values of fracture toughness show that a better match with the experiment is obtained for values of fracture toughness greater than the measured one. Initially, as the size of the fracture (notch) is very small (17 mm), the highest fracture toughness yields the best match. Towards the end of simulation the size of the fracture increases and a mid-range toughness value provides the best fit. This is consistent with the fact that, with increasing fracture size, the fracturing behaviour shifts from ductile towards brittle behaviour.

The final fracture size (radius ~ 90 mm – 100 mm) in the simulations is consistent with the values of the experiment measured after splitting of the sample.

Although our simulation results agree well, in general, with the data from the experiment, further investigations are required to understand better why and how the fracture toughness varies with the fracture propagation.

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