Applied Numerical Modeling in Geomechanics – 2020 – Billaux, Hazzard, Nelson & Schöpfer (eds.) Paper: 07-03
 ISBN 978-0-9767577-5-7

Numerical simulation of a laboratory experiment testing hydraulic fracture initiation monitored by acoustic emission

Ali Mehrabifard[1], Erik Eberhardt[1] & Branko Damjanac[2]
[1] *Geological Engineering, University of British Columbia, Vancouver, BC, Canada*
[2] *Itasca Consulting Group, Inc., Minneapolis, MN, USA*

1 INTRODUCTION

Hydraulic fracturing and stimulation practices are key for the successful development of enhanced geothermal and unconventional oil and gas projects involving ultra-low permeability reservoirs. However, the injection of large volumes of fluids and triggering of induced seismicity with these practices has raised public and regulatory concerns. Understanding the mechanisms of fault slip and influence of fault characteristics on susceptibility is critical for properly mitigating this potential hazard.

For this, numerical modeling serves as a powerful tool, but it is important to both select and validate a modeling method that properly captures the physics of the problem. Common approaches used to simulate hydraulic fracturing include those that treat the problem domain as either a continuum (e.g., finite element, Dehghan et al. 2017) or a discontinuum (e.g., distinct element, Zangeneh et al. 2015; discrete element, Zhao & Young 2009). Each of these have their strengths, but also their limitations in how they simulate hydraulic fracturing. A recent development in discontinuum modelling aimed at better simulating brittle fracturing is the 3-D hybrid lattice and bonded-particle code *XSite* developed by Itasca Consulting Group (Damjanac et al. 2016). The *XSite* software is a special-purpose numerical code developed for simulating fluid injection and hydraulic fracturing within a discontinuous domain, and has shown promising results to date (Bakhshi et al. 2018, Xing et al. 2018, Fu et al. 2019).

A key output of *XSite* is the built-in calculation of acoustic emissions (AE) derived from modeled microcracks. This output capability presents an opportunity to validate *XSite* against laboratory-scale experiments. One such experiment was selected to be modeled using *XSite* involving results reported by Stanchits et al. (2014) for hydraulic fracture initiation in a low permeability sandstone block instrumented with AE sensors.

2 EXPERIMENT AND MODEL SETUP

Stanchits et al.'s (2014) experiment involved hydraulic fracturing testing of a 279 × 279 × 382 mm block of Colton Sandstone, the properties for which are listed in Table 1. The block was independently loaded in a polyaxial load frame in three directions using flat jacks to simulate the stress conditions existing in the field (σ_V = 27.6 MPa, σ_H = 13.8 MPa, σ_h = 6.9 MPa). A 25.4 mm diameter hole was drilled in the center of the block to a depth of 241.3 mm, into which a viscous silicone oil (dynamic viscosity = 2445 Pa.s) was injected under a constant injection rate of 0.083 cm^3/s. Two longitudinal scribes were used to facilitate fracture initiation in the direction of the maximal horizontal stress, as shown in Figure 1a.

The *XSite* model was developed using the same sample dimensions and loading conditions as the experiment (Fig. 1b). The hydraulic fracture propagation was assumed to be toughness dominated (see Detournay 2016) allowing the model to be solved assuming an inviscid fluid, thus saving computational time. This assumption also allowed a higher injection rate to be used to further reduce the simulation time; it should be noted that for the case of an inviscid fluid, the injection rate does not affect the fluid pressure. Other features of the model include accounting for formation leak-off and focusing the lattice resolution to be finest in the expected direction of fracture propagation.

Table 1. Colton Sandstone Rock Properties (Casas et al. 2006, Chuprakov et al. 2014, Stanchits et al. 2014).

Rock Properties	Value
Density	$2380[kg/m^3]$
E	$20.4[GPa]$
υ	$0.2[-]$
UCS	$69[MPa]$
Tensile Strength	$7.4[MPa]$
Fracture Toughness	$0.47[MPa.m^{0.5}]$
Porosity	10.9%
Permeability	$4 \times 10^{-17}[m^2]$
Joint Aperture	$3.175[mm]$
Joint Friction Coefficient	$0.01[-]$
Joint Tensile Strength	$0[MPa]$
Joint Cohesion	$0[MPa]$

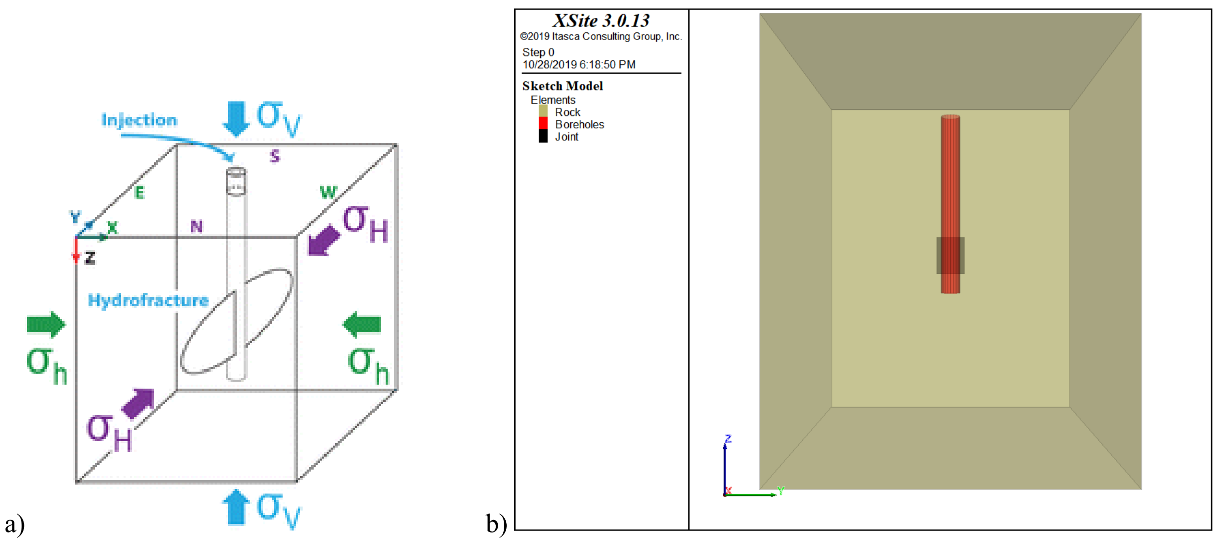

Figure 1. a) Illustration of the experimental setup used by Stanchits et al. (2014). b) *XSite* model geometry, including representation of the injection borehole, isolated section, and two longitudinal scribes used to facilitate initiation of the hydraulic fracture.

3 RESULTS AND DISCUSSION

Figure 2 compares the results of the *XSite* simulation (red dashed-lines) with the reported results of the laboratory experiment (solid blue line). These show that the normalized displacements and cumulative AE counts agree with those from the laboratory test results, including reproducing the same breakdown pressure of 31 MPa. Small discrepancies in the different outputs are most likely due to the model assuming that the rock is homogenous with no flaws present prior to the test, while the actual rock used in the lab experiment would most likely contain micro flaws and heterogeneity.

Further efforts were made to compare the spatio-temporal distribution of AE events generated by *XSite* with the laboratory experiment results. Figure 3 shows the distribution of the AE hypocenters with amplitudes larger than 75 dB recorded during the test right before the breakdown pressure was reached (the accuracy of AE hypocenter localization is reported to be about 6 mm in Stanchits et al. 2014). Similarly, Figure 4 shows the distribution of AE events modeled for the same period. Comparison of these figures indicate that the overall spatio-temporal distribution of the events are in good agreement.

Recognizing that the amplitude cutoff used significantly limited the number of AE hypocenters located, Stanchits et al. (2014) calculated the density of AE events within a sliding cube of dimensions $5 \times 5 \times 5\ mm$. These results were subsequently calculated as a normalized fraction of the maximum number of AE hypocenters counted, and are plotted in Figure 5a. Figure 5b shows the corresponding hypocenters of the AE events generated in the *XSite* simulation across the domain (without normalization). Comparison between these two plots indicate a good agreement with respect to the shape of the hydraulic fracture. Specifically, the left wing of the hydraulic fracture in Figure 5a developed slightly downwards which is also visible in the numerical results in Figure 5b. Observed discrepancies are believed to be caused by the size differences between the grain size of the rock specimen and the lattice resolution in the numerical model, as well as the previously noted simplifying assumptions of homogeneity and no flaws being present in the lattice domain.

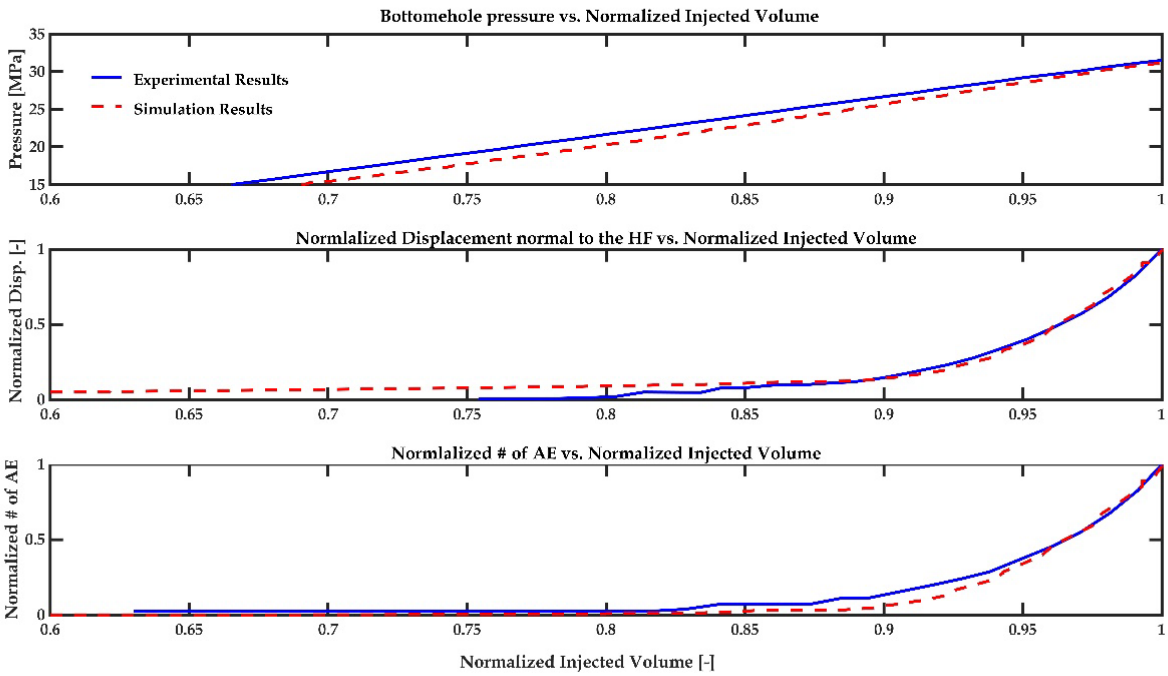

Figure 2. Comparison between the *XSite* numerical results (red dashed-line) and Stanchits et al.'s (2014) experimental results (blue solid line), for the wellbore pressurization history, normalized rock deformations perpendicular to the hydraulic fracture, and normalized cumulative AE event count as a function of the normalized injected volume.

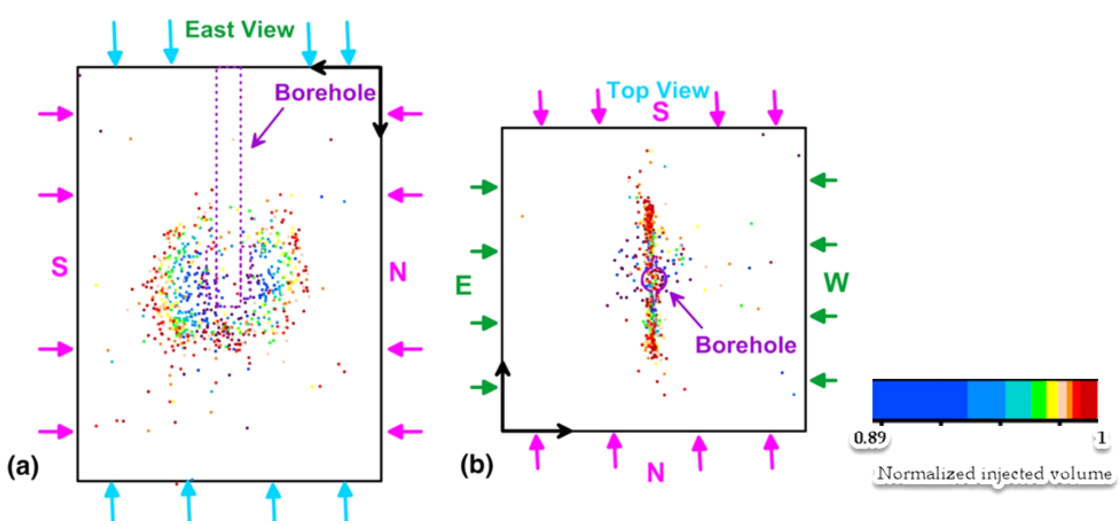

Figure 3. Orthogonal projections: a) front-view, b) top-view, of the AE hypocenters recorded with amplitude $> 75dB$ before the borehole breakdown pressure was reached in the laboratory experiment by Stanchits et al. (2014). The color coding represents the normalized injected volume.

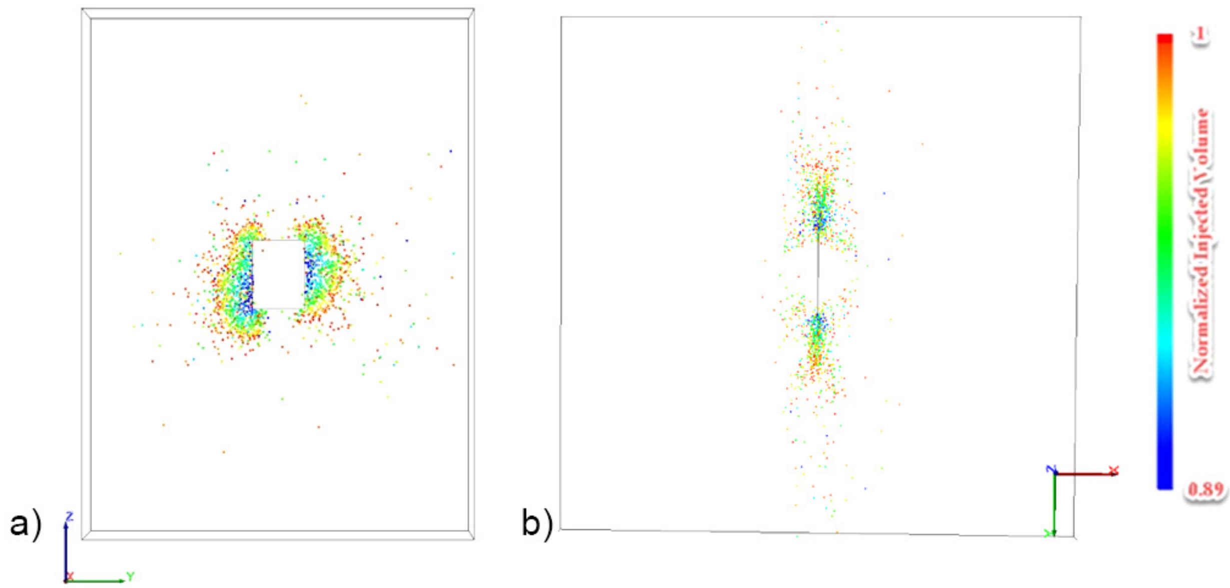

Figure 4. Orthogonal projections: a) front-view, b) top-view, of the AE hypocenters generated by the *XSite* numerical simulation before borehole pressure breakdown was reached. The color coding represents the normalized injected volume.

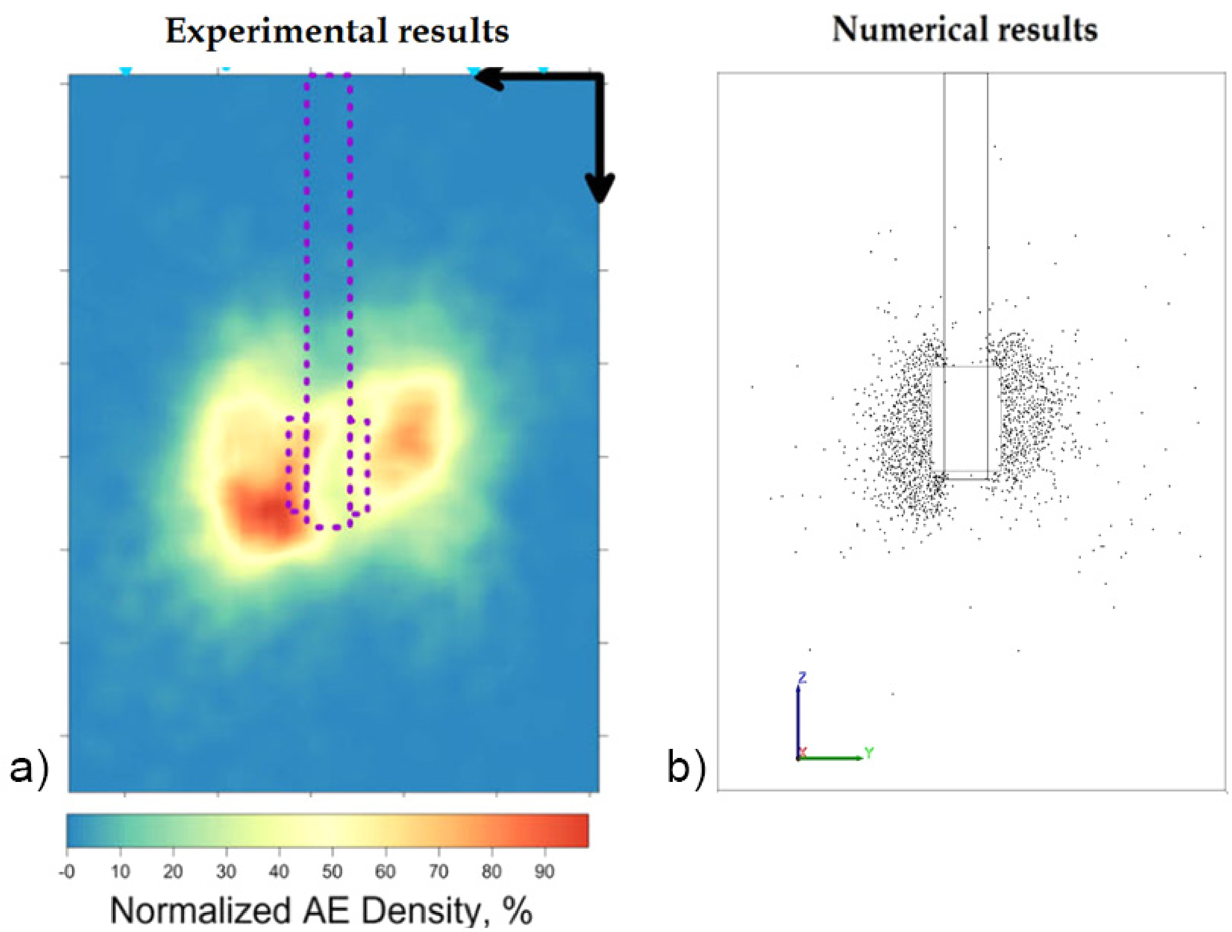

Figure 5. Side-view projections comparing: a) density mapping of AE hypocenters localized before breakdown in the laboratory experiment by Stanchits et al. (2014), and b) AE hypocenters localized before breakdown in the *XSite* numerical simulation.

4 CONCLUSIONS

A validation exercise using the 3-D hybrid lattice and bonded-particle code *XSite* was performed by simulating a laboratory-scale hydraulic fracturing test carried out by Stanchits et al. (2014). The hydraulic fracture propagation in the laboratory test was assumed to correspond to the toughness dominated regime suggested by Detournay (2016). Comparison of the observed results in the actual experiment and the *XSite* simulation showed the same breakdown pressure of 31 MPa at the same normalized injection volume. Moreover, the simulation results of the normalized-displacements and cumulative AE event counts versus the normalized injected volume were found to be in good agreement with the experimental results. This included the spatio-temporal distribution of AE hypocenters. Minor discrepancies between the experimental and modeled results are believed to be due to the differences between the nature of the rock, where heterogeneities would be present, and the numerical representation of a homogeneous rock, as well as the differences between the size of the lattice resolution and the grain size of the rock.

Based on the results of this study, it can be concluded that *XSite*, with proper calibration, is capable of reliably modeling the hydraulic fracturing behavior of intact rock, including the breakdown pressure, the location of AE hypocenters, the shape of the hydraulic fracture, and volumetric deformation. As such, it offers significant potential as a modeling tool for understanding the onset of microseismic events during hydraulic fracture initiation at the field scale, including the development of fracture width and the general propagation path of the hydraulic fracture as required for hydraulic fracture design, evaluation and production prediction.

ACKNOWLEDGEMENTS

The authors would like to thank Itasca Consulting Group, Inc. for their support in providing access to their *XSite* software for the work performed in this study. The authors would also like to thank Dr. Sergey Stanchits for his constructive comments. This research was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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