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Coupled Flow-Geomechanical Model for Hydraulic Fracturing simulation – Impact of Variable Stress Ranges and aperture dynamics

Timur Sabirov, Juliana Leung

Department of Civil & Environmental Engineering, University of Alberta

Summary

This study presents an enhanced fracture propagation model to simulate hydraulic fracturing processes, leveraging insights derived from low-frequency distributed acoustic sensing (LF-DAS) data. The model integrates coupled flow and geomechanical simulation to analyze the complex interactions of stress, strain, and pressure during hydraulic fracturing stimulation. Linear Elastic Fracture Mechanics (LEFM) approach for updating fracture aperture dynamics may offer a viable alternative to the empirical Barton-Bandis model used in previous studies (Bandis et al., 1983; Barton et al., 1985). The results suggest that differences in observed strain rate responses, often compared to LF-DAS waterfall plots, could possibly be attributed to differences in fracture aperture dynamics.

Theory and Method / Workflow

According to previous studies, the finite volume method is used for flow equations and the virtual element method is used for geomechanical computations (Chen et al., 2024). Empirical fracture aperture models, particularly the Barton-Bandis model, are among the most common in hydraulic fracture studies (Lei & Barton, 2022). However, empirical models are not the most reliable as they work only within a certain range of reservoir conditions for tested samples. According to the LEFM approach, fracture opening is modelled as a function of fracture toughness, fluid pressure and normal stress acting on the fracture. Maximum fracture opening (displacement) is calculated as (Bisdom et al., 2016):

$$d_{max} = \frac{K_c(1-\nu^2)}{E\sqrt{\frac{\pi}{8}}}\sqrt{L}, \tag{1}$$

Where K_c represents fracture toughness, ν is the Poisson's ratio, E is the Young's modulus in Pa, L is the fracture length in m.

Fracture toughness is given as:

$$K_c = \Delta\sigma_1\sqrt{\frac{\pi L}{2}}, \tag{2}$$

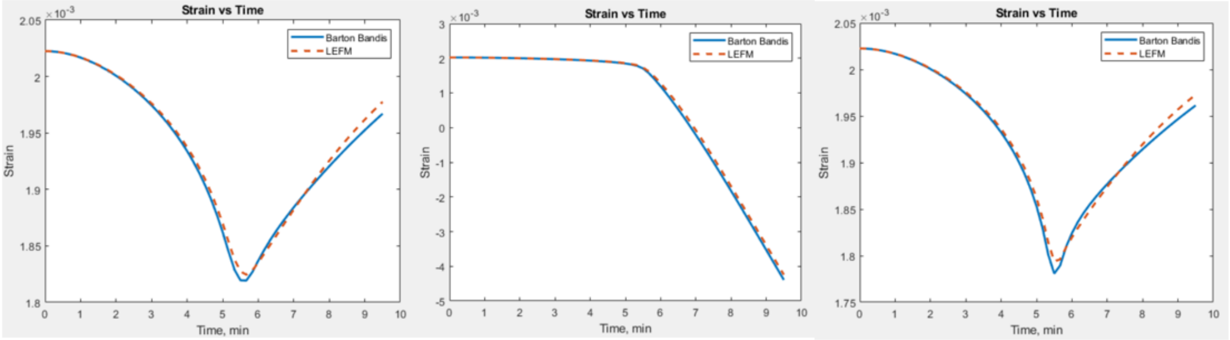
Where $\Delta\sigma_1$ is the driving stress, which represents the difference between internal fracture pressure p_f and the normal stress acting on the fracture (Bisdom et al., 2016). Combining equations (1) and (2), we obtain the following equation for the fracture aperture updating with time:

$$a = a_i + \frac{4(p_f - \sigma_n)(1-\nu^2)L}{E}, \tag{3}$$

Where a_i is the no-load fracture aperture. Different studies show that vertical (overburden) stress and varying stress magnitudes might also have an effect on a fracture propagation (Radwan & Sen, 2021; Wang et al., 2024).

Results, Observations, Conclusions

Two hydraulic fracture aperture models were tested under different ranges of horizontal and vertical stresses, including the normal faulting regime ($\sigma_v \geq \sigma_H \geq \sigma_h$) and the strike-slip faulting ($\sigma_H \geq \sigma_v \geq \sigma_h$). The model setup consists of one treatment well and one monitoring well, with a grid size of 40 × 80 m. The hydraulic fracture is located in the middle of the grid (40 m). The effect of varying well spacing (the distance between the treatment and monitoring wells) was also examined. Several stress, strain, and pressure distributions, as well as LF-DAS simulated waterfall plots for strain rate, were generated for each stress regime and well spacing.
Results for the LEFM model were consistent with those of the Barton-Bandis model for both stress regimes, with slight differences observed in the strain profile under the normal faulting stress regime (Figure 1). This indicates that the LEFM model is also suitable for hydraulic fracturing numerical simulations.



a) Location = 38 m

b) Location = 40 m

c) Location = 42 m

Figure 1. Strain profile for two aperture models and three different locations (normal faulting regime).

Regarding the simulated waterfall plots, both models produced similar results. However, the LEFM model exhibited a longer compression zone after the fracture hit (Figure 2).

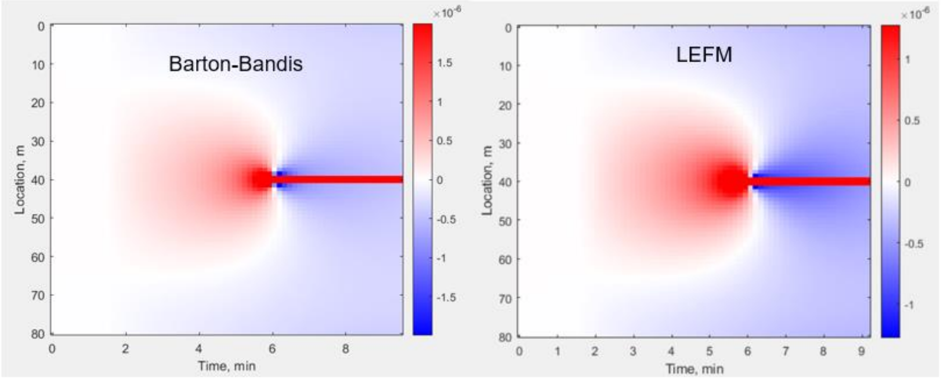


Figure 2. Strain rate map for two aperture models (normal faulting regime, y=55).

Novel/Additive Information

We incorporated vertical stress into the current hydraulic fracturing numerical simulation model to enable more comprehensive analyses of hydraulic fracture propagation under three stress conditions. Additionally, we compared the performance of the model using two different aperture models across various stress ranges. The results highlight how fracture aperture dynamics could possibly impact strain rate responses and LF-DAS waterfall plots.

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