Coupling between fluid pressure and opening during fluid injection into a single fracture

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Résumé

In low-permeability rocks such as crystalline formations, fluid transport occurs primarily through discrete fractures. Understanding how fluid injection perturbs the mechanical state of these fractures-and how fracture deformation, in turn, influences fluid flow-is essential for characterizing hydro-mechanical processes in the subsurface. In this study, we investigate the coupled interaction between fluid pressure and fracture aperture during injection into a single, zero-toughness fracture. We specifically analyze the role of normal stiffness in governing the strength of this coupling by comparing soft (low-stiffness) and rigid (high-stiffness) fracture cases.
To model the system, we first use semi-analytical similarity solutions to linear and nonlinear diffusion equations that relate pressure to aperture through a linear effective stress law. We then extend this formulation by incorporating the elastic response of the surrounding rock using a 2D elastic half-space solution, which yields a Fredholm integral equation that computes fracture deformation caused by both fluid pressure and the pressure-induced normal stress. We benchmark the semi-analytical solutions against numerical simulations using the Discrete Element Method (3DEC), where fluid is injected under constant overpressure.

Our results show that fracture stiffness has a strong influence on both aperture evolution and pressure propagation. Soft fractures exhibit greater opening and stronger aperture gradients, leading to the development of steep pressure profiles and sharp propagation fronts similar to hydrodynamic shocks. These fronts are accompanied by localized peaks in aperture gradient, tensional normal stress ahead of the front, and compressional stress near the injection point. In contrast, rigid fractures deform uniformly and show smooth pressure profiles characteristic of classical linear diffusion. The agreement between semi-analytical solutions and 3DEC simulations confirms that the square-root-of-time scaling holds in both stiffness regimes, while highlighting that stress localization and shock-like fronts emerge only under strong fluid–solid coupling.

Mots-Clés: fluid injection, fracture, hydromechanics, semi, analytical solutions, numerical simulation

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