Energy balance of fluid driven frictional rupture in a fractured rock mass

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Abstract

Re-activation of pre-existing discontinuities in the form of fractures and faults can occur due to fluid pressurization at depth. The increase of fluid pressure can facilitate the propagation of slow frictional ruptures over considerable distances and can also trigger frictional instabilities. These can occur in response to either anthropogenic fluid injection (e.g. hydraulic stimulation) or via natural occurences (e.g. serpentine dehydration). Hydraulic stimulation, a commonly employed technique in various geo-energy applications, aims to enhance the permeability of rock formations by creating new fractures or reactivating the pre-existing ones with pressurised fluid injection. This process induce slip along existing fractures, resulting in a range of behaviors from stable, slow-slip events to more rapid, dynamic ruptures.
Recent studies have made significant strides in quantifying the mechanics of fluid-induced frictional slip in single-plane systems. For instance, Sáez and Lecampion (2024) identified four distinct slip regimes for a fluid-induced slip-weakening fault in 3D, progressing from quasi-static slip to nucleation, arrest, and ultimately a runaway dynamic rupture based on three dimensionless numbers that consist information on the in-situ stress state, injection strength and peak and residual friction coefficients (1) . These findings provide a clear understanding of how single-plane fractures respond to fluid pressure. However, the response of interconnected fracture networks, which is more representative of real-world subsurface conditions, to fluid injection remains poorly understood. The intricate stress interactions that arise between multiple fractures under fluid pressure introduce an additional level of complexity that existing theoretical and numerical models have yet to fully capture. Although some numerical studies have qualitatively explored the behavior of fracture networks subjected to fluid injection, detailed quantification of energy distribution and slip mechanics within these interconnected systems have not been investigated in detail (2).

In this study, we derive an energy balance of the hydro-mechanical system consisting of the fractured rock mass and the injected fluid. Our primary goal is to understand the overall energy budget, and notably quantify the partitioning of the energy dissipated in plastic slip along major and the surrounding minor fractures. Specifically, we evaluate whether the presence of additional smaller fractures leads to a shielding effect on major fractures-where stress interactions inhibit rupture propagation-or a promoting effect, where interactions facilitate rupture growth and energy transfer, as function of in-situ stress, statistical and material properties of the discrete fracture network, as well as injection conditions.

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References:

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