Numerical investigation of coupled thermo-hydro-mechanical subsurface processes: importance of thermal effects and pressure diffusivity on post-injection seismic events

Khashayar Khezri, Centre de Géosciences, Mines Paris-PSL

Geothermal energy stored in deep hot dry rocks (HDR) offers significant potential for sustainable electricity and heat production. Enhanced Geothermal Systems (EGS) enable access to this energy by artificially stimulating reservoirs through methods such as hydraulic fracturing, acid injection, CO_2 injection, etc [1]. The extraction process involves complex interactions between fluid flow, heat transfer, and rock deformation—collectively known as thermo-hydro-mechanical (THM) coupling. A thorough understanding of these processes, along with the behavior of fracture networks, is crucial for the effective design and optimization of EGS.

One of the primary challenges in EGS is induced seismicity, particularly delayed or post-injection seismic events. These events often occur after fluid injection has stopped and can be more intense than those recorded during injection. The frequent occurrence of such delayed events highlights gaps in current scientific understanding. Moreover, earlier models that link seismicity solely to the volume of injected fluids fail to capture the full range of influencing factors [2]. This research aims to deepen our understanding of pressure and temperature diffusivity in HDR and how they interact with in-situ stress fields and fracture networks—key factors in better predicting and managing induced seismicity in geothermal systems.

This study utilizes COMSOL Multiphysics to develop and validate coupled THM models at both laboratory and field scales. These models aim to simulate the interactions between temperature, pressure, and stress fields in fractured HDR environments, providing insight into the mechanisms driving delayed induced seismicity.

A critical first step in this process is the generation of realistic fracture networks, as fracture geometry and properties have a significant impact on fluid flow, heat transport, and stress redistribution throughout the domain. To address this, fracture networks are generated based on statistical laws and incorporate simplified mechanical interactions between fractures to better represent natural systems (figure 1).

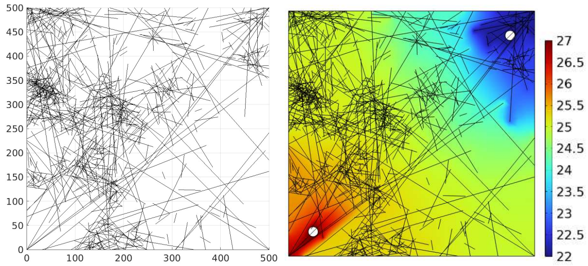

Figure 1: Generated fracture network (left) based on dual power law along with its clusters and connectivity and pressure distribution (right) in MPa

Following this, a thermo-hydraulic (TH) model is developed and validated using analytical solutions. This model is used to assess the performance of geothermal systems with different working fluids, including water and supercritical CO_2. Next, hydro-mechanical (HM) coupling is incorporated and validated against available field data to improve model reliability and applicability.

Finally, by integrating all components into a fully coupled THM model, the study simulates pressure and temperature evolution under varying initial stress states and realistic fracture network. This comprehensive model enables detailed analysis of how thermal and pressure changes influence the timing, magnitude, and frequency of induced seismic events, particularly those occurring after fluid injection ceases.

- **References**

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[2] McGarr, A., 2014. Maximum magnitude earthquakes induced by fluid injection. *Journal of Geophysical Research: solid earth*.