Effect of pore fluid properties on dynamic slip of sandstone-derived fault gouges

Chien-Cheng Hung (c.hung@uu.nl) and André Niemeijer

Introduction & Motivation

The thermal (e.g., expansivity) and hydraulic (e.g., viscosity) properties of pore fluid within the fault core significantly influence the slip behavior of faults as thermal pressurization by frictional heating is controlled by these parameters. Wet faults (water as pore fluid) in Groningen gas field lithologies have been reported to weaken significantly in a short seismic slip pulse (Hunfeld et al., 2021; Chen et al., 2023). However, the in-situ pore fluid in the gas reservoir is much more complex, consisting of a mixture of brine and methane, which have different viscosity \( \eta \) and thermal pressurization factor \( \Lambda \). To investigate and predict the potential slip behavior of faults in the gas reservoir, we conducted seismic slip-pulse rotary-shear friction experiments on Slichter sandstone gouges with different types of pore fluid at various pore fluid pressures. We then validated the experimental observations using analytical solutions. Our results indicate that thermal pressurization is the primary weakening mechanism for all types of fluid investigated. In addition, the variation in the friction, pore pressure and temperature between the measured data and the prediction suggests that the localization of slip in the gouge layer might differ between fluid. Once the experimental observation can be systematically predicted by analytical and numerical models, we can better constrain the fault behavior and weakening for the induced seismic in the Groningen gas reservoir.

Methodology: Rotary-shear friction experiment

(a) Photograph of the pressurized gouge setup installed in the RAP. (b) Photograph of the sample holder with an inner and an outer confining brass ring together with steel pistons. (c) Schematic plot of the pressurized gouge setup for RAP.

Results

Assumed reservoir and earthquake conditions for the planar slip model:

- Normal stress \( \sigma_\text{r} \): 15 MPa
- Ambient pore pressure \( P_\text{a} \): 15 MPa
- Ambient temperature \( T_\text{a} \): 100 °C
- Pore fluid: Mixture of brine and methane
- Slip velocity \( v \): 1 m/s
- Starting gouge porosity \( n_0 \): 0.15
- Assumed material properties:
  - Thermal diffusivity \( \kappa_0 \): 0.77 mm²/s
  - Fluid viscosity \( \eta_0 \): 3.5 mPas (brine)
  - Fluid thermal expansivity \( \alpha_0 \): 0.65 × 10⁻⁴ °C⁻¹ (brine, 2000)
  - Pore space thermal expansivity \( \alpha_S \): 0.19 × 10⁻⁴ °C⁻¹ (Hunfeld, 2006)
  - Fluid compressibility \( \beta_f \): 6 × 10⁻⁹ Pa⁻¹ (brine)
  - Pore space compressibility \( \beta_S \): 6.5 × 10⁻⁹ Pa⁻¹ (Rice, 2000)
  - Permeability \( k \): 2 × 10⁻⁶ m²

Resulting material properties:

- Pressurization factor \( \Lambda \): 1.23 MPa °C⁻¹
- Hydraulic diffusivity \( \kappa_f \): 0.29 mm²/s
- Maximum temperature \( T_\text{max} \): 152 °C

Our experimental results indicate that the slip process is significantly influenced by the hydraulic properties of the pore fluid. In particular, the viscosity and thermal expansivity of the pore fluid play a crucial role in the frictional behavior of the fault. We validated our model predictions against the experimental data, and the agreement is satisfactory, indicating that our approach can be used to predict the slip behavior of faults under reservoir conditions, even when the fluid properties are known.

Prediction based on analytical solution (Rice, 2006)

Figure 1

Figure 2

Figure 3

Figure 4

Summary & Future work

- Independent of the pore fluid pressure and the types of pore fluid investigated, all wet gouges show weakening due to thermal pressurization which is significantly controlled by the fluid viscosity and the pressurization factor.
- Higher temperature rise but lower pore pressure increase in the brine experiment than in water experiment suggests that the localization of slip in the gouge layer might be varied between fluid.
- Numerical modeling is required to obtain a better prediction for the experimental observation and hence to predict the slip behavior of faults under Groningen reservoir conditions, if some in-situ fluid properties are known.

Reference

- Chen et al., 2023
- Hunfeld et al., 2021
- Rice, 2006