

# **Reservoir Induced Seismicity Modelled Using a Fully Coupled Poro-Visco-Elasto-Dynamic Model with Frictional Contact and Rate-and-State Dependent Friction: Dynamics of Spontaneous Coseismic Rupture**

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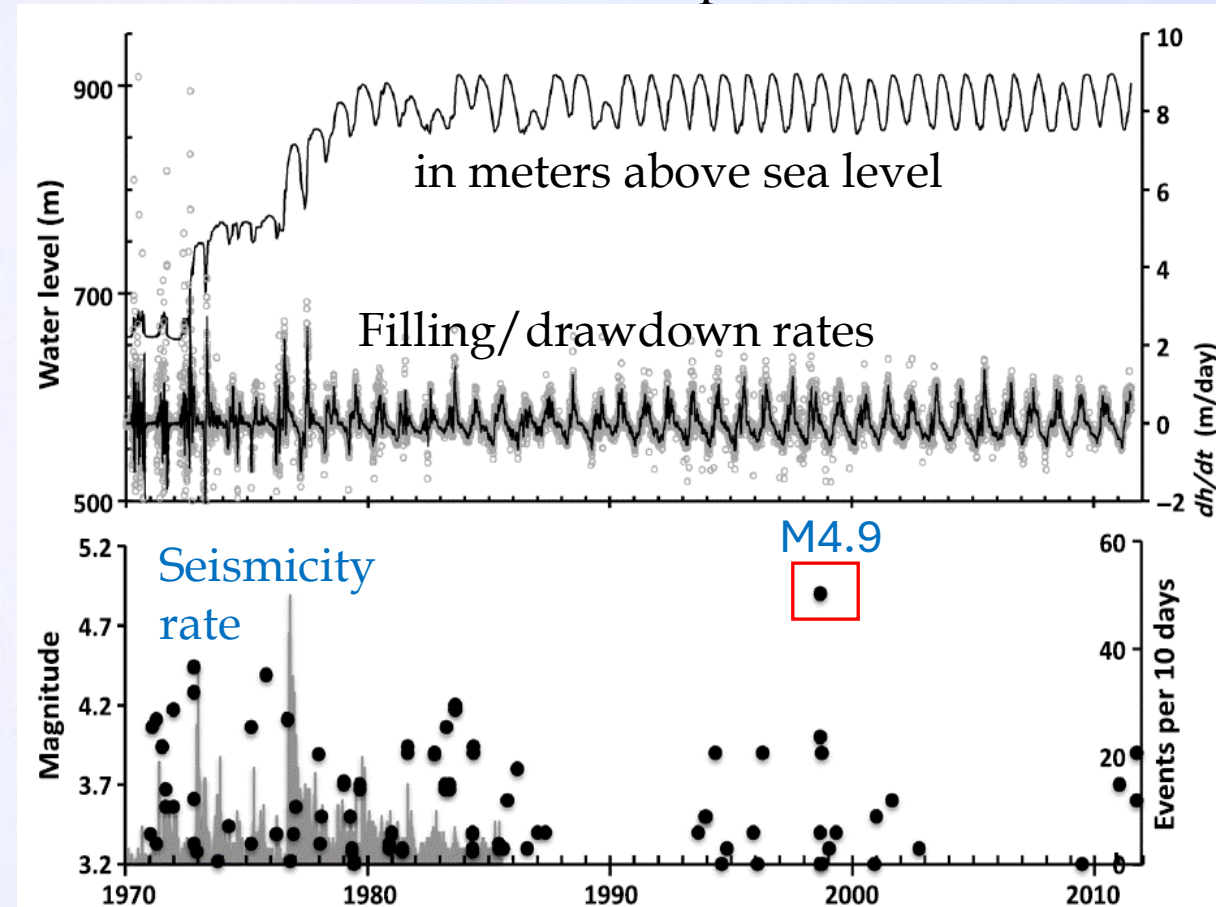
May 7<sup>th</sup>, 2026

# Introduction



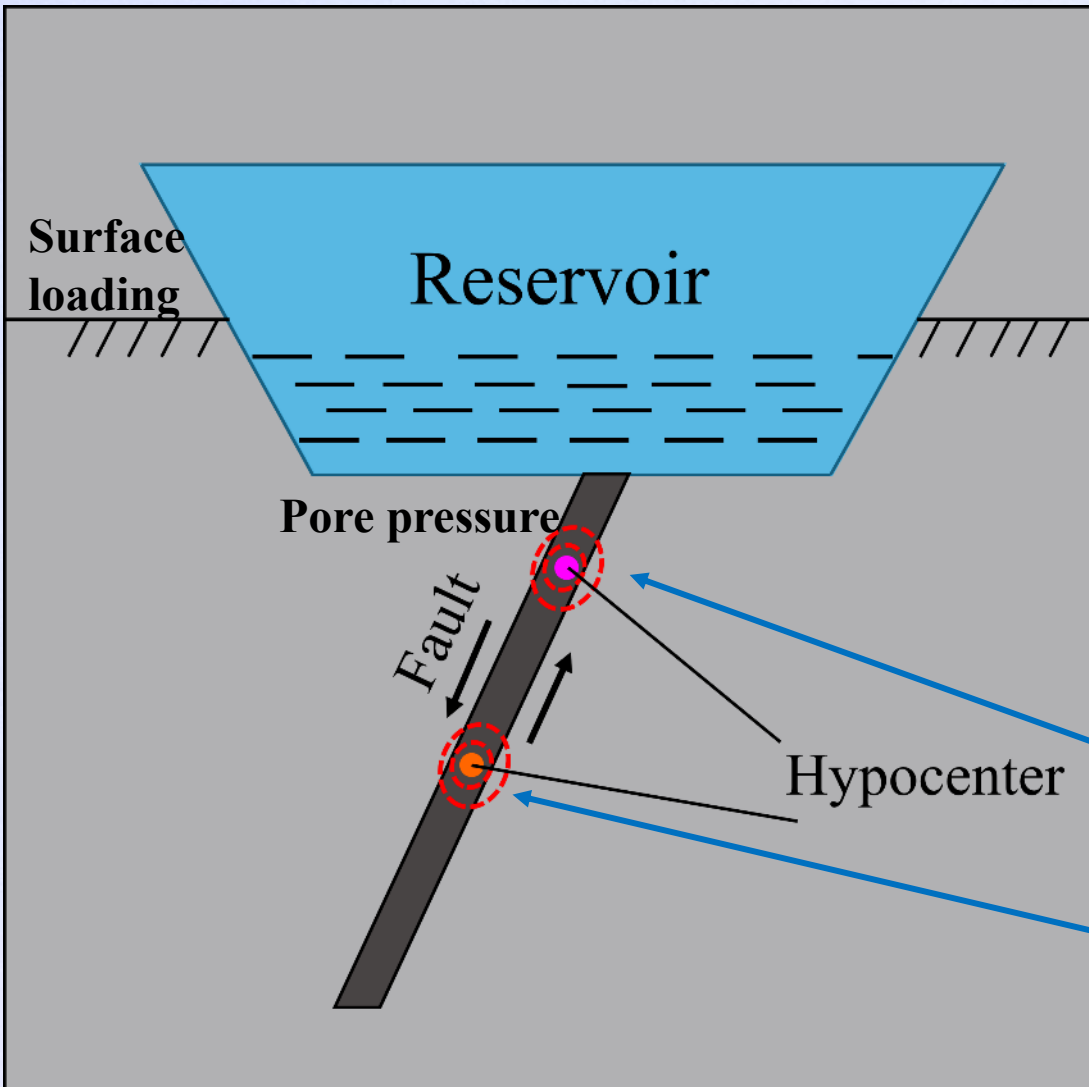
View of Koyana reservoir with Koyana dam in India, where **have been about 120 cases of triggered earthquakes**, one of the largest is M6.3 in 1967

**Reservoir Induced Seismicity (RIS)** is a kind of induced seismicity where reservoir **impoundment** and **water level fluctuations** induce the earthquakes.



*Simpson et al. (2018), Nurek reservoir, Tajikistan*

# Introduction



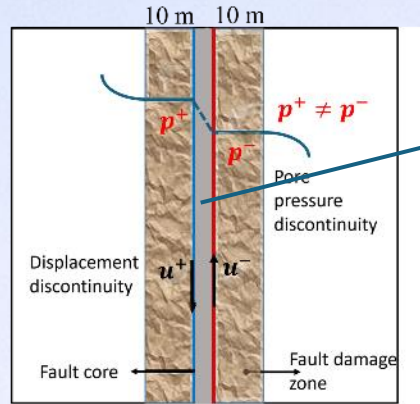
A unified model that integrates **pore pressure diffusion** over the fault, poro-visco-elastic rock response, frictional contact, and **fully dynamic** rupture processes for RIS **remains largely absent**.

**Rapid response with lower magnitude:** Appears immediately at **shallow subsurface**

**Delayed response with higher magnitude:** Associated with fluid motion from the reservoir or lake over the faults **to the depth**

# Materials and Methods

$$P = \max(p^-, p^+)$$



virtual thin-layer

- The fault is represented as a **discontinuous contact pair** with zero initial gap, allowing for an explicit treatment of **displacement discontinuity** across the interface.

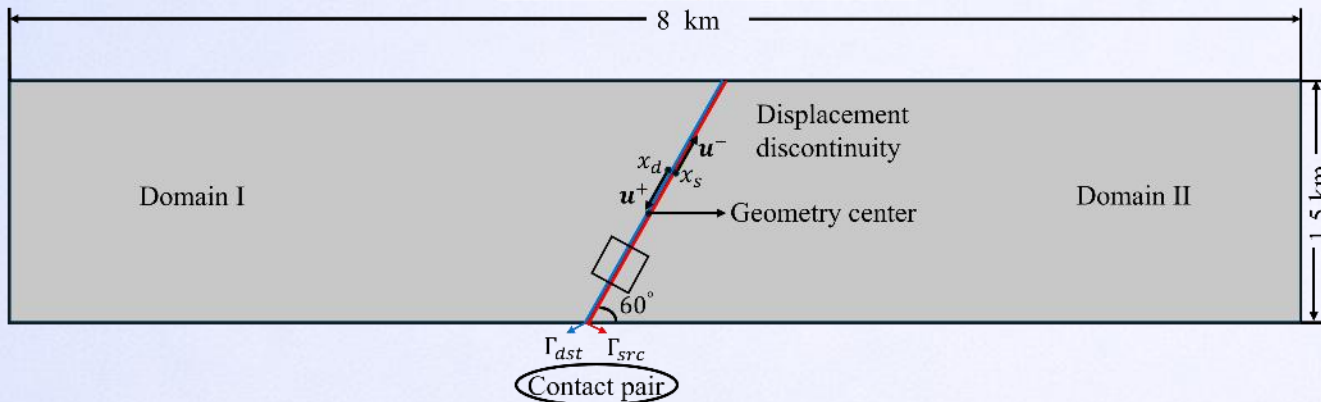
## Equations for domains

**Solid deformation**  $\rho_b \frac{\partial^2 \mathbf{u}}{\partial t^2} - \nabla \cdot \boldsymbol{\sigma} = -\alpha \nabla P + \rho_b \mathbf{g}$

**Fluid flow**  $S \frac{\partial P}{\partial t} + \nabla \cdot \left[ -\frac{\kappa}{\mu_f} (\nabla P - \rho_f \mathbf{g}) \right] = -\alpha \frac{\partial \boldsymbol{\varepsilon}_{vol}}{\partial t}$

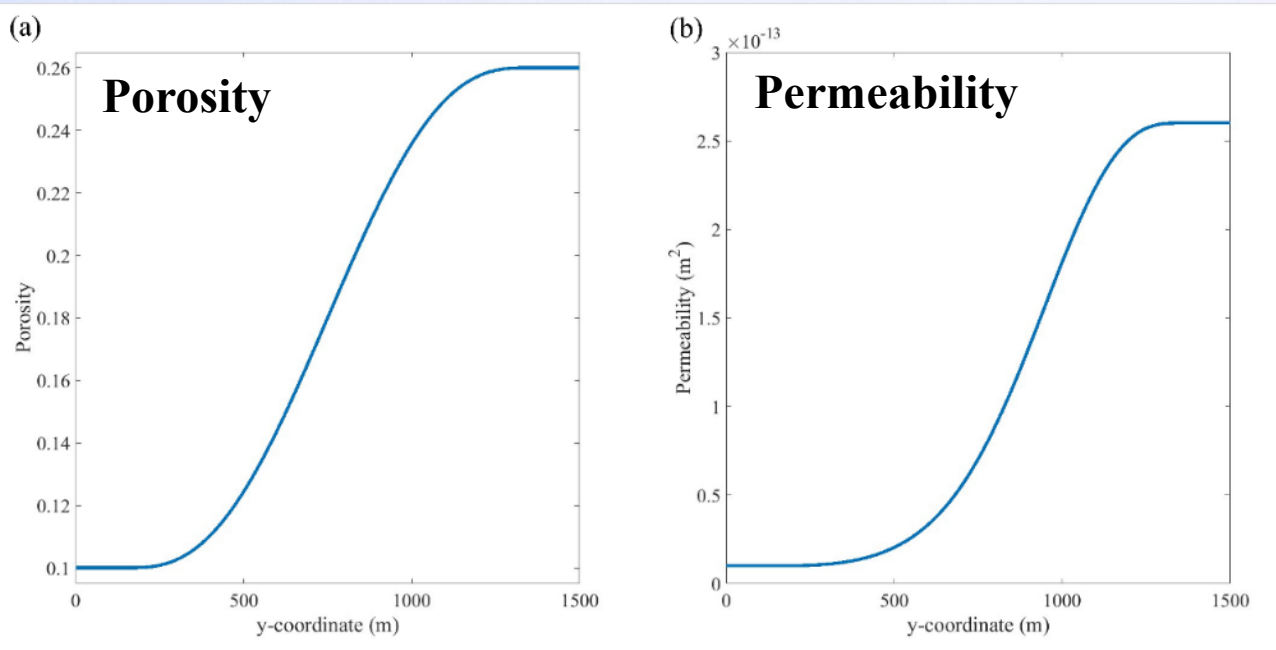
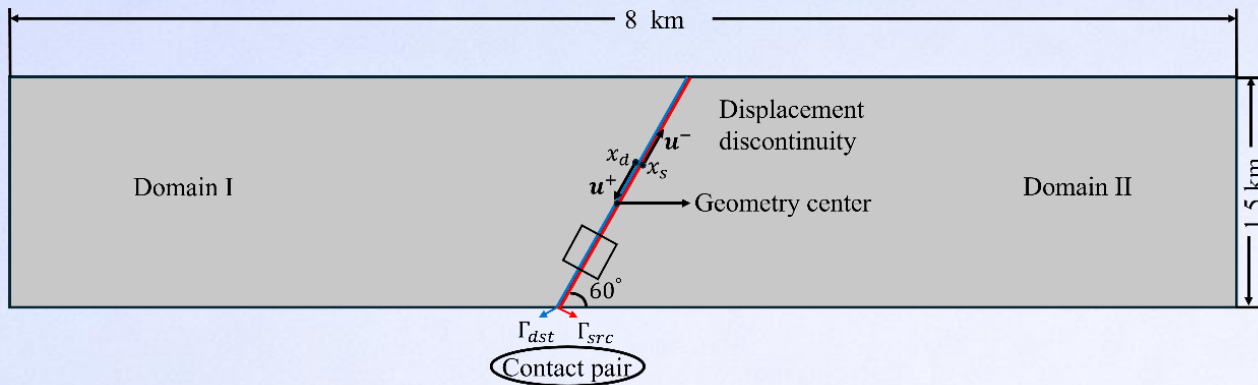
**Stresses**  $\boldsymbol{\sigma} = \boldsymbol{\sigma}_0 + \mathbf{C} : \boldsymbol{\varepsilon}_{el} + \boldsymbol{\sigma}_d$

**Kelvin-Voigt viscoelasticity**  $\boldsymbol{\sigma}_d = 2\eta \dot{\boldsymbol{\varepsilon}}_{el,dev}$



- The contact pair formulation also enables representation of **pore pressure discontinuity**.
- **The fault is modelled as fracture**, consistent with in-situ conditions where an impermeable fault core separates **permeable adjacent damage zones**.

# Materials and Methods



**Porosity (a) and permeability (b) on the fault**  
**Depth-dependent variations in porosity and permeability**

## Equations for fault (fracture)

- **Fracture flow** is represented by Darcy's law integrated across the fracture thickness.

**Porosity-permeability relations**

$$\kappa_f = \kappa_0 \cdot \frac{\phi_f^3 (1 - \phi_0)^2}{\phi_0^3 (1 - \phi_f)^2}$$

**Mohr-Coulomb failure criterion for effective stress**

$$T_{tcrit} = \begin{cases} \mu(T_{np} - P) + c_f, & T_{np} > P \\ c_f, & T_{np} \leq P \end{cases}$$

**Rate-and-State friction coefficient**

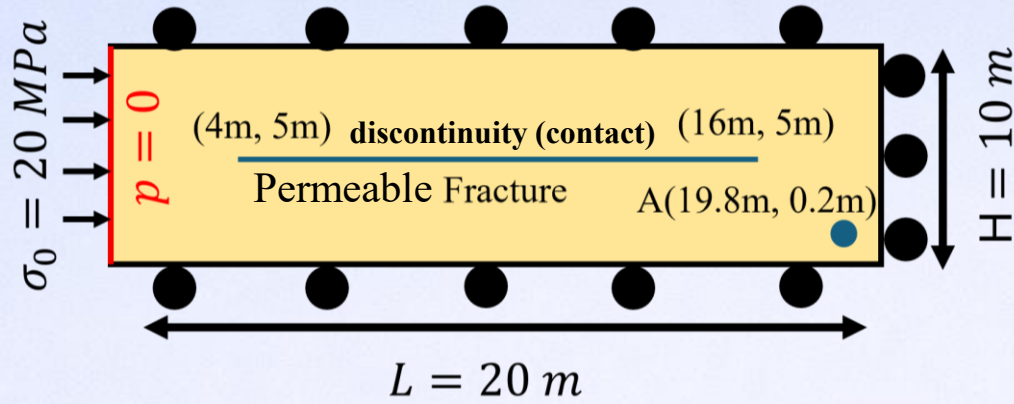
$$\mu = \mu_0 + A \cdot \ln\left(\frac{V}{V_0}\right) + B \cdot \ln\left(\frac{\theta V_0}{D_c}\right)$$

**“Aging law” for state variable**

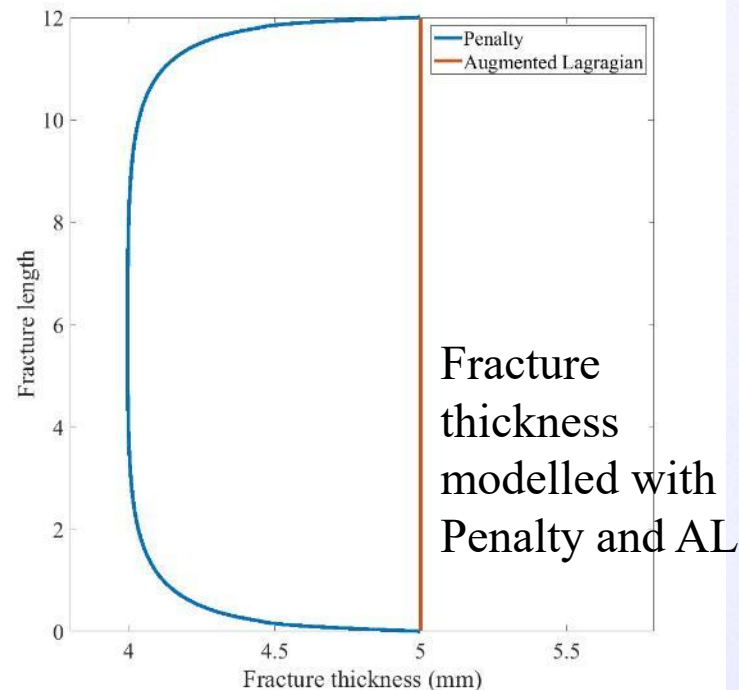
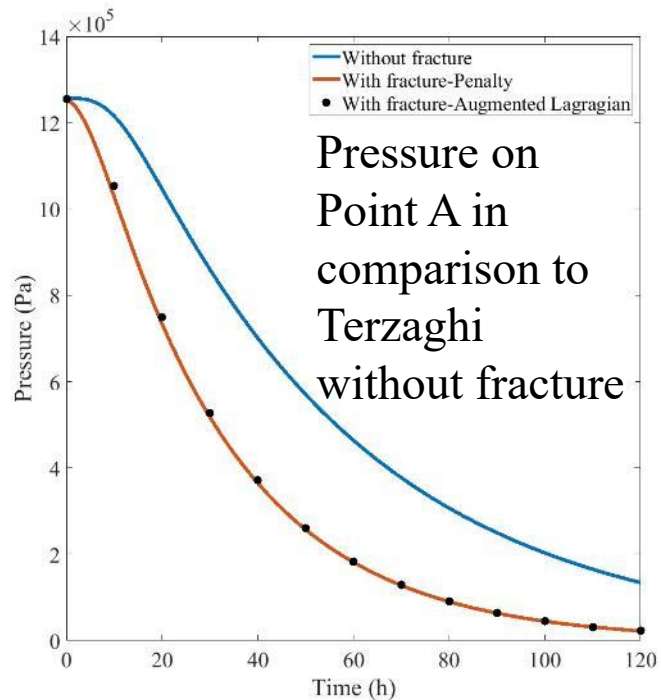
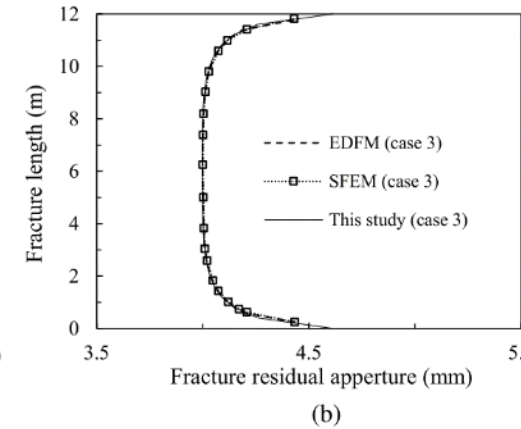
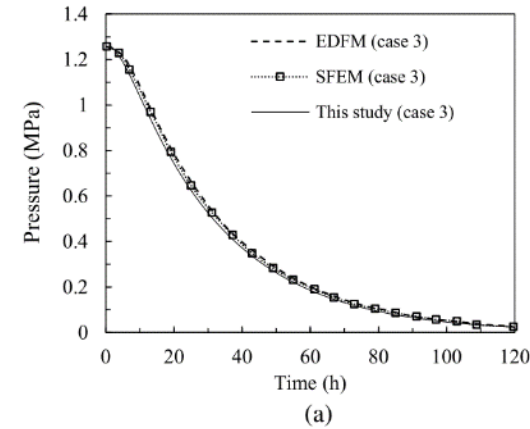
$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}$$

- **Numerical implementations:** FEM based on COMSOL Multiphysics (v6.2).

# Validation I: Terzaghi's problem with longitudinal discontinuity (contact) and permeable fracture



The results have a good agreement with the results from Damirchi et al., 2022.



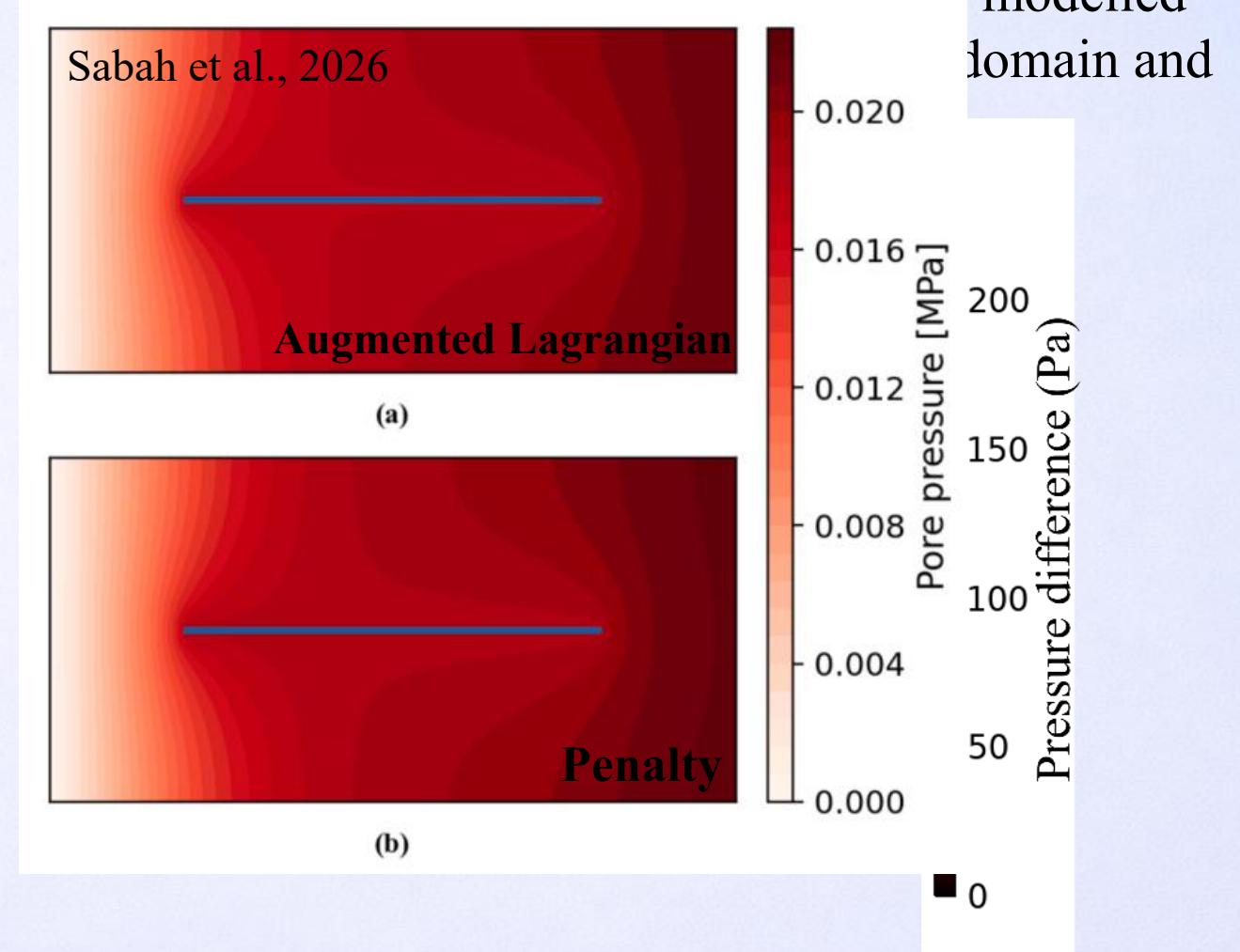
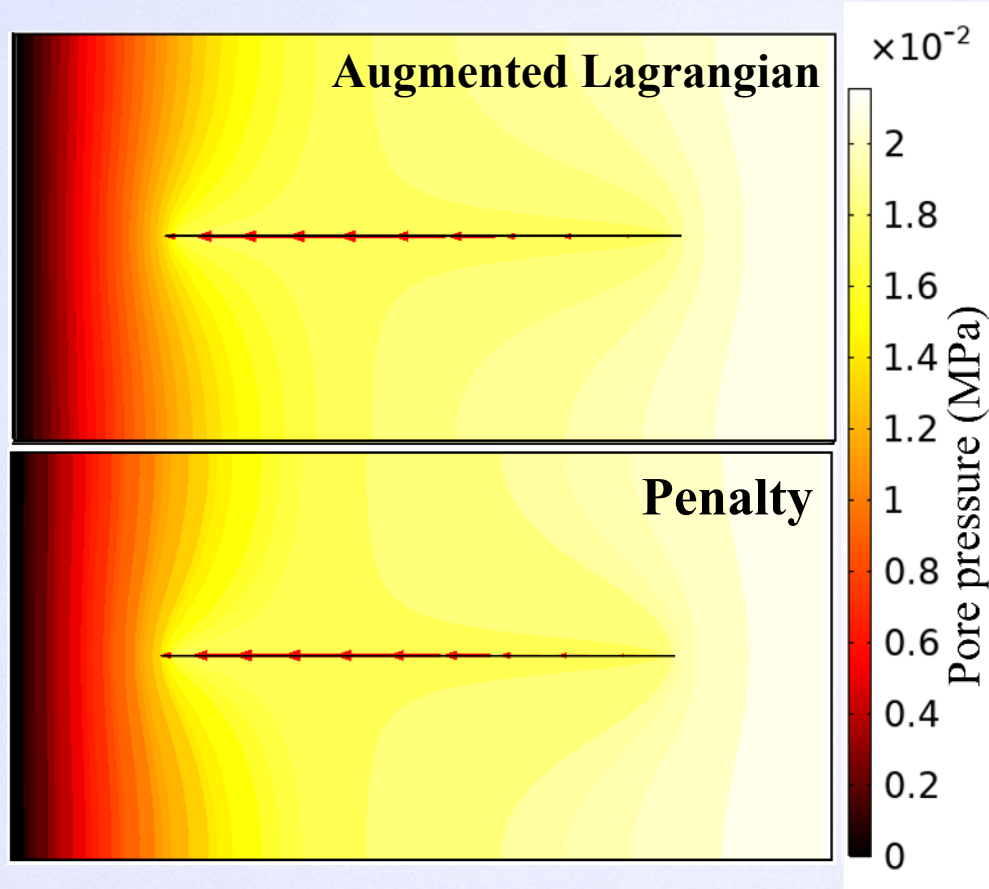
## Methods for contact implementation

- **Penalty method:** Enforces contact by introducing a high-stiffness virtual spring between the surfaces, allowing **small surfaces interpenetration**.
- **Augmented Lagrangian method:** Enforces **contact more strictly** by combining Lagrange multipliers with a penalty term.

# Validation I: Terzaghi's problem with longitudinal discontinuity (contact) and permeable fracture (cont...)

The results show a good agreement with the results from Sabah et al., 2026.

- **Enhanced fluid flow** over the fracture shown by arrows
- **Non-uniform** pressure over the domain
- **Minor difference** between the pressures modelled domain and



# Validation II: spring-slider with gravity

To validate rate & state friction implementation

## The 2D spring-slider model

### The 0D model on the red point

$$m\ddot{x} = \underbrace{k(V_s t - x)}_{\text{Driving force}} - \underbrace{F_\tau}_{\text{Frictional resistance}}$$

Driving force      Frictional resistance

Coulomb failure with gravity at contact

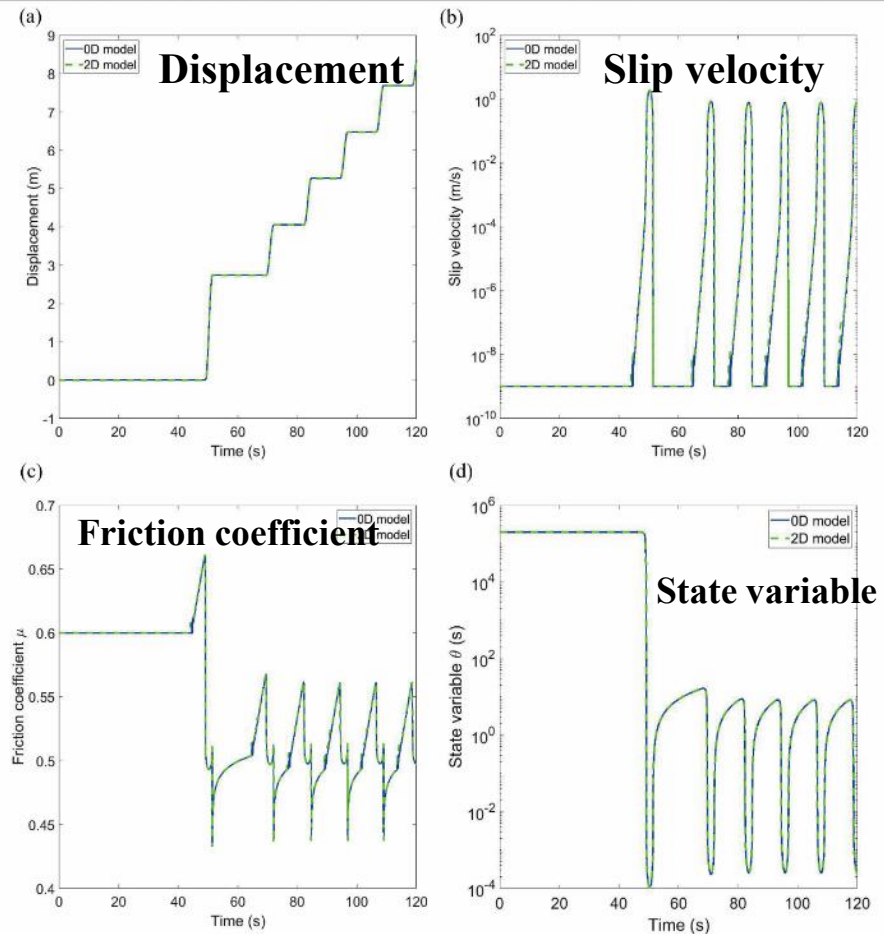
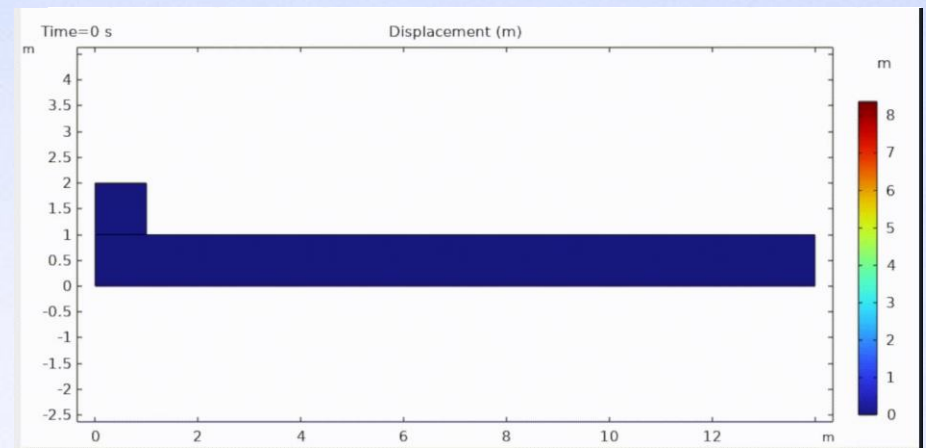
$$F_\tau = \begin{cases} \mu(F_n + mg), & \frac{du}{dt} > 0, \\ 0, & \frac{du}{dt} = 0. \end{cases}$$

Aging's law  $\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}$

Direct effect coefficient

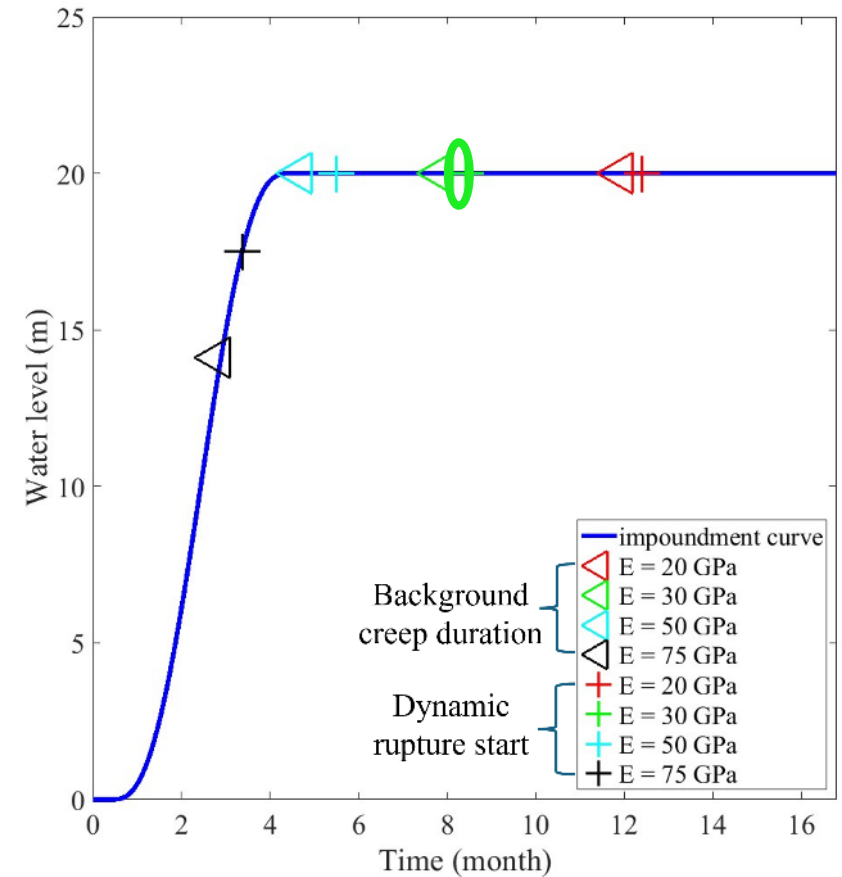
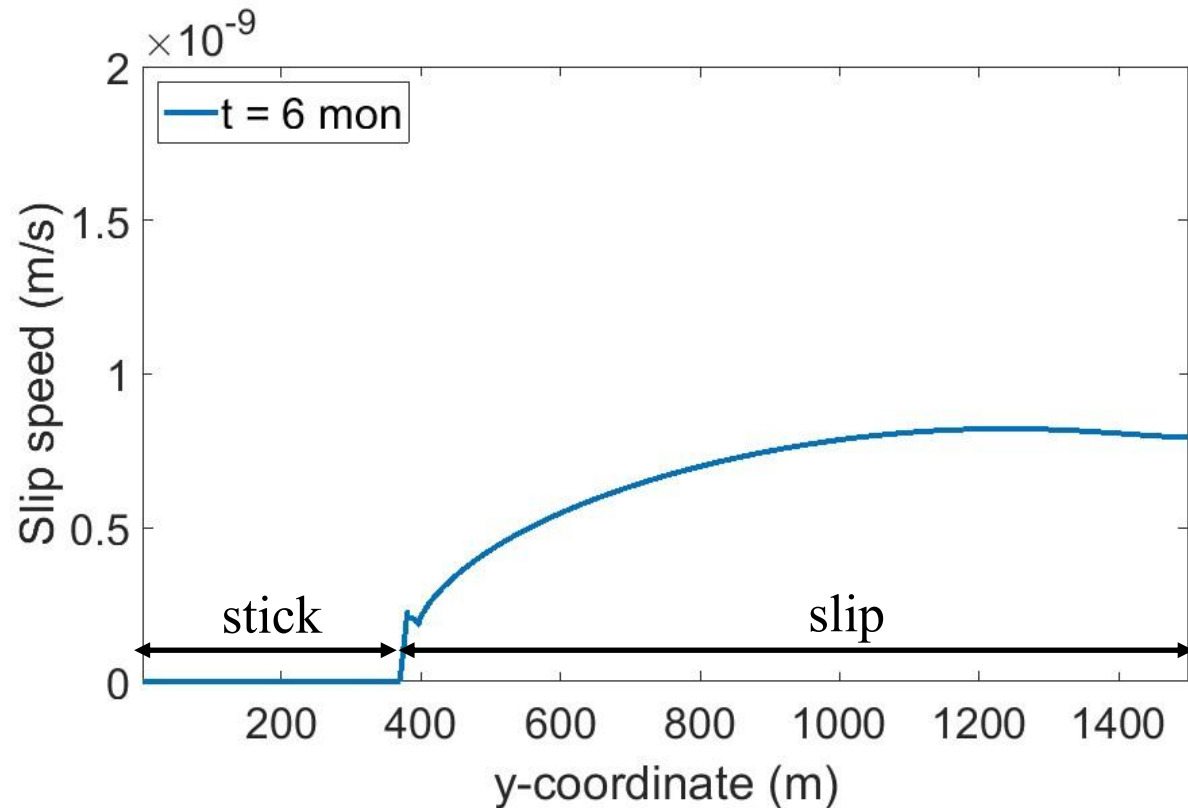
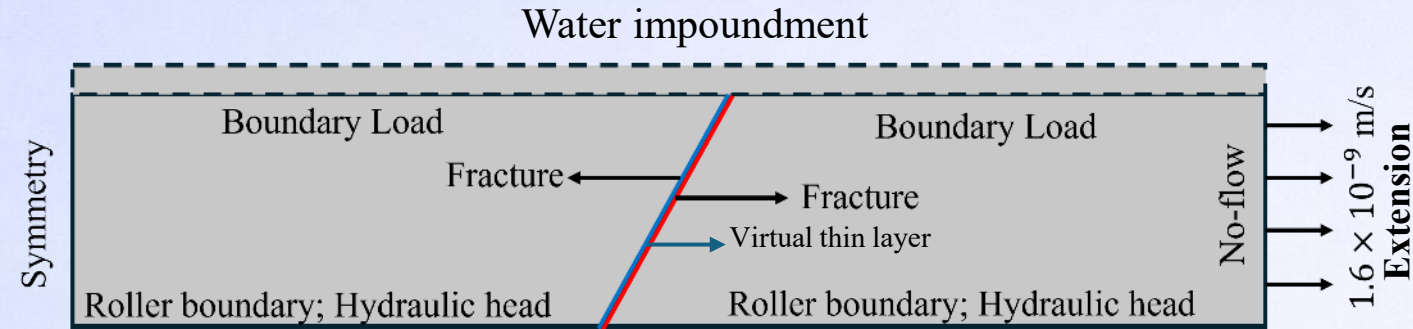
$$\mu = \mu_0 + A_c \cdot \ln\left(\frac{V}{V_0}\right) + B_c \cdot \ln\left(\frac{\theta V_0}{D_c}\right)$$

Evolution coefficient      Characteristic slip distance



# Result I: Aseismic slip

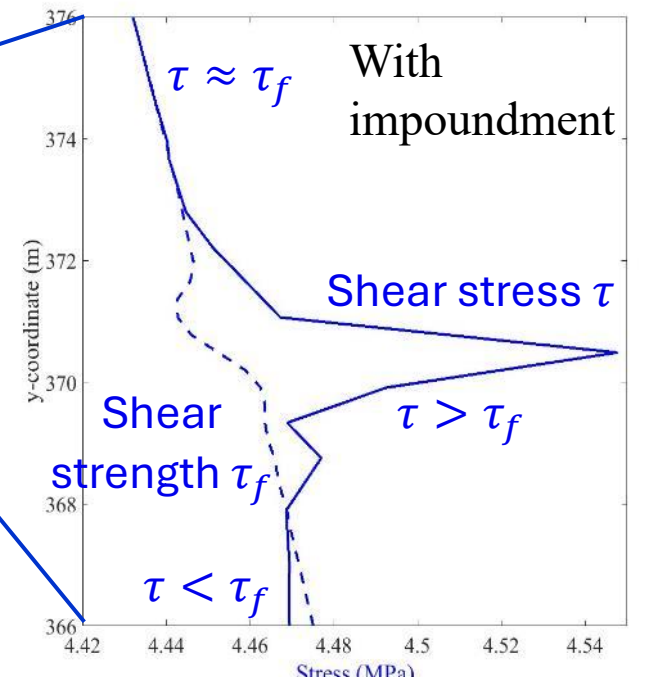
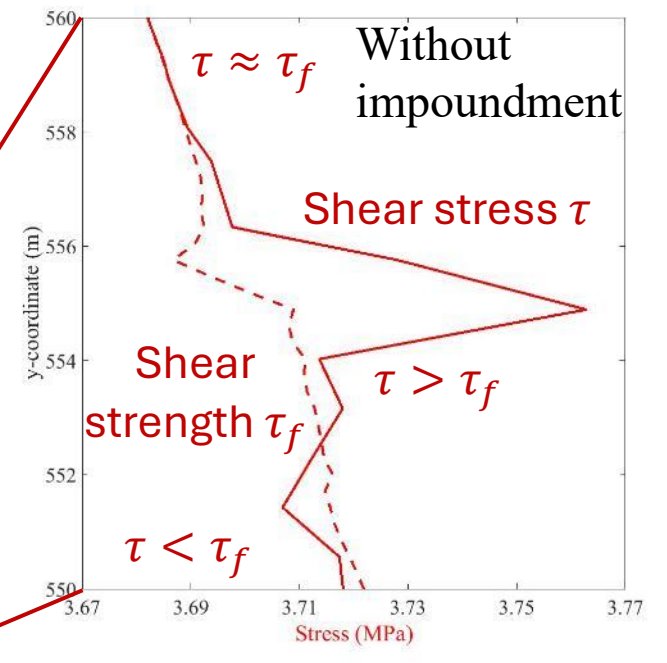
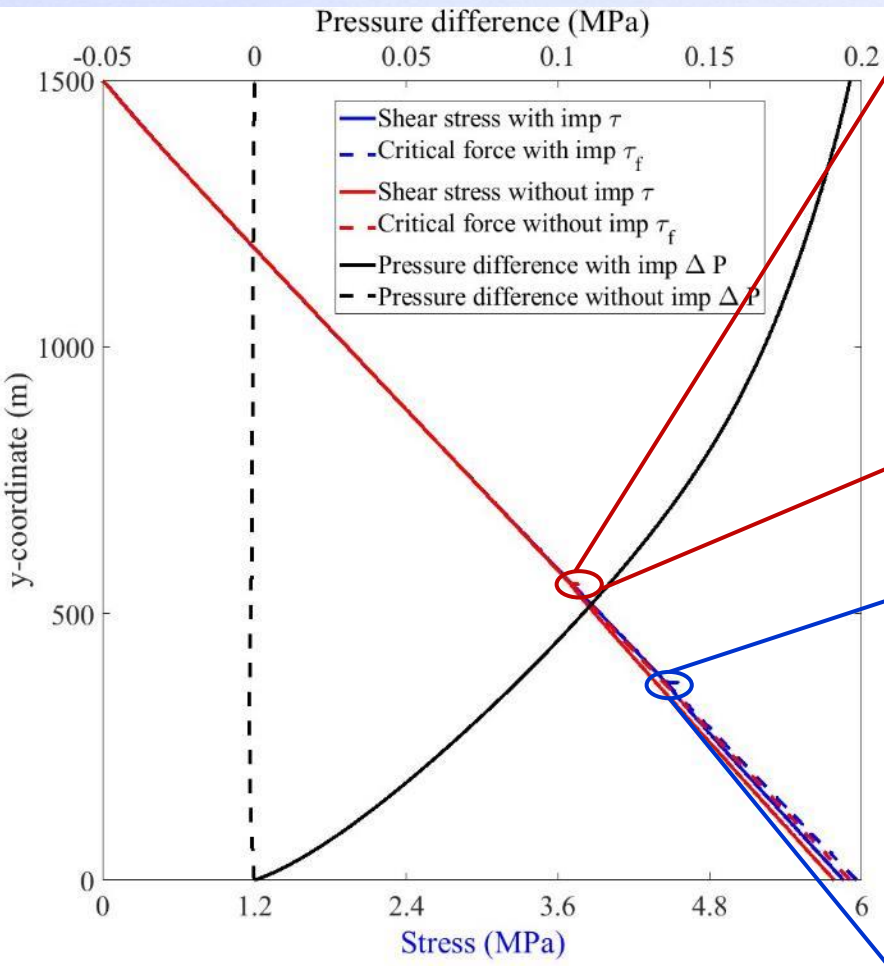
- Stage 1: **poroelastic consolidation** under gravity **before extension**.



- The aseismic slip **starts from the top** and proceeds to the bottom of the fault, while the **slip speed grows**.
- Reservoir loading first drives **aseismic creep**, and later triggers **dynamic rupture**, with timing strongly controlled by Young's modulus.

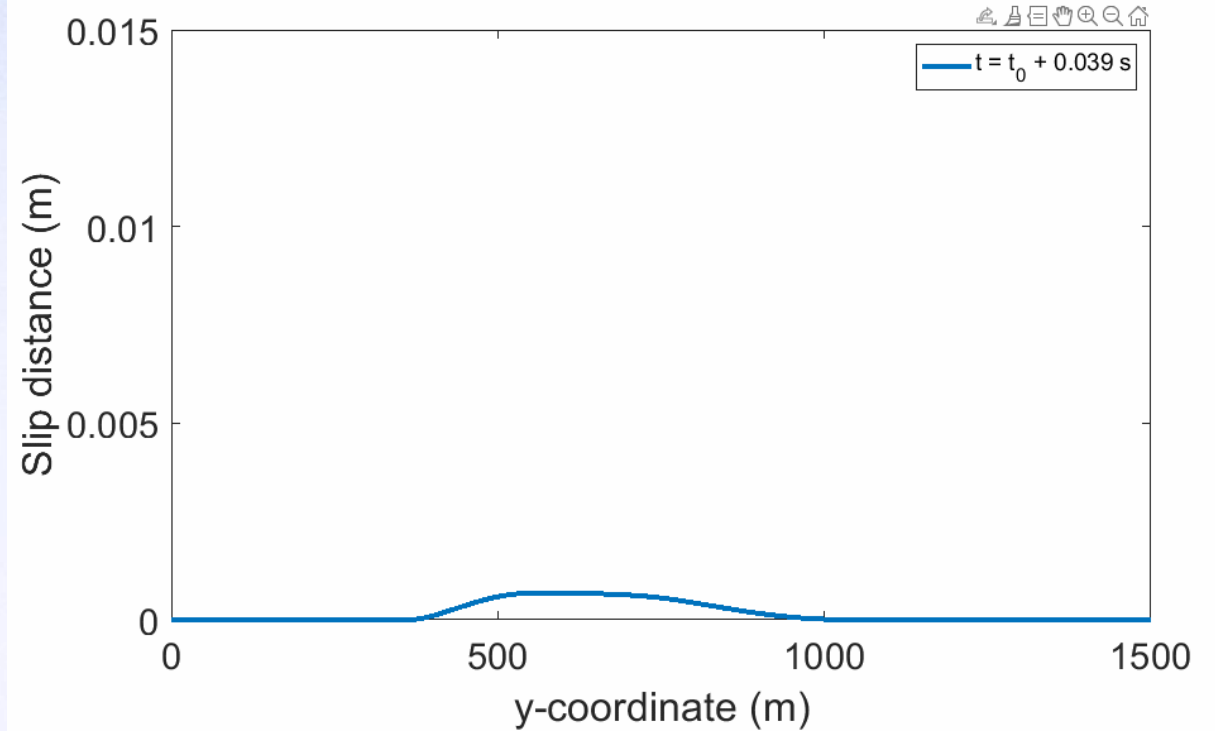
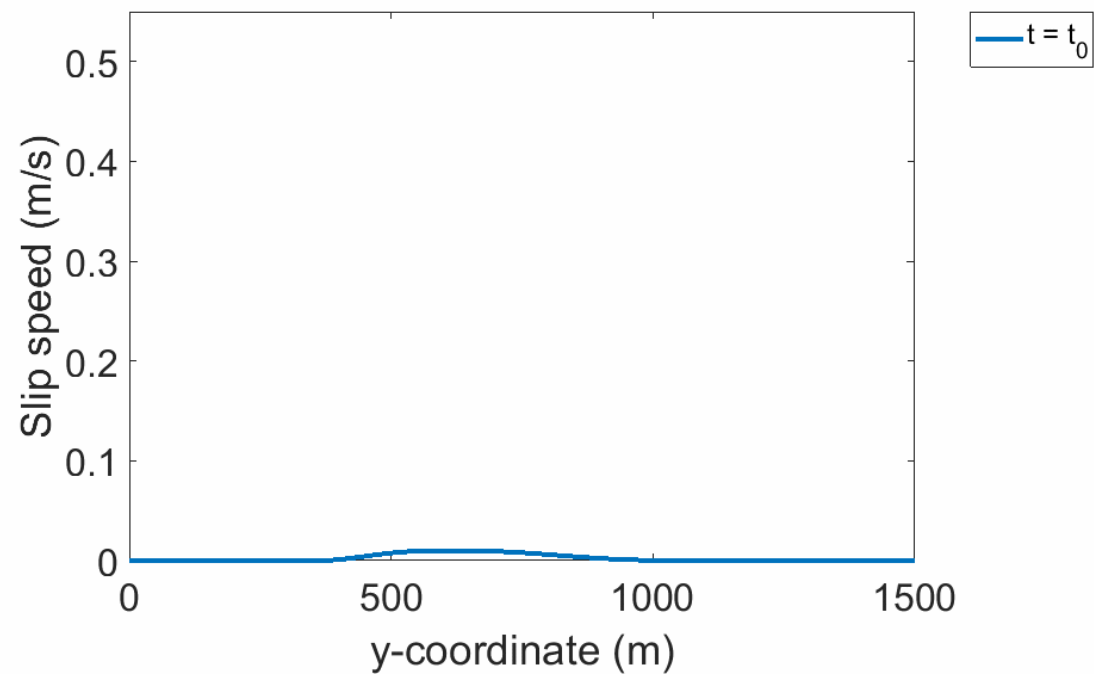
# Result I: Aseismic slip

$t = 6 \text{ mon}$



- Aseismic slip initiates near the top of the fault and propagates downward.
- Shear stress  $\tau$  slightly exceeds frictional strength  $\tau_f$  on front.
- Faster creep propagation under impoundment.

## Result II: Rupture propagation

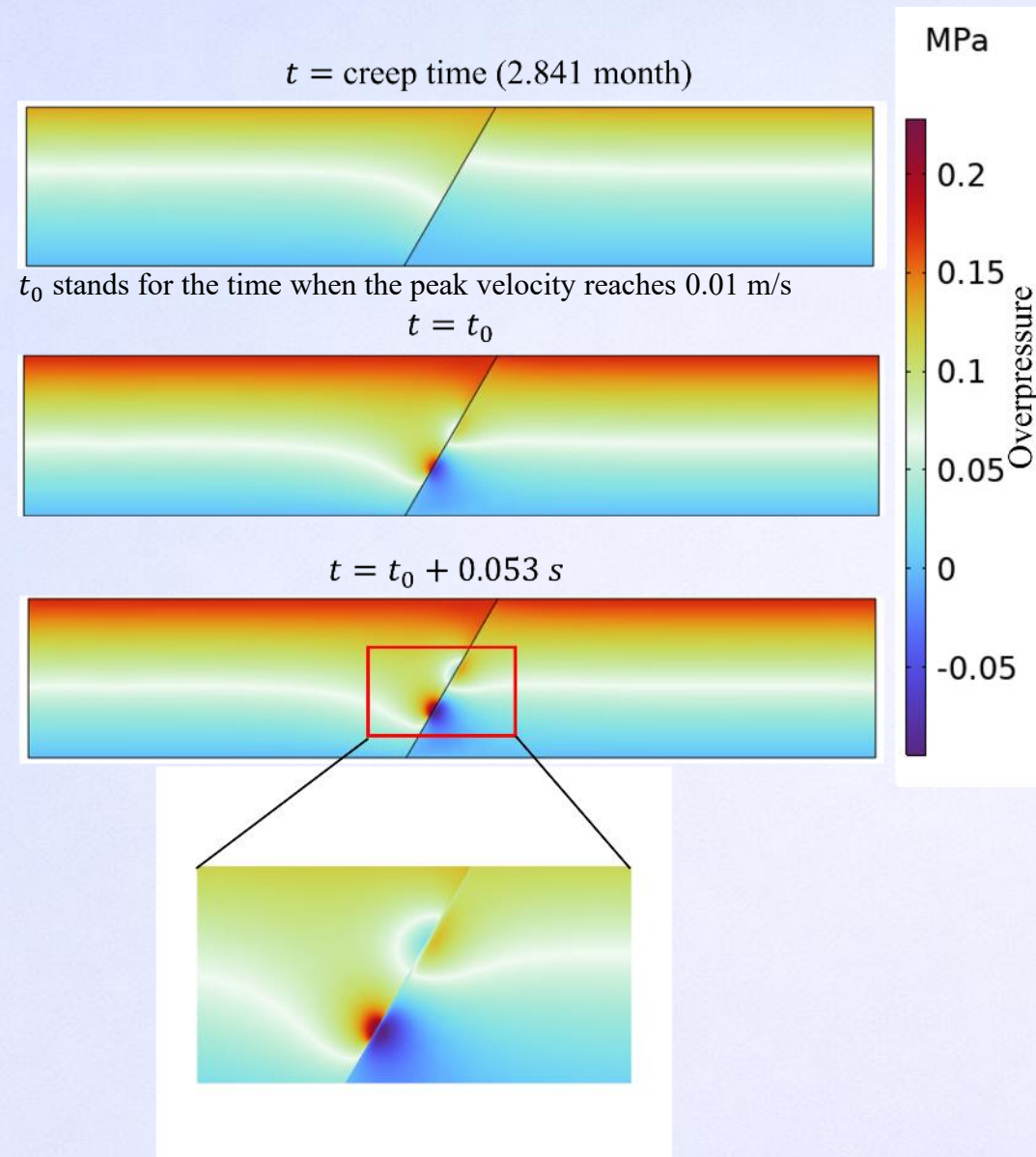


$t_0$  stands for the time when the peak velocity reaches 0.01 m/s

- The **adaptive timestep** drops from the maximum one (e.g., 50 hr in our case) applicable for creep, to ms scale (e.g.,  $\sim 10^{-4} - \sim 10^{-3}$  s) applicable for the dynamic rupture.
- As rupture propagates **asymmetrically** from the hypocenter, the increasing peak velocity splits into two peaks—with the larger peak developing near the bottom—reflecting **differential propagation along the fault (left)**.
- The smaller upper peak is likely due to **free surface interaction effects**, which causes friction hardening ahead of the crack tip.
- The slip distance (right) also shows the dynamic propagation process along the fault compared to the aseismic slip.

# Result II: Rupture propagation

## Excess pore pressure evolution



- **Excess pore pressure** develops on both sides of the fault prior to rupture, forming a **near-opposite overpressure–under-pressure pattern** at the rupture tip.
- As rupture propagates, compression ahead of the tip generates **undrained overpressure** that further weakens the fault.
- These pressure perturbations ( $\sim 0.2$  MPa), promote **asymmetric rupture**: overpressure enhances slip, while pressure drops inhibits propagation.

# Conclusions

- We developed a unified **reservoir-induced seismicity (RIS)** model that integrates **pore-pressure diffusion, poro-visco-elastic rock response, frictional contact, and fully dynamic rupture at the fault.**
- The model reproduces the poroelastic consolidation, **aseismic slip** and **dynamically propagating rupture** at the fault.
- Rupture propagation is **asymmetric** likely due to **free surface interaction effects** which causes friction hardening ahead of the crack tip.
- **Undrained excess pore pressure** at the rupture front further weakens the fault and amplifies this asymmetry.

The background features a complex, layered design. At the top, there's a solid light blue band. Below it, a series of wavy, horizontal bands in various shades of blue and white create a sense of depth and movement. A prominent white line curves across the middle, separating the upper blue sections from the lower ones. The lower portion of the image is dominated by a light blue background with a subtle, white grid pattern of thin lines forming irregular polygons. In the center of this grid, there's a small, glowing red and orange spot that fades into the surrounding blue. The overall aesthetic is clean, modern, and digital.

**Thanks!**