Bridging the Gap: Coupled Poromechanical and Earthquake Simulation to Model Induced Seismicity

PI: Matteo Cusini

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344

Budget & research team

Project timeline: October 2023 – September 2025
Budget: 300k (Y1) - **500k (Y2)** - 500k (Y3)

LLNL Research team:

- Matteo Cusini
- Kayla Kroll
- Nicola Castelletto
- Randy Settgast
- Joshua White

Collaborators (unfunded):

- Vidar Stiernström (Stanford)
- Matteo Frigo (Stanford)
- Eric Dunham (Stanford)

> *High-resolution storage estimates that more critically assess the integrity of individual storage complexes in terms of their ability to sequester CO_2 without significant leakage [..] and* ***avoid triggering of injection-induced seismicity*** *will eventually be required.*

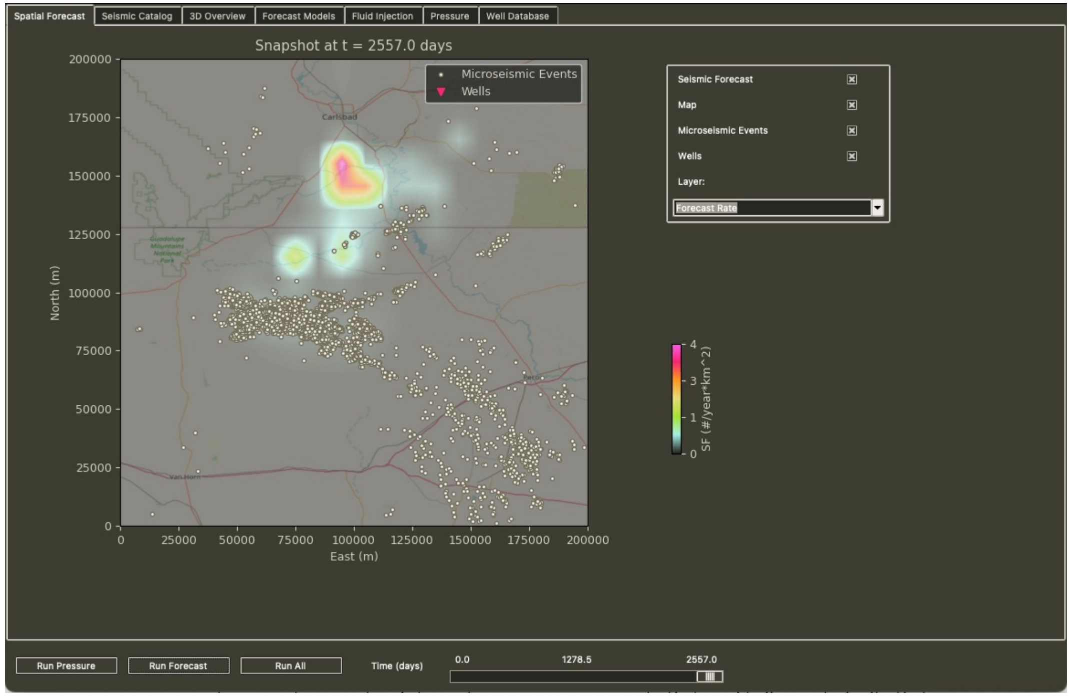
Getting to Neutral. Chapter 6, page 87, 2020.

We need models to understand **induced seismicity!**

- How can we **quantify** hazards at new site?
- What **data** are useful to reduce uncertainty?
- Which type of data is most important to quantify induced seismicity hazards?
- Are there **effective management strategies**?

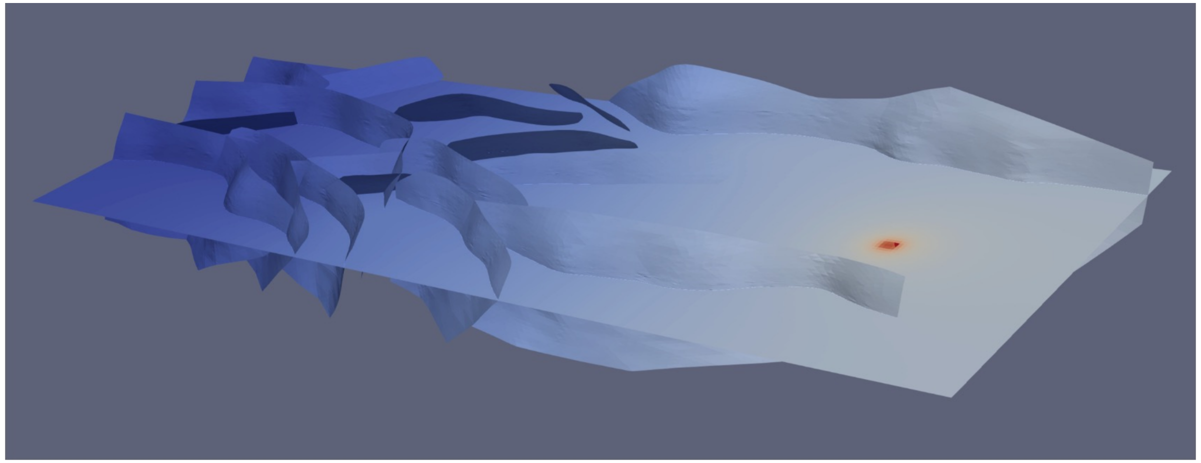
Models of induced seismicity

Reduced order models (Orion)



- Provide information about the seismicity rate
- Low computational cost
- Can be used by non-experts

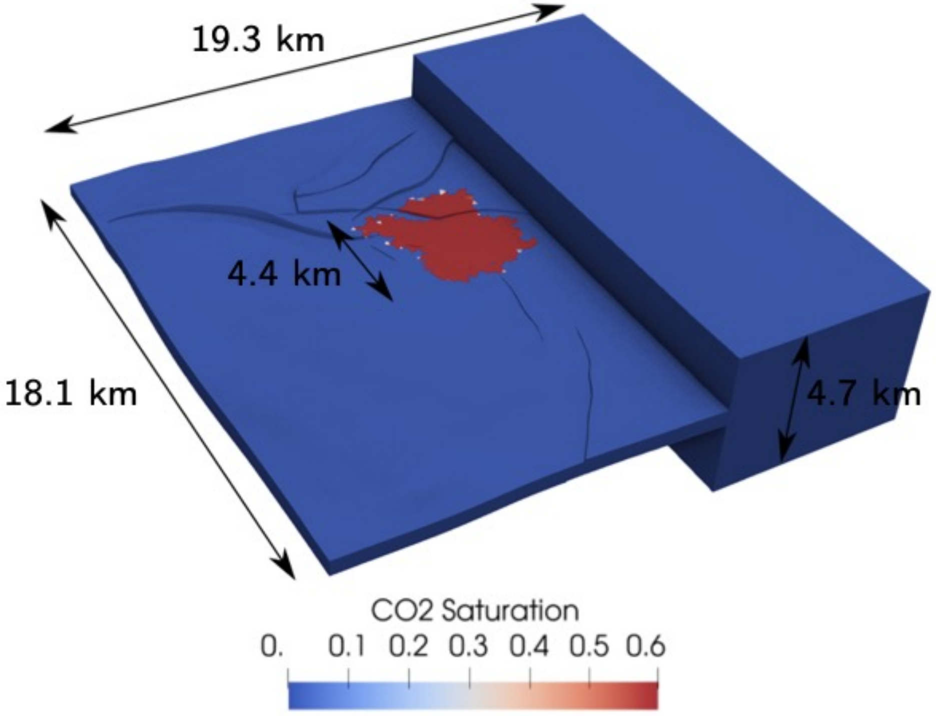
High fidelity models (this project)



- Provide event locations and magnitudes
- Computationally expensive
- Necessary to train/validate ROM

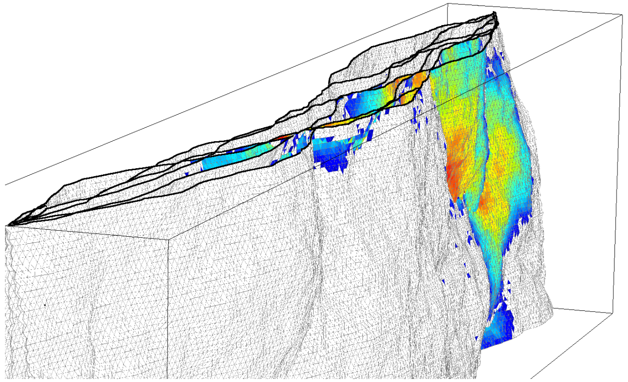
Key ingredients

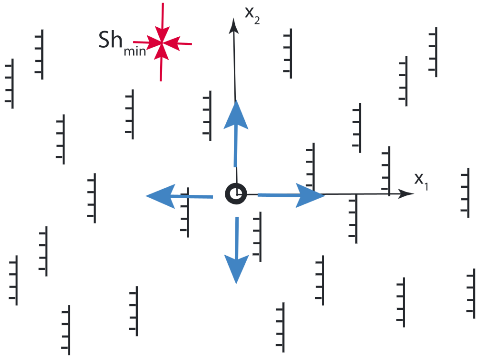
A poromechanics simulation module



Two-way Coupling

An earthquake model





[Seagall and Lu (2015)]

Objectives and subtasks

Objective: develop, within the open-source **GEOS** simulation framework, a high-fidelity coupled poromechanical and earthquake rupture simulator.

Subtask 1 – Quasi-static fault stability analysis capability

- **Deliverable:** quasi-static fault modeling capability in the open-source GEOS framework.

Subtask 2 – Quasi-dynamic fault modeling capability

- **Deliverable:** a coupled poromechanics-earthquake (HM+E) simulation capability in the open-source GEOS framework.

Subtask 3 – Demonstration of the applicability of the developed framework

- **Deliverable**: a demonstration of the applicability of the developed capabilities through the modeling of induced-seismicity at a real GCS site.

CO_2 storage simulation with GEOS

Geological Model

GEOS simulation model

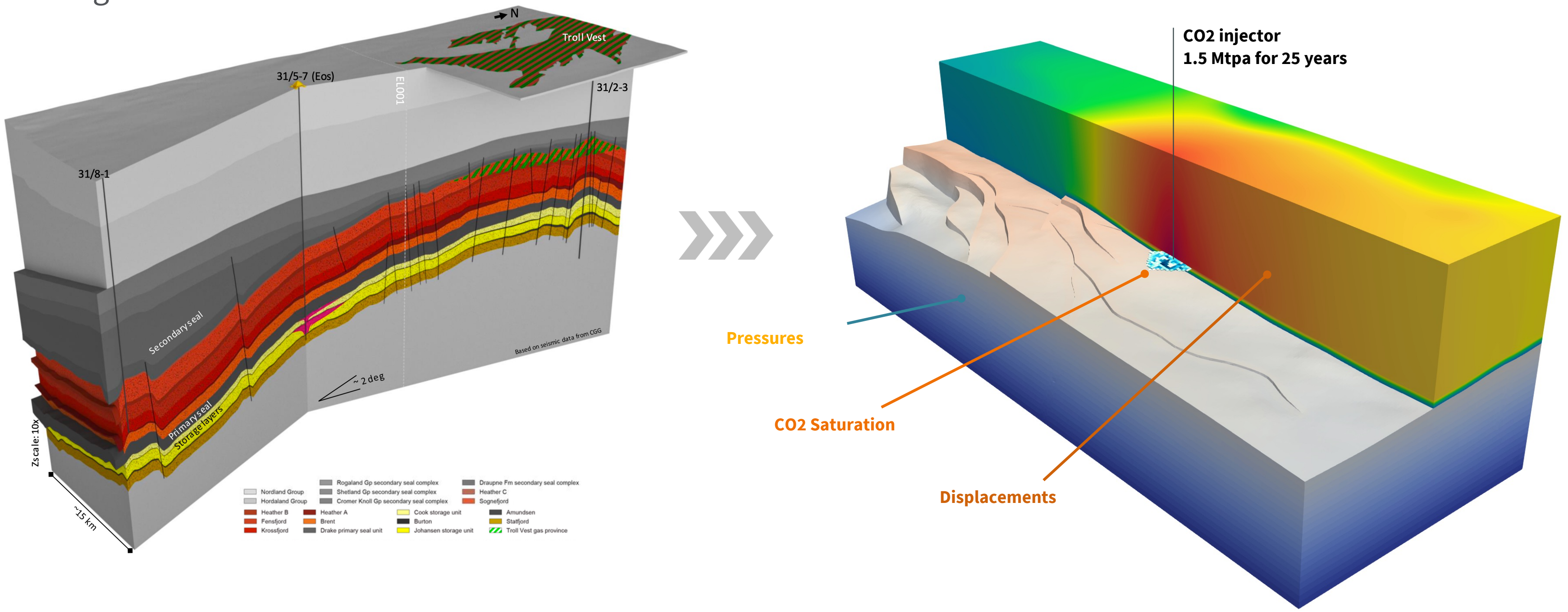


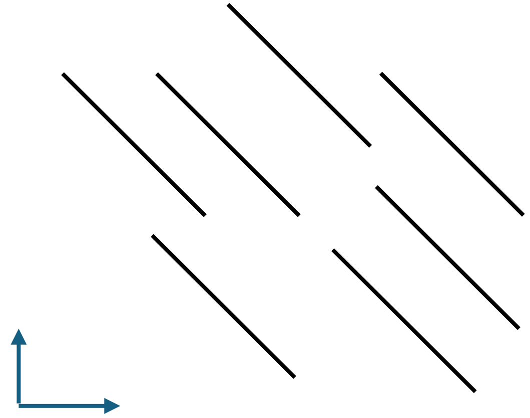
Figure: GEOS simulations of the Northern Lights storage project

- ✓ Unique coupled poromechanics capabilities
- ✓ Allows for unprecedented resolutions
- ✓ Employed for real field problems
- ➢ Fault modeling needs improvement

High-fidelity poromechanics & ROM for seismicity

- Earthquake rate equations are derived from rate-state friction

- We assume we know faults orientation



$$\dot{R} = \frac{1}{t_a}\hat{R}\left(t_a\dot{g}(t) - \hat{R}\right) \qquad t_a = \frac{a\sigma_0}{\dot{\tau_r}}$$

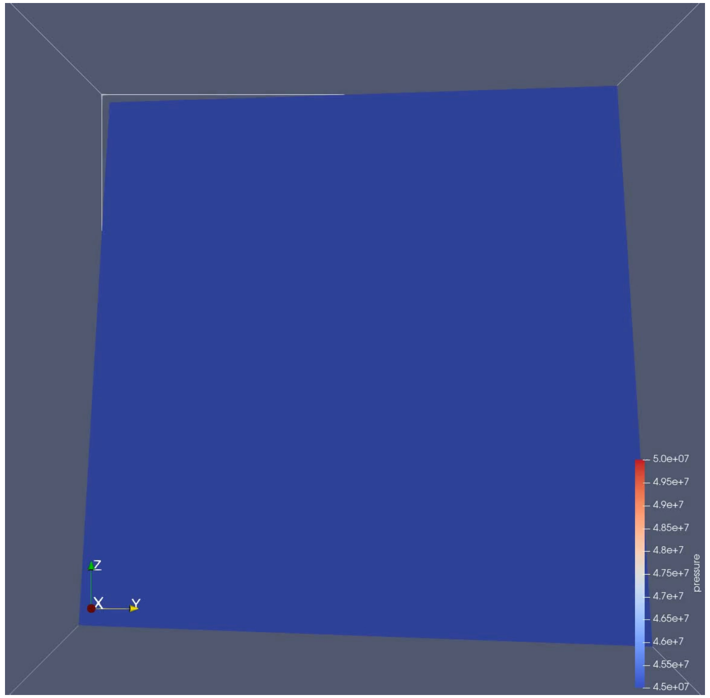
$$\dot{g}(t) = \frac{\dot{\tau}(t)\sigma(t) - \tau(t)\dot{\sigma}(t)}{a\sigma(t)}$$

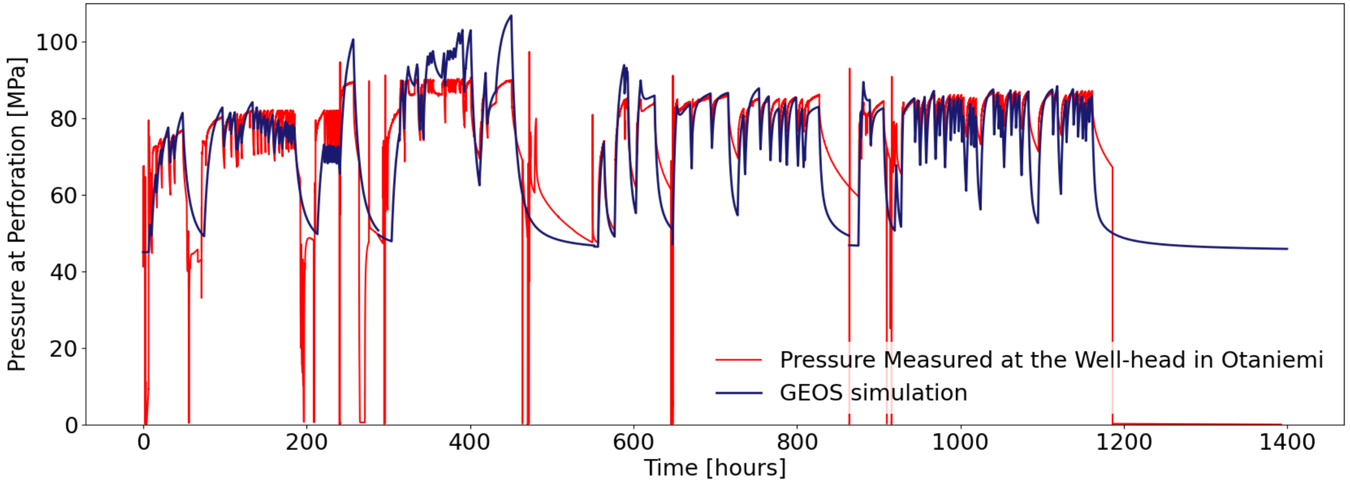
- σ and τ extracted from a poromechanics simulation.

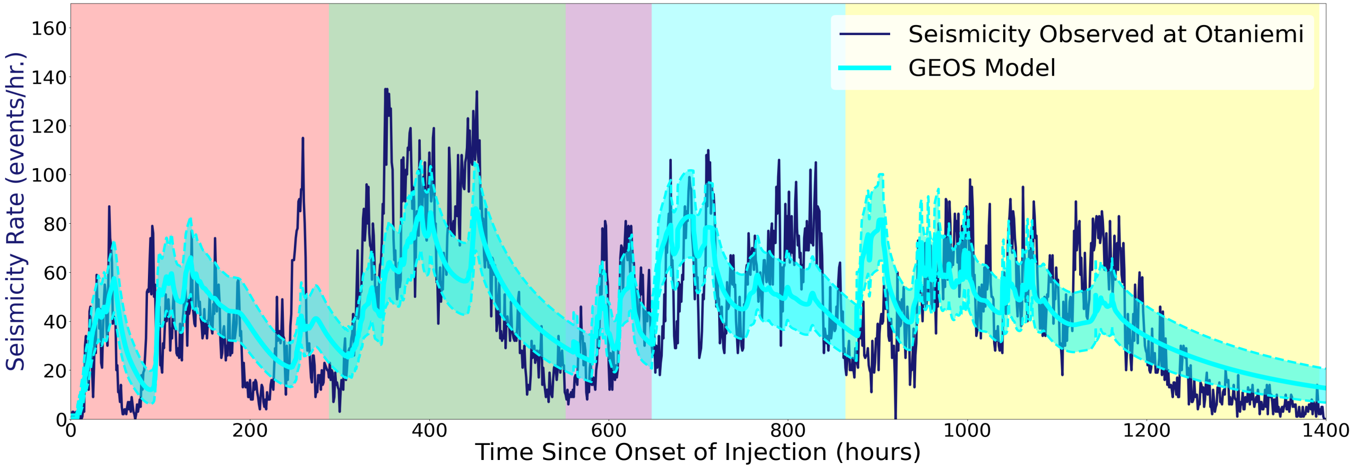
➢ Provides a seismicity rate with no information about location and magnitude of the events

[Dieterich, (1994)]

Otaniemi Geothermal field, Finland







$$\sigma_0 = 155\text{MPa}$$

$$p_0 = 45\text{MPa}$$

$$\tau_0 = 0.6\bar{\sigma}_0 = 66\text{MPa}$$

$$k = 8 \cdot 10^{-16}\text{m}^2$$

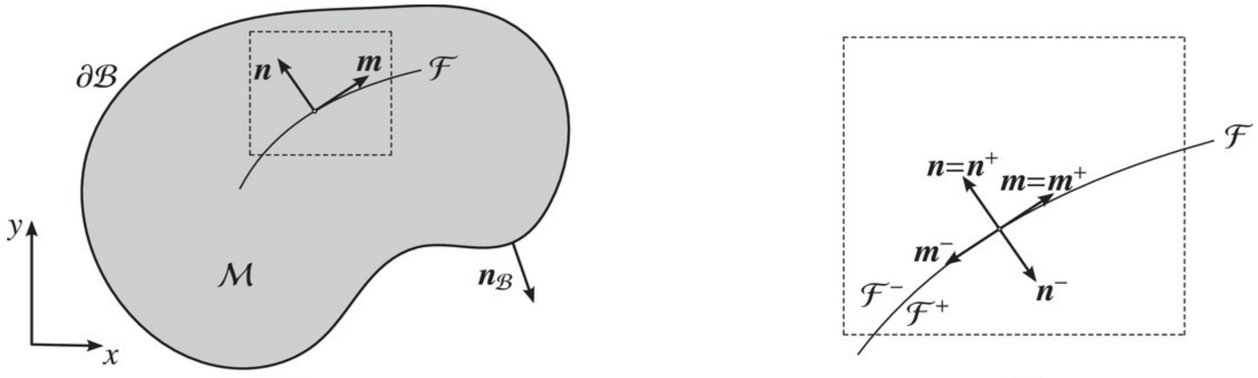
$$a = 6 \cdot 10^{-5}$$

$$\dot{\tau}_r = 1\text{kPa/yr}$$

Work in collaboration with Taeho Kim and Herve Gross (TotalEnergies)

Two-way coupled poromechanics & earthquake model

Step 1: explicitly represent faults in the poromechanical model



(A) (B)

$-\nabla \cdot (\boldsymbol{\sigma}' - bp\mathbf{1}) - \rho \boldsymbol{g} = 0$	on $\mathcal{M} \times (\mathbf{0}, \boldsymbol{T}]$	Linear momentum balance
$\dot{m}_\pi^m + \nabla \cdot (\rho_\pi \, \boldsymbol{v}_\pi^m) - q_\pi^{fm} - q_\pi^m = 0$	on $\mathcal{M} \times (\mathbf{0}, \boldsymbol{T}]$	Matrix mass balance

$[\![\boldsymbol{\sigma}]\!] \cdot \boldsymbol{n} = 0$	on $\mathfrak{F} \times (\mathbf{0}, \boldsymbol{T}]$	Stress continuity across the fracture
$\dot{m}_\pi^f + \nabla \cdot \left(\rho_\pi \, \boldsymbol{v}_\pi^f\right) - q_\pi^{mf} - q_\pi^f = 0$	on $\mathfrak{F} \times (\mathbf{0}, \boldsymbol{T}]$	Fault mass balance

Contact constraints & friction law

Normal contact conditions

$\lambda_n = \boldsymbol{\lambda} \cdot \boldsymbol{n} \leq 0$ on $\mathfrak{F} \times (\boldsymbol{0}, \boldsymbol{T}]$

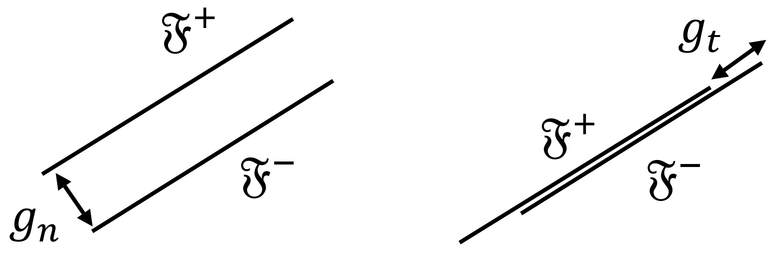
$g_n = [\![\boldsymbol{u}]\!] \cdot \boldsymbol{n} \geq \boldsymbol{0}$ on $\mathfrak{F} \times (\boldsymbol{0}, \boldsymbol{T}]$

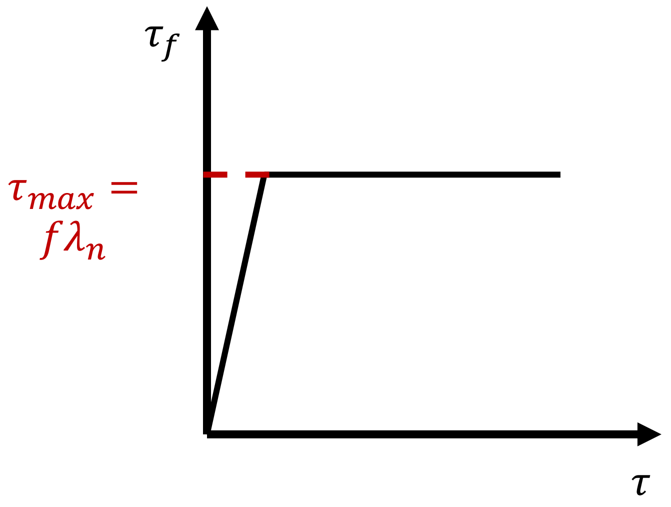
$\lambda_n g_n = 0$ on $\mathfrak{F} \times (\boldsymbol{0}, \boldsymbol{T}]$

Coulomb friction law

$\|\boldsymbol{\lambda}_t\|_2 - \tau_{max} = 0$ on $\mathfrak{F} \times (\boldsymbol{0}, \boldsymbol{T}]$

$\dot{g}_t \dot{t}_t - \tau_{max} \|\dot{\boldsymbol{g}}_t\|_2 = \boldsymbol{0}$ on $\mathfrak{F} \times (\boldsymbol{0}, \boldsymbol{T}]$





Not suited to model seismicity!

Rate- and state-dependent friction

Friction is a function of slip velocity (V) and state variable (θ):

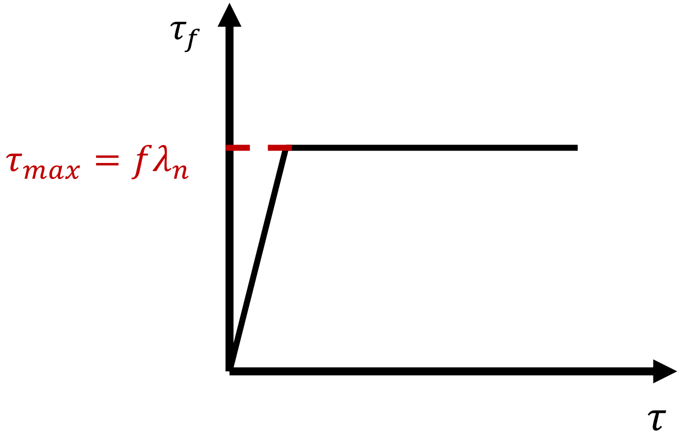
$$f = f_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{V_0\theta}{D_c}\right)$$

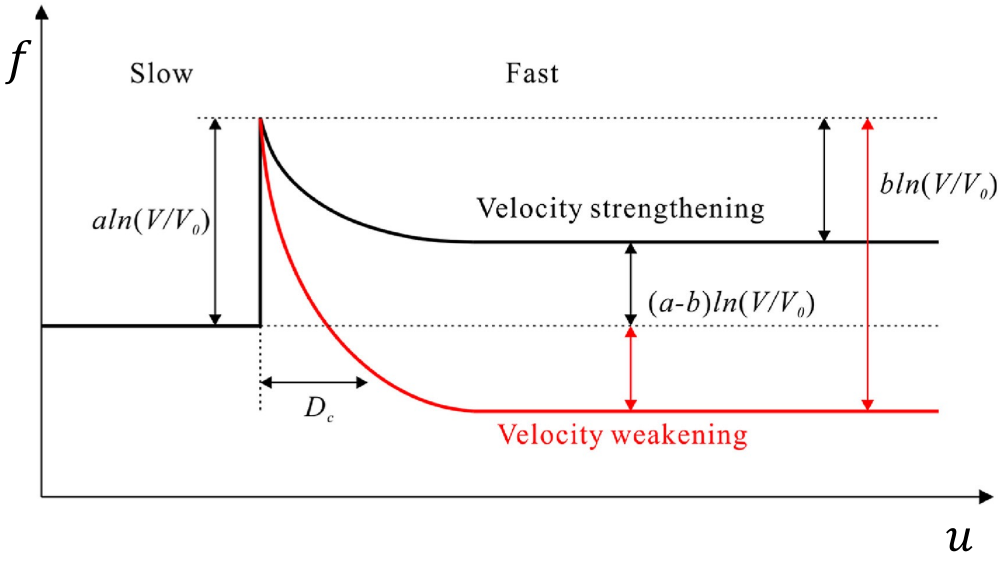
$$\frac{\partial\theta}{\partial t} = -\frac{V\theta}{D_c}\left[\ln\left(\frac{V\theta}{D_c}\right)\right] \qquad \text{slip law [Ruina, 1983]}$$

At Steady-state $\left(\frac{\partial\theta}{\partial t} = 0\right)$:

$$f_{ss} = f_0 + (a - b)\ln\left(\frac{V}{V_0}\right)$$

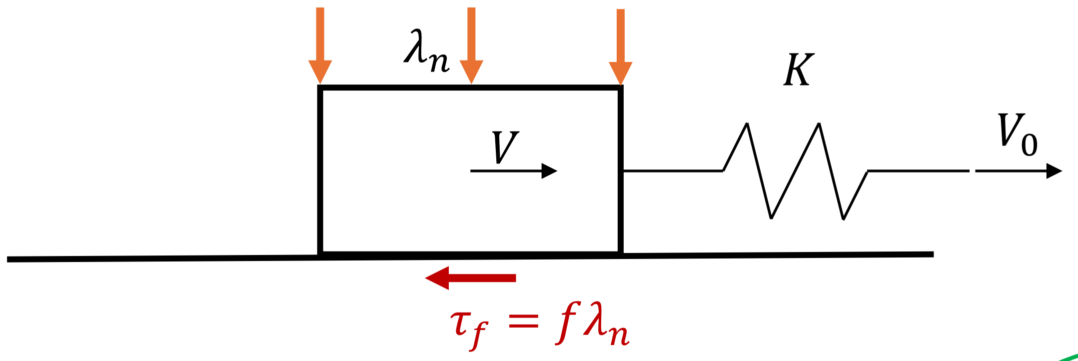
$$\begin{cases} a - b < 0 & \text{steady–state velocity } \textit{weaking} \\ a - b > 0 & \text{steady–state velocity } \textit{strengthening} \end{cases}$$





[modified after Y. Huang et al, Earthq. Research Adv. (2023)]

0D earthquake model: spring-slider system [1/3]



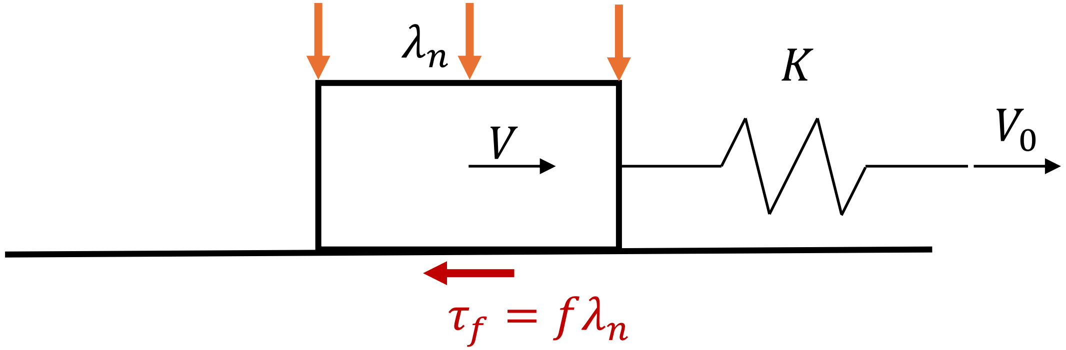
$$\lambda_t(t) = \tau_0 + \hat{\tau} \cdot t - K\delta - \boldsymbol{\eta V}$$

Quasi-dynamic approximation

$\boldsymbol{\eta V}$ is the radiation-damping term where $\boldsymbol{\eta}$ is the shear impedance

$\tau_0 + \hat{\tau} \cdot t - K\delta - \eta V - f(\theta, V)\lambda_n = 0$	Force balance
$\frac{\partial \delta}{\partial t} - V = 0$	Slip evolution
$\frac{\partial \theta}{\partial t} + G(V, \theta) = 0$	Slip/Aging law

0D earthquake model: spring-slider system [2/3]



We can discretize with Euler-backward*...

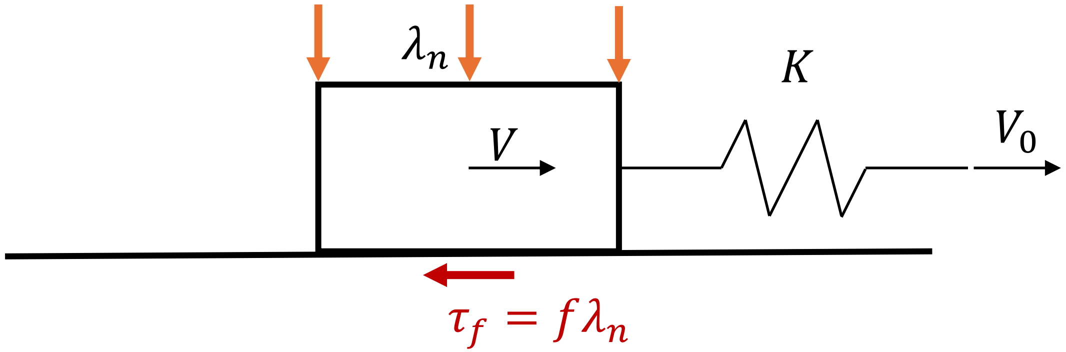
$$r_1(\theta, V) = \tau_n + \hat{\tau} \cdot \Delta t - K(\delta_n + V\Delta t) - \eta V - f(\theta, V)\lambda_n = 0$$

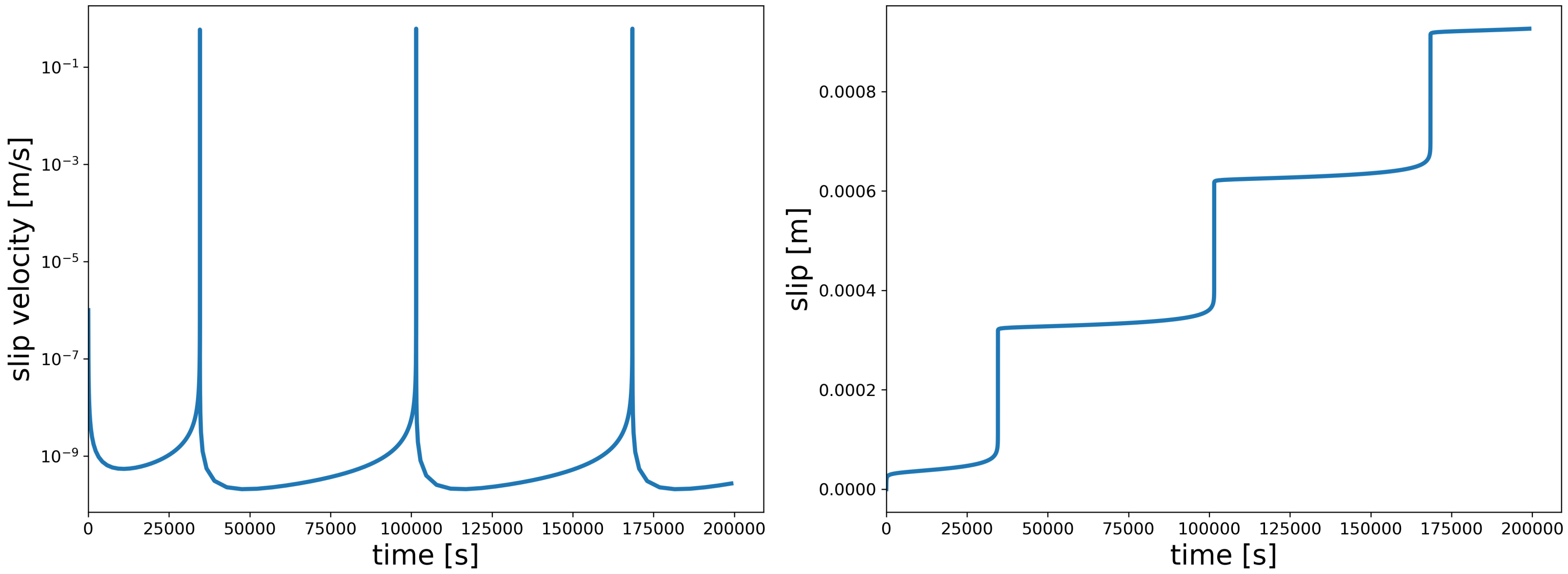
$$r_2(\theta, V) = \frac{\theta - \theta_n}{\Delta t} + G(\theta, V) = 0$$

...and solve with the Newton-Raphson method

*we have also explored other time-integrators

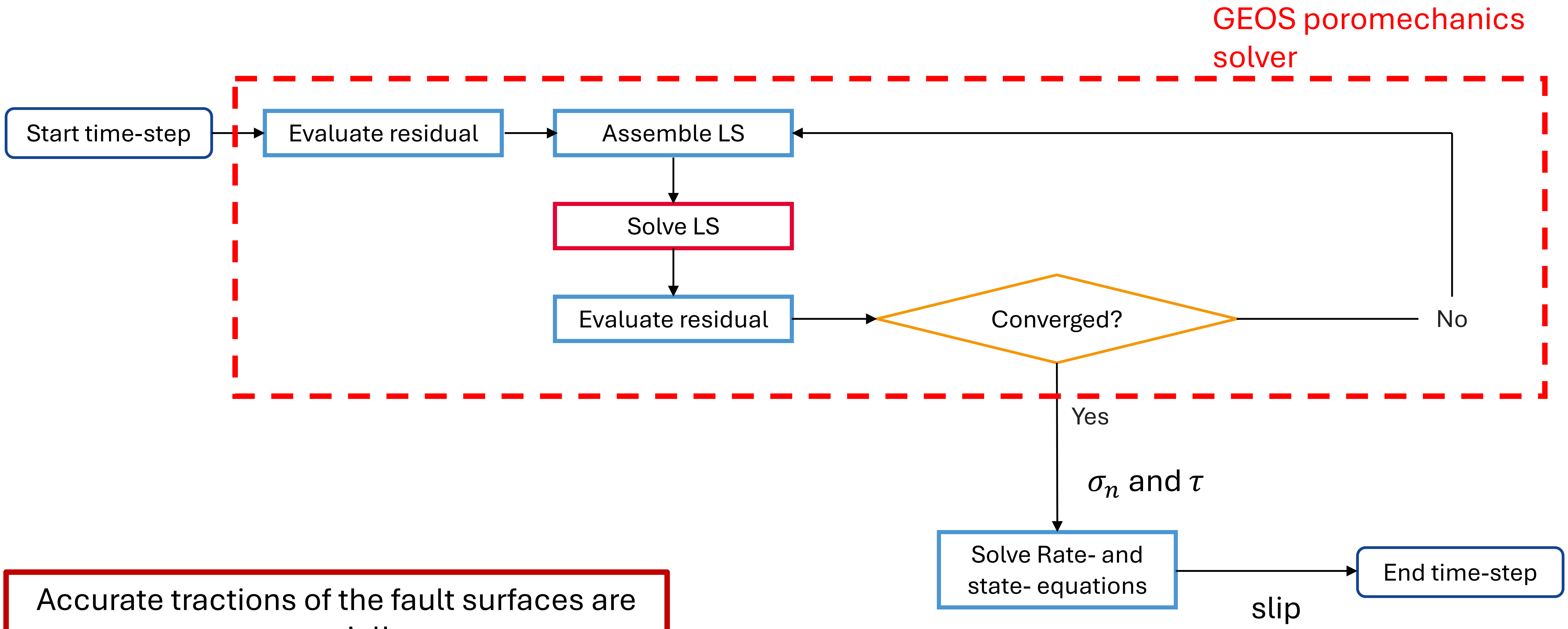
0D earthquake model: spring-slider system [3/3]





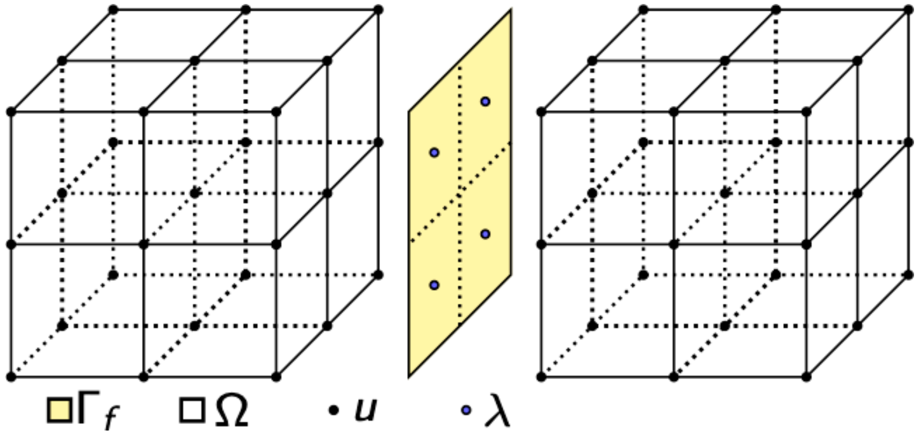
The peaks are characteristic events (i.e., quakes)

Coupled (poro)mechanics & quasi-dynamic earthquake model



Accurate tractions of the fault surfaces are crucial!

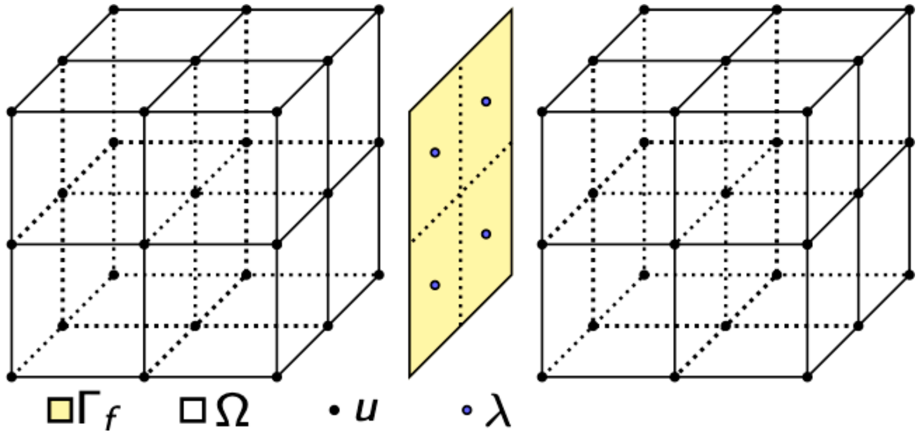
Discretization of explicitly represented faults



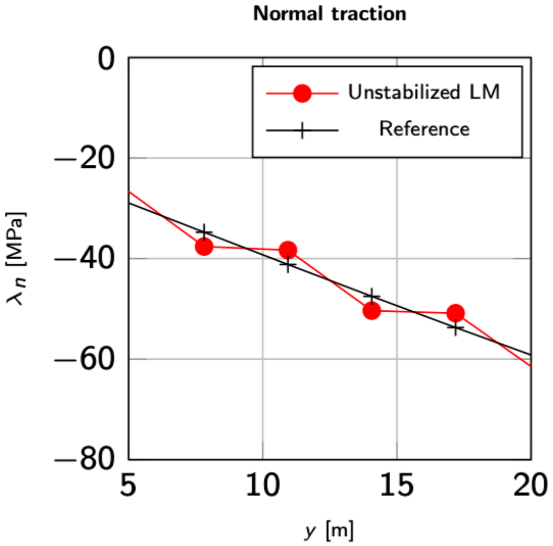
Results in the following saddle-point problem

$$\begin{bmatrix} K_{uu} & C_{u\lambda} \\ C_{\lambda u} & 0 \end{bmatrix} \begin{bmatrix} u \\ \lambda \end{bmatrix} = - \begin{bmatrix} r_u \\ r_\lambda \end{bmatrix}$$

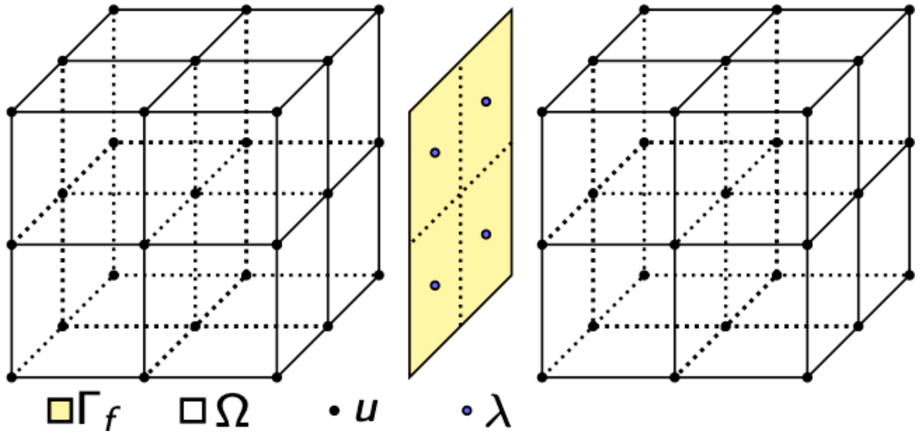
Discretization of explicitly represented faults



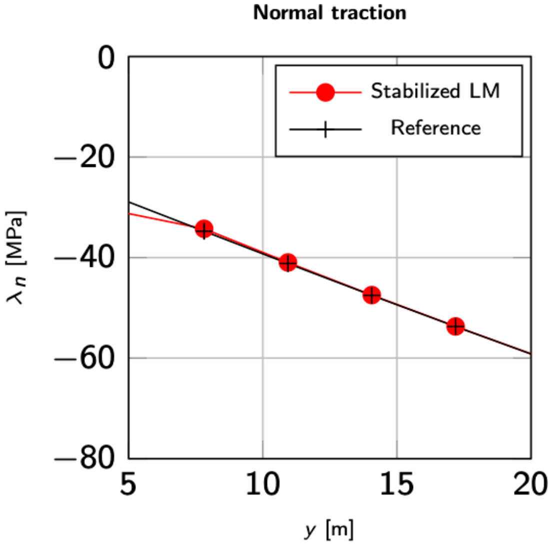
Results in the following saddle-point problem



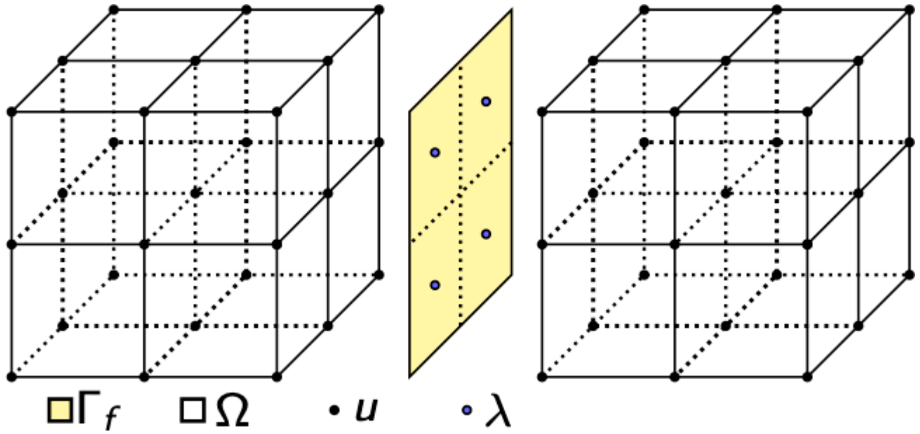
Discretization of explicitly represented faults



Results in the following saddle-point problem



Discretization of explicitly represented faults

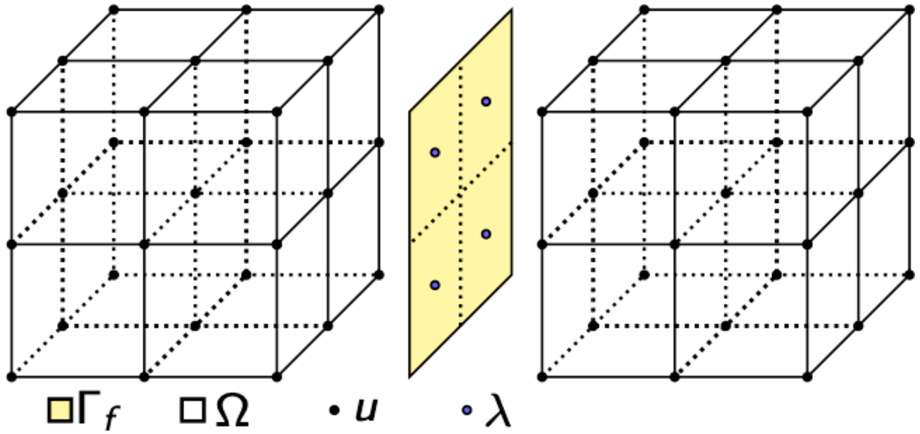


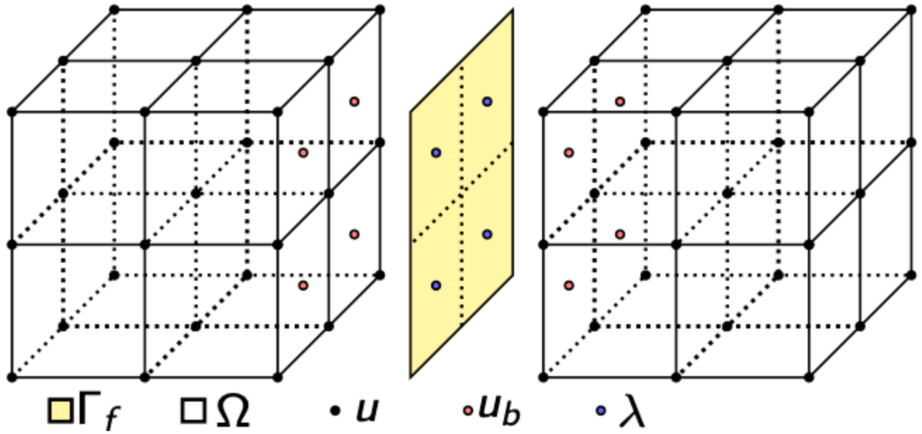
Results in the following saddle-point problem

$$\begin{bmatrix} K_{uu} & C_{u\lambda} \\ C_{\lambda u} & A_{stab} \end{bmatrix} \begin{bmatrix} u \\ \lambda \end{bmatrix} = - \begin{bmatrix} r_u \\ r_\lambda \end{bmatrix}$$

The stabilization matrix affects the solution and it is only exact for hexahedral elements.

Discretization of explicitly represented faults





Results in the following saddle-point problem

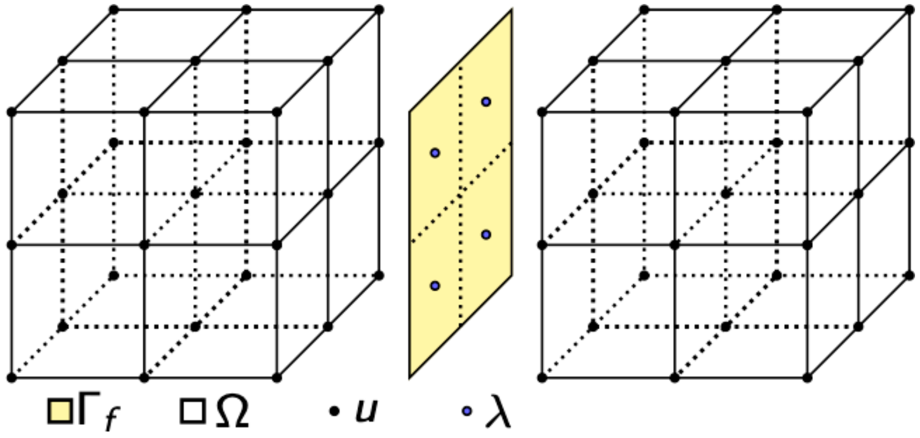
$$\begin{bmatrix} K_{uu} & C_{u\lambda} \\ C_{\lambda u} & A_{stab} \end{bmatrix} \begin{bmatrix} u \\ \lambda \end{bmatrix} = - \begin{bmatrix} r_u \\ r_\lambda \end{bmatrix}$$

The stabilization matrix affects the solution and it is only exact for hexahedral elements.

$$\begin{bmatrix} A_{bb} & A_{bu} & A_{bt} \\ A_{ub} & A_{uu} & A_{ut} \\ A_{tb} & A_{tu} & 0 \end{bmatrix} \begin{bmatrix} u_b \\ u \\ \lambda \end{bmatrix} = - \begin{bmatrix} r_b \\ r_u \\ r_\lambda \end{bmatrix}$$

- Does not affect the solution
- It is generic for all element types (as long as we can write the bubble)
- Can be statically condensed

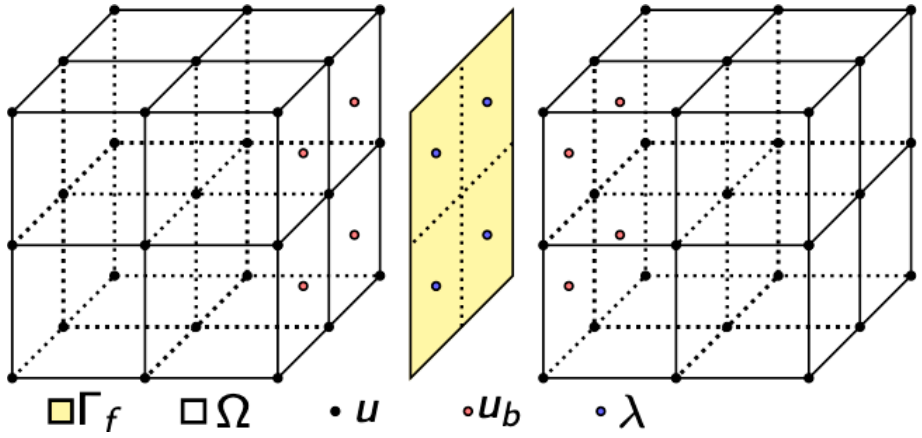
Discretization of explicitly represented faults

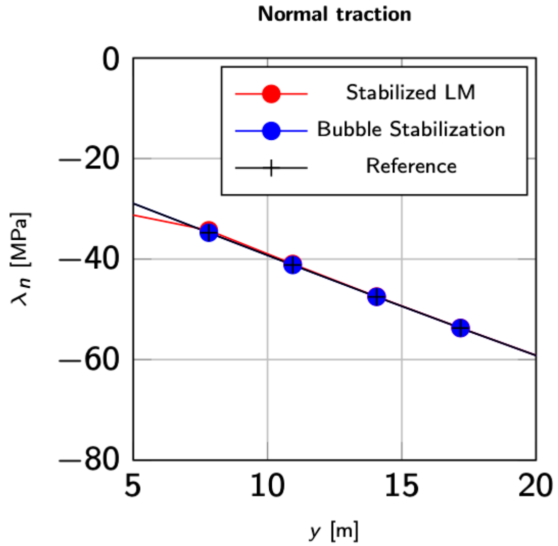


Results in the following saddle-point problem

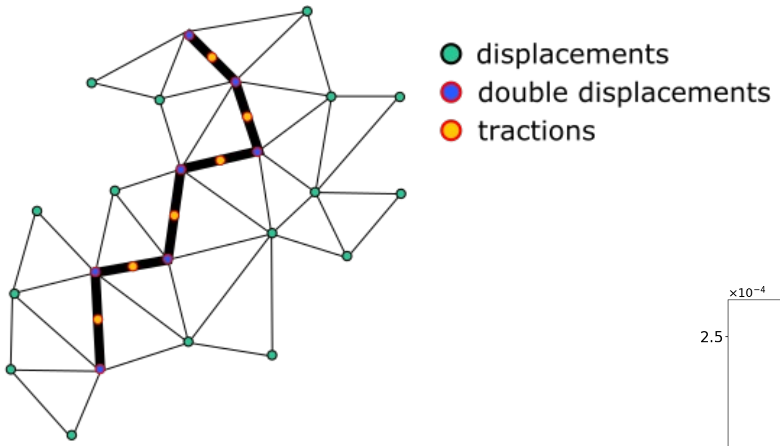
$$\begin{bmatrix} K_{uu} & C_{u\lambda} \\ C_{\lambda u} & A_{stab} \end{bmatrix} \begin{bmatrix} u \\ \lambda \end{bmatrix} = - \begin{bmatrix} r_u \\ r_\lambda \end{bmatrix}$$

The stabilization matrix affects the solution and it is only exact for hexahedral elements.

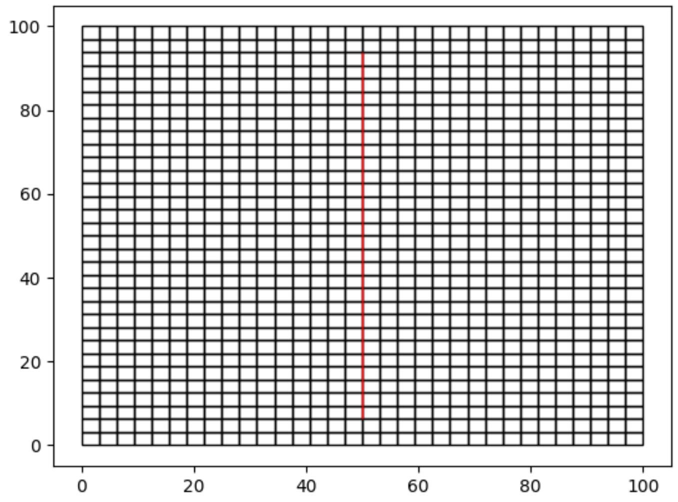


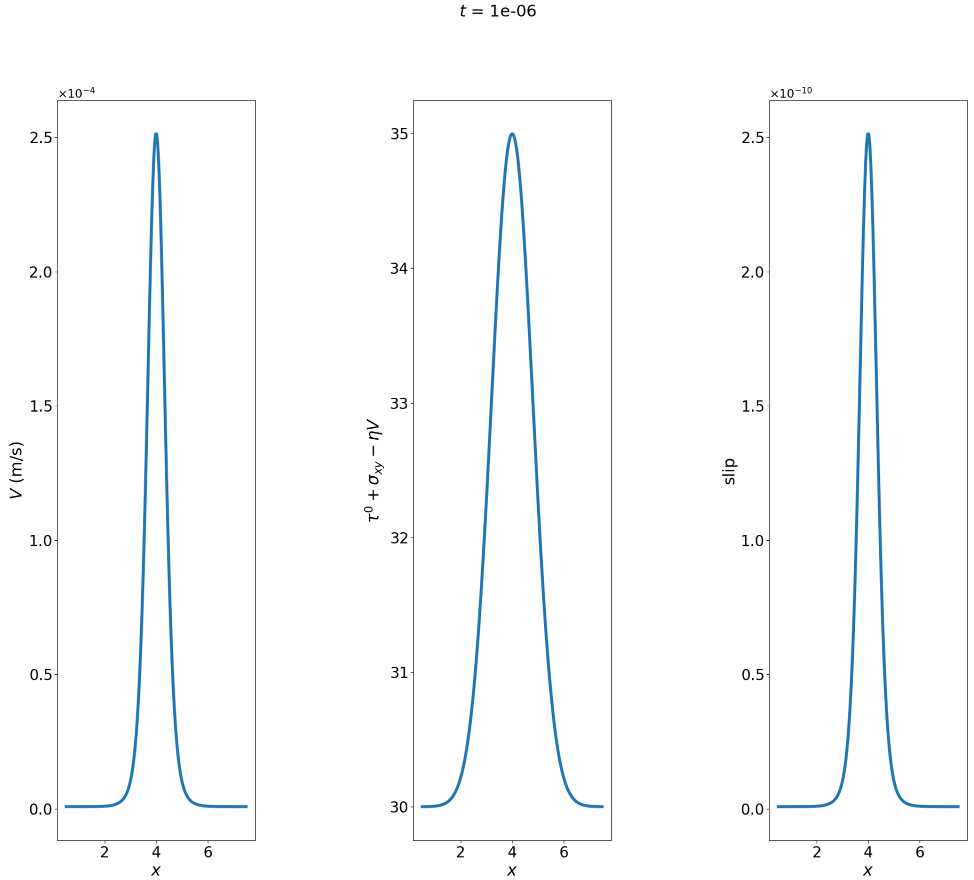


Coupled (poro)mechanics and earthquake model

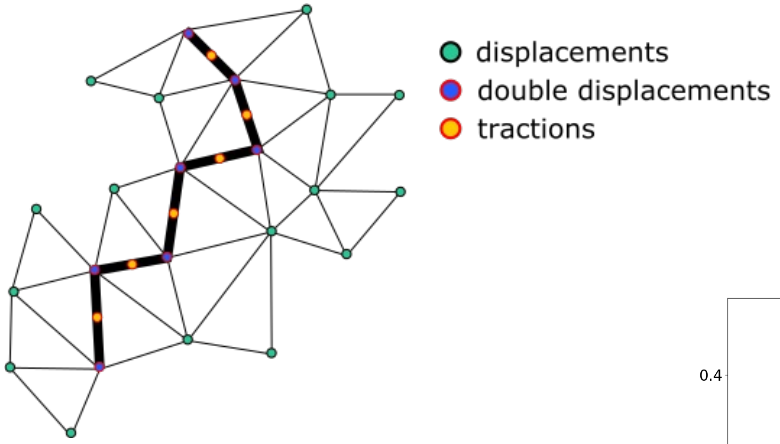


Slip is prescribed as a b.c. to the mechanics

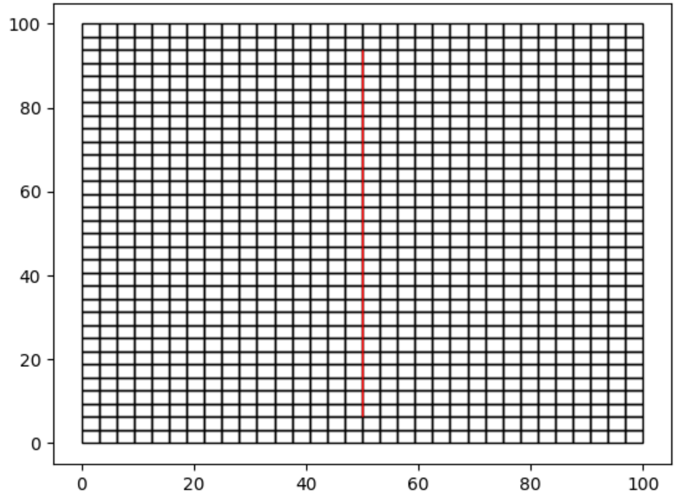


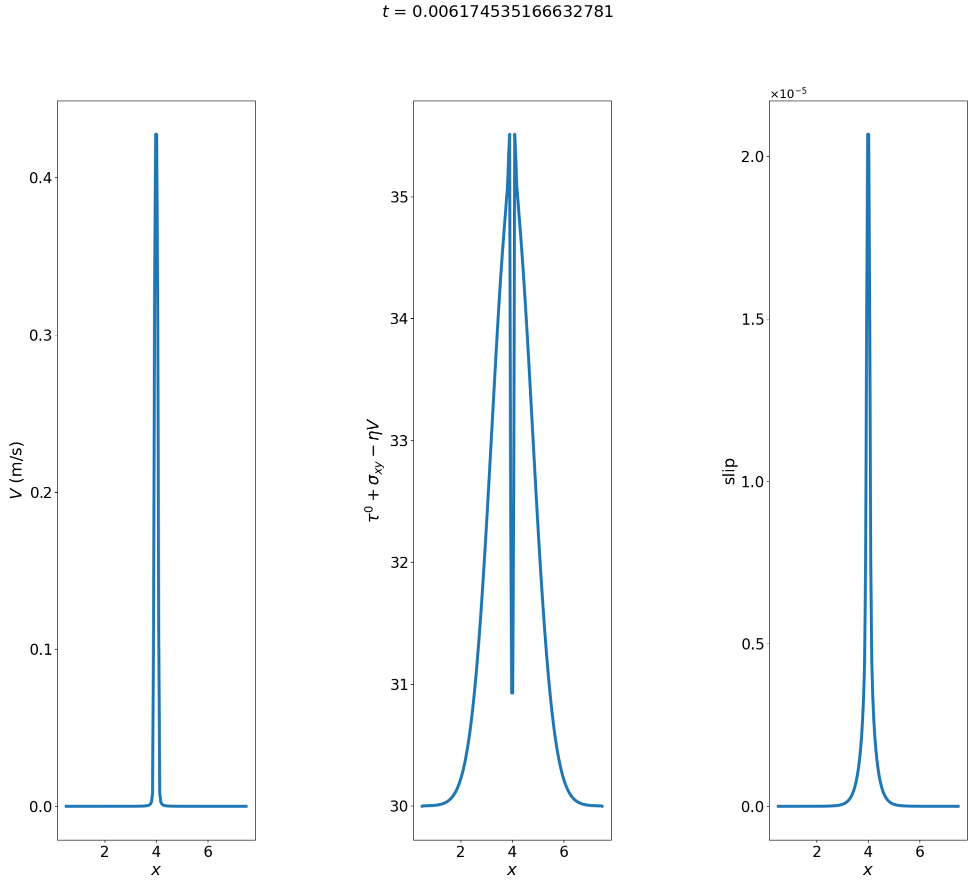


Coupled (poro)mechanics and earthquake model



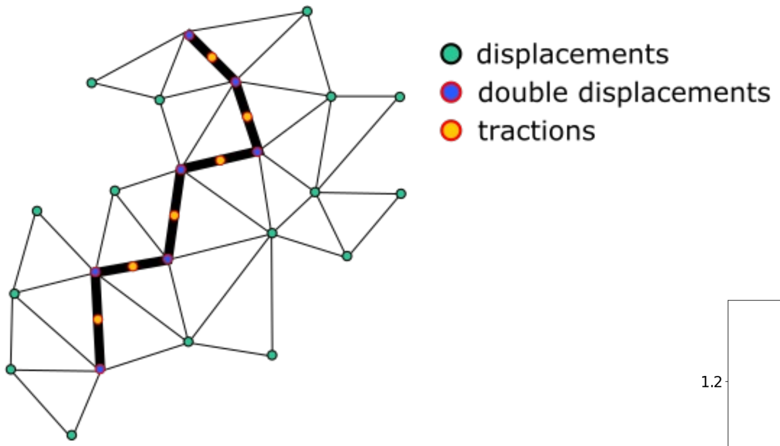
Slip is prescribed as a b.c. to the mechanics



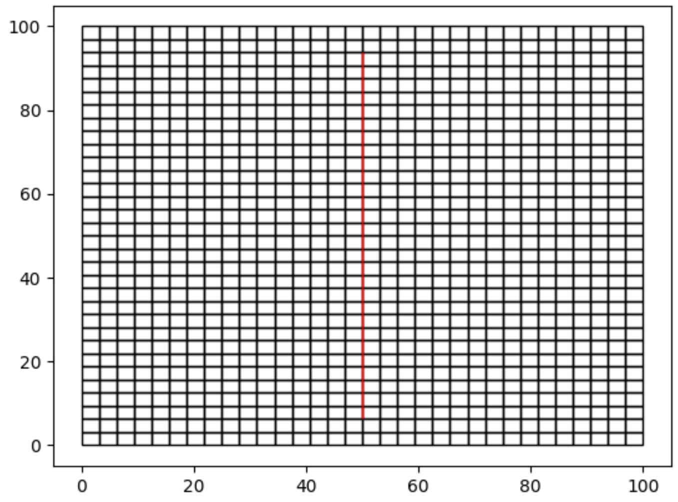


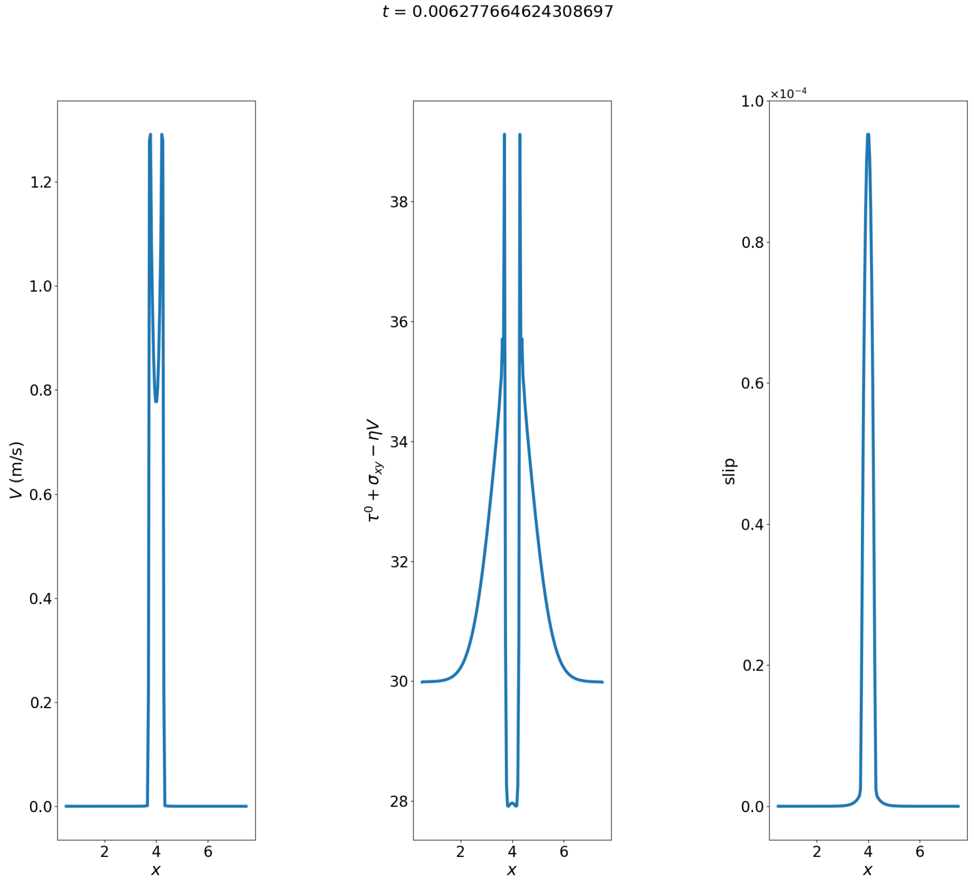
Work in collaboration with Vidar Stiernstroem, Matteo Frigo, Eric Dunham, Nicola Castelletto

Coupled (poro)mechanics and earthquake model



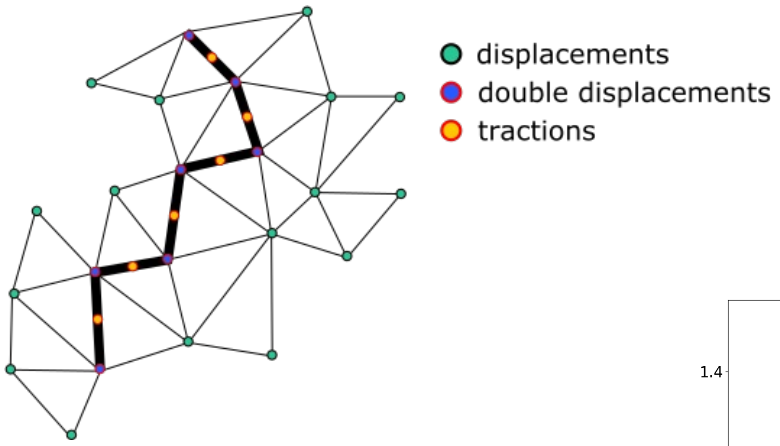
Slip is prescribed as a b.c. to the mechanics



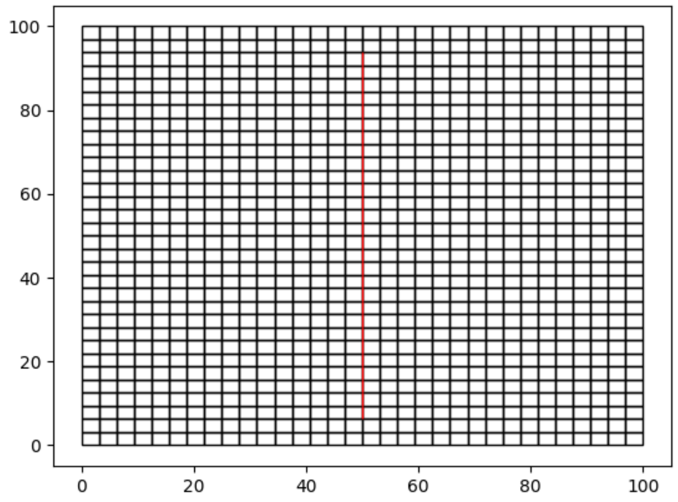


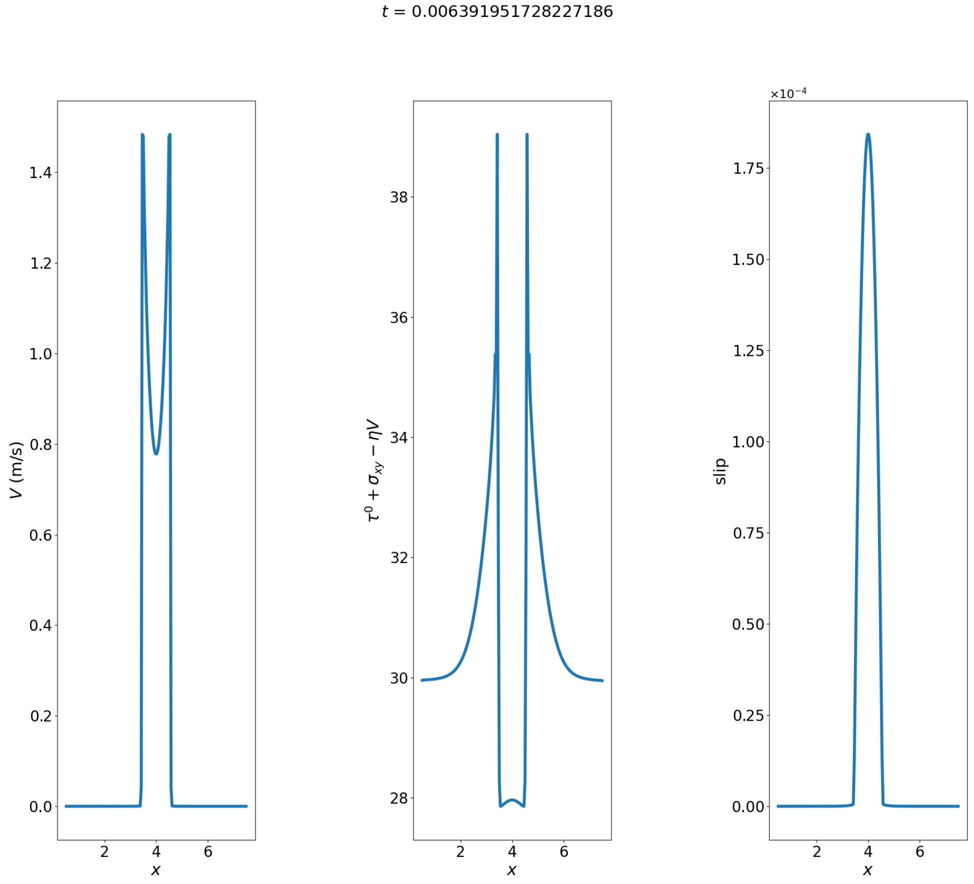
Work in collaboration with Vidar Stiernstroem, Matteo Frigo, Eric Dunham, Nicola Castelletto

Coupled (poro)mechanics and earthquake model



Slip is prescribed as a b.c. to the mechanics





Year 1: subtasks & milestones overview

Subtask 1 – Quasi-static fault stability analysis capability

- 1.1 – Implementation of a conforming discretization approach to model faults in a poroelastic medium.
- 1.2 – Implementation of constitutive laws that account for the dependency of fault permeability on stressing conditions.

Milestone 1.1: Poromechanical solver with Lagrange multiplier-based contact enforcement implemented in GEOS and validated with numerical examples (Completed).

Year 2: subtasks & milestones overview

Subtask 2 – Quasi-dynamic fault modeling capability

- 2.1 –*Implementation of a rate- and state-dependent friction model*. We enrich the framework devised in subtask 1.1 with a rate- and state-dependent friction model.
- 2.2 – *Development of a prototype quasi-dynamic earthquake rupture modeling capability*. We will develop a prototype earthquake rupture simulator and implement it in the GEOS framework.
- *2.3: Development of a strategy to couple poromechanics with a quasi-dynamic earthquake rupture physics.*

Milestone 2.1: Rate- and state- friction model implemented and validated. [Fully prototyped & GEOS implementation ongoing]
Milestone 2.2: Prototype quasi-dynamic earthquake rupture modeling capability completed. [80%]
Milestone 2.3: Prototype coupled poromechanics and quasi-dynamic earthquake rupture modeling capability completed. [50%]

Thank you

Funding from Office of Fossil Energy and Carbon Management FEW0287