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How fluid induced thermal stress changes impact fault slip on a fault in a porous geothermal reservoir

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Take home message

- In our base case model no seismic event nucleates, due to stabilization of the fault as the effective normal stress decreases.
- By introducing a fault healing time before injection, the fault strengthens and a larger stress perturbation is needed for an earthquake to occur.
- By decreasing the characteristic slip distance the fault becomes more unstable and multiple earthquakes nucleate.
- The safe utilization of the Dutch subsurface for geothermal energy is highly dependent on the in-situ fault properties.

Introduction

Simple thermo-mechanical models show that pre-existing faults in geothermal reservoirs are potential sites for induced seismicity (Fig 1). However, in these models accurate fault friction and rate effects are not accounted for.

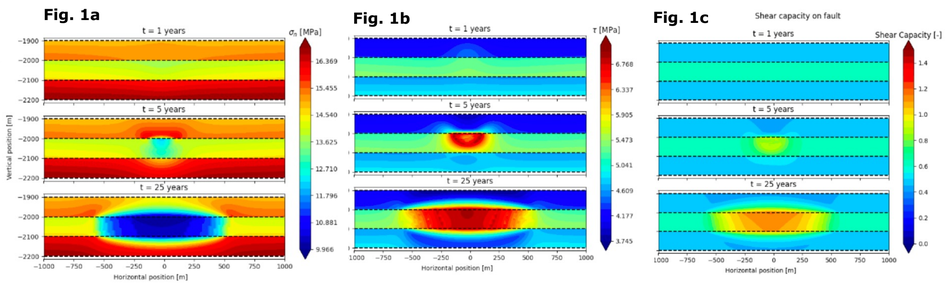


Fig 1: Normal stress (a), shear stress change (b) and shear capacity (c), due to 1 year, 5 year and 25 years of cooling on a fault. Figures are adopted from Fokker et al., 2023 [1].

Research questions

1. What happens when we update the failure criterion to a more realistic slip rate and fault age friction formulation?
2. How is the slip behaviour affected by:
   a. Fault healing time
   b. Characteristic slip distance (Dc)

Method

The SRIMA tool is used to determine the thermo- and poro-elastic stress changes on the faults from the temperature and pressure distributions [1].

$$\Delta\sigma_{ij} = 2G\left[\epsilon_{ij} + \frac{\nu}{1-2\nu}\epsilon_v\delta_{ij}\right] + \left(\alpha_{Biot}\Delta P + \beta_T\Delta T\right)\delta_{ij}$$

The tool assumes purely radial-horizontal advection inside of the reservoir and diffusion to the seal and base layers.

The stress changes are transferred to Quake-DFN [2], which is a quasi-dynamic earthquake rupture model.

$$M_i(\ddot{\delta}_i) = \sum_j \kappa_{ij}^{\tau}(\delta_{0j} - \delta_j) - \mu_i\left(\sigma'_{0i} + \sum_j \kappa_{ij}^{\sigma}\delta_j + \sigma_i'^{E}\right) - \frac{G}{2\beta}\dot{\delta}_i + \tau_i^E$$

Faults are governed by rate and state friction with aging law:

$$\mu = \mu_0 + a\log\left(\frac{V}{V_0}\right) + b\log\left(\frac{V_0\theta}{Dc}\right) \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{Dc} - \alpha\frac{\theta\dot{\sigma}}{\beta\sigma'}$$

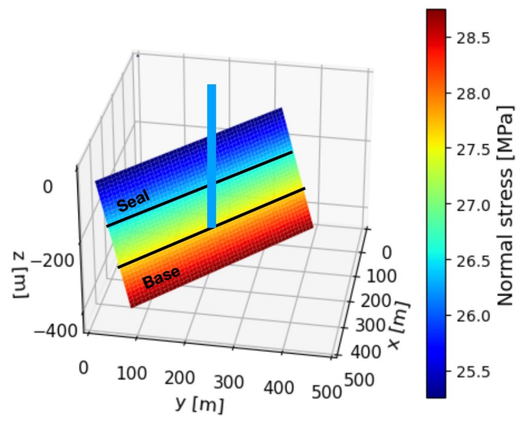


Fig 2: Normal stress at the start with in blue the injection pipe. Fault has a dip op 70° and each layer has a thickness of 100m with the reservoir in the middle. The 0m on the z-axis is actually at a depth of 2000m.

The seismic threshold is at 0.055 m/s.

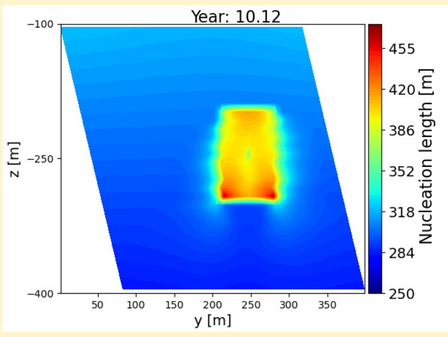
Outlook

- Parameter study to determine the likelihood of seismic events occuring in Dutch geothermal reservoirs.
- Increase healing time to match the inactivity of the Dutch subsurface.

Results

1. Base Case Model

- During the first 10 years there is no fluid injection.
- 42 days after the start of injection maximum slip rate of $7.3 * 10^{-5}$m/s is reached (Fig. 5b).



$$L_c = \left(\frac{b}{b-a}\right)^2 \frac{GD_c}{\pi b\sigma_n(1-\nu)}$$

Fig 3 left: Nucleation length on the fault after 42 days of cooling.

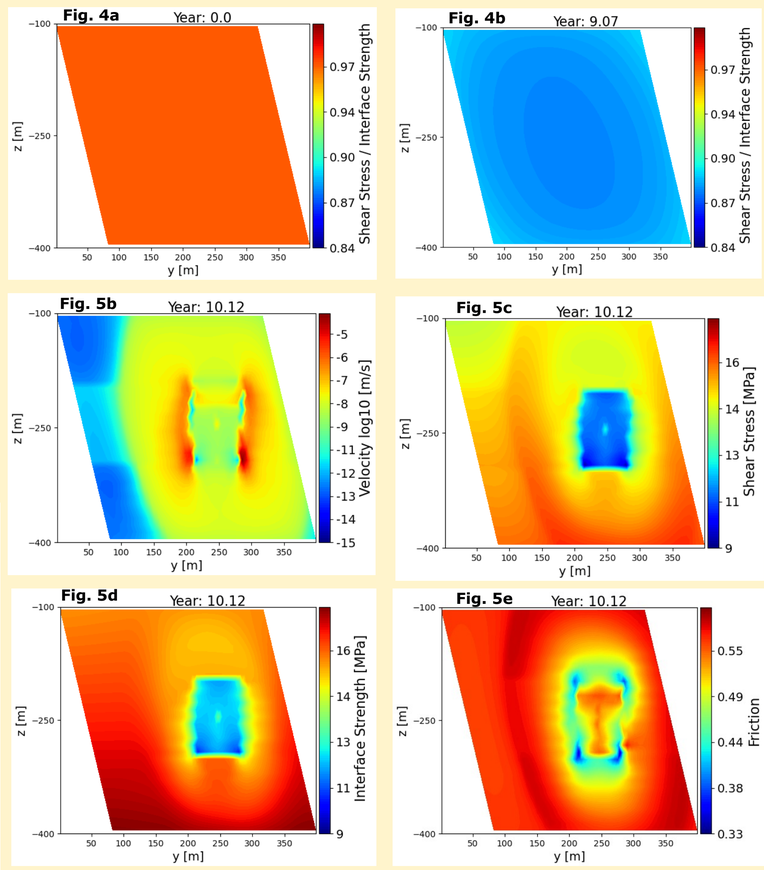
$$\Psi = \left(\mu_0 + bln\left(\frac{\theta V_0}{Dc}\right)\right)\sigma_n$$

Fig 4 below: Shear stress over interface strength at the start (a) and after 9 years of healing (b).

Two main reasons for the aseismic slip behaviour:

1. Injected-induced effective normal stress decrease stabilizes the fault by increasing the nucleation length (L_c) beyond the reservoir width (Fig. 3).

2. The interface strength (Ψ) has increased and the shear stress decreased due to healing (Fig. 4), causing the fault to be further away from failure.



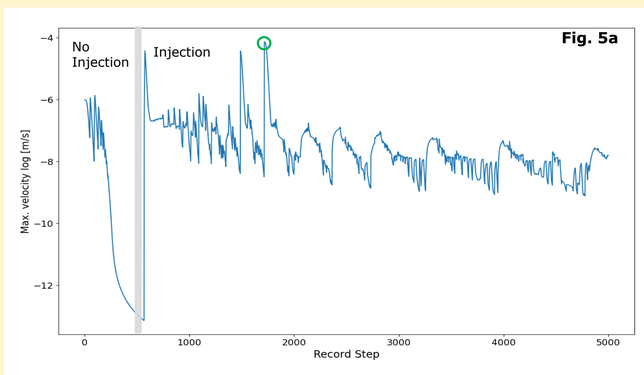


Fig 5: Maximum slip velocity throughout all timesteps (a). Green circle indicates the timestep of max. slip rate and the time of figures 5b: Slip velocity, 5c: Shear stress, 5d Interface strength (Ψ), and 5e: Friction.

2a. Healing time stabilizes

- Without healing time an aseismic event with a max. slip rate of 0.04 m/s forms after 1.2 days of injection (Fig. 6).
- An increased holding time from 10 to 1000 years decreases the max. slip rate to $3.4 * 10^{-7}$ m/s (Fig. 7).

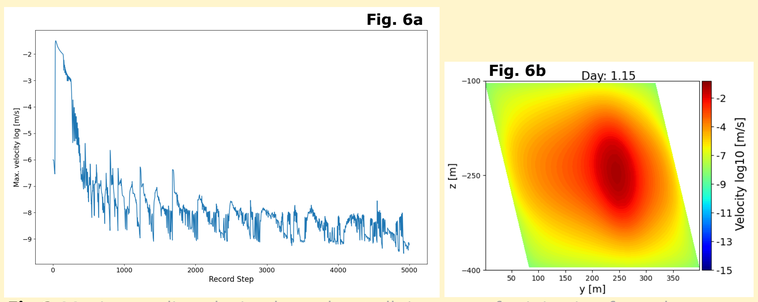


Fig 6: Maximum slip velocity throughout all timesteps for injection from the start of modelling time (a). Slip velocity, when the max. slip rate is reached (b).

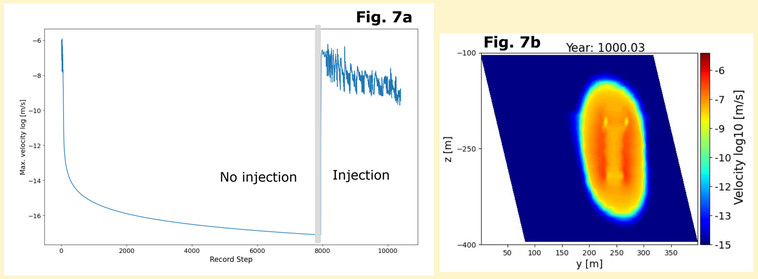


Fig 7: Maximum slip velocity throughout all timesteps for 1000 years healing (a). Slip velocity when the max. slip rate is reached (b).

2b. Characteristic slip distance (Dc) destabilizes

- A reduction of Dc by 10^{-1} causes 3 seismic events (M = 2.8, 2.5, and 2.4) to nucleate, after the start of injection.
- There are approximately 200 days between each event (Fig 8).

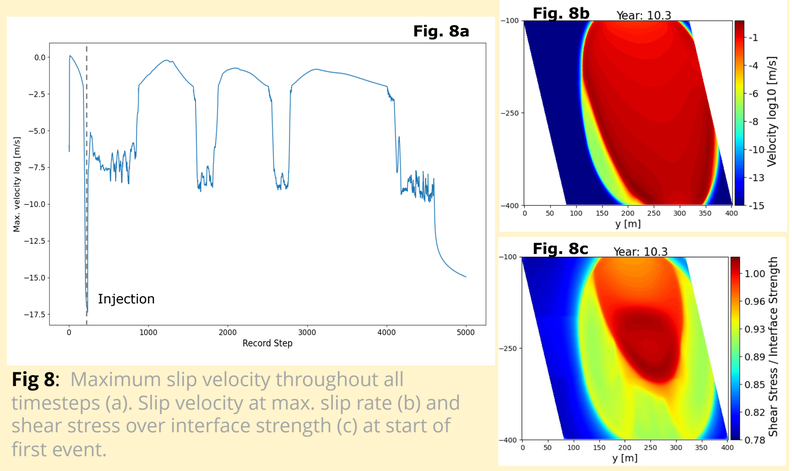


Fig 8: Maximum slip velocity throughout all timesteps (a). Slip velocity at max. slip rate (b) and shear stress over interface strength (c) at start of first event.

Decreasing Dc affects:

1. The Lc, which drops below the reservoir width. Destabilizing the fault.
2. The weakening slope ($k_{sw} = -b/D_c$), which is steeper leading to a faster shear stress drop and less energy consumed in the weakening process.

References

1. Fokker, P.A., Buijze, L and Pluymaekers, M.P.D., 2019, SRIMA: Background Information of the Python tool. *TNO Report 2023 R11303*
2. Im, K., & Avouac, J. P. (2024). Quake-DFN: A Software for Simulating Sequences of Induced Earthquakes in a Discrete Fault Network. *Bulletin of the Seismological Society of America*, *114*(5), 2341-2358. https://doi.org/10.1785/0120230299

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