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# Seismic Hazard Associated with Long-Term Fluid Injection: Trade-off Between Risk Mitigation and Operation Efficiency

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## Summary

Long-term fluid injection, such as wastewater disposal and $CO_2$ storage, potentially can cause induced seismicity. Injection operations are often constrained by many different variables, including the supply and transportation of injected fluids, and infrastructure maintenance. As a result, injection often deviates from an ideal constant-rate schedule to alternating periods of high-rate injection and shut-in. Seismic risk is commonly monitored through pore-pressure changes, yet it remains unclear whether pore pressure alone is a good proxy for operators to design an efficient and seismically safe injection schedule.

We use coupled hydro-mechanical numerical modeling to explore the trade-off between the mitigation of induced seismic risk and operational efficiency for long-term fluid injection. Cyclic injection is used to accommodate planned or unplanned downtime due to realistic variations in supply/storage/transportation of fluids. We compare a continuous baseline with several cyclic schedules that all inject the same total amount over 20 years but differ in instantaneous rate and on/off period. Seismic hazard is quantified by Coulomb failure stress change on the optimally oriented basement fault, and we decompose this into contributions from pore pressure and poroelastic stress.

Our results show that (1) cyclic injection significantly alters both the magnitude and timing of Coulomb stress changes, even when cumulative injected amount and average rate are fixed; (2) high instantaneous rates do not necessarily lead to higher seismic hazard if injection and shut-in cycles are sufficiently frequent; and (3) poroelastic stress transfer can potentially reduce or enhance the failure tendency relative to what would be inferred from pore pressure alone. These findings suggest that injection rate limits should be considered together with continuous injection duration, and that coupled hydro-mechanical modeling is a useful tool to evaluate this trade-off before and during long-term operations.

## Method

We simulate a generic injection site using a fully coupled hydro-mechanical model implemented in OpenGeoSys (OGS) (Bilke et. al., 2024). The linear poroelasticity model accounts for the feedback between pressure diffusion and porous rock deformation, so that both pore-pressure changes and poroelastic stress transfer are resolved in space and time.

The numerical domain is a 3-km thick 3D block representing a sedimentary setting with a crystalline basement overlain by a permeable reservoir and a low-permeability caprock. The

reservoir is the targeted injection layer. Material properties are chosen to be broadly representative of stiff basement, a moderately compliant sandstone reservoir, and a more compliant seal, with layer-dependent Biot coefficients and elastic moduli. Mechanical boundary conditions approximate a semi-infinite half-space, with a fixed base, roller lateral boundaries, and a traction-free top surface.

We prescribe a strike-slip stress state consistent with many intraplate and basin-center sequences. The vertical stress equals the lithostatic load. Induced-seismicity potential is evaluated on an optimally oriented fault plane for this ambient stress field, assuming faults are randomly distributed in orientation. The optimal plane is defined by the Coulomb friction theory, using a representative friction coefficient of 0.6.

Five injection scenarios are designed to isolate the effect of cycling under a fixed total injected amount. Each scenario spans 240 months (20 years) of injection followed by post-injection relaxation, and all have the same time-averaged injection rate of 5 kg/s:

- **Case 1:** Continuous injection at 5 kg/s.
- **Case 2:** 10 kg/s, 1 month on / 1 month off (50% duty cycle).
- **Case 3:** 10 kg/s, 6 months on / 6 months off (50% duty cycle).
- **Case 4:** 20 kg/s, 1 month on / 3 months off (25% duty cycle).
- **Case 5:** 20 kg/s, 6 months on / 18 months off (25% duty cycle).

These cyclic schedules can be viewed as simplified representations of variable wastewater or $CO_2$-stream supply, maintenance shutdowns, and/or transportation bottlenecks. All cases therefore represent different operational strategies under the same long-term disposal or storage obligation.

Seismic hazard is expressed as the Coulomb failure stress change on the optimally oriented basement fault:

$$\Delta CFS = \Delta\tau + \mu(\Delta\sigma_n + \Delta p)$$

where $\Delta\tau$ is the change in shear traction in the slip direction, $\Delta\sigma_n$ is the change in normal stress (tension positive), $\Delta p$ is the pore-pressure change, and $\mu$ is the friction coefficient. We decompose $\Delta CFS$ into a hydraulic part, $\mu\Delta p$, and a poroelastic part, $\Delta CFS - \mu\Delta p$, to separate the direct effect of pressure from stress changes caused by rock deformation. Spatial patterns and time series of these quantities are extracted at a monitoring point 100 m below the injector in the basement and along a vertical cross-section through the well.

## Results and Conclusions

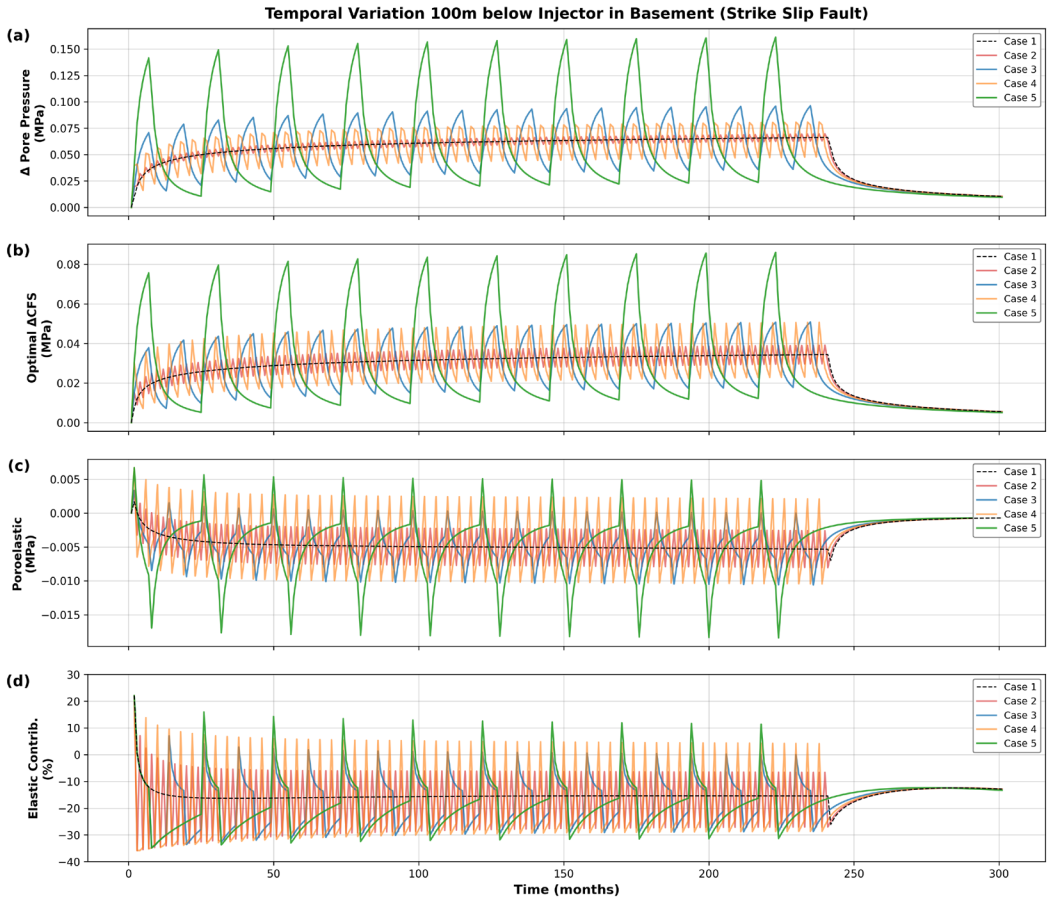



*Figure 1. Temporal evolution of pressure and failure metrics at a monitoring point 100 m below the injector within the basement for the strike-slip-faulting stress regime. Time series show (a) pore-pressure change Δp (MPa), (b) Coulomb failure stress change on the optimally oriented fault plane, ΔCFS (MPa), (c) poroelastic (elastic stress-transfer) contribution to ΔCFS (MPa), and (d) elastic contribution expressed as a percentage of ΔCFS (%).*

The simulations show that higher instantaneous injection rate does not necessarily translate into higher seismic hazard when the same total amount is injected. Cyclic scenarios with elevated rates (10–20 kg/s) but frequent on–off cycles produce peak Coulomb failure stress changes comparable to, or lower than, those obtained for the continuous 5 kg/s baseline at the basement monitoring point. In contrast, scenarios with long uninterrupted injection periods at the same average rate can lead to larger and more abrupt stress excursions when injection is stopped. This indicates that, for a fixed injected amount, the time history of injection and shut-in controls the amplitude and timing of fault loading as much as the nominal rate itself. Regulating operations solely through upper limits on instantaneous rate is therefore insufficient, because it does not account for the stabilizing effect of frequent cycling or the potential accumulation of stress under long continuous injection.

Although pore pressure is the most accessible quantity to monitor and regulate, it is not a complete parameter for seismic risk in this setting. At 100 m below the injector, the

pore-pressure history of Case 4 appears more stable comparing to that of Case 3, while their Coulomb failure stress histories vary at similar amplitude around the baseline. The poroelastic term reduces the net Coulomb stress by tens of percent relative to a pressure-only estimate. Thus, a control strategy based solely on keeping pore pressure below a given threshold could mischaracterize the true failure tendency, because it neglects the concurrent evolution of shear and normal tractions arising from deformation of the rock matrix.

These results also have implications for balancing seismic-risk mitigation with operational efficiency. Because all tested schedules deliver the same cumulative injected amount, the cyclic cases demonstrate that occasional periods of higher injection rate can be compatible with an acceptable Coulomb stress response, provided that the cycles are sufficiently short to allow partial hydraulic and mechanical relaxation between injection episodes. In other words, maintaining the same level of seismic risk throughput the lifespan of an injection operation does not always require a strictly constant rate over decades; it can also be achieved through carefully designed cycles that accommodate logistic constraints while avoiding large stress build-up. Within reasonable limits, temporary increases in the injection rate can therefore be used as one of the effective operational tools to satisfy necessary supply and/or infrastructure downtime without dramatically increasing the corresponding seismic hazard, as long as cycle period and shut-in duration are chosen with the coupled hydro-mechanical response in mind.

Overall, our study results indicate that seismic hazard associated with long-term fluid injection is governed by the combined evolution of pore pressure and poroelastic stress, and by the detailed timing of injection and shut-in cycles. We conclude that (1) high instantaneous rates are not inherently unsafe, (2) pore-pressure thresholds alone do not fully capture induced seismic risk, and (3) occasional rate increases can be acceptable when embedded in appropriately frequent cycles. Effective regulation and operational design should therefore treat injection schedule as a key control parameter and employ coupled hydro-mechanical modeling to evaluate how different injection rate–duration combinations trade off between risk reduction and operational efficiency.

## Acknowledgements

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**References**

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