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Importance of hydraulic process in induced seismicity modeling

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Induced seismicity is often modeled as the reactivation process of a fault due to pore pressure change. The known inputs are mostly the injected fluid flux and well-head pressure. The output is the spatio-temporal distribution of the seismicity, detected by the seismograms. The medium should be hydraulically and mechanically heterogeneous and complex and its characteristics are often calibrated with the on-going process. From the point of view of earthquake generation process, we often take into account the non-linearity or randomness of the faulting in friction, while the diffusion process of the fluid is often over simplified. In the infinite, isotropic and homogeneous porous medium, the pore pressure change can be analytically written, noting that there remains a singular point at the injection point. On the other hand, it is also possible to consider that the porosity or permeability of the medium evolves with time and on-going fracturing process in the numerical simulations. Here, we assume that **the permeability is a function of effective normal stress**.

Model

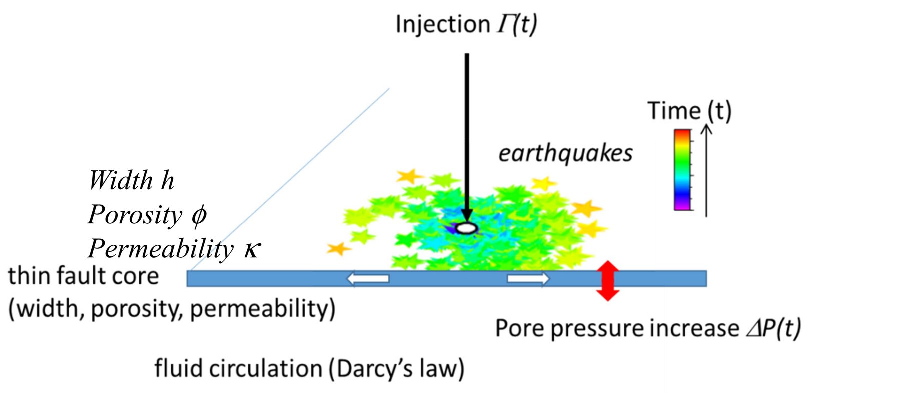


Fig1: Schematic view of fault reactivation model (Aochi et al., 2014; others)

Basic Equations

- Darcy's law $\vec{q} = -\rho \dfrac{\kappa}{\eta} \nabla P$
- Continuity of fluid mass $\nabla \cdot \vec{q} + \dfrac{\partial (\rho\phi)}{\partial t} = \rho\dot{\Gamma}$
- Conservation of porous mass $\dfrac{d}{dt}\left((1-\phi)\rho h\right) = 0$

Model concept (Aochi et al., 2014)

- A permeable planar fault surrounded by impermeable medium.
- Fluid flux is given directly on the fault.
- Fluid diffusion is solved according to the Darcy's law and mass conservation of fluid and porous medium.
- Fractal earthquake 'bins' are randomly distributed on the fault plane.
- Rupture criterion is govern by Coulomb friction.
- Stress equilibrium is computed on static kernel in 3D homogeneous, infinite medium.

Traditional assumption on porosity: Walder and Nur (1994), Segall and Rice (1995)

$$\frac{d\phi}{dt} = \dot{\phi}_{elastic} + \dot{\phi}_{plastic} = \frac{\partial \phi_{elastic}}{\partial p}\frac{\partial p}{\partial t} + \dot{\phi}_{plastic} = \phi\beta_\phi \dot{P} + \dot{\phi}_{plastic}$$

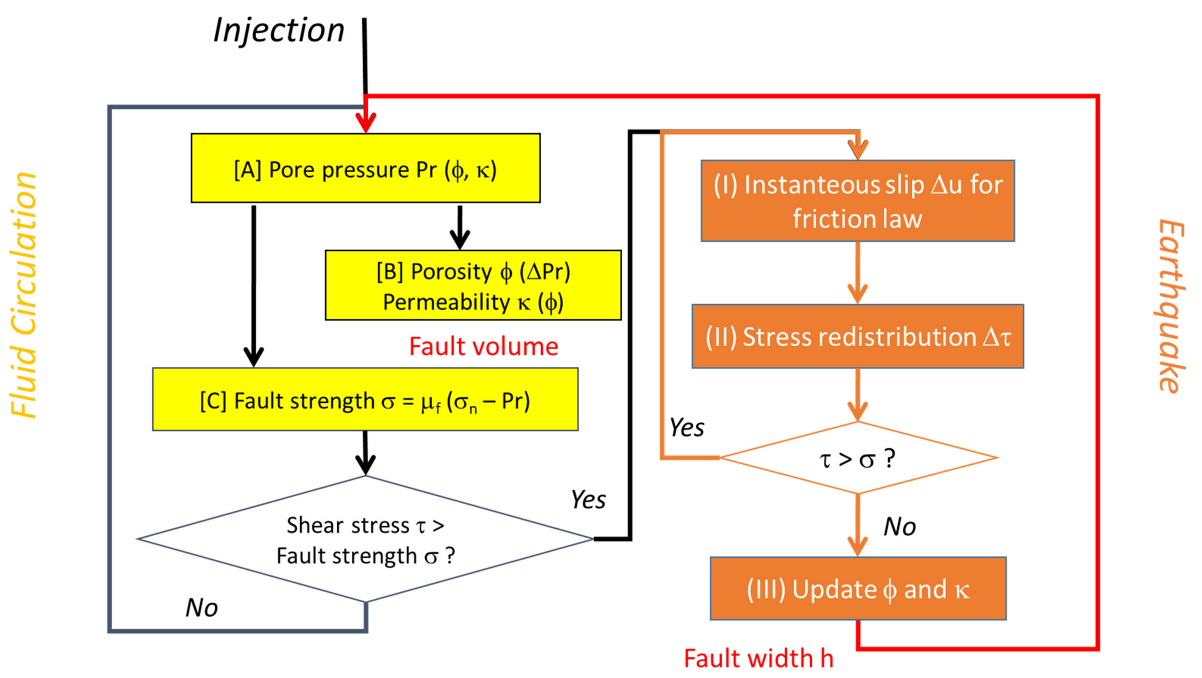
$$\frac{dh}{dt} = 0 \longrightarrow \dot{P} = \frac{1}{\phi(\beta_f + \beta_\phi)}\left[\nabla\left(\frac{\kappa}{\eta}\nabla P\right) - \dot{\phi}_{plastic} + \dot{\Gamma}\right]$$

$$\boxed{\frac{dh}{dt} \neq 0 \longrightarrow \dot{P} = \frac{1}{\phi(\beta_f + \beta_\phi)}\left[\nabla\left(\frac{\kappa}{\eta}\nabla P\right) - \phi\frac{\dot{h}}{h} - \dot{\phi}_{plastic} + \dot{\Gamma}\right]}$$

Hypotheses on permeability

1. Constant, $\kappa = \kappa_0$
2. Power low between permeability and porosity, $\kappa = \kappa_0 \left(\dfrac{\phi}{\phi_0}\right)^n$
3. Toggle change (co-seismic and healing) $\kappa = \begin{cases} \kappa_1 (\Delta u = 0) \\ \kappa_2 (\Delta u \neq 0) \end{cases}$; and then $\dfrac{d\kappa}{dt} = -\beta(\kappa - \kappa_1)$
   Miller & Nur (2000)
4. Constrained from effective normal stress. $\kappa = \kappa_0 \exp\left(-\dfrac{\sigma_n^{eff}}{\sigma_0}\right)$, $\sigma_n^{eff} = \sigma_n - \Delta P$

Fig2: Simulation steps between hydraulic process and earthquake generation (Aochi et al., 2014)



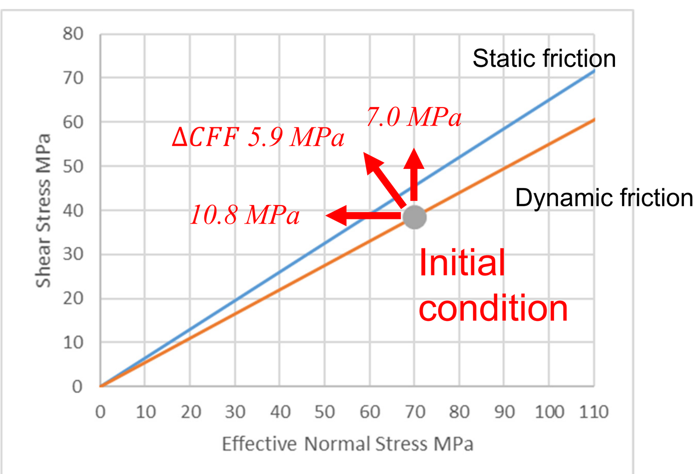


Fig3: Initial stress setting and rupture criterion under the given parameters in Coulomb diagram. This concerns the distributed earthquake bins only. The background of the fault is regarded as barrier.

Model parameters

Fixed parameter	Quantity (unit)
Static frictional coeff	0.65
Dynamic frictional coeff	0.55
Normal stress	100 MPa
Fluid viscosity η	2×10^{-4} Pa.s
Fluid density ρ	1×10^{3} kg/m^3
Fluid compressibility β_f	5×10^{-10} Pa^{-1}
Meduium compressibility β_ϕ	5×10^{-11} Pa^{-1}
Ridigidy of medium μ	30 GPa

Variable parameter	Initial value or its range (unit)
Initial fault width	5 m
Permeability κ	$(10^{-16}, 10^{-12})$m^2 ; See Graph
Initial porosity ϕ	0.05; elastic change only
Initial pore pressure ΔP	30 MPa
Initial shear strses τ	38.5 MPa (=dynamic stress level)

Note: In the given framework, it is necessary that the pore pressure increases enough to rupture, but not too much to vanish the effective normal stress.

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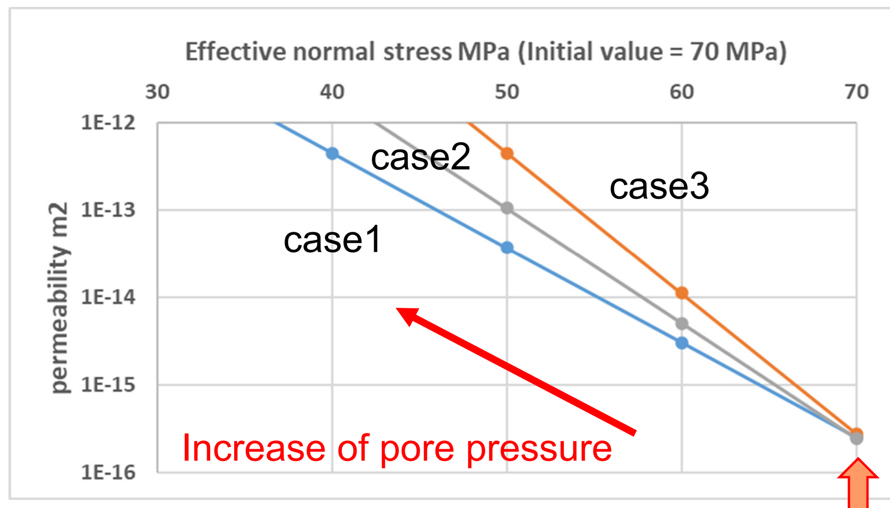
Simulation results

Model setting

- Fault dimension of 3 km x 3 km.
- Injection point at the center.
- Injection flow rate is given by **the stimulation experience in 2000 at Soultz-sous-Forêt, France.**
- We test three (3) different permeability evolutions.

Note: A constant permeability case was not so successful. The fluid flows so quickly or is stagged at the injection point.



Initial condition

Fig4: Assumed permeability behavior in function of effective normal stress (condition 4). The permeability increases more quickly from Case 1 to Case 3. This allows the fluid diffuses quickly and smoothly.

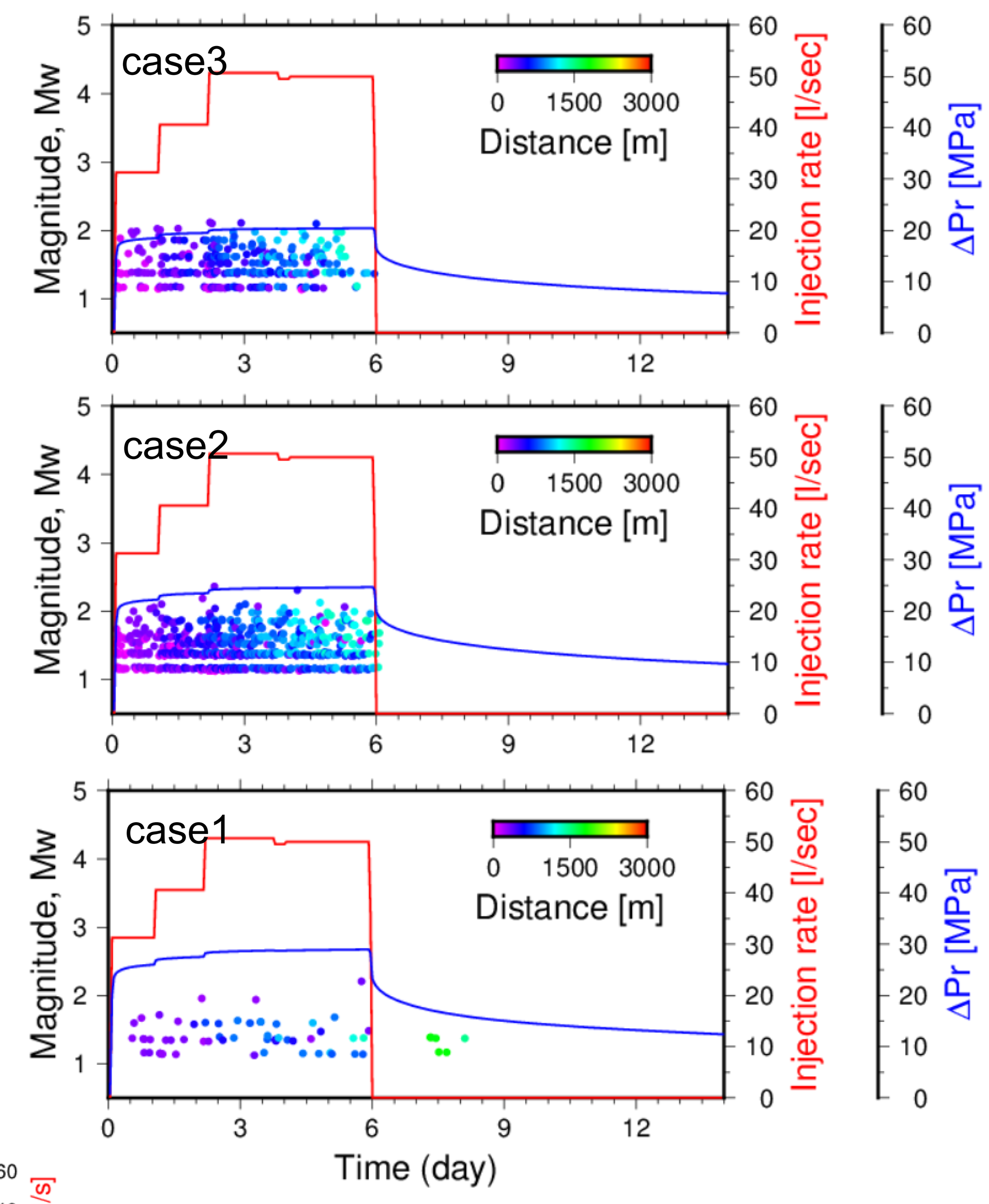
Fig5: Simulation results for three different cases. The injection rate history is the same (red). Pore pressure change at the injection point is shown in blue line. The seismicity is plotted as dots (time and magnitude), whose color indicates the distance from the injection point.

Note: Pore pressure change is immediate at the beginning. It is less sensible to the further steps. After the arrest, it decreases gradually. It it not always the case for the other permeability conditions.

Pore pressure change remains moderate and less sensible to a jump in injection late.
The seismicity is moderate.

Pore pressure change remains moderate.
The seismicity is the most.

Pore pressure change is high around the injection point.
The seismicity disperses with delayed earthquakes.



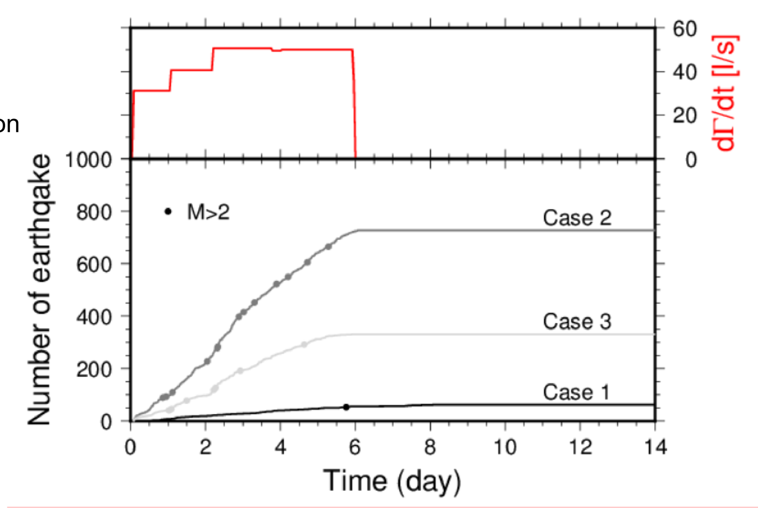


Fig5: The evolution of cumulative number of earthquake for three cases from the same simulation as in Fig. 4. The given injection history is given on top panel. The dots represent the earthquakes whose magnitude is larger than 2.

Note: The second step in injection (day 2) gives a remarkable seismicity rate change here. (See poster Maury et al.)

Conclusion

In general, it is expecated that the permeablity is not homogeneous and not constant. It should vary with the on-going process. The effective normal stress-dependent permeability is a good compromis.

Low (case 1) or high (case 3) permeability does not always lead to a high seismicity rate. The earthquake generation process is hightly nonlinear and a strong coupling appears for certain combination (case 2). It should be also related to the initial condition and rupture criterion we choose.

In order to examine the spatio-tempral evolution of the seismicity even during the operation phase, this mechanical approach will be helpful.

References

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