Induced aseismic slip and the onset of seismicity in displaced faults

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Science4Steer – towards operational control

• Aim: A scientific basis for developing production and reinjection strategies to minimize induced seismicity
• 5-year program at TU Delft and Utrecht University - part of DeepNL
• Combined experimental and numerical approach

WP 1: Lab-scale compaction experiments
WP 2: Lab-scale friction experiments
WP 3: Lab-scale friction and seismicity exp.
WP 4: Model development and upscaling
WP 5: Multi-scale simulation of multi-well/fault
WP 6: Optimal control to minimize seismicity

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Increasing spatial scale
Science4Steer – WP 3; Lab Experiments

- Investigators: Milad Naderloo and Auke Barnhoorn @ TU Delft
- Triaxial cell with 30 x 30 x 30 cm blocks
- Induced seismicity resulting from differential pressure and/or pressure decline in displaced faults
Science4Steer – WP 3; Lab Experiments

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Earlier work – numerical

2D displaced normal fault model

Fault throw: \( t = b - a \)
Reservoir height: \( h = a + b \)
Also known as “elastic thin sheet”
Inclusion theory (1)

Elsheby, 1957: cut and weld operation to simulate response to inelastic deformation (e.g. thermal strain, dislocations, pore pressure)

Total strains = elastic strains + eigen strains: $\epsilon_{ij} = e_{ij} + \epsilon_{ij}^*$

For porous media: $\epsilon_{ij}^* \delta_{ij} = \frac{\epsilon^*}{3} = \frac{\alpha p}{3K}$
Inclusion theory (2)

After several steps:

\[ u_i(x, y) = D \int \int_{\Omega} g_i(x, y, \zeta, \xi) \, d\Omega, \]

\[ \sigma_{ij}(x, y) = C \left[ \int \int_{\Omega} g_{ij}(x, y, \zeta, \xi) \, d\Omega - 2\pi \delta_{ij} \right] \]

where

\[ D(\zeta, \xi) = \frac{(1 - 2\nu) \alpha p}{2\pi (1 - \nu) G}, \quad C = GD \]

and \( g_i \) and \( g_{ij} \) are Green’s functions for \( u_i \) and \( \sigma_{ij} \).


Link to “nucleus of strain” concept: Rudnicki (2002)
Typical integral (for rectangle)

\[
\frac{\sigma_{xx}}{C} (x, y) = \int_p^q \int_r^s g_x(x, y, \zeta, \xi) d\xi d\zeta
\]

\[
= \left\{ \ln \left[ (x - q)^2 + (y - \frac{\sigma_{xx}}{C}) \right] - \ln \left[ (x - p)^2 + (y - s)^2 \right] \right\} \times \frac{y - s}{4}
\]

\[
- \left\{ \ln \left[ (x - q)^2 + (y - r)^2 \right] - \ln \left[ (x - p)^2 + (y - r)^2 \right] \right\} \times \frac{y - r}{4}
\]

\[
+ \left\{ \arctan \left( \frac{y - s}{x - q} \right) - \arctan \left( \frac{y - r}{x - q} \right) \right\} \times \frac{x - q}{2}
\]

\[
- \left\{ \arctan \left( \frac{y - s}{x - p} \right) - \arctan \left( \frac{y - r}{x - p} \right) \right\} \times \frac{x - p}{2}
\]
Incremental stresses due to injection
Incremental stresses due to injection
Stresses - definitions

Solid mechanics: tension positive; compression negative
Soil mechanics: compression positive; tension negative

Soil mechanics: $\sigma = \sigma' + p$ (Terzaghi) or $\sigma = \sigma' + \alpha p$ (Biot)
Solid mechanics: $\sigma = \sigma' - p$

$0 << \alpha < 1$: Biot coefficient (measure of grain compressibility)
Total stresses: $\sigma$; effective stresses: $\sigma'$

Initial total stresses: $\sigma^0$ (representing geological history)
Incremental total stresses: $\sigma$ (due to injection or depletion)
Same for effective stresses: $\sigma^0'$ and $\sigma'$
Stresses and slip boundaries

\[ p^0 = 35 \text{ MPa} \]
\[ p = 20 \text{ MPa} \]
\[ p^{tot} = 55 \text{ MPa} \]
Stresses and slip boundaries

\[ p = 20 \text{ MPa} \]
Stresses and slip boundaries: \[ \sigma^{slip} = \pm \mu \sigma_{xx} \]

\[ p = 20 \text{ MPa} \]
Stresses and slip boundaries

\[ p = 20 \text{ MPa} \]
Injection and production

SCU = 0.88 @ $\mu_{st} = 0.6$
SCU = 1.05 @ $\mu_{dyn} = 0.5$

$p = 0 \text{ MPa}$

\begin{align*}
&\text{a) Stresses (injection) (MPa)} \\
&\text{b) Stresses (production) (MPa)}
\end{align*}
Injection and production

\( p = 5 \text{ MPa} \)

\( p = -5 \text{ MPa} \)
Injection and production

$p = 5 \text{ MPa}$

$p = -5 \text{ MPa}$

Slip
Injection and production

\[ p = 20 \text{ MPa} \]

\[ p = -20 \text{ MPa} \]
Injection and production

$p = 35 \text{ MPa}$

![Graph showing stresses for injection at $p = 35 \text{ MPa}$](image)

$p = -35 \text{ MPa}$

![Graph showing stresses for production at $p = -35 \text{ MPa}$](image)
Injection and production

a) Stresses (injection) (MPa)
b) Stresses (production) (MPa)
Scaled stresses in the fault

Normal stresses

Shear stresses
Shear stresses and slip boundary in case of no-slip

- Even small depletion results in (small) slip (if we forget about healing)
- Numerical results that show a “non-slip depletion threshold” should be mistrusted – probably a grid effect

Singularities at $y = \pm a, y = \pm b$
Coulomb stresses in case of no-slip

\[ \sigma_C = \sigma_\parallel - \mu \sigma_\perp \]
Shear stresses around a dislocation

\[
\bar{\sigma}_{xy}(x, y) = \frac{\lambda G}{2\pi(1-\nu)} \frac{y(y^2 - x^2)}{R^4}
\]
Shear stresses and slip around dislocations
Slip around a distributed dislocation

\[
\tilde{\sigma}_\parallel(y) = A \int_{y_-}^{y_+} \frac{\chi'(\xi)}{y - \xi} \, d\xi;
\]

\[
A = \frac{G}{2\pi(1 - \nu)},
\]

\[
\chi'(\xi) = \left. \frac{\partial \lambda(y)}{\partial y} \right|_{y = \xi},
\]

\[
\int_{y_-}^{y_+} \frac{\chi'(\xi)}{y - \xi} \, d\xi = \lim_{\epsilon \downarrow 0} \int_{y_-}^{y_+ - \epsilon} \frac{\chi'(\xi)}{y - \xi} \, d\xi + \lim_{\epsilon \downarrow 0} \int_{y_+ + \epsilon}^{y_+} \frac{\chi'(\xi)}{y - \xi} \, d\xi.
\]
Frictionless vertical fault (1)

\[ \bar{\sigma}_||(y) = A \int_{y_-}^{y_+} \frac{\lambda'(\xi)}{y - \xi} \, d\xi; \]

\[ \bar{\sigma}_|| = \bar{\sigma}_{xy} = \frac{Ac}{2} \ln \left[ \frac{(y - y_+)^2}{(y - y_-)^2} \right] \]
Frictionless vertical fault (2)

\[ \tilde{\sigma}_\parallel(y) = \gamma C \left( \int_{-b}^{-a} \frac{-1}{y - \xi} d\xi + \int_{a}^{b} \frac{1}{y - \xi} d\xi \right) = -\frac{\gamma C}{2} \times \ln \left[ \frac{(y - a)^2(y + a)^2}{(y - b)^2(y + b)^2} \right] \]
Inverse relationship

\[ \bar{\sigma}_\parallel(y) = A \int_{y_-}^{y_+} \frac{\lambda'(\xi)}{y - \xi} \, d\xi; \]

\[ \lambda'(y) = -\frac{\sqrt{(y - y_-)(y_+ - y)}}{\pi^2 A} \int_{y_-}^{y_+} \frac{\bar{\sigma}_\parallel(\xi)}{\sqrt{(\xi - y_-)(y_+ - \xi)(y - \xi)}} \, d\xi, \]

provided that

\[ \int_{y_-}^{y_+} \frac{\bar{\sigma}_\parallel(y)}{\sqrt{(y - y_-)(y_+ - y)}} \, dy = 0 \]

\[ \int_{y_-}^{y_+} \frac{y \bar{\sigma}_\parallel(y)}{\sqrt{(y - y_-)(y_+ - y)}} \, dy = 0 \]
Segall (2010) – Chebyshev polynomials
Coulomb stresses in case of no-slip

\[ \sigma_C = \sigma_\parallel - \mu \sigma_\perp \]
Slip for constant Coulomb-type friction

\[ \mu(y, t) = \mu_{st} = 0.52. \]
Slip patch boundaries – Coulomb-type friction
Slip patch boundaries – Slip-weakening friction
Slip patch boundaries – Slip-weakening friction

Nucleation: eigenvalue/vector problem (Uenishi and Rice 2003)
Effect of fault throw

Nucleation pressure

Nucleation patch length

Seismic moment

\[ t/h = 0 \quad t \text{ (m)} \quad t/h = 1 \]
Take home messages:

- Injection results in Coulomb stress peaks at the external reservoir/fault corners; depletion produces stress peaks at the internal corners.
- Injection results in slip patches growing outward; depletion in patches growing inward (and possibly merging)
- Searching for a “slip free” incremental pressure is not very meaningful. Numerical results are mesh-dependent.
- Positive Coulomb stresses correspond to potential slip patches. Once slip actually occurs the corresponding patches are somewhat larger.
- Induced slip may be aseismic or seismic: nucleation (i.e. unstable patch growth) requires a reduction in slip resistance with increasing slip: slip weakening, velocity weakening or “rate and state dependent” friction. Lithology dependent!
- Maximum stresses shear stresses occur for dimensionless fault throw \( t/h = 1 \); maximum seismic moment however for intermediate throws.
References

Directly related to this presentation

• Jansen, J.D. en Meulenbroek, B.J., 2022.: Induced aseismic slip and the onset of seismicity in displaced faults. *Netherlands Journal of Geosciences* **101** e13. [https://doi.org/10.1017/njg.2022.9](https://doi.org/10.1017/njg.2022.9)


Recommended further reading


