Induced seismicity and GeoEnergies: lessons learned from coupled hydro-mechanical modeling

Antonio P. Rinaldi
and many others....
GeoEnergy applications and induced earthquakes belong together

Grigoli et al. (2017)
Recent examples of induced seismicity

Wastewater injection (e.g., Oklahoma, US)

Largest event: $M=5.8$

Langebruch and Zoback, 2016
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Wastewater injection (e.g., Oklahoma, US)

Enhanced geothermal system (e.g., Pohang, South Korea)

Largest event: $M=5.8$

Largest event: $M_w=5.5$

Grigoli et al., 2018

Langebruch and Zoback, 2016
Recent examples of induced seismicity

Wastewater injection (e.g., Oklahoma, US)

Enhanced geothermal system (e.g., Pohang, South Korea)

Deep geothermal energy (e.g., St. Gallen, Switzerland)

Largest event: $M=5.8$

Largest event: $M_w=5.5$

Largest event: $M_L=3.5$
GeoEnergy applications and induced earthquakes belong together

**2016 Canada, Fox Creek**
Shale Gas extraction
Magnitude 4.4

**2011 USA, Oklahoma**
Wastewater injection
Magnitude 5.6

**2010 UK, Blackpool**
Shale Gas extraction
Magnitude 2.3

**2012 Netherlands, Groningen**
Gas extraction
Magnitude 3.6

**2013 Spain, Gulf of Valencia**
Gas storage
Magnitude 4.2

**2016 USA, Oklahoma**
Wastewater injection
Magnitude 5.8

**1982 USA, California**
Geothermal energy
Magnitude 4.6

**1967 USA, Colorado**
Wastewater injection
Magnitude 4.8

**2006 Switzerland, Basel**
Geothermal energy
Magnitude 3.5

**2008 China, Zipingpu**
Water impoundment
Magnitude 7.9

**2013 Australia, New Castle**
Mining operations
Magnitude 5.6

**2003 Australia, Cooper basin**
Geothermal energy
Magnitude 3.7

**Grigoli et al., 2017**
GeoEnergy applications and induced earthquakes belong together
Working on Induced Earthquakes

Understanding how to use and control micro-earthquakes is both an urgent need and a win-win for the team oil & gas + renewable energy.

PS: It is also a fascinating science ...
To induce or not to induce: an open problem

Induced seismicity not just a side effect but a tool.

- Enhances fluid circulation, hence **energy production**.
- Can be (somehow) **controlled**.
- Known location allows for **better monitoring**.

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*Colorado SoM (2012)*

[Diagram of EGS development cycle]
Interdisciplinary research at its best

Seismology

Earthquake Physics

Fluid Dynamics

Numerical Modeling

Social Science

Geological Modeling

Risk Assessment

Exploration Geophysics

Rock Physics

Sensors

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Relevant questions

- Is my operation save and in compliance with regulations?
- How do I convince others that my operation is save?
- Is my future injection plan save and in compliance with regulations while maximizing at the same time my chance of commercial success?
- What alternative injection strategy should I follow to be save and commercially successful?
- What mitigation strategy should I follow when things develop in unfavorable ways?
State of the art: Traffic light systems

- No physical/reservoir model
- Uncertainties not accounted for
- Limited use for scenarios modeling
- Etc. ...

Grigoli et al., 2017

Bosman et al., 2016
Moving on to “Adaptive, data-driven Traffic Light Systems”

- ATLS are dynamically updated, forward-looking and fully probabilistic models that forecast the future seismicity and reservoir evolution based on a range of relevant key parameters (e.g., K, P, T, ...).
- Consider also ‘low probability-high consequence events’.
- Robustness through ensemble forecasting.
- Validation!
Adaptive Traffic Light System (ATLS)

Grigoli et al., 2017
Adaptive Traffic Light System (ATLS)

Modeling plays a major role

Grigoli et al., 2017
Several non-isothermal multiphase flow coupled with geomechanical processes simulators have been applied to deep geoengineering coupled modeling within the last few years.

Some are based on linking established codes whereas others are standalone:

**TOUGH-FLAC** (Rutqvist et al. 2002), **FEMH** (Deng et al., 2011), **OpenGeoSys** (Kolditz et al., 2012), **CodeBright** (e.g. Vilarrasa et al., 2010), **STARS** (Bissell et al., 2011), **CSMP++** (e.g. Paluszny & Zimmerman, 2011), **GEOS** (Settgast et al., 2016), **FALCON** (Gaston et al., 2012), **DYNAFLOW** (Preisig and Prévost, 2011), **CFRAC** (McClure, 2012) and other linked multiphase flow codes (e.g. **TOUGH2, ECLIPSE, GEM, GPRS**) and geomechanics codes (Rohmer and Seyedi, 2010; Ferronato et al., 2010; Tran et al., 2010; Jha & Juanes, 2014).

And many more in recent years....
TOUGH-FLAC coupled simulator

**Direct couplings** (solid arrow): Pore volume change, effective stress, thermal strain, and swelling

**Indirect couplings** (dashed arrow): Changes in mechanical and hydraulic properties

**Variables and Properties**
- **C** = Cohesion
- **G** = Shear modulus
- **K** = Bulk modulus
- **k** = Intrinsic permeability
- **P** = Pressure
- **Pc** = Capillary pressure
- **SH** = Hydrate saturation
- **T** = Temperature
- **ε** = Strain
- **ϕ** = Porosity
- **μ** = Coefficient of friction
- **σ'** = Effective stress

**Mechanical Properties**
- **K**, **G**, **C**, **μ**

**Hydraulic Properties**
- **ϕ**, **k**, **Pc**
TOUGH-FLAC coupled simulator

Mechanical Properties
$K, G, C, \mu$

TOUGH

THM MODEL

FLAC3D

Hydraulic Properties
$\phi, k, P_C$

Permeability, porosity, and capillarity pressure as function of:
- Mean effective stress;
- Effective normal stress;
- Volumetric strain;
- Plastic tensile and shear strain;
- and more....
Fully-coupled models: insights on the physical processes

- 100 m storage aquifer, bounded by 150 m caprock
- Pre-existing normal fault with dip angle 80°
- CO2 injection at -1500 m, 500 m from the fault
- Isothermal with gradient 25°C/km
- Extensional stress regime $\sigma_H = 0.7 \sigma_V$
- Damage zone as high permeability zone and Fault core with ubiquitous-joint model with oriented weak plane in a Mohr-Coulomb solid

Stress and strain dependent permeability:

$$k_{hm} = k_0 \left[ \frac{a}{c(c\sigma_n + 1)} \sqrt{\frac{\phi_0}{12k_0}} + \frac{e_{ftp} + e_{fsp} \tan \psi}{\phi_0} \right]$$

$a$ and $c$ empirical constants for normal-closure hyperbola (Bandis et al., 1983)
Fully-coupled models: fluid injection

\[ \tau \geq \tau_s = C + \mu_s \sigma_n' \]
Fully-coupled models: fluid injection

\[ \tau \geq \tau_s = C + \mu_s \sigma_n' \]
Fully-coupled models: increased pressure only?

Mazzoldi et al., 2012
Fully-coupled models: stress drop

Mazzoldi et al., 2012

Strain-softening model: friction as function of plastic shear strain

\[ \mu_s = 0.6 (\varphi = 31^\circ) \]
\[ \mu_d = 0.2 (\varphi = 11^\circ) \]
\[ \varepsilon_p^c = 10^{-5} \]
Fully-coupled models: stress drop

Strain-softening model: friction as function of plastic shear strain

\[ \tau = \mu_d \sigma_{n'} \]

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Mazzoldi et al., 2012
Fully-coupled models: rupture zone

Mazzoldi et al., 2012
Fully-coupled models: fluid injection

\[ M_0 = G \times d_{ave} \times A \]
\[ M_w = (\log M_0 - 9.1) / 1.5 \]

Mean Slip = 4.5 cm
Max Slip = 7.0 cm
Rupture = 307.14 m
Magnitude = 2.69
Moment = 1.35E+13 N\cdot m
Energy = 6.75E+08 J

Mazzoldi et al., 2012
Leakage evaluation

“safe” leakage 0.1% / year
Hepple & Benson (2005)

50 kg/s – $10^{-14}$ m²
After 5 years of active injection
CO₂ upper aquifer: ~584 tons/m
Total injected mass: ~7800 tons/m

~7.5 % total injected mass
Induced seismicity and potential leakage (SCENARIO I)

**LEAKAGE:**
- CO₂ leakage into upper aquifer compared to total injected amount as function of injection rate \(q=2-100\) kg/s and initial fault permeability \(\kappa=10^{-16} - 10^{-14} \text{ m}^2\)
- High percentage only for high \(\kappa\) and \(q\), with about 30% in the worst case scenarios

**FAULT REACTIVATION:**
- Events only for \(q > 30\) kg/s \((M\sim 2-3.5)\)
- High \(q\) requires less time for reactivation, but triggers smaller event
- High \(\kappa\), requires more time for reactivation, but trigger bigger events (pressure distribute more along fault)
Injection vs production

Candela et al., 2018
Fluid production:  
same physics, different timing

Zbinden et al., 2017
And we can learn much more...

- Effect of fault heterogeneities and/or size of caprock/aquifer
- Dynamic earthquake simulations
- Frictional laws
- Hydrofracturing/hydroshearing (with proper approximation)
- ...of course can be extended to 3D
Modeling induced seismicity with fully coupled simulator

- Very complex to simulate multiple faults
- Porous medium approximation does not always hold (e.g. EGS in fractured reservoirs)
Modeling induced seismicity in fractured reservoir

Norbeck et al., 2018
Modeling induced seismicity in fractured reservoir

Norbeck et al., 2018
Modeling induced seismicity in fractured reservoir

- Quite hard to discriminate which process is more relevant.
- We don’t really know the position of all the fractures (maybe the larger ones, and only if they cross the well)
- Quite computationally expensive. How can we use this in real-time for an adaptive traffic light system?
Modeling induced seismicity in fractured reservoir

- Quite hard to discriminate which process is more relevant.
- We don’t really know the position of all the fractures (maybe the larger ones, and only if they cross the well)
- Quite computationally expensive. How can we use this in real-time for an adaptive traffic light system?
- What if we have gas phase? Even more computationally expensive...
Understand relevant processes and model them in a “smarter” (simpler) way

### Fully coupled models

- Reliable in terms of physics, but computationally expensive

### Statistical models

- Ideal for real-time applications, but not complete description of processes
Understand relevant processes and model them in a “smarter” (simpler) way

- **Fully coupled models**: Reliable in terms of physics, but computationally expensive.

- **Statistical models**: Ideal for real-time applications, but not complete description of processes.

- **Hybrid models**: Mixing some statistical approach with physics-model, not fully developed.
Hybrid models @ SED

- Seeds = potential earthquakes reactivating for critical pressure (Mohr-Coulomb)
- Each seed with given stress state, and local b-value from differential stress.
- At each failure a stress drop and a new stress state associated (also with CFS) and possible retriggering

1D with COMSOL & Seed model

2D with SUTRA & Seed model

TOUGH2-Seed Full 3D model With k change

HFR-Sim: 3D Discrete Fracture Modeling & Seed model

Gishig & Wiemer, 2013
Goertz-Allman & Wiemer, 2013

Gishig et al., 2014

Rinaldi & Nespoli, 2017

Karvounis & Wiemer, 2018
TOUGH2-seed: permeability changes

Reversible Pressure dependent permeability

\[ \phi_{hm} = (\phi_0 - \phi_r)e^{\alpha \Delta P} + \phi_r \]

\[ \kappa_{hm} = \kappa e^{c_1 \left( \frac{\phi_{hm}}{\phi_0} - 1 \right)} \]

Irreversible slip-dependent permeability (assigned to grid block where seed is reactivating)

\[ \Delta d = \frac{M_0}{G\pi} \left( \frac{16\Delta \tau}{7M_0} \right)^{3/2} \]

\[ \kappa_{hm} = \kappa_0 \left[ 1 + C_2 \left( 1 - \frac{e^{-\Delta d}}{d^*} \right)^n \right] \]
Application to Basel EGS

(a) Measured vs Simulated Pressure changes (MPa)

(b) Pressure and Number of events/12h changes (MPa)

(c) Basel Data

(d) Simulation single realization
Modeling two-phase fluid flow: the case of St. Gallen

Zbinden et al., in prep

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Other “hybrid” models

Segall & Lu, 2015

Dieterich et al., 2015
Prototype ATLS based on models

Kiraly-Proag et al., 2018

Stop injection at end of LP
What do we need for a full development of ATLS?

✓ A multidisciplinary approach is essential: we still lack a complete physical understanding of the induced seismicity (from hydrogeology to seismic waves!)

✓ We do need a combination of probabilistic and deterministic modeling (e.g. more sophisticated hybrid models) and we do need to compare several models.

✓ Model learning from data:
  ➢ Data stream and analysis in real-time is essential for building up reliable and adaptive models, based on physical processes
  ➢ For testing and evaluating future performances

✓ Current models applied to past datasets are solid, but we miss applications in real time:
  ➢ Underground labs
  ➢ Pilot/test projects