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Simulation of Fluid Injection Induced Seismicity and Fault Reactivation Slip using Discrete Element Model

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1. Introduction

Occurrence of Seismic Events of Economic Concern (SEECo, Grünthal 2014) induced by fluid injection in Enhanced Geothermal Systems (EGS) development, (e.g. M_w3.2 in 2006 Basel) has led to heightened sensitivity towards hydraulic fracturing practices and induced seismicity. It has promoted necessity for better understanding of the relevant physical processes and development of numerical tools that can simulate the coupled hydro-mechanical-dynamic process.

We present simulation of dynamic rupture process of intact rock and pre-existing faults induced by fluid injection. Besides pressure and stress changes the model output is a catalog of synthetic seismic events with location, time and magnitude. The simulation tool uses the commercial code PFC2D (Itasca) that is based on the discrete element method. Hydro-mechanical coupling is implemented by which failure of porous medium by fluid migration/diffusion is explicitly simulated. Dynamic rupture algorithm is implemented to convert the fluid driven failure to a seismic event with magnitude and energy release (Zang et al. 2013; Yoon et al. 2014).

2. Fluid flow model

Pore fluid pressure builds up a pore space bounded by particles. Fluid flow between pores is governed by Cubic law at particle contact.

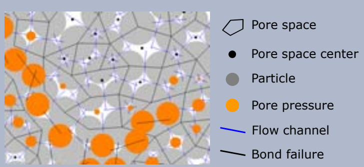
$Q = e^3 \Delta P_f / 12\mu L$ --- eqn.(1)

e = hydraulic aperture;
$\Delta P_f/L$ = pressure gradient between pores;
L = flow channel length;
μ = fluid viscosity

Fluid pressure buildup is computed by:

$P_f = \int (K_f/V_d)(\Sigma Q dt - \Delta V_d) dt$ --- eqn.(2)

K_f = fluid bulk modulus;
V_d = pore volume;
ΔV_d = pore volume change



3. Magnitude computation

Magnitude of event by bond failure is computed by moment tensor using contact force change around the bond failure:

$M_{ij} = \Sigma \Delta F_i R_j$ --- eqn.(3)

ΔF = change in contact force;
R = distance from contact point and event centroid

Seismic moment is computed:

$M_0 = (\Sigma m_j^2/2)^{1/2}$ --- eqn.(4)

m_j = eigenvalues of the moment tensor M_{ij} (j=1,2)

Seismic moment of an event by reactivation slip of joint/fracture is computed by:

$M_0 = GAd$ --- eqn.(5)

G = 30 GPa; A = joint/fracture surface (m²);
d = slip displacement (m)

Moment magnitude M_w of events is computed by:

$M_w = 2/3\log(M_0) - 6$ --- eqn.(6)

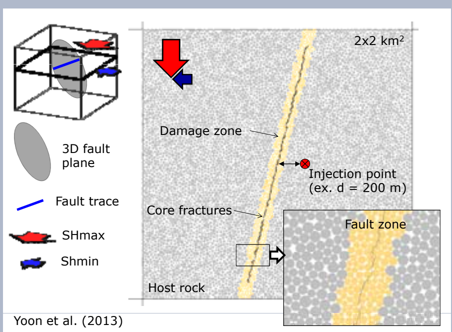
Stress drop of an event is calculated by:

$\Delta\sigma = 7M_0/16R^3$ --- eqn.(7)

M_0 = seismic moment; R = event source radius (m)

4. Model description

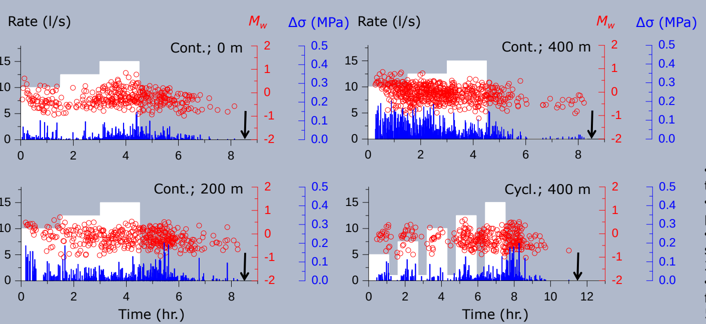
- 2 km x 2 km in size
- inclined through-going fault zone, length 1.5 km
- fault zone: damage zone + core fractures
- SHmax = 40 MPa
- Shmin = 30 MPa
- Rock permeability k = 1e-12 m² (fractured reservoir rock)
- Injection location distance from fault zone center: d = 0 (at center), 200, 400 m
- Total volume of injection: 200 m³
- Injection rate histories:
  - continuous (10-12.5-15 l/s)
  - cyclic (5-7.5-10-12.5-15 l/s)



Mechanical model parameters	Host rock	Damage zone	Fault fracture
Density (kg/m³)	2630	2630	-
Friction coefficient	0.9	0.9	0.9
Young's modulus (GPa) and Poisson's ratio	50/0.25	30/0.25	-
Tensile strength, mean±stdev (MPa)	9±6	2±0.5	1
Cohesion, mean±stdev (MPa)	25±7	5±1	5
Friction/dilation angle (Deg.)	53/0	30/0	30/3
Normal/shear stiffness (GPa/m)	-	-	300/50

5. Results

Figures below show the applied rate of injection (white bar), magnitude of the induced events (red), and their stress drop (blue). Time at which fluid pressure contours are constructed is indicated by the black arrows (4 hr. after shut-in).



6. Induced seismicity and fault reactivation

Temporal and spatial distribution of the seismic events are shown in Fig.1 where the size of the symbol is scaled to the stress drop of the events and color coded according to the time of occurrence, i.e. early events are in red and late in blue. Contour line shows the location of fluid pressure front. Fig.2 shows magnitudes of the fault fracture reactivation magnitude, which are scaled to M_w=2. Table below summarizes the results.

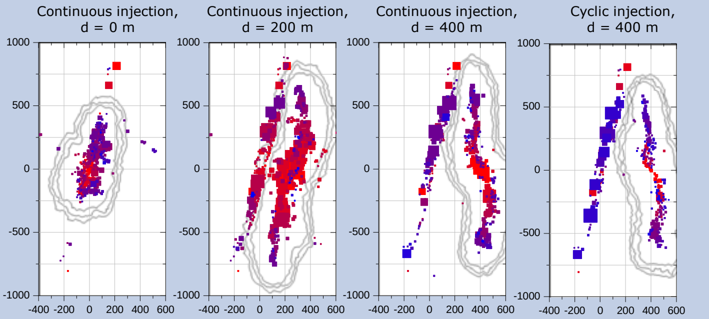


Fig.1: Distribution of induced events. Symbol size is scaled to the stress drop and colored according to relative time of occurrence (red: early; blue: late). Three levels of fluid pressure (0.001 MPa-outermost; 0.01; 0.1 MPa-innermost) 4 hr. after shut-in are shown by the contours.

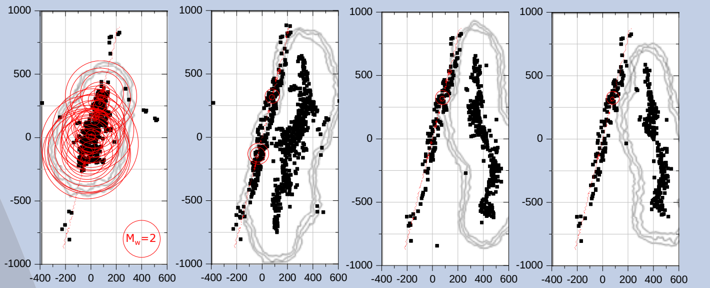
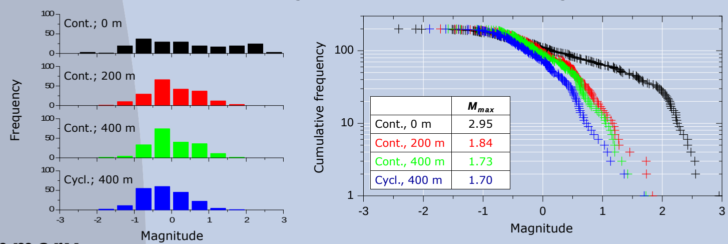


Fig.2: Spatial relation between fault fracture reactivation magnitude (red, scaled to M_w=2), induced seismic events (black, unscaled) and three levels of fluid pressure contours (0.001;0.01;0.1 MPa) 4 hours after shut-in.

Results	Cont.; 0 m	Cont.; 200 m	Cont.; 400 m	Cycl.; 400 m
No. seismic events	582	806	601	528
Avg. Δσ (MPa)	0.02	0.04	0.03	0.03
Min./Max. induced event M_w	-0.98/0.85	-1.12/0.86	-1.00/0.71	-1.02/0.60
Min./Max. fault fracture reactivation M_w	-2.41/2.95	-1.71/1.84	-1.58/1.73	-1.90/1.70

7. Magnitude-frequency distribution

Magnitude of events by reactivation of fault fracture is computed using eqn.5 and eqn.6. Histograms of the magnitudes are shown left and their cumulative frequency-magnitude distributions are shown right. Injection into the fault (Cont., 0 m) results in wider distribution of the magnitude but also the largest magnitude M2.95. Cyclic injection at 400 m distance results in narrower distribution of the magnitude as well as the lowest magnitude M1.70



8. Summary

- Injection into fault zone results in the largest magnitude events. This model resembles the Basel EGS setting where the fluid is injected into the cataclastic fault zone.
- Seismicity and the fault fracture reactivation slip are mitigated by the increase of the injection distance to the fault zone.
- Seismicity can be remotely induced at the fault zone by the fluid pressure perturbation less than 0.01 MPa.
- Cyclic injection results in similar pattern of induced seismicity cloud, but lowered magnitude (Zang et al. 2013; Yoon et al. 2015). Fault fracture reactivation slip tends to be less influenced by the fluid injection near the fault done in cyclic way.

References

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