ABSTRACT
This paper presents discrete element fracture network model designed to simulate hydraulic fracturing and induced seismicity in crystalline fracture rock mass at great depth. Among many tested, results from three fluid injection scenarios are examined which include (i) spatiotemporal distribution of induced seismic events, (ii) moment magnitudes, (iii) source mechanisms, (iv) stress drop of induced events. Comparisons are made with field observations from literatures, 1) to examine how close the model is capable of capturing and reproducing the field EGS induced seismicity; 2) to have an idea how large magnitude induced events, in particular in post-shut-in period, can be mitigated by changing the style of injection; and finally 3) to examine the potential (also limitations) of the presented methodology for more practical use in EGS research and industry.

INTRODUCTION
Hydraulic stimulation is essential in developing Enhanced Geothermal Systems (EGS) to increase reservoir permeability and maximize heat energy extraction. Byproduct of hydraulic stimulation of geothermal reservoirs is induced microseismic events that are hardly felt at the surface, but sometimes trigger larger magnitude events that can cause damage to surface structures. One example is Basel EGS where local magnitude 3.4 event is triggered by the hydraulic stimulation operation performed under city Basel, which has lead to damages of buildings, economic losses paid for property damages and suspension of the entire project, pending seismic hazard and risk analysis. What makes it difficult to control larger magnitude induced events is that very often they are triggered after the injection stop, i.e. in post-shut-in period.

Induced seismicity and in particular, occurrence of large post-shut-in induced event has been a critical issue in worldwide EGS community, both scientific and industry. This results in increased attention to 1) better understand hydro-mechanical-(thermal) coupled geoprocesses in reservoir, 2) develop reliable numerical models that can simulate the relevant geoprocesses occurring in reservoir.

This paper presents Discrete Element-Fracture network Model (referred to hereafter as DEFM) where hydro-mechanical coupling scheme is implemented enabling simulation of fluid flow in porous media and dynamic process of fluid driven fracture initiation and propagation.

Various scenarios of fluid injection in DEFM reservoir are presented and results are compared (with field observations) to be of practical use in EGS related industry and research.

DISCRETE ELEMENT FRACTURE NETWORK MODEL (DEFM)

Figure 1 shows the DEFM representing fractured geothermal reservoir constructed for this study. Detailed description of the model and how hydro-mechanical coupling scheme works can be found in Al-Busaidi et al. (2005), Yoon et al. (2013). For intact rock matrix, strength and deformation attributes are assigned to resemble crystalline rock mass of Soultz-sous-Forêts France. Mechanical and hydro-mechanical coupled parameters for the discrete fractures are taken from also crystalline environment, but from Forsmark site Sweden. Modeling parameters can be found in Yoon et al. (2013, their Table 1).

Failure of rock matrix and pre-existing fractures is governed by Mohr-Coulomb criterion and resulting seismic magnitudes and focal mechanisms of the induced events are computed using moment tensor computing routine (Yoon et al. 2013) which was modified from the original version of Hazzard and Young (2002, 2004).

The constructed model is 2 km (horizontal) and 2 km (vertical) in size and subjected to compressive in-situ
stresses with $S_H = 75$ MPa acting vertical and $S_v = 60$ MPa acting horizontal, following the depth-stress relation from Soultz site (Cornet et al. 2007), assuming that the model section is at 4.5 km depth.

**HYDRAULIC STIMULATION SCENARIOS**

Figure 2 shows three scenarios of fluid injection: a) sequential step-wise increase of injection rate (Fig.2a), b) cyclic increase of injection rate (Fig.2b), and c) cyclic decrease of injection rate (Fig.2c). Right ordinates represent well pressure monitored at the injection points.

First injection scenario consists of three sequences: (1) fluid injection with rate of 10 liter per second (l/s) maintained for 2 hours, followed by (2) 12.5 l/s and (3) 15 l/s, maintained also for 2 hours each. The resulting amount of fluid injected volume in this scenario is 270 cubic meter.

Second injection scenario consists of five cycles, which increases from 5 to 15 l/s maintained for 2 hours and four intervals between the cycles with 1 l/s maintained for 1 hour. This scenario results in 374.4 m³ of total injected volume. Third injection scenario is very opposite of the scenario 2, resulting same injected volume.

**RESULTS AND DISCUSSION**

**Induced event hypocenter distance from injection point and moment magnitude**

Figure 3-5 shows induced event hypocenter distance from the injection point (D) and moment magnitude (Mw) with respect to time for the three presented injection scenarios.
Figure 4: Results of cyclic injection scenario. Distance of induced event hypocenters from injection point (D), moment magnitude (Mw).

Distribution of induced seismic events

Figure 6-8 are collections of figures showing spatial cumulative distribution of the induced events for three injection scenarios divided into two stages: pre-shut-in (Fig.6a, 7a, 8a) and post-shut-in (Fig.6b, 7b, 8b).

For sequential injection scenario, time span for pre-shut-in period is 0-6.5 hr. For cyclic and reversed cyclic injection scenarios, pre-shut-in periods end at 14.5 hour.

In sequential injection scenario, early events (red) are induced near the injection points, and the elliptic event cloud elongates in NS direction, which is the direction of maximum compressive stress ($S_{HH} = 75$ MPa). Slight deviation from NS direction attributes to pre-existing fracture network, which has influence on changing of shear stress term, $\tau_{xy}$, resulting in reorientation of maximum and minimum principal stress directions. How the principal stress direction changes with time is under investigation.

Large magnitude events (LME) with Mw>1 occurred in post-shut-in period (Fig.6b, red stars). Post-shut-in LME locates mostly at outer-rim of the stimulated event cloud, which is in fair agreement to field observation. One LME at far right is an exception, which is caused by reactivation of existing fractures outside the cloud.

Cyclic injection results in narrow event cloud and branching in Y shape (Fig.7). Branching of the fracture propagating North occurs parallel and conjugate to the pre-existing fracture network. Fracture growth to South is almost parallel to maximum compressive stress direction. Cyclic injection results in less number of induced events and post-shut-in LME are absent.

Reversed cyclic injection, however, results in isotropic shape of event cloud with LME occurring all in pre-shut-in period (Fig.8).

Figure 6: Distribution of induced events that occurred during (a) pre-shut-in period (time range: 0-6.5 hr.) and (b) post-shut-in period (time range: 6.5-30 hr.), in sequential injection scenario.
Figure 7: Distribution of induced events that occurred during (a) pre-shut-in period (time range: 0-14.5 hr.) and (b) post-shut-in period (time range: 14.5-30 hr.), in cyclic injection scenario.

Figure 8: Distribution of induced events that occurred during (a) pre-shut-in period (time range: 0-14.5 hr.) and (b) post-shut-in period (time range: 14.5-30 hr.), in reversed cyclic injection scenario.

Induced event source parameters and stress drop

Moment tensor of each induced event is analyzed and decomposed into isotropic and deviatoric components using equations:

\[ \text{ISO} = \frac{\text{tr}(M)}{|\text{tr}(M)+\Sigma|m_i^*|} \]
\[ \text{DEV} = 100 \cdot |\text{ISO}| \]

where, \( \text{tr}(M) \) is the sum of the eigenvalues; \( \text{tr}(M) = m_1 + m_2 + m_3 \); \( m_i^* \) are the deviatoric eigenvalues, \( m_i^* = m_i - 1/3 \text{tr}(M) \) (Feignier and Young 1992).

Ratio of isotropic to deviatoric component (\( R = \text{ISO/DEV} \)) is used for classification of the event source mechanisms, i.e. tensile source if \( R > 30\% \), shear source if \(-30\% < R < 30\% \), implosional source if \( R < -30\% \) (Feiniger and Young 1992).

Figure 9-11 show \( R \) values of the induced events with time for three injection scenarios. Gray bar in bottom panel of the figures represent shear source \( R \)-value (-30\%<\( R <+30\% \)), i.e. double couple source.

Three figure show that large number of induced events with \( R > +30\% \) and < -30\%, indicating that they are non-double couple sources.

For sequential injection scenario, total population of the induced events is 786, among them, tensile and implosional source (\( R > +30\%, R < -30\% \)) take up 73\% of the total population.

Figure 9 shows that during the time of injection (0-6.5 hr.), there are not many induced events with shear (double couple) source, and most have tensile and implosional character (non double couple sources). This is because that injected fluid tends to expand the void and open up the fractures oriented parallel with the maximum compressive stress direction, and at the
same time closing other voids and fractures lying perpendicular to the maximum stress direction.

After injection stops (at 6.5 hr.), there appear lots of induced events with more portion of shear source, compared to pre-shut-in period. Occurrence of shear source events results from pore pressure diffusion into the surrounding rock, therefore translates the Mohr circle leftward by the amount of pore fluid pressure increase and makes it touch the failure envelop.

The results agree well with the field observations by Šílený et al. (2009) who investigated source mechanisms of seismicity induced by hydraulic fracturing in the Carthage Cotton Valley, east Texas, gas field. Their analysis indicates predominantly non-double couple source mechanisms with positive volumetric component consistent with opening cracks oriented close to expected hydraulic fracture orientation. Ross and Foulger (1996) analysed P- and S-wave polarities and suggested that about 20% of earthquakes at The Geysers geothermal area have significantly non double couple focal mechanisms. Ross et al. (1999) again showed that most of the induced events have significant non double couple components in their source mechanisms. Explosive and implosive sources were observed in approximately equal numbers, resulting from opening of cavities during massive injection and closing after shut-in and during fluid withdrawal. Larger number of implosion source in the numerical result and their analysis can be explained by cavity collapse resulting from the removal of fluid causing a fall in the pore pressure supporting the cavity (Ross et al. 1999).

Figure 10: Cyclic injection scenario. Moment magnitude (Mw) and ratio of isotropic and deviatoric component (R) of the moment tensor of the induced events.

Figure 10 shows R versus time for cyclic injection scenario. Unlike in Figure 9 where the number of shear source event is low during the time of injection (0-6.5 hr.), shear source events are evenly distributed in all cycles. This is because of the residual injection between the cycles, which is maintained for 1 hour. During the residual cycles, pressurized fluid in previous cycles diffuses into the surrounding and results in shear failure of the rock matrix and the pre-existing fractures. It is expected that more shear source events can be induced with longer duration of the residual injection. Effect of residual injection rate and duration time on stimulated pattern and occurrence of shear source event is under investigation.

Figure 11 shows R versus time for reversed cyclic injection scenario. Starting with higher rate injection produces isotropic stimulated pattern, similar to detonation of an explosive with larger magnitude events confined within the cloud. In cyclic injection scenario where injection starts with lower rate, slowly pressurized fluid have enough time to find the flow path with largest aperture. But, fluid pressurized rapidly cannot have enough time to determine the easiest flow path to discharge the rapidly accumulating fluid volume. Therefore the fluid flows through all surrounding paths leaving larger number of events with all sources relatively in short time.

Residual injection between the cycles, in this reversed cyclic scenario, does not act like in the cyclic injection scenario, where it buys some time for the pressurized fluid to diffuse into the surrounding and results in shear source events. In cyclic injection, downhole pressure tends to decrease during the residual time (Fig.2). However, in reversed cyclic scenario, except for the first residual period, downhole pressure increases which indicates fluid flowing back to the injection point.
Brune’s stress drop ($\Delta \sigma$) of the induced event is computed using equation (Brune 1970, Mukhira et al. 2013):

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

where, $R$ is source radius and $M_0$ is seismic moment.

Talebi and Boone (1998) analyzed source parameters of microseismic events ($M<1$) associated with high flow rate water injections in a shale formation at a depth of 220 m and observed that non-double couple events had smaller stress drops compared to double couple events.

We analyzed the stress drop versus source mechanism of the induced events. However, we were not able to see the similar trend (no clear indication of linearity between them) found by Talebi and Boone (1998). More investigation is needed on this issue.

Figure 12 shows, for three injection scenarios, stress drop of induced events and their distance from the injection points. Gray dots are pre-shut-in event data and red are post-shut-in event data.

**CONCLUSIONS**

From this numerical study, the following conclusions are drawn.

- Discrete element fracture network model is presented which enables simulation of fluid flow in porous media and fluid pressure driven dynamic failure and seismicity. The model is suited and applied to hydraulic fracturing and induced seismicity.
- Three fluid injection scenarios are simulated: sequential, cyclic and reversed cyclic injections. From comparison of results which include: 1) spatial distribution of induced events, 2) magnitude distribution, 3) source mechanisms of induced events and stress drop.
- Sequential injection resulted in (i) fat and elliptic induced event cloud with longer axis parallel with maximum in-situ stress direction, but slight deviation is due to local effect, pre-existing fractures, (ii) occurrence of post-shut-in larger magnitude events at outer-rim of the stimulated event cloud, (iii) larger number of non-double sources during injection and double couple source after shut-in which match well with field observations.
- Cyclic injection resulted in (i) slim and long stimulated event cloud, (ii) no post-shut-in larger magnitude events, (iii) evenly distributed double couple sources in each injection cycles.
- Reversed cyclic injection resulted in (i) fat and isotropic stimulated event cloud, (ii) relatively larger number of larger magnitude events located within the stimulated cloud, (iii) increasing downhole pressure during low rate injection period indicating backflow.
- No significant trend of stress drop in all three scenarios is found.

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**REFERENCES**


