1. FISHA

The Forward Induced Seismic Hazard Assessment – FISHA (Hakimhashemi et al. 2014a,b) is a general workflow which links the output of hydromechanical-numerical models of geothermal reservoirs, either in terms of seismicity catalogue (Hakimhashemi et al. 2014a) or in the form of spatiotemporal changes in the stress field (Hakimhashemi et al. 2014b), to a time-dependent probabilistic seismic hazard assessment in terms of the time dependent occurrence rate of the Seismic Events of Economic Concern – SEECo (Grünthal, 2014).

2. Discrete element fluid injection model

- Discrete element fracture network model using the Itasca PFC2D code with additionally implemented hydromechanical coupled routine (Yoon et al. poster presented in the workshop).
- Output of the model: Synthetic seismicity catalogues including occurrence times, x-y coordinates of hypocenters, and moment magnitudes of events.

3. Hazard model

Here, the hazard is defined as the max. of time-dependent hourly occurrence rate of SEECo (Hakimhashemi et al. 2014a). First we estimate the magnitude completeness $M_c$ for the given catalogue. Then the time-dependent parameters $a(t)$ and $b(t)$ of the frequency-magnitude relation are calculated using a maximum likelihood estimator on successive overlapping time-windows. Finally, the hazard is calculated as:

$$\vartheta(t) = a(t) \exp(-b(t)(M_{SEECo} - M_c)),$$

where $\vartheta(t)$ is the hourly occurrence rate of events with mag. $\geq M_{SEECo}$ at time $t$ elapsed after the beginning of the injection and $M_{\text{mag}}$ is the magnitude of SEECo.

4. Application

In this study, FISHA is applied to the synthetic seismicity catalogues of different scenarios of multiple injection to study the effect of the inclination of the injection points on the hazard. Scenarios are, 1) Horizontal injection, 2) Inclined 1 with $v/h=1/10$, and 3) Inclined 2 with $v/h=1/5$. The injection flow rates are 15 l/s and the duration is five hour, i.e. one hour for each stage starting sequentially from stage 1 to 5. $M_{\text{mag}}$ is considered 2.5.

5. Results of different scenarios

- **Horizontal injection**
  - Inclined 1 injection
  - Inclined 2 injection

The estimated parameters as well as the estimated hazard corresponding to each scenario are given in the following table.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$M_{\text{mag}}$</th>
<th>$\Delta a$ [eq]</th>
<th>$\Delta b$ [eq]</th>
<th>min(b) [eq]</th>
<th>hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>0.32±0.01</td>
<td>1176±[−38, 31]</td>
<td>1.246±0.037</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Inclined 1</td>
<td>0.36±0.02</td>
<td>815±[−50, 37]</td>
<td>1.218±0.028</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Inclined 2</td>
<td>0.31±0.03</td>
<td>419±[−35, 27]</td>
<td>1.326±0.045</td>
<td>0.12</td>
<td></td>
</tr>
</tbody>
</table>

6. Interpretation

- The time-dependent hourly occurrence rate of SEECo inversely responds to the $b$-value.
- The $a$- and $b$-values are reversely correlated.
- Inclination can result in reduced hazard in multiple fluid injection case, which we considered in this study.

References

