MULTIPLE-WELL, MULTIPLE-RESERVOIR, LONG TERM THERMAL MODELING AT SOULTZ EG SITE

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ABSTRACT
Lessons learned from reservoir modeling using a Discrete Fracture Network (DFN) approach in the framework of EGS activity have gradually helped us to better understand a number of coupled THM processes. This resulted in a general improvement of our numerical toolbox FRACAS. The present contribution illustrates a new step forward, which is applied to simulate the exploitation of a multiple-cell reservoir, as it is now the case at Soultz geothermal site. The new hypothesis formulated here is that the fracture network properties in a DFN approach can be regionalized in space according to the sets of micro-seismicity events recorded during the hydro-shearing stimulation phases of the various parts of the reservoir. Special care is given to the numerical treatment of seismic data sets ranging in different catalogues. Main inflow/outflow zones at the 4 deep wells (GPK1, GPK2, GPK3, GPK4) are considered in an explicit way. Hydraulic parameters for the present day exploitation are extracted from past studies, in the upper 3km reservoir tested in 1997, in lower reservoir experienced at 4.5 km depth and partly re-calibrated from the last 2010 circulation phase, with a GPK2 production of about 18 l/s. Extrapolation of hydraulic and thermal behaviors are made for the next 5 years, with an enlarged production rate (+25%), testing the impact of a partial re-injection of cold fluid in GPK1, as experienced in 2011. Model results do confirm in qualitative and quantitative ways, the possibility on running a balanced circulation with limited re-injection pressures. The negative impact on temperature production of fluid re-injected in upper parts of the reservoir and pushed toward production zones at intermediate depths in GPK2 is highlighted.

INTRODUCTION
The ability of random discrete fracture network to simulate mass and heat transfer for geothermal purposes in fractured hard rocks has been partly demonstrated by a number of site specific applications including the pioneering Rosemanowes HDR site (Bruel, 1995), and the early reservoir developed at intermediate depth at Soultz site (Bruel, 2002). Numerical methods specific to DFN are continuously improved (Maryska et al. 2004, Xu et al., 2010), and can now also account for matrix effects (Roubinet, 2010).

The DFN approach is proven adapted to hydro-mechanical developments as well, provided the natural pre-existing fracture network has some connectivity at large scale (Willis-Richards et al., 1996, Baujard et al., 2006, Bruel, 2007). In these approaches, fractures are distinct objects merged into a 3D stress tensor. Given their orientation and a fluid pressure, effective normal stress and shear stress acting on the fracture can be obtained and the discussion whether or not the shear strength of the fracture is exceeded follows. Closed fractures, e.g. those that do not shear, do not interact because the rock separating them is too stiff in comparison. These fractures are termed ‘joint stiffness-dominated’ and flow is controlled by a normal compliance behavior. When fluid pressure allows shearing and some slip-displacements to take place, the question of induced Coulomb stress change is put forward because the rock matrix may deform and transmit loads farther. However Schoenball et al. (2012) showed that at Soultz volumetric reservoir, most of the coseismic static stress perturbations induced by sliding effects shadow each other at the next triggered hypocenter and that the resulting stress increment at this new
location is of minor importance with regard to the pressure perturbation.

When tensile conditions are met at some injection point, true hydraulic fracturing can develop and interactions in between the new fracture and the pre-existing ones, as depicted by Fu et al. (2011) or Williams-Stroud et al. (2012), can be described using appropriated numerical schemes. In this case shear ruptures are simultaneously generated and propagated, equivalent to micro-earthquakes swarms, and passive seismic monitoring is most often used to control the size of the created reservoir.

Dealing with the present Soultz site analysis, we demonstrate in a previous work (Bruel, 2007) that shear was migrating along a pre-existing network with a hydraulic diffusivity in agreement with the SBRC approach (Shapiro et al. 1997, Rothert et al., 2003) and that some geometric characteristic of the network could derived from the ‘b’ value of the recorded seismic catalogues. No new fractures derived from tensile rupture was necessary since tensile regime was not obtained at any time. Schoenball et al. (2012) conclusions reinforce this idea that fully coupled geomechanics and discrete flow modeling are useless at this site, at least to describe GPK2 stimulation experiments performed in 2000.

The purpose of this paper is to take some additional benefit from passive seismic monitoring, once a stimulation of a reservoir at a particular site has been performed and the location and focal mechanisms of the seismic sources delivered. Because a seismic event is basically linked to a pressure perturbation, it cannot be directly associated to a flowing path. However an increase in hydraulic property can be expected and therefore early developments in EGS industry were first aimed at imaging volume and shape of stimulated reservoirs and delineating continuous structures at large scale as potential targets for future boreholes (Jupe et al. 2003, Sausse, J. et al. 2010). Shapiro et al. (1997) derived an in situ hydraulic diffusivity of a rock mass prior to the stimulation from a spatio-temporal analysis of the migration front of the seismic events. Much more challenging is the work by Tarrahi et al. (2012), who intend to derive a final spatial distribution of hydraulic rock properties within a stimulated reservoir from the mapping of discrete events measurements. Our present proposal is aimed at introducing a non-homogeneous Poisson’s process, where properties of the point pattern are defined in disjoint sub-regions according to the characteristics of the recorded seismic activity in that sub-region.

**GENERAL APPROACH AND FRACAS CODE IMPROVEMENTS**

**Network generation**

The principles of the FRACAS DFN code can be obtained in the references. The approach assumes that fractures are disk shaped, with a size distribution that follows a power law. In (Bruel, 2007), we discuss a way to derive the $d_{50}$ index that gives the average fracture area per unit volume of rock, from in situ hydraulic experiments. Because this index combines in a non-unique way fracture density and fracture size distributions, we also suggest that the size distribution could be constrained by the slope of the log-log frequency-magnitude distribution (b value) obtained from the stimulations. In turn, the density expressed in ‘fracture number /unit volume’ can be determined if a fracture permeability (resp. hydraulic aperture) is assumed.

When many catalogues of seismic events, thousands of events each, are made available at various part of a reservoir, we identify at first the ‘b’ value for each set, and then the appropriate network density for each set. For practical reasons, events with magnitudes lower ta 0 are discarded, as they correspond to fractures with a metric radius, too small for our approach. In case some part of the distribution is missing, for instance events with magnitudes in between 0 and 1, we first estimate how much events would have been observed assuming that the ‘b’ value given for this stimulation by events with magnitudes larger than 1 is valid. At the global scale, space is divided into adjacent cells, 100 m in size. For a given stimulation, the measured seismic events are distributed into these cells. Given the number obtained into a cell, a local density is derived (that accounts for the correction mentioned above) and the corresponding set of disc is generated in this current cell using a homogeneous Poisson’s process at that scale, with sizes sampling the corresponding power law distribution. Orientations are taken at random in a Fisher distribution with a polar direction aligned with the most probable direction for shear rupture at the corresponding depth. The process runs similarly for all the stimulations catalogues. In case some cells remain empty at the end of the process, the algorithm allows to combine disc sets at these places, with density and size that are user defined and with hydraulic properties representative of a pre-stimulation state. A proportion of fractures with an orientation non favorable to shear with regard to stress can be added. This can be quantified from statistic analysis of trace orientations along boreholes.
Once this generation step is finished, the pre-existing FRACAS routines are working again, with superimposition of local fractures seen at boreholes and automatic recursive sub-meshing of large discs. The connectivity analysis is performed starting from all the boreholes and unconnected discs are rejected. The hydraulic hypothesis that flow is occurring in 1D deformable flat channels linking the centers of the connected discs, result in a non-structured grid of finite volumes, e.g. a 3D network of 1D pipes.

**Governing equations**

**Mass conservation**

The standard conservation equations are used (Bruel, 2002, 2007) in a finite volume formulation written along the grid described above. The cubic law relating hydraulic conductivity to fracture aperture applies and fracture aperture is controlled by a stress dependent stiffness coefficient. The matrix does not participate to flow.

**Energy conservation**

The FRACAS code has been updated to allow more realistic long-term numerical simulation. In the former version (Bruel 2002), heat is extracted by conduction from local rock blocks, adjacent to the fracture walls, toward the fractures and then advection takes place in the fracture network. The local blocks are thermally independent. The upgraded version considers a double media so that the local blocks do influence each other.

In the fractured continuum, the balance equation for energy content is written, according to a classic heat diffusion equation (1). The reservoir at large scale is divided into regular cubic cells for simplicity. Each one of these sub-volume, of size a, contains a set of fractures that can easily be identified. The heat exchange rate (2) from the fracture network to the matrix continuum is expressed thanks to a source or sink term \( r_m \) [W m\(^{-3}\)], calculated at time \( t \) from the changes in temperature profile \( \theta_{im} \) normal to each fracture \( i \) of the sub-set of fractures contained in each of those cubic cells:

\[
\text{div}(K_m \nabla T_m) = m S_m \frac{\partial T_m}{\partial t} + r_m 
\]  
(1)

\[
r_m = \frac{1}{a^2} dt \sum_i A_i l_i m S_m (\mbox{< } \theta_{im} \mbox{>}) 
\]  
(2)

where the \( < > \) signifies an averaged temperature change over the adjacent block. The local temperature profile \( \theta_{im} \) is obtained by solving (3) with the boundary condition (4).

\[
K_m \frac{\partial^2 \theta_{im}}{\partial y^2} = m S_m \frac{\partial \theta_{im}}{\partial t} 
\]  
(3)

The link with the global temperature field \( T_m \) is obtained by setting the boundary condition of equation (3) at the distance \( y=l_i \) of the local fracture \( i \), according to relation (4), where \( T_m \) is the average temperature of the sub-volume containing this fracture \( i \).

\[
(\theta_{im})_{y=l} = T_m 
\]  
(4)

**DATA SPECIFIC TO THIS STUDY**

The Soultz reservoir has been extensively studied with the help of the FRACAS DFN approach. The modeling of the upper reservoir, circulated between wells GPK1 and GPK2 in 1997 is presented in Bruel (2002), while the deepest part experienced at 4.5 km in depth from 2004 to 2005 with wells GPK2, GPK3 and GPK4 is discussed in Baujard et al. (2006). Both systems are now merged into a single model with the new approach for describing the geometry of the fracture network. Figure 1 shows the sets of seismic events that were made available and that resulted from the stimulation phases respectively performed in 1993(GPK1 well), 1995(GPK2), 1996(GPK2), 2000(deepened part of GPK2), 2003(GPK3), 2004(GPK4) and 2005(GPK4). A last set of events recorded during the circulation test in 2010 is added. The four deep wells with their deviated trajectories are included as well as a set of explicit fractures (Table 1). Most of the other required parameters, stress tensor, fracture closure behaviour, rock thermal parameters are extracted from both earlier studies.

**Table 1:** Characteristics of the explicit fractures cross cutting the deep wells and superimposed to the random network

<table>
<thead>
<tr>
<th>well</th>
<th>TVD [bsl m]</th>
<th>Dip-dir</th>
<th>dip</th>
<th>size</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPK1</td>
<td>-3064</td>
<td>60</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>GPK1</td>
<td>-3332</td>
<td>257</td>
<td>63</td>
<td>150</td>
</tr>
<tr>
<td>GPK2</td>
<td>-3082</td>
<td>60</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>GPK2</td>
<td>-3182</td>
<td>120</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>GPK2</td>
<td>-3307</td>
<td>60</td>
<td>60</td>
<td>150</td>
</tr>
</tbody>
</table>
The hydraulic regime we want to use to re-calibrate the global reservoir model corresponds to the 2010 circulation phase (Genter et al., 2012). The table below recalls the main parameters of this quasi steady state hydraulic regime.

**Table 2: Hydraulic regime at Soultz during year 2010. After (Genter et al., 2012)**

<table>
<thead>
<tr>
<th>Well</th>
<th>status</th>
<th>Flow (kg/hr)</th>
<th>T[C]</th>
<th>P[MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPK2(*)</td>
<td>injection</td>
<td>-3692</td>
<td>234</td>
<td>64</td>
</tr>
<tr>
<td>GPK2</td>
<td>production</td>
<td>-4545</td>
<td>250</td>
<td>65</td>
</tr>
<tr>
<td>GPK2</td>
<td>production</td>
<td>-4668</td>
<td>250</td>
<td>65</td>
</tr>
<tr>
<td>GPK2</td>
<td>production</td>
<td>-4782</td>
<td>250</td>
<td>65</td>
</tr>
<tr>
<td>GPK3</td>
<td>injection</td>
<td>-4539</td>
<td>234</td>
<td>64</td>
</tr>
<tr>
<td>GPK3</td>
<td>production</td>
<td>-4735</td>
<td>46</td>
<td>61</td>
</tr>
<tr>
<td>GPK4</td>
<td>production</td>
<td>-4530</td>
<td>276</td>
<td>81</td>
</tr>
<tr>
<td>GPK4</td>
<td>production</td>
<td>-4569</td>
<td>257</td>
<td>85</td>
</tr>
<tr>
<td>GPK4</td>
<td>production</td>
<td>-4655</td>
<td>255</td>
<td>69</td>
</tr>
</tbody>
</table>

The modeling results obtained with the set of parameters described above, applied to the 2010 multiple well exploitation scheme is depicted in figure 2. The main discrepancy is at temperature production modeling at the final date (320 days). However the obtained value should be compared with a downhole measurement, which is not available, and not with a well head observation as reported here.

**RESULTS**

**Calibrated parameters and against 2010 circulation data**

The main parameters to be calibrated are the apertures under zero normal stress which are attributed to the different sets resulting from the different stimulation phases. Within the generation process of a given stimulation phase, the apertures of the discs are obtained at random, using a lognormal distribution, with a mean and a deviation. Deviation is arbitrarily set to 0.3 for all sets and calibrated mean values are as follows (Table 3). The aperture under zero normal effective stress for the explicit fractures listed in Table 1 are set at $0.75 \times 10^{-3} \text{ m}$.  

**Table 3: Calibrated parameters used for the generation of the random networks depicting the stimulated zones. Average radius is about 17.5 m for the upper part reservoir and 20 m for the lower part of the reservoir**

<table>
<thead>
<tr>
<th>Stimulated zone [year]</th>
<th>nb of frac.</th>
<th>Mean aperture under 0 normal eff. stress [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPK1-1993</td>
<td>5460</td>
<td>0.61</td>
</tr>
<tr>
<td>GPK2-1995</td>
<td>2030</td>
<td>0.75</td>
</tr>
<tr>
<td>GPK2-1996</td>
<td>2200</td>
<td>0.75</td>
</tr>
<tr>
<td>GPK2-2000</td>
<td>10800</td>
<td>0.68</td>
</tr>
<tr>
<td>GPK3-2003</td>
<td>4300</td>
<td>0.72</td>
</tr>
<tr>
<td>GPK4-2004</td>
<td>1790</td>
<td>0.70</td>
</tr>
<tr>
<td>2010</td>
<td>150</td>
<td>0.66</td>
</tr>
<tr>
<td>Intermediate zone</td>
<td>2500</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The hydraulic regime we want to use to re-calibrate the global reservoir model corresponds to the 2010 circulation phase (Genter et al., 2012). The table below recalls the main parameters of this quasi steady state hydraulic regime.

**Table 2: Hydraulic regime at Soultz during year 2010. After (Genter et al., 2012)**
Figure 2: Modelling of the 2010 circulation phase.
Green color items refer to in situ measurements, blue are used as prescribed conditions in the modeling and yellow are model results, to compare with green data.

Discussion: simulation of 2011 tests et exploration of additional scenarios

The 2010 circulation test at Soultz showed that a number of difficulties were not yet solved. It was observed that seismic activity does exist under circulation conditions, even when re-injection pressure levels at GPK3 are limited, in the order of 5 MPa. Therefore any optimization scenario of the energy production at the surface, which implies an increase of the production rate, has to face the question of how to re-inject the cold fluid. To avoid further unwanted seismicity from GPK3, the tested solution was to use the GPK1 well to reinject a part of the produced fluid.

The calibrated model is therefore used to investigate two new options that have been validated during year 2011.

Option 1: Use GPK1 to reinject most of the produced fluid and produce about 25% more than in 2010. After one year of circulation, the results given by the model are: Reinjection pressure, 4.1 MPa, reinjection rate, 24 L/s, Production rate 22 L/s, with a downhole temperature of 168°C (55% from deep reservoir at 187°C, 45% from above leak zone, at 147°C).

Option 2: Partitioning of the reinjection rate, half of the rate in each well: After 1 year of circulation, the re-injection rate in GPK1 is 12 L/s (2.6 MPa) and 10.8 L/s in GPK3 (3.7 MPa). The GPK2 production rate is about 23.5 L/s at 175.9°C (71% from deep reservoir at 188°C and 29% from above the leak off zone, at 147°C).

CONCLUSION

Although a number of strong assumptions have been made all along this modeling effort, it is interesting to notice that a direct use of a heterogeneous point process, the seismic events located in space, can be made in such a way, that numerical modelings at the reservoir scale are tractable. Hydraulic tests in steady state regimes have been successfully simulated and thermal performances obtained. Validation against tracer transport can be envisaged. The results obtained at Soultz site are qualitatively and quantitatively close to in situ observations. Interestingly, reinjecting in the upper part of the reservoir with the well GPK1 makes it easier for controlling induced seismicity by limiting pressure increase in the deepest part of the reservoir. But this option does increase the contribution of some intermediate zone in GPK2, known in previous phases as a leak off zone in GPK2. This effect is not in favor of the overall energy production, as the temperature of this production zone is less than 150°C. Moreover it is likely that this intermediate part of the reservoir will be more sensitive in the next future to cooler reinjected fluids coming from above.

REFERENCES


