EGS Probabilistic Seismic Hazard Assessment with 3-D Discrete Fracture Modeling

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ABSTRACT

Hydraulic fracturing is essential for many deep reservoir engineering projects which rely on permeability enhancement due to injections of fluid that has high pressure. The stimulation of such reservoirs induces felt seismicity which causes public anxiety and in some occasions may be a potential hazard for the local population and structures. The progress of novel technologies, such as Enhanced Geothermal Systems (EGS), has decelerated due to this induced seismicity. Hazard and risk assessment tools, such as sophisticated traffic light systems, which operate during the well stimulation, can assist in the safe development of EGS sites located close to urban areas.

We present here the modeling approach for such a near-real time traffic light system that is currently under development. This system uses a hybrid model that solves the mass conservation equations for a reservoir model that has a dynamically changing fracture network, similar to an EGS, and applies stochastic models for the creation of synthetic catalogs. It is based on HFR-Sim, which is an EGS simulator that uses an adaptive hierarchical discrete model and models flow and heat transport in EGS reservoirs. This EGS simulator provides the necessary input to the stochastic models employed for the induced seismicity. The newly triggered seismic events are included in the flow model as an enhancement to the permeability of the existing ones and, thereafter, are treated as discrete fractures. The presented model is expected to use real time data for calibration and will consecutively create catalogs that include seismic events, magnitudes and well logs. These can be used afterwards for performing probabilistic induced seismicity hazard assessment (PISHA) of the planned stimulation strategy. This way, the well operators will be assisted in their decision making. Additionally, HFR-Sim can perform simulations of the production phase inside the network of fractures that is obtained once each induced seismicity simulation is over.

Here, it is explained how this traffic light system with the 3D discrete fracture modeling is expected to work and demonstrative behavior is presented in artificial scenarios. The model is used for simulating an artificial scenario which includes the stimulation of two wells and the production phase of the EGS reservoir afterwards.

1. INTRODUCTION

The gradual phase out of nuclear power plants, decided by many countries including Switzerland, promotes the further development of geothermal technologies. Geothermal power plants have low greenhouse emissions and can uninterruptedly supply electrical power. Therefore, they can supply a portion of the power that was previously produced by nuclear stations. Currently, 10 GW of electrical power are produced globally with geothermal technologies and according to estimations, the electrical power production with geothermal technology is expected to rise to 70 GW by the year 2050. If the Enhanced Geothermal Systems (EGS) technology is successfully developed, then an additional 70 GW of electrical power could be produced (Bertani, 2012).

EGS (or Petrothermal) technology extracts heat from reservoirs that are located at drillable depths and does not require significant quantities of water to be already in place. It relies on artificially enhancing the permeability of naturally fractured reservoirs so that large rates of geo-fluid can be circulated through the wells. Once the EGS wells are drilled, cold fluid (usually water) is injected at high pressure through each well to induce hydro-shearing and to reduce the overall reservoir impedance. Such reservoir stimulations are considered successful when the resulting impedance allows the circulations of fluid at commercially interesting flow rates and the induced seismicity causes neither nuisance nor damage.

However, the development of EGS technology has decelerated during the last years due to this induced seismicity hazard, since felt earthquakes may occur. Unless the seismic activity induced during the stimulation of the wells remains under control, the technology cannot be applied in urban environments which are areas of prime interest since the waste heat can also be used for heating. Such was the case in Basel, Switzerland, where an EGS project was cancelled due to a 3.4 magnitude earthquake induced during the stimulation of its reservoir (Kraft et al. 2009).

In order to apply the technology in urban environments, sophisticated traffic light systems are required to assess the seismic hazard in time for taking any precautionary measures. Such tools operate during the EGS stimulation, collect field data, pre-process this data in a representative geological model and perform Probabilistic Induced Seismicity Hazard Assessment (PISHA). Afterwards and according to the PISHA results, the EGS operators can decide whether there is a ‘green’ light for continuing the fluid injection as planned or whether risk mitigation actions should be taken. Such a tool is currently under development by the Swiss Seismological Service (SED) and aims to assist in the safe stimulation of EGS reservoirs. Fig. 1 illustrates the framework for this traffic light system showing that forecasting models are important elements. Forecasting models are divided into statistical and hybrid models.
Figure 1: The algorithmic framework for the real time traffic light system is illustrated above. The hybrid and the statistical models, post-process the real time data and prior information, in order to return synthetic catalogs. These catalogs are used for performing PISHA and for changing the injection rate accordingly. The image is adapted by the webpage of the Induced Seismicity group in SED.

Statistical models are based on the applied injection rates and as Bachmann et al. (2011) and Mena et al. (2013) demonstrated, they are partly able to forecast expected seismicity a few hours in advance. Some of the statistical models that were tested are approaches similar to the Epidemic Type Aftershock Model (Ogata, 1992). Also, the model proposed by Shapiro et al. (2010) was tested, which forecasts the rate of induced seismicity in a site by computing the seismogenic index for this site. Although these methods are very efficient and return results quickly, they are solely data-based and do not include any physical process that is relevant for injection-induced seismicity.

The hybrid models that couple pressure solutions with stochastic processes can be used instead of the statistical models. Goetz-Allmann and Wiemer (2013) combined stochastic geo-mechanical modeling with the analytical solution of the linear pressure diffusion. There, the well is treated as a source point embedded inside a homogeneous and isotropic reservoir. Gischig and Wiemer (2013) employ a similar stochastic geo-mechanical model and use the numerical solution for a line source non-linear pressure diffusion problem. There, the depth of the simulated reservoir equals the length of the open case well, while the permeability of the modeled reservoir depends on pressure evolution and distance from the well. The so-called ‘seed points’ are employed for the mechanical modeling in both approaches. The seeds are potential earthquake locations and can be triggered only by elevated fluid pressure. With these hybrid models both the wellhead pressure curve and the seismicity characteristics of the Basel stimulation experiment in 2006 can be roughly reproduced. However, these models consider reservoirs of reduced dimensions, where permeability is initially homogeneous, isotropic and can increase only in an isotropic manner. Fine spatial pressure variations, due to large fractures, cannot be captured and important information regarding fractures that penetrate the well may be neglected. Also, these approaches do not model heat transport hence injection strategies cannot be tested towards their commercial target for financial sustainability.

In order to overcome these limitations a discrete fracture model (DFM) needs to be employed for the flow and heat transport modeling. DFM approaches, contrary to continuum methods, use less assumptions regarding the modeled fractures, thus they can capture such fine spatial effects. DFM has been employed by many EGS simulators since it is an important feature for EGS simulations (Sanyal, 2000). The FRACAS code which was developed by Bruel et al. (2001) assumes disc shaped fractures that intersect with each other, however it also assumes a completely impermeable rock. Kohl et al. (1995) apply the Finite Element Method on a grid that forces the boundaries of the rock elements to conform with the shape of the discrete fractures. Hydraulic, mechanical and heat transport modeling is performed on this grid by the code FRACture. A similar approach with a conforming grid is adopted by McClure and Horne (2011), where the Displacement Discontinuity method is coupled with a flow simulator that also requires a conforming grid. In order to perform PISHA with conforming DFMs, all foreseeable fractures need to be prescribed and discretized, independently of whether they participate in the flow or not. This increases the computational cost, since an unnecessarily complicated grid needs to be obtained throughout each simulation.

This cost can be avoided with flow models that use an embedded DFM, which treats discrete fractures as lower dimensional source/sink manifolds embedded in a permeable medium. The EGS simulator HFR-Sim (Karvounis and Jenny 2011, Karvounis 2013) employs an embedded DFM. This EGS simulator models flow and heat transport in an EGS reservoir and the pre-description
of all fractures is not necessary there, since discrete fractures can be included in models of HFR-Sim without the need of re-meshing.

Here, the modeling framework for a hybrid model is presented. It aims to combine the seed model approach with more realistic solutions for the pressure field inside an EGS reservoir. Modeling of flow and heat transport is treated by HFR-Sim, while the seed model by Gischig and Wiemer (2013) is extended into three dimensions. Triggered seeds are modeled by HFR-Sim as discrete fractures that suddenly become significantly more permeable and thus, are treated as discrete fractures thereafter. Finally, triggered seeds create in the HFR-Sim model a network of fractures. HFR-Sim can then forecast the thermal power revenues that the EGS power plant should expect from such a fracture network. This new hybrid model will be used in the future for real time PISHA and simultaneously will assess the expected thermal revenues.

2. MODELING FRAMEWORK AND GOVERNING EQUATIONS

During the PISHA calculations, each hybrid model needs to be used numerous times until a large number of equally probable synthetic catalogs are produced. This will allow estimating the probability of inducing a seismic event that has a magnitude larger than a certain value. Additionally, simulations of the production phase need to be performed for a subset of those scenarios. This will allow estimating the expected thermal revenues for a given stimulation strategy.

The hybrid model that is presented here consists of the HFR-Sim software and the stochastic ‘seed model’. At the beginning of each simulation, an HFR-Sim model is constructed, which consists of the well, some discrete fractures and an effective continuum. The time-marching simulation starts afterwards. At each time step, HFR-Sim returns an approximation of the pressure distribution and subsequently, the seed model performs all the geomechanical modeling; i.e. it decides which seeds have high enough pressure to be triggered. Before proceeding to the next time step the network of discrete fractures is updated. Creation phase can be simulated for numerous days after injection has been stopped. Once the creation phase is simulated, then HFR-Sim can simulate scenarios of the production phase for the resulting network of fractures. It is noted, that the HFR-Sim model that is constructed at the beginning of the simulation is expected to include many of the field observations. However, history matching approaches for this kind of problems are not discussed here.

2.1 Flow and heat transport calculations with HFR-Sim

Henceforth, a three-dimensional EGS reservoir domain \( \Omega \in \mathbb{R}^3 \) is considered, inside which single phase Darcy flow and the Oberbeck-Boussinesq approximation are assumed. According to the Oberbeck-Boussinesq approximation variations of fluid density \( \rho \) can be neglected, if they are not multiplied with the gravitational acceleration \( |g| \), where \( g \) is the vector for gravitational acceleration.

Mass conservation on \( \Omega \) and in a Cartesian grid can now be expressed as

\[
\frac{\partial \varphi}{\partial t} - \nabla \cdot \left( \frac{k}{\mu} (\nabla p - \rho g \nabla z) \right) = q,
\]

where \( q \) is a source term, \( \varphi \) the porosity, \( \mu \) the dynamic fluid viscosity, \( k \) the permeability tensor, \( p \) the fluid pressure and \( z \) the depth. According to Darcy law, the fluid velocity \( u \) inside \( \Omega \) equals \( u = \frac{k}{\mu} (\nabla p - \rho g \nabla z) \). Here, the density \( \rho \) and the viscosity \( \mu \) of the fluid are assumed constant.

For the same coordinate system, energy conservation can be expressed as

\[
\frac{\partial h}{\partial t} = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (u h) - w,
\]

where \( h \) denotes the specific enthalpy, tensor \( \lambda \) the heat conductivity of the material, \( T \) the temperature and \( w \) is a heat source term.

An EGS reservoir is a highly fractured hot rock and thus, domain \( \Omega \) is characterized by a highly heterogeneous and anisotropic permeability tensor \( k \). Along the fractures the permeability tensor can be many orders of magnitude larger than the permeability across them or the permeability on the intact hot rock, while the permeability tensor \( k \) can even be considered discontinuous across the two surfaces of a fracture. Moreover, the permeability tensor can also change dynamically, e.g. when the permeability of fractures increases due to hydro-shearing or new fractures are created due to hydro-fracking. Thus, the accurate solution of Eqs. (1) and (2) without a discrete representation of fractures can be very challenging problem.

Here, both the flow and the heat transport modeling are treated by HFR-Sim, which employs an adaptive hierarchical embedded DFM. Large dominant fractures are treated as lower dimensional manifolds and are embedded inside a continuum that is called ‘damaged matrix’ and captures the effect of the small fractures. The damaged matrix is divided into smaller control volumes by a rather coarse and structured grid. Each large fracture is also discretized by a lower dimensional structured grid. The boundaries of the cells of these grids do not have to conform to the boundaries of cells from other grids. Figs. 2a-2c illustrate such a gridding.

Once the damaged matrix and the discrete fractures have been divided into smaller control volumes, a node is assigned to each control volume and connections are added between nodes, where mass exchange can occur. Mass exchange can occur only between i) adjacent damaged matrix cells, ii) adjacent cells from the same discrete fracture grid, iii) intersecting cells from two different discrete fractures and iv) from intersecting cells where one belongs to a discrete fracture and the other to the damaged matrix. HFR-Sim also employs a simple well model. The fluid pressure along the open case of the well is considered constant and thus, each
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Figure 2: (a) Illustration of the hydraulic coupling between two large 2D fractures and a 3D damaged matrix. (b) A simple structured grid is employed for the damaged matrix. (c) Each large fracture is discretized by a simple 2D orthogonal structured grid and only nodes within the permeable area of the fracture are considered by HFR-Sim. (d) Further connections are added that couple each cell from a large fracture with the damaged matrix cells, as well as cells from other large fractures, that intersect it.

open case well corresponds to a single control volume. Connections are also introduced between the control volume of a well and intersecting cells. Fig. 2d shows all the connections that belong to the fracture cells of this gridding example.

The resulting HFR-Sim mesh is unstructured and consists of many independent structured grids. Hence, HFR-Sim avoids tiny fracture volumes that would reduce the time-step size and increase the computational cost. New discrete fractures can be added to the computational domain of HFR-Sim without the need of re-meshing and re-computing the fluid properties on a new mesh. A new discrete fracture is added simply by adding few more control volumes and their connections to the existing grid.

This discretization of the domain $\Omega$ into smaller control volumes is used by HFR-Sim in order to estimate the mean fluid pressure $P_M$ inside each control volume $M$. The transmissibility $C_{M,J}$ is assigned at each connection from node $M$ to node $J$, such that volume flux from volume $M$ to volume $J$ equals $F_{M,J} = C_{M,J} \left( \frac{P_M - P_J}{Z_M - Z_J} \right)$, where $Z_M$ corresponds to the average depth of volume $M$. Transmissibility $C_{M,J}$ is derived by applying the finite volume method to equation (1). When one of the nodes $M$ or $J$ is a well volume, then $C_{M,J}$ is equal to the production index of the well. This production index is similar to the well model suggested by Peaceman (1978). The equation of mass conservation results into a discretized system of $N$ equations, where $N$ is the total number of nodes in the unstructured grid and each equation $M$ is

\[
\frac{\partial V_M}{\partial t} + \sum_{J=1}^{N} C_{M,J} \left( P_M - P_J - (Z_M - Z_J) \right) |k| J = Q_M,
\]

where $Q_M$ is the rate of the injected fluid and $V_M$ is the size of the volume $M$.

Henceforth, it is assumed that $\frac{\partial V_M}{\partial t} = 0$, if $M$ is a well volume, and $\frac{\partial V_M}{\partial t}$, $\frac{\partial P_M}{\partial t}$, otherwise. The derivative $\frac{\partial V_M}{\partial t}$ is treated as constant.

The solid rock domain can be decomposed with a structured grid into $N$ control volumes, where each control volume $m$ has a size $\Omega_m$ and equation (2) can be explicitly discretized with a system of $N$ equations. Energy conservation for each node $M$ becomes

\[
\frac{\partial \dot{H}_M}{\partial t} + \sum_{J=1}^{N} F_{M,J} \left( H \left( F_{M,J} \right) \dot{H}_M + H \left( - F_{M,J} \right) \dot{H}_J \right) = W_M + \sum_{m=1}^{N'} K_{m,M} \left( T_m - T_M \right),
\]

where $\dot{H}_M$ is the amount of enthalpy stored in volume $M$, $H(\cdot)$ is the Heaviside step function that is introduced here instead of the upwind scheme that is employed, $K_{m,M}$ are the effective coefficients that quantify energy fluxes from the hot rock to the working fluid, $T_M$ the mean temperature inside volume $M$ and $T_m^\infty$ the mean temperature inside rock volume $m$.

Energy conservation for each solid rock $m$ gives

\[
\frac{\partial \dot{H}_m}{\partial t} \Omega_m = \sum_{J=1}^{N} K_{m,J} \left( T_m^\infty - T_J \right) \Omega_m + \sum_{m=1}^{N'} K_{m,M} \left( T_m^\infty - T_M \right) \Omega_m.
\]

where $\dot{H}_m$ is the amount of enthalpy stored in rock volume, $K_{m,J}$ quantifies head diffusion from rock volume $m$ to and $w_m^\infty$ is the mean value of source term $w$ inside volume $m$. 

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Finally, it is noted that HFR-Sim uses an algebraic multigrid (AMG) solver with a Gauss-Seidel method as a smoother. The solver is used in order to solve equation (3) implicitly. Eqs (4) and (5) are solved numerically with an explicit scheme, and shared memory multiprocessing is performed using OpenMP.

2.2 Seed model

We consider a number of $N_s$ potential earthquake locations (seeds) which are uniformly distributed in space. Each seed $i$ is located at $x_i^0(x', y', z')^T$ and lays on a fault with pole unit vector $P_i$. Three principal compressive stress vectors $\sigma_i^1$, $\sigma_i^2$, and $\sigma_i^3$ that are representative of the ambient stress field as well as friction coefficient $\mu_i$ and cohesion $C_i$ are assigned to each seed $i$. The normal stress vector $\sigma_{n,i}$ and shear stress vector $\tau_{i,n}$ can be computed analytically for each seed point. The value of the effective normal stress equals to

$$\sigma_{n,i}^{\text{eff}} = |\sigma_i^3| - P_{\text{hydro}} - p(x'),$$

where $P_{\text{hydro}}$ is the hydrostatic pressure. Here, the pressure of the fluid $p$ is interpolated from the results returned by HFR-Sim and is the only term in equation (5) that changes with time.

A fault slips around the seed point $i$ and an earthquake is triggered, when the Mohr-Coulomb failure criterion is satisfied and

$$|\sigma_i^3| - C_i - \tau_{i,n}(\mu_i - \sigma_{n,i}^{\text{eff}})/\sigma_{n,i}^{\text{eff}} = 0.$$  

A $b'$ value, which describes a Gutenberg-Richter distribution, is assigned to each seed point when it is triggered. This $b'$ value increases linearly as the differential stress $\Delta \sigma = |\sigma_i^3| - |\sigma_i'|$ decreases. Afterwards, a random magnitude $M_{i,0}'$ is drawn from a Gutenberg-Richter distribution with the $b'$-value $b'$.

The fault is here assumed to have the shape of a circle which is centered in $x_i$ and the vector $P_i$ is normal to it. Moment $M_{i,0}'$ is computed from $M_{i,0}'$ by using the Hanks and Kanamori (1979) relationship

$$M_{i,0}' = 10^{0.53(M_{i,0}' + 6.05)}.$$

The stress drop $\Delta \tau$ is considered constant for all earthquakes and equal to $\Delta \tau = 3.0 \text{ MPa}$. According to Eshelby (1957), the radius size $r'$ of such a slip is

$$r' = \sqrt[\Delta \tau]{\frac{6 M_{i,0}'}{17 \text{ MPa}}}.$$  

When the radius size $r'$ of an earthquake justifies discrete fracture representation, then a ‘new’ discrete fracture that represents the slipped fault segment is introduced in the HFR-Sim flow model. The hydraulic aperture $h_{i,n}$ of the new fracture is defined by the user and is the same for all new fractures. Consequently, all new fractures have the same permeability.

Figure 3: Three principal compressive stresses are assigned to each seed $i$ as well as an orientation (pole vector). Thus, effective normal and shear stress can be computed on the seed. The seed approaches the unstable region with increasing fluid pressure $p$. When the seed crosses the Mohr-Coulomb failure line then the seed triggers and an earthquake event with stress drop $\Delta \tau = 3.0 \text{ MPa}$ is considered.
Figure 4: (a) The assumed injection strategy is shown as well as the evolution of the simulated well pressure. (b) Each dot corresponds to a seed which is triggered at that moment and produces an earthquake of that magnitude. The seeds above the thin red line introduce discrete fractures to the flow model of HFR-Sim. (c) The pole vectors of the triggered seeds are plotted in this stereoplot and are compared with the direction of the principal compressive stresses. Here, all pole vectors have a direction towards the surface and the stereoplot shows the projection of these vectors. (d) The epicenters of the induced seismicity and the strike lines of the HFR-Sim discrete fractures are plotted versus time.

3. EXEMPLARY SIMULATION

Here, two exemplary simulations are presented. The HFR-Sim model of the EGS reservoir is the same at the beginning of both simulations. It has the shape of a cube, where each of its sides is 1.6 km and the bottom of the reservoir lies at a depth of 5.76 km. The open case of the well is 368.0 m long, has a radius of 0.18 m and reaches a depth of 5.0 km. Initially, the model has no discrete fractures inside it and only the damaged matrix continuum is considered. The permeability of the damaged matrix is 5·10⁻¹⁵ m² and its porosity \( \varphi = 1\% \). The injected working fluid has constant density \( \rho = 10^3 \) kg/m³ and constant viscosity \( \mu = 2.5\cdot10^{-4} \) Pa·s, while gravitational effects are not considered here. All discrete fractures have a mean aperture \( b = 10^{-4} \) m and permeability \( |k| = \left| b \right|^{1/2} = 8.3\cdot10^{-10} \) m²; for simplicity reasons, it is assumed that their mechanical aperture equals their hydraulic aperture. It is also assumed that \( \left( \frac{\partial p}{\partial d} \right)_{\text{damaged}} = 10^{-10} \) Pa⁻¹ for the damaged matrix and \( \left( \frac{\partial p}{\partial d} \right)_{\text{discrete}} = 10^{-11} \) Pa⁻¹ for the discrete fractures. The term \( \left( \frac{\partial p}{\partial d} \right)_{\text{Sim}} \) can be derived from this value afterwards. Heat transport modeling is included only in the second scenario. There, all specific heat capacities and densities are treated as constants. The specific heat capacity of the working fluid is \( c_p = 4.18\cdot10^3 \) J/kg/°C, the density of the hot rock is \( \rho' = 2.7\cdot10^3 \) kg/m³ and its specific heat capacity \( c_p' = 920 \) J/kg/°C.

The seed model assumes that the hydrostatic pressure equals 45.0 MPa, the principal stress \( \sigma_1 \) is vertical, \( \sigma_2 \) parallel to vector \((1, 1, 0)\)^T and principal stresses can never be larger than 232.0 MPa or less than 45.0 MPa. The b-value for each seed is \( b' = 3.5 \) for \( \Delta \sigma' > 136.0 \) MPa and \( b' = 1 - \frac{1}{136.0 \cdot \Delta \sigma'} \), otherwise.

It is noted that neither the seed model nor the HFR-Sim model has been subjected to any calibration in order to reproduce existing EGS scenarios.

3.1 Homogeneous stress field

The hybrid model assumes a homogeneous stress field, where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) equal 180.0 MPa, 90.0 MPa and 75.0 MPa for all seeds, respectively. The seeds are uniformly distributed in a 800.0 m × 800.0 m × 568.0m rectangular parallelepiped, with the bottom of this volume located at 5.1 km depth and the well is centered inside this box. In total \( N_s = 20\,000 \) seeds are used, a uniform distribution is employed for the orientation of their pole vectors and a sampled pole vector can have any direction. Cohesion \( C \) and friction coefficient \( \mu \) are the same for all seeds and equal 7.0 MPa and 0.85, respectively. A discrete fracture is added to the HFR-Sim model only when the induced earthquake at the location of the seed is larger than \( M_s = 1.274 \). The simulated injection scenario is a 6-step scenario, where every 36 hours injection increases by 7.5 l/s and the well is shut-down after the 6-th step.

Fig. 4a shows the simulated injection scenario (red line) as well as the wellhead pressure computed by HFR-Sim. In total, 1949 seeds are triggered during one simulation. The magnitude of the corresponding earthquakes and the moment at which they occur is plotted in Fig. 4b. Seeds that correspond to faults that either have a strike line (which is defined as their projection on a horizontal plane) or a pole vector parallel to the orientation of the first principal stress are rarely triggered. Fig. 4c illustrates this behavior. The presented stereoplot, shows the pole vector that is assigned to all the seeds that are triggered during the simulation. Initially, earthquake events are located close to the injection point, since this is the area of high pressure. Events at further locations occur only when the front of high pressure reaches there. Fig. 4d shows how the distance of the earthquakes from the well increases in time as well as the strike line for each discrete fracture considered by HFR-Sim.

3.2 Complete EGS scenario

This illustrative simulation consists of three parts. First, the stimulation of a single well is modeled with the hybrid model and a catalog of induced seismicity is obtained. Then, the model is used for simulating the stimulation of a second well, which is located
in a distance of few hundred metres from the first well. The discrete fractures ‘created’ during the first simulation are included in the HFR-Sim model employed for the second well-stimulation; i.e. at the beginning of the new simulation, the flow model consists of the well, an unstimulated area around it and a stimulated area with many discrete fractures further away. When the second stimulation is over, then all discrete fractures are used for simulating a simple production phase scenario; cold fluid is injected through the one well, it circulates inside the discrete fractures and it is produced from the other well. The probability of extracting an amount of heat larger than a target value can be assessed for these injection strategies by performing numerous simulations like that.

3.2.1 Stimulation of first well

The seeds for the first well are uniformly distributed inside a 300m × 300 m ×568m orthogonal rectangular parallelepiped that surrounds the well. The well is located in the center of the flow model. The direction of the principal stresses remains the same as before. Three normal distributions are employed for the values of the principal stresses. The mean values of these distributions are $< \sigma'_1 > = 185.0$ MPa, $< \sigma'_2 > = 90.0$ MPa and $< \sigma'_3 > = 75.0$ MPa, and their standard deviations equal 18.5 MPa, 9.0 MPa and 7.5 MPa, respectively. Cohesion $C$ equals 2.0 MPa and the friction coefficient is 0.65. In total $25,000$ seeds are sampled. $5,000$ of those have a pole vector whose direction is sampled from a uniform distribution and can have any direction. Uniform distribution is employed for the orientation of the rest $20,000$ seeds but their sampled range is reduced. Their pole vectors cannot differ more than $60^\circ$ (spherical coordinates) from two preferential vectors. All the sampled pole vectors can be seen in the stereoplot in Fig. 5c.

The stimulation strategy is a three step scenario, where every two days the injection rate increases by $15$ l/s. In Fig. 5a this injection strategy and the evolution of the simulated well pressure is plotted. At the beginning of the stimulation and due to a rather large time-step, the simulated wellhead pressure reaches $140.0$ MPa. However, the seismicity that is induced due to this high pressure rapidly drops the pressure at the well. In total, 5,918 seeds are triggered and $591$ discrete fractures are considered by HFR-Sim. The threshold magnitude of an earthquake above which a discrete fracture is considered thereafter is 1.496. A plot with the magnitude of these earthquakes and the moment at which they are induced is shown in Fig. 5b. In Fig. 5d the direction of the faults that slipped is shown again with a stereoplot of the pole vectors. Finally, the propagating cloud of induced seismicity is plotted in time in Figs. 5e-5h. Although injection stops on the 6-th day of the stimulation, seismic events continue to be triggered and increase the size of the seismic cloud.

3.2.2 Stimulation of the second well

The second well is located $400.0 \sqrt{2}$ m away from the first well and lies on the direction of the first principal stress, which they also share. The new seeds are uniformly distributed inside a similar 300m × 300 m ×568m parallelepiped that surrounds the well. The same normal distributions are employed for the stresses. Now the sampled pole vectors can have any direction. Cohesion $C$ and the friction coefficient $\mu'_i$ remain equal to 2.0 MPa and to 0.65, respectively.

Figure 5: (a) The assumed injection strategy is shown as well as the evolution of the simulated well pressure. (b) Each dot corresponds to a seed which is triggered at that moment and produces an earthquake of that magnitude. The thin red line is the threshold magnitude above which a discrete fracture is considered thereafter. (c) The pole vectors of all the sampled seeds are plotted in this stereoplot and in (d) the pole vectors of all the seeds that are triggered. (e)-(h) Epicenters of the induced seismicity and the strike lines of the discrete fractures for every few days. The gray circles in (e)-(h) represent earthquakes that were induced earlier in the simulation.
Figure 6: (a) Injection strategy and simulated pressure at the well are plotted in time. (b) Magnitude of induced earthquakes during the simulated period. The thin red line is the threshold magnitude, above which discrete fractures are added to the EGS model. (c) The pole vectors of the triggered seeds are plotted. (d) Strike lines of all discrete fractures at the end of the 2nd well-stimulation simulation. (e)-(h) Epicenters of all earthquake events during the 13-days scenario. The light gray earthquake events represent seismic events that occurred earlier in the simulations.

The HFR-Sim model includes the 591 discrete fractures that hydro-sheared during the previous simulation. None of these fractures penetrate the second well, but some of them lay inside the sample space of new seeds. The stimulation strategy is now different. The injection rate increases by 7.5 l/s every 1.5 days and 6 injection steps are applied before the well is shut-down.

In Fig. 6a the new injection strategy and the simulated pressure at the well are plotted. Figs. 6b and 6c show the magnitude of the induced earthquakes during this period and the orientation of the faults that slipped. In total 4933 earthquakes are induced, out of which 553 corresponds to large faults that are treated discretely. In Fig. 6d the strike lines of these 553 faults are plotted as well as the strike lines of the 591 discrete fractures that were included from the previous simulation. It is noted, that in Fig. 6d the 1st well is located at (x,y)=(0,0) and the 2nd well at (x,y)=(-400,400). In Figs. 6e-6h the hypocenters of the earthquakes and the strike lines of the large slips are plotted in time. The cloud of seismic events expands while fluid is injected (Figs. 6e-6g) and detaches from the well after the shut-down.

3.2.3 Simulation of production phase for the two wells

At this point, the EGS model consists of (591+533)=1124 large discrete large fractures that are embedded inside a continuum with very low permeability. In order to quantify the commercial potentials of this EGS model, a simple scenario of the production phase is considered, according to which 40 l/s circulate through the wells. Water is injected at temperature equal to 5°C and the temperature profile of the hot rock is similar to the one measured in Basel. Water is rarely injected at such a low temperature. Here, this temperature is chosen in order to accelerate the cooling of the rock and to offer a quick insight in the thermal behavior of the fracture network. The first 30 days of operation are simulated. The pressure difference that is required in order to circulate 40 l/s of water between the two wells of the model is 87.7 MPa.

Figure 7: On the left, the production history is plotted for the EGS model. On the right, the temperature distribution on 2D planes inside the 3D EGS model is shown at a time t=30 days.
CONCLUSION

A hybrid model has been presented, which combines modeling of flow with stochastic geomechanical considerations. The EGS simulator ‘HFR-Sim’ is used for modeling flow and heat transport inside EGS models. It employs an adaptive hierarchical discrete fracture representation, which allows HFR-Sim to be coupled with stochastic models that model induce seismicity. At each iteration step, the pressure field is computed by HFR-Sim and the seed model updates the catalog of seismicity with new events. The large earthquake events introduce new discrete fractures in the EGS model. These fractures have a size and an orientation consistent with the seed model. This hybrid model will be used for near-real time probabilistic induced seismicity hazard assessments. Additionally, the EGS models obtained by the end of each simulation are employed by HFR-Sim and simulations of production phase are performed on them in order to quantitatively assess potential of generating power. Exemplary simulations have been performed with this novel hybrid model, have been presented and discussed. The simulation of two well-stimulations and of the subsequent production phase has been presented and discussed.

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REFERENCES


Bruel D., and Jeong W.C.: Numerical modeling of the coupling between mechanical and hydraulic properties in a granite rock mass subject to high-pressure injection experiments. (2001)


