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SENSITIVITY ANALYSIS OF THERMO-HYDRO-MECHANICAL (THM) COUPLED PROCESSES IN A HOT-DRY-ROCK RESERVOIR

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ABSTRACT

We present an uncertainty analysis of thermo-hydro-mechanical (THM) coupled processes in a typical hot-dry-rock (HDR) reservoir in crystalline rock. The conceptual model is an equivalent porous media approach which is adequate to available data from the Urach Spa and Falkenberg sites (Germany). The finite element method (FEM) is used for the numerical analysis of fully coupled THM processes, including thermal water flow, advective-diffusive heat transport, and thermoelasticity. Reservoir parameters are considered as spatial random variables and their realizations are generated using conditional Gaussian simulation. The related Monte-Carlo analysis of the coupled THM problem is computational very expensive. To this purpose, parallel FEM is utilized to conduct the numerous simulations. The results show the influence of parameter ranges on the reservoir evolution during long-term heat extraction taking into account fully coupled THM processes. We found that the most significant factors are permeability and heat capacity variations. The study demonstrates the importance taking parameter uncertainties into account for geothermal reservoir evaluation in order to assess the predictability of numerical modeling.

INTRODUCTION

Data uncertainty is one of the major problems in subsurface reservoir analysis. Direct borehole measurements are very limited due to technical issues and costs. Normally data are available from core samples and well bore logging for the local scale and geophysical measurements (e.g. microseimic monitoring) for a larger scale (e.g. Tenzer et al. (2000) for Urach Spa site and Weidler et al. (2002) for Soultz site). Thus, subsurface models are derived from limited information and include uncertainties. Dealing with uncertainty analysis is a common tool e.g. for safety assessment of nuclear waste repositories (Rautman and Treadway, 1991).

For HDR geothermal systems, aspects of uncertainty have been investigated in the framework of sensitivity analysis and parameters identification so far. Fractal and statistical Discrete Fracture Network (DFN) models have been developed, e.g. by Watanabe and Takahashi (1995); Willis-Richards (1995); Tezuka and Watanabe (2000); O'Sullivan et al. (2001). DFN models can represent the structural reservoir geology, but they are still restricted to simplified processes. Inversion methods have been used to identify physical rock parameters in order to reproduce the observed reservoir behavior (Finsterle and Pruess, 1997; Lehmann et al., 1998).

Monte-Carlo analysis is one common method to quantify parameter uncertainty and the corresponding system evolution. Using geostatistical techniques, e.g. sequential Gaussian simulation and indicator simulation, enables the generation of multiple stochastically equivalent realizations which take into account the status of the incomplete knowledge (Pebesma and Wesseling, 1998; Chilés and Delfiner, 1999; Deutsch, 2002). Before starting stochastic simulations, assumptions concerning parameter distribution, e.g histogram, spatial correlation, correlation with other parameters, have to be decided. Usually those assumptions are determined from site observation data. However, little information about histogram and variogram analysis for deep crystalline rocks is available in the literature.

The plan of this work is to develop a methodology for uncertainty analysis of THM processes in deep geothermal systems during massive heat extraction.

CONCEPTUAL MODEL

The data base for this study mainly comes from former and recent German Hot-Dry-Rock projects at Urach Spa (Haenel, 1982; Tenzer et al., 2000; Weidler et al., 2002). In order to develop a stochastic model for a typical HDR geothermal reservoir in crystalline rock we include data from other geothermal test sites such as Soultz-sous-Forets and Falkenberg. A data compilation for relevant parameter ranges of these HDR sites is given in Table 2 in the Appendix. We use an equivalent porous medium approach to represent the reservoir structure as there is not sufficient data available in order to justify a discrete fracture network model as for the Soultz site (Kolditz, 2001). The equivalent porous medium approach corresponds to highly fractured reservoirs (McDermott et al., 2006). The physical processes and their governing equations are briefly described in the next section. Material properties of geothermal fluids are non-linear functions of salinity, temperature and pressure (Beinhorn et al., 2005; McDermott et al., 2006).

Governing equations of THM processes in porous media

Heat transport

For heat transport problem, we consider advective and diffusive fluxes in saturated porous medium. The governing equation of heat transport is

$$c_p \rho \frac{\partial T}{\partial t} + c_p^l \rho^l \mathbf{v} \cdot \nabla T - \nabla (\lambda_e \nabla T) = Q_T \qquad (1.1)$$

where $c_p \rho = n c_p^l \rho^l + (1-n) c_p^s \rho^s$ is heat storage of porous medium with n porosity, c_p^l specific heat capacity of fluid, ρ^l fluid density, c_p^s specific heat capacity of rock and ρ^s rock density. T is temperature, $\mathbf{v}$ flow velocity, Q_T heat source/sink term, $\lambda_e = n\lambda^l + (1-n)\lambda^s$ heat conductivity of porous medium with λ^l the fluid, λ^s the rock heat conductivity.

Saturated flow in deformable porous media

Saturated flow in deformable porous media is described by the following fluid mass balance equation,

$$S_s \frac{\partial p}{\partial t} - \nabla \cdot \left(\frac{\mathbf{k}}{\mu} (\nabla p + \rho^l \mathbf{g} \nabla z) \right) + \nabla \cdot \left(\frac{\partial \mathbf{u}}{\partial t} \right) = Q_f \qquad (1.2)$$

where S_s is specific storage, p fluid pressure, $\mathbf{k}$ intrinsic permeability, μ fluid dynamic viscosity, $\mathbf{g}$ gravity acceleration, z the reference depth, $\mathbf{u}$ solid displacement vector and Q_f fluid source/sink term.

Thermo-poro-elastic deformation

Thermo-poro-elastic deformation is described by the momentum balance equation in the terms of stress tensor as

$$\nabla \cdot (\sigma - \alpha_b p \mathbf{I} - \alpha_T E \mathbf{I} \Delta T) + \rho \mathbf{g} = 0 \qquad (1.3)$$

where σ is effective stress tensor of the porous medium, α_b is the Biot's constant with $\alpha_b \in [0,1]$, α_T is thermal expansion coefficient, E is Young's modulus, ΔT is temperature increment, $\mathbf{I}$ is identity tensor. The density of the porous medium is composed by two phases, liquid and solids $\rho = n\rho^l + (1-n)\rho^s$. Displacement $\mathbf{u}$ is the primary variable to be solved by substituting the constitutive law for stress-strain behavior

$$\sigma = \square\, \varepsilon \qquad (1.4)$$

$$\varepsilon = \frac{1}{2} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \qquad (1.5)$$

with $\square$, a forth-order material tensor and ε, the strain. The elasticity tensor $\square$ is,

$$\square := \lambda \delta_{ij} \delta_{kl} + 2G \delta_{ik} \delta_{jl} \qquad (1.6)$$

where δ is the Kronecker delta, $G = E / (2(1+\nu))$ is shear modulus, $\lambda = 2G\nu / (1-2\nu)$ is the so called Lamé constant with Poisson ratio ν.

Porosity-permeability relationship in micro fissured crystalline rock

Porosity-permeability relationship is considered for the following uncertainty analysis. Pape et al. (1999) derived a functional relationship based on fractal theory for fractured crystalline rocks. The corresponding $k(n)$ function for micro fissured granite at the Falkenberg site is,

$$k = \left(2.34 \times n^{1.25} + 20.94 \times (10n)^{3.88} \right) \times 10^{-16} \, [\mathrm{m}^2] \qquad (1.7)$$

STATISTICAL APPROACH

The present statistical approach to the uncertainty analysis consists of three parts: (1) determination of statistical models for parameter distributions, (2) stochastic realizations of parameter fields using conditional Gaussian simulation based on the defined stochastic models, and (3) Monte-Carlo analysis with numerical simulation of fully coupled THM processes using randomly generalized multiple parameter distributions.

Assumptions

Most important is the definition of an appropriate stochastic model to represent realistic parameter heterogeneity of a geothermal reservoir. Our basic assumptions are:

- Parameters of thermal, hydraulic, and mechanical processes are considered as spatial random variables.
- Parameter distributions have spatial correlation as well as heterogeneity over the reservoir.
- As the parameters in principle can be measured in the borehole (i.e. from cores), the parameter values are assumed to be known along the boreholes.
- We do not consider fractures explicitly in the model as statistical properties are not available and would be, therefore, purely speculative.

In addition, we make the following specific assumptions concerning the stochastic model:

- Probability distributions for the random variables follow the normal (Gaussian) distribution.
- Mean value of a parameter field is identical to sample mean.
- Spatial variance is identical to sample variance.
- Spatial correlation takes place with the close neighborhood, i.e. spatial correlation length is the distance of grid size, 50m.
- Parameters do not have correlation to each other. Spatial distributions of each parameter are determined individually.

Probability distributions can be determined from measurements if frequency distributions of the parameters are available. As we can rely only on minimum / maximum values for the parameters and the statistical properties are not known very well, we use the simplest case: normal distributions. In addition, because of the normal distribution, the shape of parameter distributions can be decided in a deterministic way from parameter range given by site measurements or literature. A number of authors have investigated the coupling between parameters relationships such as relationships of permeability and porosity as well as porosity and rock heat conductivity (Pape et al., 1999; Popov et al., 2003; Surma and Geraud, 2003).

Stochastic model

Based on the above assumptions, a spatially correlated random field is used to generate the parameter distributions. The stochastic properties of the random field are probability distribution (frequency) and spatial correlation.

Spatial correlation can be defined with a variogram model. A variogram is a function of a separation lag distance and it describes spatial variability. A variogram model is fitting an empirical variogram, which is determined from measured data. There are different shapes of variogram models such as spherical, exponential and Gaussian distributions.

The spatial dependency of a parameter reduces as the distance between locations becomes larger and it will converge to an asymptotical value (Sill) from a certain lag (Range). Those models are different in how spatial dependency reduces. In the uncertainty analysis, the spherical model is used for all parameters because of the simple linearity and to demonstrate our methodology.

APPLICATION

The idea of the application case study is to demonstrate the methodology for an uncertainty analysis of THM coupled processes in a typical geothermal reservoir in crystalline rock. The study is based on a great data set for the Urach Spa geothermal site compiled in several research projects.

Model set-up

Urach Spa location was originally designed as a scientific geothermal pilot project. The proposed boreholes (U3 and U4) dipole flow circulation system (i.e. a ”doublet”) are located 400m apart. Based on the large amount of scientific data available on the Urach Spa reservoir, we developed a three-dimensional model of the reservoir system. Parameters relevant to reservoir fluid flow and heat transport that were used in the model were based on the results of previous studies. The hydraulically active areas allowing the reservoir to be represented geometrically as a cuboid are 300m high, 300m wide and 800m long (Figure 1). The observation point is selected to be rather close to the injection borehole as the significance of THM coupling during the heat extraction is more evident in this area.

The reservoir depth is between 3850m-4150m. Concerning the initial conditions ($t = 0$), we assume linear depth-dependent hydrostatic pressure, lithostatic stress, and temperature distribution. The geothermal gradient according to the temperature logs in the reservoir depth range of U3 is ω = 0.3K/m:

- $T(t = 0) = 435.15 + \omega(-4445.0 - z)$ [K]

The injection well is considered to have an overpressure of 10MPa and the production well an underpressure of 10MPa. Fluid injection temperature is assumed to be 50°C (McDermott et al., 2006).

- $\mathbf{u} \cdot \mathbf{n} = 0$ at the lateral and bottom surface

Table 1. Assigned statistical properties for the HDR geothermal reservoir

Parameter	Symbol	Mean	Unit	Std.
Permeability (logarithm with base 10)	$\log 10(k)$	-15.738	(m^2)	0.3077
Undisturbed permeability	k	21.8×10^{-18}	m^2	7.17×10^{-18}
Porosity	n	4.05×10^{-3}	-	8.2×10^{-4}
Rock heat conductivity	λ^s	2.79	W/(mK)	0.08
Rock specific heat capacity	c_p^s	850	J/(kgK)	55.5
Young's modulus	E	64	GPa	0.8
Poisson ratio	ν	0.225	-	0.08

- $\frac{\partial \sigma_{zz}}{dz} = \rho^s g z$ at the top surface

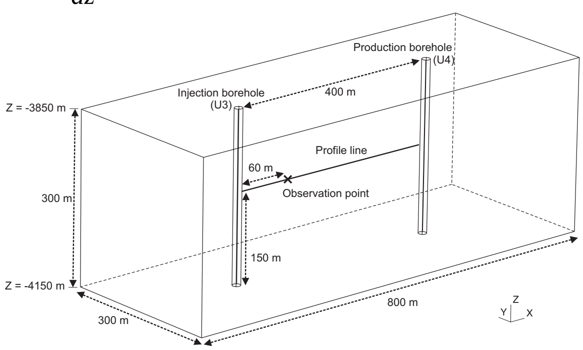

Figure 1. Cuboid reservoir model with a borehole doublet (U3 and U4)

Stochastic model for reservoir parameterization

The statistical parameters of rock properties for the typical HDR reservoir are summarized in Table 1. Probability distributions correspond to the normal distribution and variogram models with spherical shape. Range of the variogram model is 50m. Sill is sample variance. Nugget effects are not considered. Rock density and thermal expansion coefficient are kept constant as not enough data for a statistical representation are available.

For the following sensitivity analysis, we assume that the permeability histogram follows the Gaussian distribution shown as logarithm with base 10. The permeability values vary from 10^{-17} to 10^{-15} m^2 corresponding to the laboratory measurement and stimulated reservoir permeability in Urach respectively (McDermott et al., 2006).

Numerical model

A finite element (FE) model is used for the stochastic analysis which takes into account fully coupled thermo-hydraulic-mechanical (THM) processes. The present numerical THM model GeoSys/RockFlow is verified against TOUGH-REACT and ROCMAS in a code comparison study (Rutqvist et al., 2008). The FE formulations and details of the coupling algorithms can be found in Kolditz and de Jonge (2004); Korsawe et al. (2006). Hexahedral elements are used for the finite element mesh. The stochastic parameter distributions are assigned with finite element properties.

RESULTS AND DISCUSSION

The uncertainty analysis is conducted in two steps. First, using a relatively few number of (10) Monte-Carlo simulations we "screen" the variability effect of the THM parameters on the long-term reservoir behavior as well as examine the importance of different statistical distributions. Second, for the most sensitive parameters we conduct a larger number of (100) Monte-Carlo simulation to provide statistically representative results. The reason for this two step procedure is the enormous computational expense for the 3-D fully coupled THM numerical simulations.

Sensitivity analysis

The idea of the sensitivity analysis is to assess the importance of the individual THM parameters on the thermal reservoir evolution. To this purpose we compare the results for a homogeneous reservoir using minimum and maximum values of the parameter range (Table 2) and smaller number of (10) realizations using the stochastic model. The remaining reservoir parameters correspond to mean values (Table 1).

The analyzed parameters are T (rock heat conductivity, rock specific heat capacity), H (permeability, porosity), M (Young's modulus, Poisson ratio). Results for two important properties are shown in Figure 2 and Figure 3, i.e. rock specific heat capacity and permeability respectively. It can be seen that the permeability ranging from values for undisturbed k = $10^{-17} m^2$ and stimulated areas k =

$10^{-15}m^2$ is clearly the most important parameter. Next to permeability, rock specific heat capacity representing heat storage effects, is the second most important parameter. The variances of mechanical (M) parameters, porosity, Young's modulus and Poisson ratio are of less importance. As expected all stochastic simulation results are captured by enveloping curves produced with the minimum and maximum parameter values, respectively. Interesting is the fact that the min/max values put strong bounds to the stochastic results. As this needs to be more elaborated, the uncertainty of reservoir permeability is investigated in a more detailed Monte-Carlo analysis. Actually, assuming an overall maximum value for permeability means a completely stimulated reservoir (i.e. maximum permeability in the entire reservoir). In order to make the reservoir model more realistic, the permeability increase as a result of the massive hydraulic stimulation is considered to be dependent on the borehole distance as proposed by Weidler et al. (2002); Baisch et al. (2004).

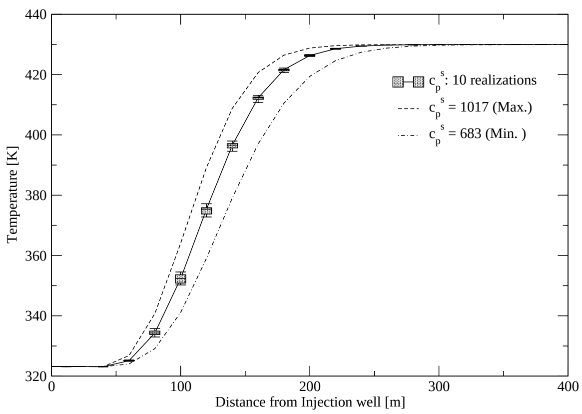

Figure 2. Sensitivity analysis of rock specific heat capacity

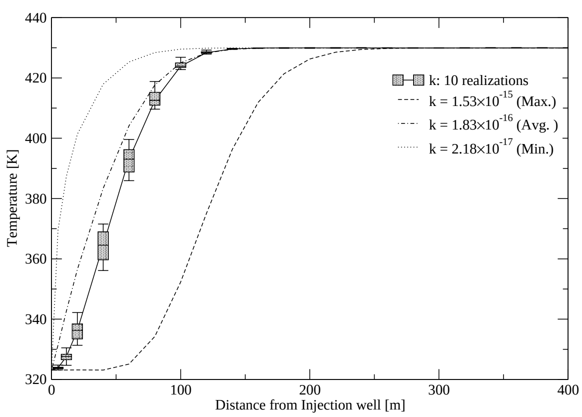

Figure 3. Sensitivity analysis of permeability

Monte-Carlo analysis

Stimulated reservoir model

In the above analysis we examined the statistical sensitivity of THM parameters. Aside of parameter uncertainty, a realistic reservoir model should address the effect of reservoir stimulation as well. As a result of massive hydraulic stimulation, the reservoir permeability could be increased by factor 100 at least in the vicinity of the boreholes (Baisch et al., 2004). In this section we conduct a Monte-Carlo analysis to assess the thermal reservoir evolution by a superposition of stochastic parameter heterogeneity and hydraulic reservoir stimulation. We represent the heterogeneity of the undisturbed reservoir using a spherical variogram model with a correlation length of 50m range. Hydraulic stimulation is mimicked by a scaling factor between 1 (undisturbed) and 100 (fully stimulated) which is depending from the borehole distance. Figure 4 illustrates an example of a produced reservoir permeability distribution.

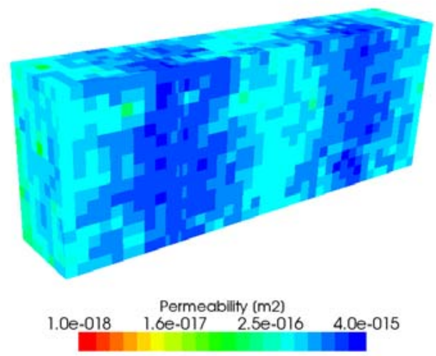

Figure 4. Permeability distribution in stimulated reservoir by double boreholes and quadratic enhancement functions

Monte-Carlo simulation

For the Monte-Carlo analysis we use the statistical properties given in Table 1. We consider a reservoir type, where hydraulic stimulation is conducted in two boreholes with a quadratic permeability enhancement factor and the porosity-permeability relationship corresponds to that from the Falkenberg site. To perform a representative Monte-Carlo simulation we conduct 100 stochastic simulations. In order to be able to run this number of fully coupled THM simulations, a parallelized version of the numerical code was used.

For presenting and discussing the results we use different illustrations: variances, frequencies, and envelope curves. Figure 5 shows the average temperature as well as the standard deviation (Figure 6) in a horizontal cross-section through the reservoir center after 15 years operation. The largest variances appear at places where temperature gradients are highest, i.e. around the cooling fronts. Maximum standard deviation is large, i.e. about 8. Figure 7 depicts temperature "frequencies" in the observation point at different operation times (1, 2, 5, 10, and 15 years). The frequency plot represents the number of calculated temperature values. The frequency range is time dependent: it is narrow in the early (1 year) and late (15 years) stages (i.e. almost undisturbed or cooled reservoir) and it is widely distributed in the middle of the reservoir ”lifetime” (5-10 years). During this time a prediction of a reservoir temperature is most uncertain. This finding correspond to Figure 6 that the uncertainty is largest around the propagating cooling front due to the dominating advective heat transport. Figure 8 illustrates the 20%, 80% and 100% uncertainty zones of the 100 temperature profiles between the boreholes after 15 years. The 20% zone covers 20% of 100 obtained temperatures around the median. 100% zone provides an envelope to all 100 realizations with a maximum temperature difference of about 40K.

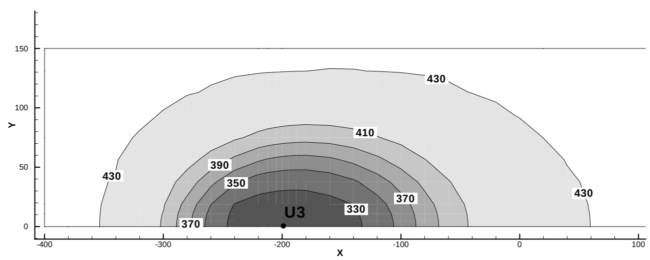

Figure 5. Average of temperature in a horizontal cross-section after 15 years

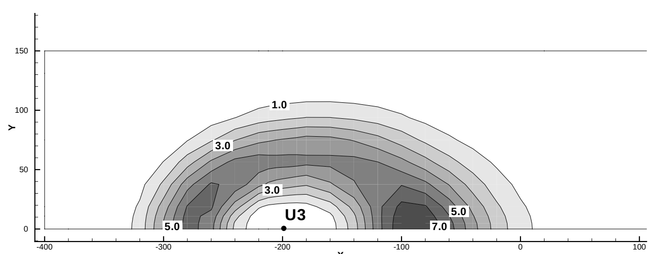

Figure 6. Standard deviation of temperature in a horizontal cross-section after 15 years

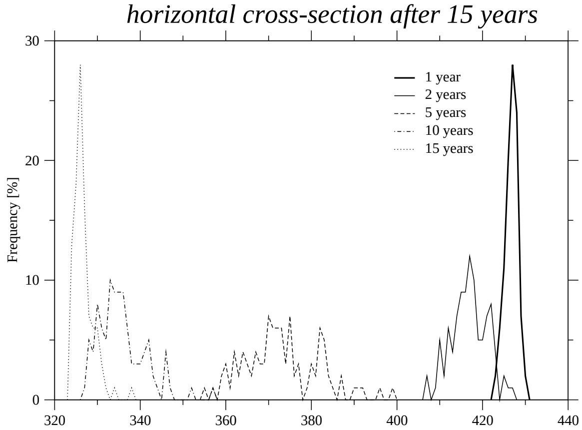

Figure 7. Temperature frequencies at the observation point

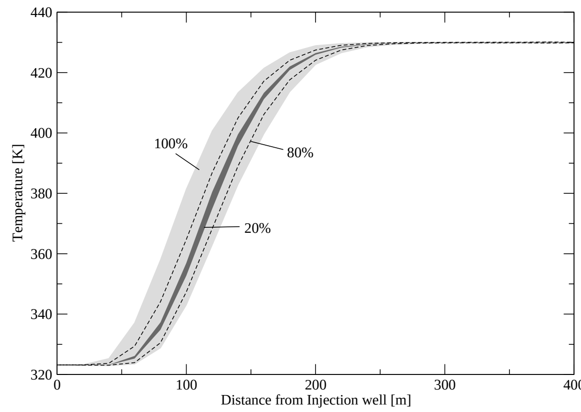

Figure 8. Uncertainty ranges of temperature profiles after 15 years heat extraction

PARALLEL SPEED-UP

We used a parallel computer to conduct the Monte-Carlo method with fully coupled THM model. Exploiting 8 CPUs was the optimum use for single numerical simulation of THM model. Therefore, 10 parallel jobs were submitted at the same time to 80 CPUs. By this way the cluster was optimally operated to conduct the Monte-Carlo analysis consisting of 100 statistical realizations at the same time as about 2 realizations on a single CPU machine with a sequential code version. In other words, the entire Monte-Carlo analysis could be finished within one day using the parallel cluster instead of 2 month which would have been necessary on a single CPU computer. The parallelization method for FEM is based upon the domain decomposition concept (Wang et al., 2008).

CONCLUSIONS AND OUTLOOK

A fully coupled THM model is developed based on the general balance equations for fluid mass, momentum, and thermal energy as well as constitutive equations for variable fluid properties, thermo-poro-elastic deformation and a phenomenological porosity- permeability relationship for crystalline rock taking into account hydraulic stimulation effects. The stochastic concept is a combination of the fully coupled numerical THM model and the Monte-Carlo method. Based on the stochastic THM model which considers statistical heterogeneity of geothermal reservoirs, we present an uncertainty analysis of thermal, hydraulic, and mechanical parameters on long-term geothermal reservoir evolution. The sensitivity analysis shows that permeability and rock specific heat capacity are most important reservoir parameters. Less relevant is rock heat conductivity. The variability of the mechanical parameters in the site specific range (Table 1), porosity, Young’s modulus and Poisson ratio is negligible. As a result of the stochastic THM analysis, we found a maximum temperature uncertainty range of about 40K after 15 years reservoir exploitation (Figure 6). For the computational efficiency, parallel computing is an important technical prerequisite for THM Monte-Carlo analysis.

Despite the achievements, the stochastic THM concept has to be further developed in future work. Due to the limited available information, it is difficult to obtain statistical properties of geothermal HDR reservoirs. This is a typical situation for deep geological reservoirs where little data are available. This situation makes uncertainty analysis questionable and at the same time important as the only way to assess the uncertainty of reservoir evolution. Numerical studies of virtual reservoirs provide important information for the purpose of reservoir management such as parameter ranking and stimulation scenarios. In addition, fractures are not explicitly considered in the present study as there is not enough data available in order to justify a discrete fracture network model as for the Soultz geothermal site for treating large-scale fractures in a hydraulic analysis (Kolditz, 2001). The conceptual model for the geothermal reservoir analysis in the present study is an equivalent heterogeneous porous medium approach. Concerning the model development, a stochastic fractured-porous medium model for fully coupled THM analysis is a future challenge, however, it should be also motivated by data availability.

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APPENDIX

A. Influence of different varigoram models

In the present uncertainty analysis we assumed a spherical distribution with a correlation length of 50m length. As the statistical properties of HDR reservoirs are not known very well, we examined different variogram models and properties. In order to inspect the effect of different variogram properties on the reservoir behavior, we conduct numerical simulations with 10 realizations of specific heat capacity of rock for each variogram type. Statistical analysis of the results shows that mean thermal evolutions are similar for all variogram types but variances are different. Figure 9 depicts that the variance of thermal evolution becomes larger near the injection borehole. Possible temperature ranges in the observation point are different depending on variogram type (Figure 10). As an example, there is

10K difference in minimum and maximum temperature for a Gaussian model with 50m range whereas 4.4K for a Spherical model with the same correlation length. These findings quantify the influence of the selected statistical model on the predicted thermal evolution.

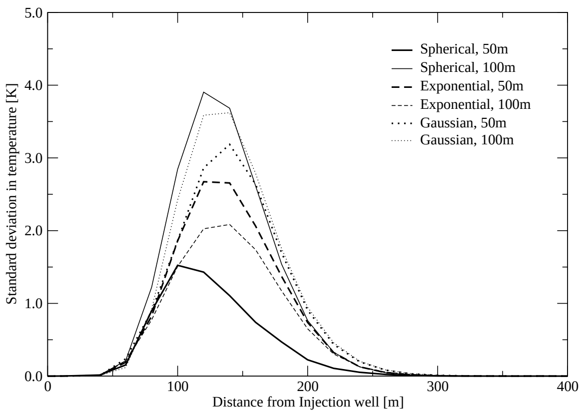

Figure 9. Profiles of standard deviations of temperature after 15 years for different variogram models

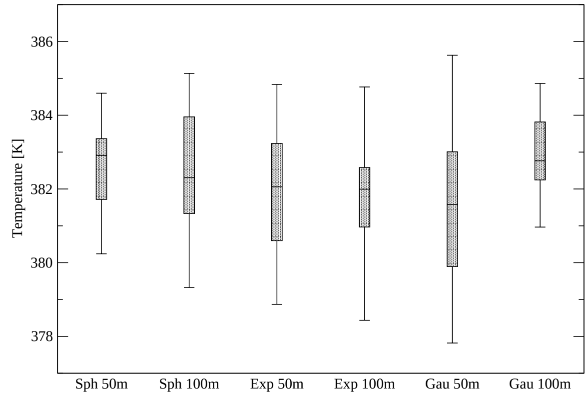

Figure 10. Statistical analysis of temperature at the observation point after 4 years

B. Reservoir properties in HDR geothermal sites

Table 2. Reservoir properties

Location	Urach	Soultz-sous-Forets	Urach
Rock type	Gneiss	Granite	Gneiss
Source	Haenel (1982)	CORE TEAM (1991), Genter et al. (1991), Jung (1991), Rummel and Baumgärtner (1991), Schellschmidt and Schulz (1991), Tenzer and Heine-mann (1991), Baria et al. (1992)	McDermott et al. (2006)
Rock thermal conductivity [W/(mK)]	2.55-3.03	2.58±0.2	3.2
Rock specific heat capacity [J/(kgK)]	850	1098 ± 215	-
Porosity	0.16-0.65%	≤ 1.0%	0.5%
Matrix permeability [m^2]	0.3-43.3×10^{-18}	-	-
Transmissivity [Dm]	-	-	0.3 (k_x=1.53×10^{-15} , k_y = k_z = 3/8k_x)
Young's modulus [GPa]	64	64-69	85
Poisson ratio [Pa s]	0.225	0.27-0.29	-