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Numerical determination of long-term alterations of THM characteristics of a Malm geothermal reservoir during continuous exploitation

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ABSTRACT

The INSIDE research project aims at quantifying the coupled processes triggering induced seismicity and ground deformation during geothermal exploitation of the deep Malm aquifer near Munich. This study focuses on the joint analysis of scientific data from borehole and survey to predict the physical behavior of the Pullach geothermal reservoir in terms of fluid flow and heat transport. Various geological, geophysical, and experimental data were evaluated and/or used as input parameters to develop a thermo-hydro-mechanical, THM, coupled FE reservoir model. Thereby, the TIGER application allows for quantifying the THM processes and their mutual interaction in the reservoir. The developed calibrated reservoir model indicates that sustainable exploitation is possible under current operational conditions. A long-term increase in porosity and permeability can be expected due to thermo-poro-elastic effects in the vicinity of injection well Pullach Th3.

1. INTRODUCTION

The INSIDE research project, supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), is being carried out jointly with the two operators of geothermal plants, Stadtwerke München (SWM) and Innovative Energie für Pullach (IEP) as well as the company Erdwerk and coordinated by the research university of the Karlsruhe Institute of Technology (KIT). The common goal of the project is to quantify the dynamics of coupled processes that can lead to induced seismicity and ground deformation during the exploitation of deep geothermal Malm reservoirs. These findings shall be incorporated into the future monitoring, modeling, and power plant operation.

The Pullach geothermal power plant is one of the project sites where a deep geothermal reservoir in the Malm has been successfully developed with three wells between 2005 and 2011. More than a decade of continuous operation opens up the rare opportunity not only to predict long-term changes in the thermo-hydro-mechanical (THM) characteristics of the geothermal reservoir but also to confirm these changes based on measurement data. These measurement data can be used not only for the operating history of the power plant but also for the calibration of 3D numerical models of geothermal reservoirs and all physical processes involved (Egert et al., 2020; 2021; Konrad et al., 2019).

This study focuses on the joint analysis of different scientific and operational datasets to predict the physical behavior of the Pullach Malm reservoir. These data, including hydraulic, temperature, and seismic measurements are evaluated and used as input and calibration parameters for the definition of the boundary conditions in a fully coupled finite element (FE) reservoir model. Albeit the potential of modeling is manifold, we focus on two objectives. The primary objective is to quantify the geothermal potential in terms of heat and potential flow rates to forecast the thermo-hydraulic behavior in long-term power plant operation. A secondary objective is the identification of areas surrounding the injection well in which thermo-poroelastic effects cause long-term alterations in the stress regime and reservoir properties (e.g., porosity).

2. NUMERICAL MODELING

The numerical simulations are performed using the open-source application TIGER (THMC sImulator for GEoscience Research) (Gholami Korzani et al., 2020). The code is based on the parallel, finite-element (FE) MOOSE (Multiphysics Object-Oriented Simulation Environment) framework (Permann et al., 2020). TIGER is particularly designed to solve thermo-hydro-mechanical-chemical questions in porous and fractured geothermal reservoirs in a fully coupled manner. The application allows flexible and manifold 3D lithologies, 2D fractures, and the open-hole sections of wells to be integrated into the models as independent features and the associated physical processes to be solved.

2.1 Governing equations

The Pullach reservoir is solved for the THM processes involved according to the following equations. The hydraulic field is solved by combining the mass and momentum balances (Bear & Cheng, 2010) for the matrix as well as the lower-dimensional elements as:

$$bS_m \frac{\partial P}{\partial t} + \nabla . b\boldsymbol{q} = Q \qquad [1]$$

$$\boldsymbol{q} = \frac{\boldsymbol{k}}{\mu}(-\nabla P + \rho^f \boldsymbol{g}) \qquad [2]$$

where t is the time; P is the pore pressure; S_m the specific storage of the mixture; Q is a source/sink for mass changes; k is the permeability tensor; μ is the fluid dynamic viscosity; ρ^f is the fluid density; g is the gravitational acceleration; $\boldsymbol{q}$ is the Darcy velocity vector. b is a scale factor to apply on 2D fractures (aperture) or 1D well paths (diameter).

Heat transport is considered as advection-diffusion equation considering Fourier's law:

$$b\rho c_p \frac{\partial T}{\partial t} + b\left(-\boldsymbol{\lambda}\nabla . \nabla T + \rho^f c_p^f \boldsymbol{q}\nabla . T\right) = Q \qquad [3]$$

where T denotes the temperature, ρc_p and $\boldsymbol{\lambda}$ are the mixture heat capacity and thermal conductivity, respectively. $\rho^f c_p^f$ is the fluid heat capacity.

Deformation of a saturated porous medium is given by the momentum balance equation and reads as follows for the form of effective stresses (Jaeger et al., 2007):

$$\nabla . (\sigma' - \alpha P) + \rho^s \mathbf{g} = 0 \qquad [4]$$

where σ' is the effective stress tensor, ρ^s is the solid rock density and α is the Biot's coefficient. The deformation is solved for the displacement vector **u**, which is related to the effective stress tensor by the stress-strain relationship through the following constitutive law:

$$\Delta\sigma' = C\left(\Delta\varepsilon - \frac{1}{3}\beta\Delta T\right) \qquad [5]$$

$$\varepsilon = \frac{1}{2}(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T) \qquad [6]$$

where C is the elasticity tensor, ε the strain, β the volumetric thermal expansion coefficient. The thermo-poroelastic evolution of porosity and permeability follows the exponential form described in Chen et al. (2009).

2.1 Numerical model

The numerical model focuses on the Pullach geothermal power plant. The structural model is based on various 2D as well as 3D seismic data from the greater Munich area (GRAME project) and the southward located city of Baierbrunn. The seismic gap between both models was interpolated carefully. The model includes seven different lithologies, ranging from crystalline to Tertiary, and additionally divides the potential reservoir rocks of the Mesozoic Malm into the three different sections of the lower, middle, and upper Malm. The three wells Pullach Th1a, Th2, and Th3 are included with their open-hole sections and their real well trajectories. Furthermore, a severely karstified zone around the well Th3 is included as an additional discrete unit (Lafogler et al., 2016). A single fault zone, which is located between boreholes Th2 and Th3 and which was not drilled, is included as a lower-dimensional feature. The orientation of the model is chosen to be consistent with the stress field in the South German Molasse Basin (Ziegler & Heidbach 2020).

The mesh for the numerical study is shown in Figure 1 and extends 11 (E-W) x 11 (N-S) km and is located between 1000 and 4000 m below sea level (vertical depth). The mesh is developed using MeshIt (Cacace & Bloecher, 2015) and contains 136'575 nodes, which are connected by 825'127 elements. The thickness of the lithological units is variable and has been determined from the structural model.

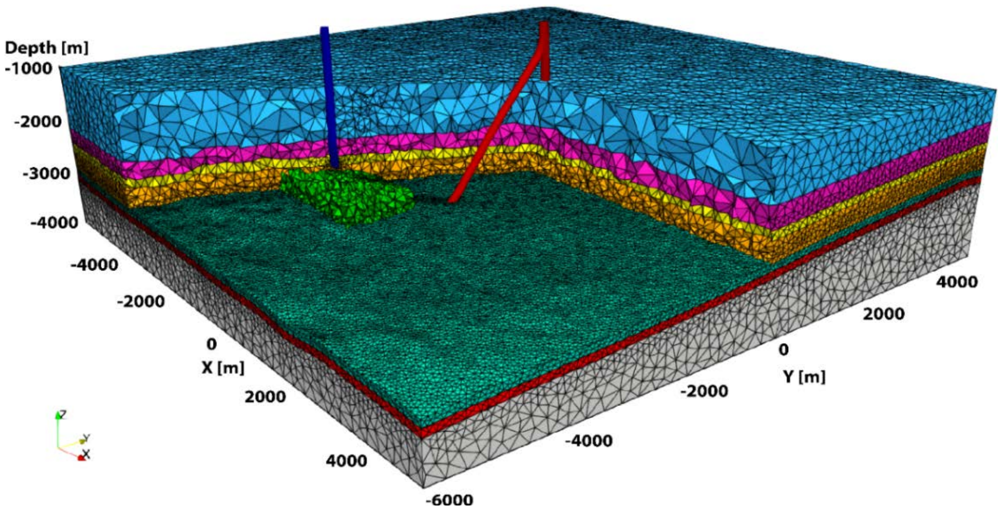

Figure 1: Finite element model of the Pullach geothermal reservoir including the wells Pullach Th1a, Th2 and Th3 as discrete lower-dimensional features and the seven different lithologies as different colors. The green lithology represents to middle Malm reservoir.

Refinement is applied around and along the three well open-hole sections as well as in the main reservoir units, resulting in element sizes between 300 m (along the edge of the crystalline basement and tertiary) and 10 m (close to and along with the wells). The distance between each well in the reservoir is about 2500 m. The boundary (BCs) and initial conditions (ICs) are determined from the various pressure and temperature measurements and both follow a linear gradient with depth within the model geometry. Both variables are applied as constant Dirichlet BCs on the lateral surfaces of the model. The vertical boundaries are constrained as no flow Neumann BC. Injection and extraction are considered as transient mass-flux-function at the top of the open-hole sections. Displacement on the boundaries is applied as depth-dependent external forces on the lateral boundaries, while the model is fully constrained at a single point in the center of the bottom boundary. According to Spivey et al. (2004), a brine with a constant density of 965 $kg.m^{-3}$, compressibility of $4.62x10^{-10}$ $Pa^{-1,}$ and dynamic viscosity of $2.64x10^{-4}$ Pa.s, representing a fluid at a temperature of 109 °C and pore pressure of 26 MPa is assumed. Although the karstified limestone reservoir exhibits a high degree of heterogeneity, for the purpose of simplification a uniform porosity of 0.1% in the crystalline and overlying sediments and 2% in the dolomitized limestone reservoir is assumed. Fluid thermal conductivity is 0.6 $W.m^{-1}K^{-1}$ and heat capacity is 4200 $J.kg^{-1}K^{-1}$. The surface mean temperature is 8 °C. Further material parameterization focuses on the Malm reservoir; therefore, for the overlying lithologic units and their THM parameterization, a median is determined and applied.

2. THERMO-HYDRAULIC CALIBRATION

The thermo-hydraulic calibration will focus on the Malm reservoir around wells Th1a, Th2, and Th3. Model initial pressure and temperature gradient are inferred from temperature and pressure well-log data. Since there are no long-term interference experiments at all three wells, the hydraulic parameters of the reservoir are calibrated individually. Both the production and in the recovery phases of the experiments are used. The calibration focuses on the reservoir, and the model includes only the open hole sections, so well effects such as skin and wellbore storage. The drawdown as well as the recharge phase of the experiments is used for calibration.

A pumping test conducted after completion of the well in 2011 is used to calibrate Pullach Th3. In this multi-stage test, reservoir fluid was continuously produced for 6.5 days at flow rates between 40 and 80 $kg.s^{-1}$. The pressure was measured via a depth sensor at the top of the Malm aquifer. At maximum flow rate, a pressure decrease in the reservoir of about 0.5 MPa could be obtained (Figure 2). Based on the 3D seismic results and the high productivity of the well, it can be assumed that this well is hydraulically connected to multiple units of the Malm.

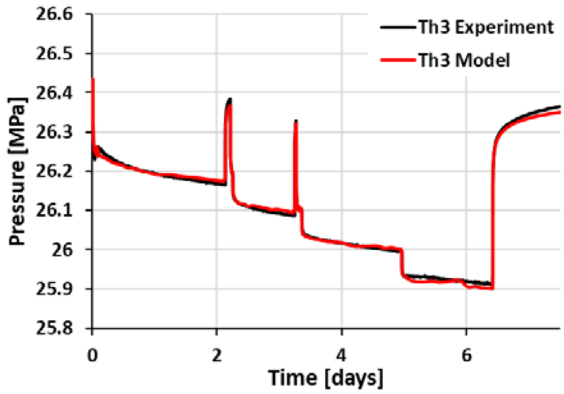

Figure 2: Simulated pressure (red curve) compared with the measured data (black curve) for Th3 and a circulation experiment in 2011.

For wells Pullach Th1a and Th2, both drilled in 2005, only pressure and flow rates at pumping level are available. The pressure in the reservoir was interpolated from these measurements via density correction. A two-day pumping test was conducted in April 2005, continuously producing water at flow rates between 15 and 40 $kg.s^{-1}$. During this test, a maximum pressure drop of less than 3 MPa was determined (Figure 3).

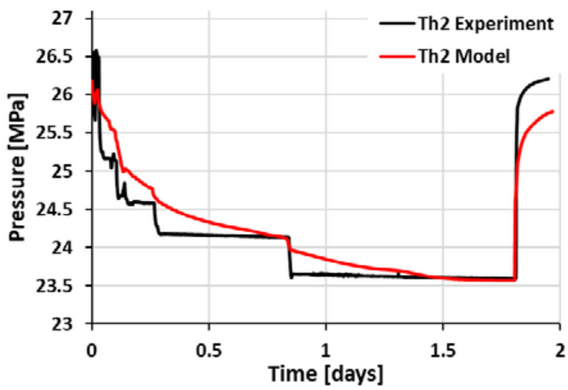

Figure 3: Simulated pressure (red curve) compared with the measured data (black curve) for Th2 and a circulation experiment in 2005.

Similarly, a two-day pumping test was carried out on the well Th1a in July 2005. In this test, production increased at flow rates between 20 and 40 $kg.s^{-1,}$ and reservoir pressures were recorded to decrease by less than 2 MPa (Figure 4). In addition, slight pressure differences in the Th2 well could be recorded and also simulated.

The reservoir temperature is calibrated using temperature logs and production temperatures during hydraulic testing (Lafogler et al., 2016). A linear temperature gradient of 3.52 $K.km^{-1}$ is determined resulting in temperatures at the top Malm between 102 °C and 108 °C. The mechanical parameterization follows the studies of Potten (2020) and Bohnsack et al. (2021) and in the first step of this study only distinguishes between crystalline, Malm reservoir, and the overlying lithologic units.

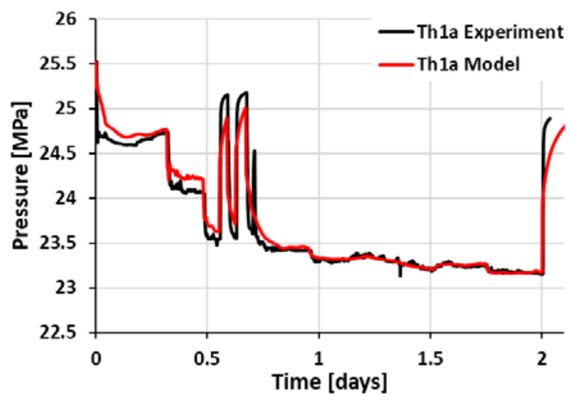

Figure 4: Simulated pressure (red curve) compared with the measured data (black curve) for Th1a and a circulation experiment in 2005.

3. LONGTERM RESERVOIR ALTERATIONS

The calibrated thermo-hydraulic reservoir model serves as basis for further investigations regarding sustainable power plant operation and alterations in the reservoir.

3.1 Thermo-hydraulic forecast modeling

In the first step, the calibrated model is used to predict the long-term reservoir behavior during continuous operation. For this purpose, the production (Pullach Th1a and Th2) and injection rates (Th3) of the individual wells are averaged for the year 2020 and used as transient Dirac kernels at the respective wells. Constant flow rates of 26 kg.s^{-1} (Th1a) and 24 kg.s^{-1} (Th2) are assumed for production and 50 kg.s^{-1} for injection (Th3) to ensure mass conservation. The demand-dependent reinjection temperature is averaged over the 2020 entire annual cycle so that a constant reinjection temperature of 62 °C is incorporated into the model as a Dirichlet boundary condition at the top of the Pullach Th3 open section. Based on these framework conditions, a continuous power plant operation over 50 years is simulated.

The simulation results reveal a hydraulic connection between all three wells involved in the operation within the middle Malm aquifer. After less than one-year, continuous pressure gradients have developed between the injection well and the two production wells, which become static within the first ten years of continuous operation (Figure 5 a, b). The maximum pressure changes in the reservoir are about 1.4 MPa for production (pressure decrease) and 0.8 MPa for injection (pressure increase). Due to the cold-water injection, a cooling front forms around Th3, initially extending radially and with time along the pressure gradient in the reservoir towards the production wells (Figure 5c, d). Within the simulation period of 50 years, the results indicate a cooling radius of 1 K about 1 km, but no thermal breakthrough. Further modeling confirms the trend of the directional cooling front with increasing operating time. A fault zone near Pullach Th3, which is not used for the calibration presented, could have a negative effect on the propagation of the cooling front towards Th2. On the other hand, the lack of this fault zone explains overestimated near-wellbore long-term pressure in the simulation. Since this fault zone is not directly drilled, long-term circulation experiments are necessary to calibrate it.

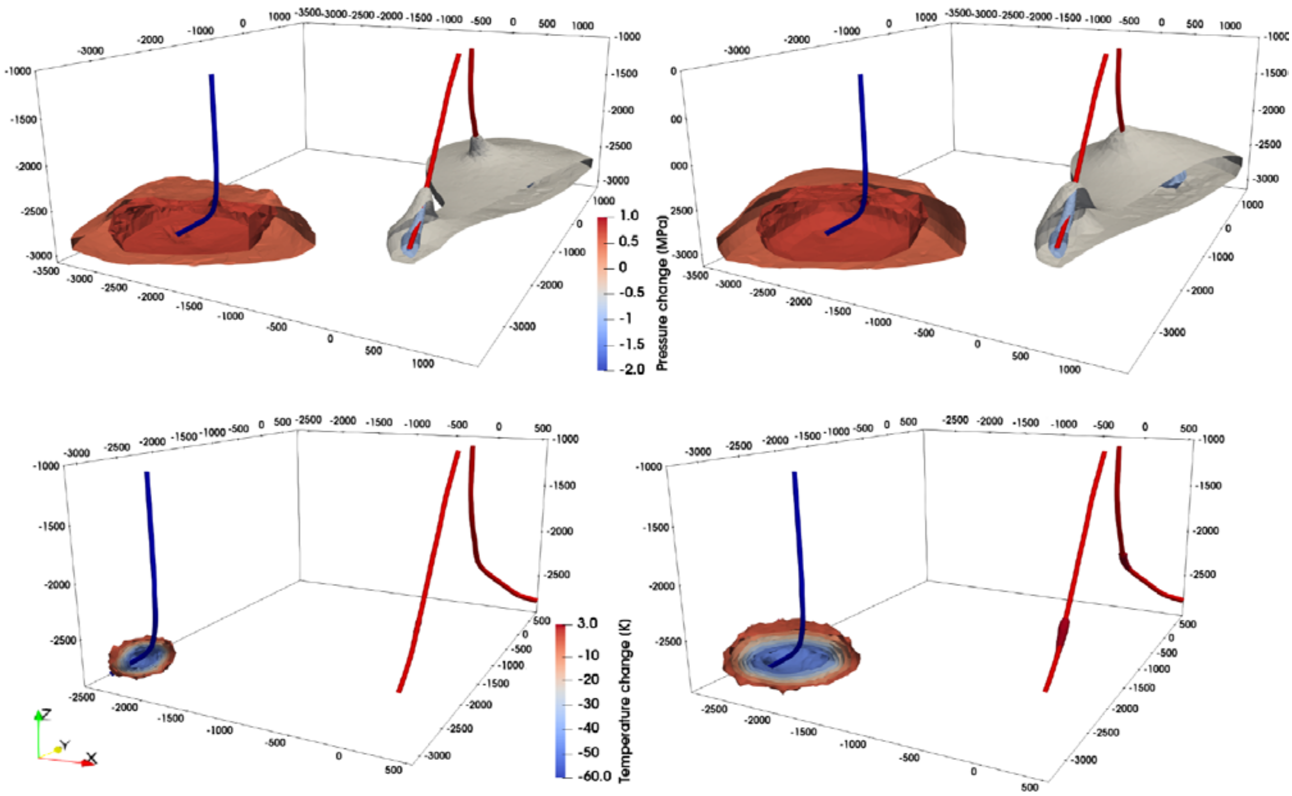

Figure 5: Simulation results for 50 years of continuous circulation. First row: Pressure change after a) 10 years and b) 50 years. Seconds row: Propagation of the cooling front around Th3 and temperature rise at Th1a and Th2 after c) 10 years and d) 50 years.

3.2 THM reservoir alteration

The calibrated long-term model can also be used to determine thermo-poroelastic changes within the reservoir caused by both pressure and temperature changes. Near the two production wells, the continuous extraction and pressure decrease only leads to minor, purely poroelastic alterations. Negative stress changes (Figure 6a) around the well lead to a slight reduction in porosity (Figure 6b).

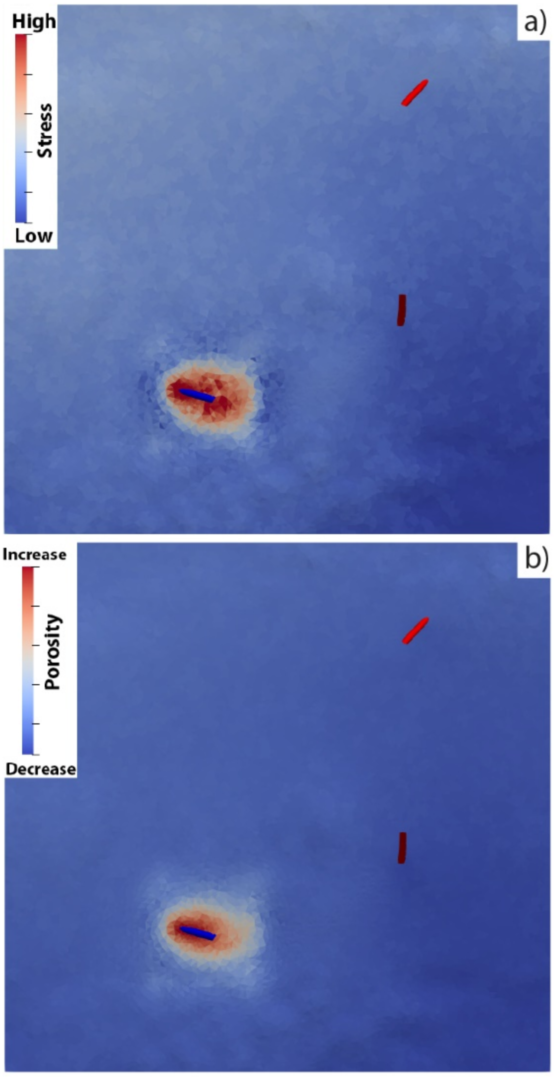

Figure 6: a) Thermo-poroelastic stress change due to continuous production and reinjection. b) Resulting porosity increase due to cooling and pressure increase.

More dominant are the changes near the well Th3. Here, both an increase in pore pressure (poroelastic) and contraction due to cooling effects (thermoelastic) of the surrounding reservoir rock cause a significant increase in principal stresses (Figure 6a). As a result, the pore space within the porous medium increases, leading to an increase in porosity (Figure 6b) and permeability within the middle Malm aquifer with time.

3. CONCLUSIONS

In the scope of the study shown, a wide variety of geological, geophysical, and experimental data was compiled to develop a three-dimensional calibrated thermo-hydraulic reservoir model of the Pullach geothermal power plant. Using this model and subsequent numerical forecast simulations, it can be shown that a sustainable reservoir operation under the prevailing operating parameters is possible for more than 50 years and that a thermal breakthrough is unlikely to occur.

In the next step, further calibrations will quantify the influence of an existing fault zone and take into account the prevailing Molasse stress field and different mechanical rock properties of the reservoir lithologies. The goal is a fully coupled THM-calibrated reservoir model in which it is possible to predict stress changes caused by continuous exploitation.

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