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Modelling of Thermo-Hydro-Mechanical coupled processes for faulted geothermal reservoirs

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Understanding the coupling between thermo-hydro-mechanical processes in saturated porous media is of interest for geothermal power production. Indeed, characterization of pore pressure, temperature and stress distributions within a reservoir during injection and production of fluid can help to understand reservoir behaviour and constrain reservoir productivity. This study presents a physical framework for describing the coupling between thermo-hydro-mechanical processes within geothermal reservoirs. This framework includes, among diverse processes, evolution of transport properties (porosity and permeability) as induced by effective stress, pore pressure and temperature changes based on formulations consistent with the theories of poro- and thermoelasticity. This study aims to describe thermo- and poroelastic behaviour of geothermal reservoirs in order to better estimate reservoir productivity during geothermal operations. In addition, attention is given to the integration of geological complexity (fault geometry or anisotropic formations) into coupled thermo-hydro-mechanical processes modelling.

The above formulations have been implemented into a Finite Element Method based software to carry on forward thermo-hydro-mechanical simulations. This software, developed by use of the MOOSE Framework (Multiphysics Object Oriented Environment) (Gaston et al. (2009), *Nucl. Engrg. Design*) provides an implicit fully coupled scheme with user-defined physics which is of high interest for the highly coupled problem here considered.

In a first part, the consistency of these formulations is verified using calibration parameters as provided by experimental laboratory data under drained hydrostatic compressions of sandstones (Blöcher et al. (2013), *Int. J. Rock Mech. Min. Sci.*). Experimental setup as well as numerical setup for 3D simulations are summarized in Fig 1. By use of a crack closure theory (Morlier, (1971), *Rock Mech.*), non-linear effects for stress-strain relation and for porosity and Biot's coefficient evolutions can be reproduced with satisfying accuracy. Progressive closure of micro-cracks are responsible for such non-linearity (see Fig. 2).

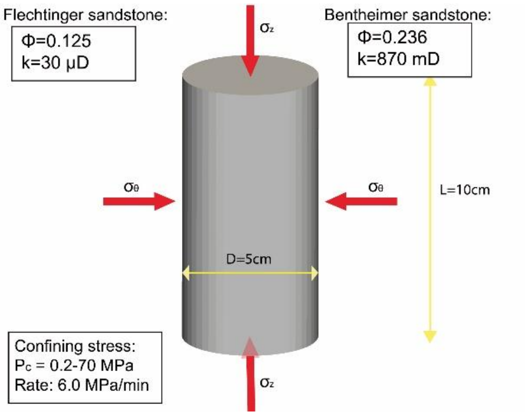

Figure 1: Setup for simulating drained hydrostatic compressions of sandstones

In a second part, the geothermal research site of Groß Schönebeck (40 km north of Berlin, Germany) which consists of a doublet system at a target depth of about -4100 m in which both injection and production wells have been hydraulically stimulated is considered.

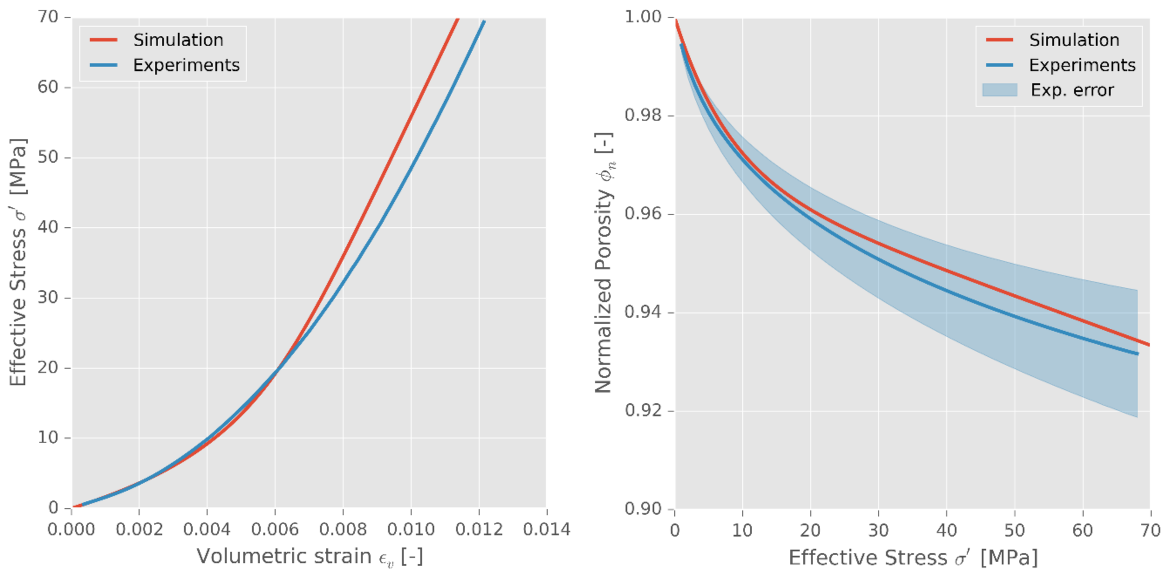

Figure 2: Stress-strain relation (left) and porosity evolution (right) during hydrostatic compression.

First, the stimulation treatment of the geothermal well GrSk 4/05 will be presented. This well, drilled in 2005 was stimulated in August 2007 by conducting cyclic changes of low and high flow rates (up to 160 L/s) in order to increase reservoir productivity. Details of this procedure can be found in Zimmermann et al. (2010), *Geothermics*. This study is focused on the poroelastic response of the reservoir during this stimulation, and particularly on the pressure response in a nearby well (450 m away from GrSk 4/05). Figure 3 shows the pressure response recorded and simulated by mean of an appropriate poroelastic formulation.

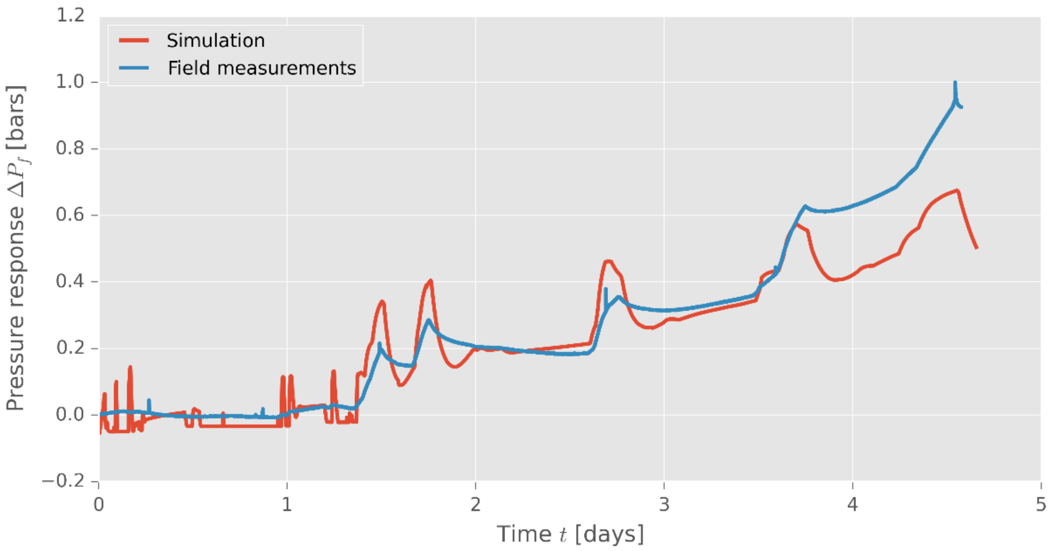

Figure 3: Pressure response during hydraulic stimulation of a geothermal well.

General increase of pore pressure is recorded due to pressure diffusion within the reservoir. Local maxima for pressure are also recorded following instantaneous peaks of injection rate into the stimulated well. These results provide valuable insights for understanding poroelastic behaviour of geothermal reservoirs.

Finally, a 3D reservoir model including all geological layers, major natural fault zones and hydraulic fractures is integrated in the finite-element method-based simulator for modelling coupled THM processes during geothermal activity (see Fig. 4).

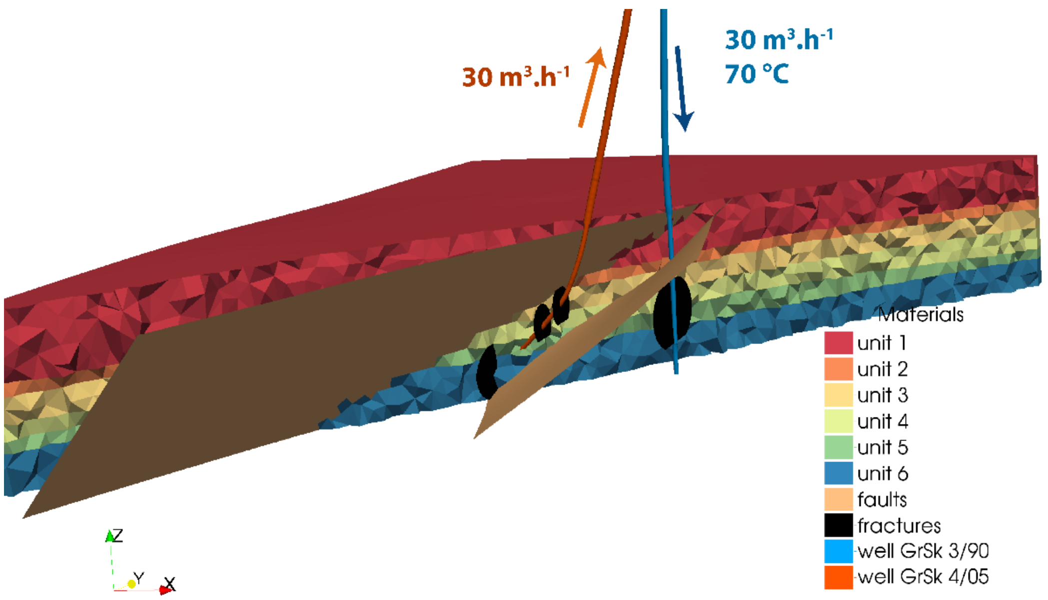

Figure 4: Overview of the 3D reservoir model of the Groß Schönebeck geothermal reservoir.

Numerical simulations allow to quantify porosity and permeability enhancements due to injection of cold water. An increase of porosity of 3% as well as an increase of permeability of about 38% have been recorded around the injection well due to thermal enhancement (see Fig. 5). In this context, thermal breakthrough time of the geothermal system has been found to occur at 18 years after the start of injection by numerical simulations. Particular attention is also given to the understanding of the impacts of the faults on reservoir productivity and of dynamic evolution of the reservoir including fault slip behaviour during geothermal activities.

Calculated productivity index during simulation is also compared to available field data (case lift test and communication experiments).

The results presented here provide therefore valuable insights for understanding the porosity and permeability distributions and their evolution during geothermal energy production and their impacts on reservoir performance.

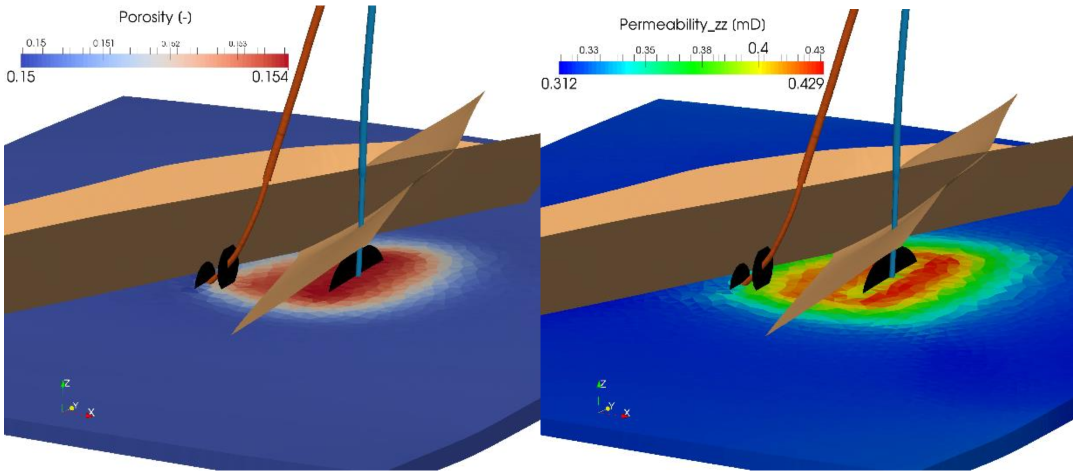

Figure 5: Porosity (left) and vertical permeability (right) distributions after 90 years of geothermal operations

Current work is focused on integrating new processes related to fault mechanics to better describe the damage area around a fault and its hydraulic and mechanical properties controlling the impact of a fault on fluid flow.