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Hydro-mechanical Evolution of Transport Properties in Porous Media: Constrains for Numerical Modeling of Geothermal Systems

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Quantifying variations of transfer properties of porous material is of interest for geothermal operations. The basic transport properties of the rocks, which are porosity and permeability can affect if not control the reservoir performance. Variations of these properties are a result of the coupled deformation and thermal processes. Significant pore pressure and temperature changes can occur during injection and production of fluid and affect the reservoir performance. However impacts of elastic deformation processes on transfer properties is often dominant compared to the impacts of the thermal processes in the context of geothermal operations. Understanding the coupling between deformation of the porous material and variation of its properties for mass and energy transfer is therefore a major focus for any geothermal operations. Pore pressure changes due to injection or production of fluid have direct impacts on the stress-field within a geothermal reservoir. Deformation of a porous material filled with fluid is based on variations of bulk and pore volumes and affects therefore the basic transport properties of the rock. The phenomena involved in this hydro-mechanical behavior of porous materials are however hard to observe and quantify at the field scale. This is why studies of hydro-mechanical behavior of porous rocks are often conducted at the laboratory scale where impacts can be measured. Variations of the transport properties can be expressed by theoretical formulations based on experimental observations and then integrated into models which can be used to predict reservoir performance at the field scale.

Numerical simulations are nowadays a common tool to predict reservoir performance during geothermal operations. By constraining parameters involved in the theoretical formulations defined during experimental tests, numerical simulations provide a powerful tool to quantify effect of deformation of porous rocks on the reservoir productivity. It has been chosen to work with the open-source finite element method based software for thermal-hydraulic-mechanical-chemical coupled processes (T-H-M-C) OpenGeoSys. This software provides also a hybrid approach for fluid flow through fractures by considering discrete fractures and continua models (Watanabe et al. 2009, 2012; Kolditz et al. 2012). Use of numerical simulation allows also to quantify each process (elastic, plastic deformation, thermal creep, etc…) separately which is not possible anatycally.

The aim of this study is to develop a complete poroelastic formulation capable of explaining and quantifying fluid-rock interactions within a faulted region. Stress-sensitive structures such as faults are of importance for the hydro-mechanical behavior of the rocks, especially due to fracturing. As shown on figure 1, different domains can be identified in a faulted system: an impermeable fault core surrounded by a damage zone where the rocks are highly fractured and the permeability oncreases and intact or poorly fractured rocks far away from the fault core. Figure 1 illustrates also typical evolutions of two properties: permeability which explains the hydraulic behavior and elastic modulus which illustrates the mechanical behavior or the faulted region.

The first step of this study which will be presented consists in implementing in the open-source software OpenGeoSys H-M formulations to quantify porosity variations and non-linearity in the stress-strain curve during isothermal drained hydrostatic compression of intact porous rocks. Numerical description of the physical phenomena involved for such behavior requires to account for the coupling between deformation and hydraulic processes and the relations between different scales. Three different formulations are studied which are based on the theories of poroelasticity and crack closure. The first one has been developed by (Zimmerman 1991) and relates porosity variations to the drained bulk modulus evolving with effective stress. The second one developed by (Blöcher et al. 2013) is based on quantifications of the bulk and pore volumes changes which are expressed with volumetric strain. And the last one developed by (Chin et al. 2000) for hydrocarbon applications relates porosity variations to volumetric strain. These three formulations are tested on two different kinds of sandstones (Flechtinger and Bentheimer sandstones) by comparing simulations to experimental results. It is then possible to constrain some parameters involved in these porosity formulations.

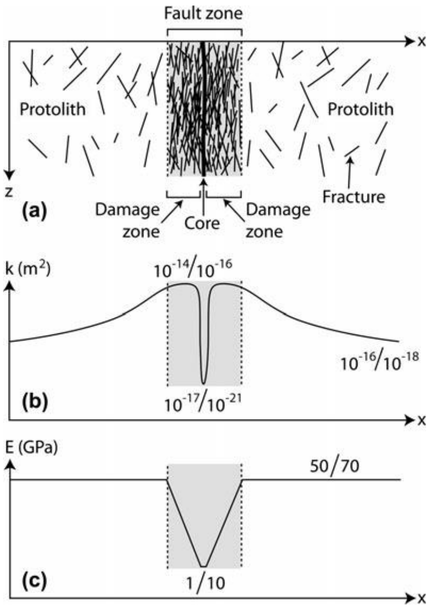

Figure 1: Fault zone configuration - example of the permeability and Young's modulus distributions (Cappa 2009)

Hydro-mechanical behavior of porous media has been formulated in the theory of poroelasticity (Terzaghi 1943; Biot 1956,1973) and micro-cracks closure. A main variable in these theories is the Terzaghi effective stress defined as the confining stress corrected by the pore pressure:

$$\sigma_e = \sigma_c - p_p \tag{1}$$

Setup for simulations is presented on figure 2. Confining stress is increased from 0 to 70 MPa with a rate of 6, 0 MPa per minute. The rock samples are cylindrical with a 5 cm diameter and 10 cm length. Figure 2 presents also initial conditions in term of porosity and permeability for the two kinds of sandstones.

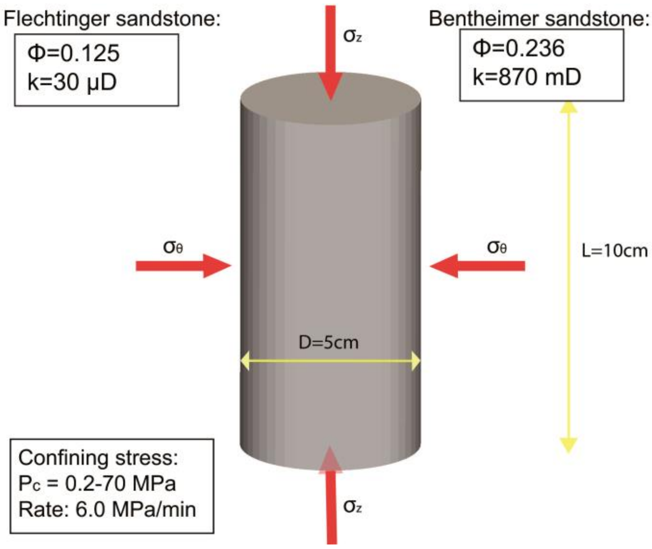

Figure 2: Setup for simulating drained hydrostatic compressions of the two considered sandstones

During drained hydrostatic compression, porosity of the porous rocks decreases with increasing effective stress. Two different domains can be identified as seen on figures 3 and 4:

- A non-linear decrease for low effective stress (under 20 MPa for the Flechtinger sandstone and under 10 MPa for the Bentheimer sandstone). In this range of effective stress, porosity is decreased by 5% for the Felchtinger sandstone and by 1, 5% for the Bentheimer sandstone.

- A linear decrease for higher effective stress. Above 20 MPa porosity of the Flechtinger sandstone decreases linearly with a rate of 0, 5% every 10 MPa (above 10 MPa for the Bentheimer with a rate of 0, 17% every 10 MPa).

To sum up, at 70 MPa porosity is decreased by 8, 1% for the Flechtinger sandstone and by 1, 4% for the Bentheimer sandstone. Impacts of such porosity decreases are studied by considering the Kozeny-Carman poro-perm relation under some assumptions on the shape of the pores to quantify the permeability as main property controlling transport of mass and energy in porous media. Qualitative estimation of the permeability decrease induced by porosity changes allows to study impacts of the hydro-mechanical phenomena on the geothermal reservoir productivity.

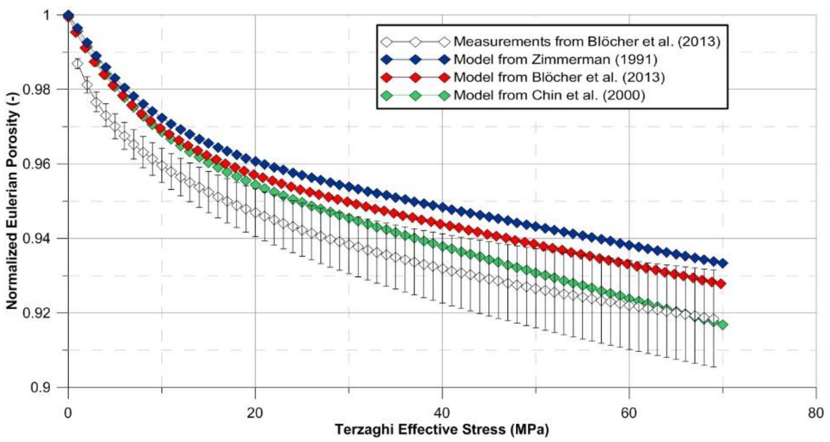

Figure 3: Porosity variations of the Flechtinger sandstone during drained hydrostatic compression considering the three different models.

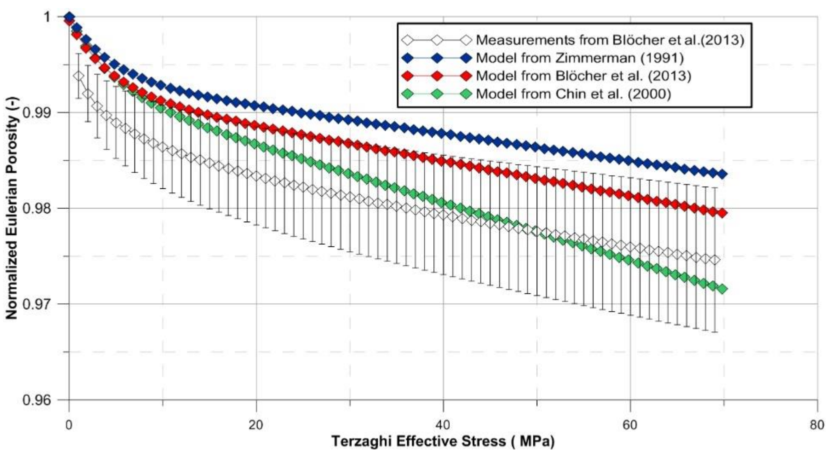

Figure 4: Porosity variations of the Bentheimer sandstone during drained hydrostatic compression considering the three different models.

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