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Far field poroelastic response of geothermal reservoirs to hydraulic stimulation treatment: Theory and application at the Groß Schönebeck geothermal research facility

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ABSTRACT

Enhanced geothermal systems (EGS) are engineered reservoirs developed to extract heat from low permeability and low porosity geological formations. Cyclic hydraulic stimulation treatments can be used in some cases to create hydraulic fractures and gain access to the target formation fluids, drain the geothermal fluid and increase the overall productivity of the reservoir. During these operations, successive cycles of injection at high flow rates are conducted to decrease the effective minimum principal stress to the tensile strength of the material, developing a mode I fracture. Opening of the newly developed fractures induces additional deformation of the reservoir rocks whose impact on the far field reservoir hydraulics has not been addressed so far for real case applications. These rates of compressive deformation can be significantly high in the context of cyclic stimulation treatments and can lead to a poroelastic pore pressure increase which spans quasi-instantaneously at greater distances than diffusive processes. In this study, such a poroelastic response resulting from cyclic deformation during hydraulic stimulation treatment of a well is investigated using hydromechanical coupling between pore pressure variations and rock deformation. The effects of this poroelastic response on the hydromechanical state of a reservoir is illustrated with field measurements of a cyclic hydraulic stimulation treatment conducted at the Groß Schönebeck geothermal research site in August 2007. This study demonstrates that the pore pressure increase monitored in a neighbor well located approximately 475 m away from the stimulated well at reservoir depth is controlled by diffusive processes responsible for the long-term increase of pore pressure, but also by poroelastic effects responsible for the quasi-instantaneous local peaks in pore pressure. The results from this applied study helped to quantify the relevance of the poroelastic behavior of stimulated reservoir rocks in a way than can improve current understanding of such hydraulic stimulation settings.

1. Introduction

Understanding the hydromechanical behavior of fluid-saturated porous rocks has gained great relevance over the last few decades for a number of different applications, including: geothermal energy production; radioactive waste disposal; or enhanced oil recovery from deep and high-pressure reservoirs. In these reservoirs, interactions between hydraulic and mechanical processes are indeed common due to the presence of deformable pores within the solid matrix. Therefore the hydromechanical state of such systems is likely to be controlled by the stiffness of the porous rock matrix but also by the behavior of the fluid-filled pores. Studying the coupling of processes governing the deformation of a porous material and the dynamics of the circulating fluid (theory of consolidation or poroelasticity) was first introduced by Terzaghi[1] for a one-dimensional case and was later extended to three dimensions by Biot.[2,3] This theory has been the subject of several studies ever since[4–7] and has now reached a level of general consensus in the community, especially concerning its mathematical description. Several critical observations associated with nonlinear pore pressure responses demonstrated the relevance of hydromechanical coupling both at the laboratory scale (with the so-called Mandel-Cryer effect[8,9]) and at the field scale ([10–12], including the Noordbergum effect[13,14]).

In this study, we aim to understand and quantify the far-field effects of poroelastic coupling on reservoir rocks as occurs during cyclic

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hydraulic stimulation treatments. Such stimulation treatments are usually conducted to gain access to low permeability and low porosity geological formations by inducing artificial fluid pathways, i.e. hydraulic fractures. During these treatments, high pressure fluid is injected into the reservoir target formation thus leading to the generation of new fractures or to an enhancement of existing ones. Fluid injection leads to pore pressure increase, therefore decreasing the effective principal stress, which finally might lead to a tensile failure of the rock.[15,16] By alternating high and low flow rates it is possible to influence the aperture and length with which the fracture grows.[17] Other concepts of stimulation treatments have been developed, including thermally induced fracturing and chemical/acid stimulations.[18]

Several studies in the literature improved the current understanding of the fracturing process both from a theoretical but also from a more applied point of view.[19–21] However, these studies often focused on processes responsible for fracture development and/or their sustainability near the injector, while they generally neglected the impacts of such stimulations on the hydromechanical state of the far field surrounding reservoir rocks. The opening of a hydraulic fracture likely induces compression of the surrounding reservoir rocks preferably in a direction orthogonal to the fracture plane. Since high flow rates are injected into the reservoir, rates of induced deformation can build up and propagate at some distances throughout the porous matrix. Therefore, in such situations, the pore pressure response to the stimulation observed in the surrounding rocks is not only controlled by a pore pressure diffusion process, but it likely involves an additional poroelastic component. In this study, we perform a number of 3 D numerical tests in order to demonstrate and quantify, (i) how such poroelastic processes builds up during hydraulic stimulation treatments and (ii) to which degree this affects the hydromechanical state of the surrounding rocks.

Numerical modelling has become an essential tool nowadays to assess the hydromechanical state of geological reservoirs. Forward numerical simulations can be used either for making predictions at the field scale of geothermal operations,[22] or for process understanding based on operational field data as presented in this study. Several simulators have been developed to tackle these challenges, such as the open-source finite-element based simulator OpenGeoSys,[23] the parallel computing tool for coupled thermo-poro-mechanical processes during fluid injection[24] or the TOUGH-FLAC family of codes mainly targeting operations related to carbon sequestration.[25] In this study, we rely on the GOLEM simulator[26] which is built on top of the MOOSE framework.[27]

This contribution is organized as follows: first, the governing equations for fully-coupled hydromechanical behavior of porous rocks are introduced. A simplified generic model, is presented in Appendix A, using an analytical solution based on numerical inversion of Laplace transforms.[28] The model serves as a benchmark for the numerical implementation of the hydromechanical governing equations and is illustrative of poroelastic effects. Proceeding this, field measurements from a cyclic hydraulic stimulation treatment conducted in August 2007 at the Groß Schönebeck geothermal platform are used to illustrate the impacts of this poroelastic effect at the reservoir scale.

2. Problem formulation and numerical implementation

2.1. Governing equations

Modelling of coupled hydromechanical processes requires solving for the governing equations for fluid-flow and deformation of the porous medium. These equations are derived from balance statements for the fluid and solid mass and momentum. In this section, the governing equations for hydromechanical modelling of a porous rock fully-filled with water are presented based on the Biot's theory of consolidation.[2,3] Details about their derivation and the underlying assumptions can be found in 26.

The governing equation for pore pressure p_f is derived from the conservation of fluid mass as:

$$\frac{1}{M_B}\frac{\partial p_f}{\partial t} + \alpha\frac{\partial \epsilon_{kk}}{\partial t} + \nabla\cdot\boldsymbol{q}_D = Q_f \tag{1}$$

where α is the Biot's coefficient, ϵ_{kk} the volumetric strain, Q_f a sink or source term and M_B is the Biot's modulus (reciprocal of the storage coefficient) defined in Biot's consolidation theory[2,3] as:

$$\frac{1}{M_B} = \frac{\phi}{K_f} + \frac{(\alpha-\phi)}{K_s} \tag{2}$$

where ϕ is the porosity, K_f the fluid elastic bulk modulus and K_s the elastic bulk modulus of the solid grains. The specific discharge $\boldsymbol{q}_D$ can be expressed from the conservation of fluid momentum (within the limits of Darcy's approximation) as:

$$\boldsymbol{q}_D = \phi(\boldsymbol{v}_f - \boldsymbol{v}_s) = -\frac{\boldsymbol{k}}{\mu_f}\cdot(\nabla p_f - \rho_f\boldsymbol{g}) \tag{3}$$

where $\boldsymbol{v}_f$ and are the fluid and solid velocities respectively, $\boldsymbol{k}$ is the permeability tensor, μ_f the dynamic fluid viscosity, ρ_f the fluid density and $\boldsymbol{g}$ the gravity vector. Governing equations for the deformation of the porous medium are derived from the momentum balance in terms of the effective stress $\boldsymbol{\sigma}'$ as:

$$\nabla\cdot(\boldsymbol{\sigma}' - \alpha p_f\mathbb{1}) + \rho_b\boldsymbol{g} = 0 \tag{4}$$

where $\mathbb{1}$ is the rank-two identity tensor and ρ_b the bulk density, as defined by the following mixing rule: $\rho_b = \phi\rho_f + (1-\phi)\rho_s$ where ρ_s is the solid density. The effective stress tensor is defined here after Carrol and Katsube[29] as a function of the Cauchy's stress tensor $\boldsymbol{\sigma}$, the pore pressure p_f and the Biot's coefficient as:

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} + \alpha p_f\mathbb{1}. \tag{5}$$

The primary variable solved for deformation of a porous medium is the displacement vector $\boldsymbol{u}$ which is linked to the effective stress tensor via the following constitutive stress-strain law:

$$\Delta\boldsymbol{\sigma}' = \mathbb{C}:\Delta\boldsymbol{\epsilon} \tag{6}$$

where the strain tensor $\boldsymbol{\epsilon}$ is calculated using the small strain approximation:

$$\boldsymbol{\epsilon} = \frac{1}{2}(\nabla\boldsymbol{u} + \nabla^T\boldsymbol{u}). \tag{7}$$

where the superscript ^{T} denotes the transpose operator. In this study, only linear elasticity is considered to describe the deformation of the reservoir rocks. Therefore, the elastic material tensor can be described via the generalized Hookes's law as:

$$\mathbb{C}_{ijkl} = \lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) \tag{8}$$

where δ is the Kronecker delta, λ the first Lamé modulus and μ the second Lamé modulus or shear modulus. The fully coupled hydromechanical behavior of a porous medium is therefore modelled using Eqs. (1)–(8).

2.2. Implementation

The GOLEM simulator is based on the MOOSE (Multiphysics Object Oriented Simulation Environment) framework[27] which provides a powerful and flexible platform to solve for multiphysics problems implicitly and in a tightly coupled manner on unstructured meshes. This framework is based on two main libraries, the finite element library libMesh[30] and the solver library PETSc.[31] Based on these two libraries, the MOOSE framework allows the users to develop models with high flexibility and to deal with realistic scenarios, including complex geometries and non-linear physics by maintaining computational efficiency and code portability.

The weak forms of Eqs. (1)–(8) are solved in a tightly coupled