Poroelasticity Response of Geothermal Reservoir with a Thermo-Hydro-Mechanics Simulation

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ABSTRACT
The purpose of the research is to demonstrate a semi-analytical model that accurately captures the effect of fluid flow, heat and geomechanics in geothermal reservoirs due to fluid injection. During heat extraction of a geothermal reservoir, the reservoir pressure and temperature are often varying. These variations will affect or alter rock stresses. The alteration of rock stresses may lead to rock deformation and affect the opening or closing of fractures in the system. The opening fracture on its turn will ultimately affect the performance of reservoir. We demonstrate a thermo-hydro-mechanics coupled model able to capture the fluid and mechanics influences. A semi-analytical approach is used to be able to do fast calculations and be prepared for history matching, data assimilation and optimization. Induced horizontal stresses are determined. The stresses, pore pressures and displacements are calculated as a function of time and position. These are then input in a permeability update procedure in order to assess the stimulation effect of an operation. The fast-model approach facilitates quick assessment of scenarios, efficient model updating and coupling to production optimization.

1. INTRODUCTION
A reservoir simulation is used to see how the reservoir behaves as a result of production or injection. During these processes, the reservoir pressure and temperature are often varying. These variations in temperature and pressure will affect or alter rock stresses. The alteration of rock stresses may lead to rock deformation and associated opening or closing of fractures in the system. The changing fracture apertures on their turn will affect the productivity of the wells. The combined development of fluids physical properties and mechanical properties of rocks have consequences for the productivity performance of the geothermal reservoir. In the present study a thermo-hydro-mechanics coupled model is demonstrated to capture the fluid and mechanics influences.

The behavior of naturally fractured reservoir systems is controlled by three interacting processes; thermal, hydrological and mechanical, generally referred to as Thermo-Hydro-Mechanics (THM) coupled processes (Cui and Jin, 2017). In geothermal energy, a lot of research has been conducted to dual-porosity reservoir (Zimmerman et al., 1992; Bower and Zylowsk, 1997; Cui and Jin, 2017; Rutqvist et al., 2002), specifically in Enhanced Geothermal System (Fakcharoenphol and Wu, 2011; Gelet et al., 2012; Ruhaak and SASS, 2013) with most studies using a numerical approach. A semi-analytical method has been developed for estimating thermo-poro-elastic stresses in a fractured geothermal system, and seismicity rates based on the model of Dieterich (Candela and Fokker, 2017). That model is based on a single-fracture injection model with thermo-elastic stressing around the fracture. The interaction between multiple fractures has been modelled with complex numerical approaches (Izadi and Ellsworth, 2010; McCulter and Horne, 2010; Taron and Ellsworth, 2009). These thermo-hydro-mechanics coupled models are time-consuming and physical parameters cannot be updated by a data assimilation scheme (Candela and Fokker, 2017). Most thermo-hydro-mechanics coupled researches are in Enhanced Geothermal System (hot dry rock reservoir) because natural cracks and fractures are typically scarce. Hydraulic fractures are required to provide high permeable path for heat and fluid flow to the wells (Fakcharoenphol and Wu, 2011).

It is necessary to develop a coupled heat-flow and geomechanics model to capture the overall influences of pressure, temperature, stress, fractures opening/closing, and permeability changes to accurately predict the well or reservoir performances. Most studies use a numerical approach for thermo-hydro-mechanics model. It typically couples the fluid and heat flow computer codes and rock mechanics computer codes. The codes are linked through external coupling modules (Rutqvist et al., 2002). The numerical approach will create a time-consuming model when used in a data assimilation scheme (Candela and Fokker, 2017). In order to accelerate the simulation process, a semi-analytical approach can be used. A fast and flexible tool facilitates better history matching. A fast thermo-hydro-mechanics modellng tool has been developed for poro-thermo-elastic-plastic behavior (Fokker and Wassing, 2019, Fokker, Singh and Wassing, 2019). The modelling tool is called THYMA (Thermo-Hydro-Mechanics Analysis) which then will be used in this paper. It has been validated with a coupled FLAC-TOUGH model (Fokker and Wassing, 2019). THYMA focuses on the transient problem of pressure diffusion and heat flow coupled with elastic-plastic mechanics in radial system which can be used for geothermal operation such as stimulation.

This paper presents an application of the fast thermo-hydro-mechanics model in a geothermal well in a hydrothermal volcanic system. The geothermal field with naturally fractured rocks was selected because the fracture network is activated and stimulated by the pressures and temperatures due to water injection. The Wayang Windu geothermal field in Indonesia is an example of a field in a hydrothermal volcanic system. Wayang Windu field is interpreted to be transitional between vapor dominated and liquid dominated systems (Bogie, 2008). It consists of a lateral series of two-phase zones at shallow levels capped by a low permeability argillic layer (Mulyadi and Ashat, 2011). The Wayang Windu field is a densely fracture system. The interaction between in situ stresses and the orientation of fractures affect the permeability and fluid flow. The assessment of fracture distribution and relative stresses can provide better understanding of the reservoir performance and the exploitation of natural fractures to increase production. Wayang Windu indeed requires stimulation to open the pre-existing fracture in order to increase the production.
2. THM MODEL

The thermo-hydro-mechanics coupled model (Fokker and Wassing, 2019; Fokker, Singh and Wassing, 2019) provides a semi-steady-state solution for coupled elastoplastic thermal-hydro-mechanical behavior in a radially symmetric porous medium. It starts with a description of linear thermo-poro-elasticity. Then the semi-steady-state approximation to formulate the pressure field is developed, and the fields in the plastic zone are described. Finally, to close the loop between successive time steps, an update for the permeability field is formulated.

2.1 Linear poro-thermo-elasticity

Linear poro-thermo-elasticity involves a linear relationship between stress and strain. The poroelasticity and thermoelasticity extend that by a linear effect of pore pressure and temperature on stress. A relationship between induced total stress (σij), strain (εij), the increase pore pressure (ΔP) and the increase temperature (ΔT) (Palacios & Domenico, 1982):

\[ σ_{ij} = 2G [ε_{ij} + \frac{κ}{1-ν^2} ε_{\delta ij}] - (α_m ΔP + β_\Gamma ΔT) δ_{ij} + σ_0^{in} \]  \hspace{1cm} (1)

The coefficients α_m and β_\Gamma are the product of thermal expansion coefficient and bulk modulus. Solutions are formulated under the assumption of axial symmetry of permeability, cylindrical elastic-plastic zone boundaries and radially symmetric stresses. The stress equilibrium in radial symmetry gives

\[ \frac{∂σ_r}{∂r} + \frac{σ_r - σ_θ}{r} = 0 \]  \hspace{1cm} (2)

The full transient diffusivity equation is formulated which diffusivity constant different from the classical one where only flow is considered: the effect of the poromechanical and thermomechanical response is incorporated. However, the analytical solution of the diffusivity equation cannot be used for the effects of temperature changes and stimulation. Therefore, a semi-steady-state solution which is applicable close to the well is used: within the radius where the pressure is disturbed we have (Fokker and Wassing, 2019, Fokker, Singh and Wassing, 2019)

\[ \frac{dp}{dr} = - \frac{Q_{inj}}{2πk_l h r} \]  \hspace{1cm} (3)

An energy balance approach is used for the temperature disturbance: the thermal energy in the cooled zone around the wellbore must equal the thermal energy from injection. The cooling also affects the flow due to the temperature-dependent viscosity of the fluid.

When there are no pressure and temperature disturbances, the elastic solution is the well-known elastic stress solution around an open borehole. For an isotropic horizontal stresses with a negative sign for compressive normal stress, the solutions are

\[ σ_{rr} = σ_0^{in} - \frac{z_1^2}{r^2} \]  \hspace{1cm} (4)

\[ σ_{θθ} = σ_0^{in} + \frac{z_1^2}{r^2} \]  \hspace{1cm} (5)

\[ σ_{zz} = σ_0^{in} \]  \hspace{1cm} (6)

The integration constant Z_0^p is determined by the requirement of zero effective radial stress at the wellbore radius.

2.2 Plastic zone

The Mohr-Coulomb criterion is used for failure. Failure will occur when the shear stress exceeds a maximum which is linearly dependent on effective normal stress. The Terzaghi definition, σ_i^p = σ_i + Pδ_i, is used for effective stress in plasticity. Failure will occur when the Mohr circle touches the failure envelope if the plane of failure is not predetermined. This can be translated to a relationship between the maximum and minimum effective principal stresses, σ_1^p and σ_2^p (Fokker and Wassing, 2019; Fokker, Singh and Wassing, 2019; Jaeger, Cook and Zimmerman, 2007; Fjaer et al., 2007).

\[ σ_i^p = -2S_\sigma \sqrt{ γ} + γ σ_3^p, \text{ with } γ = \frac{1+sin φ}{1-sin φ} \]  \hspace{1cm} (7)

In the plastic zone, it is assumed that the stress is at the failure line (Fokker and Wassing, 2019; Han and Dusseault, 2003; Masoudian and Hashemi, 2016). The equilibrium equation then reduces to an ordinary differential equation:

\[ \frac{dε_r}{dr} = (\gamma - 1) \frac{ε_r'}{r} = -1 \left[ \frac{Q_{inj}}{r_\Gamma 2πk_l h} + 2S_\sigma γ \right] \]  \hspace{1cm} (8)

Then, the horizontal plastic effective stresses are

\[ σ_{rr} = -ΔP(r) + r^{-1} \left[r_\Gamma \sigma_1^p \left[ σ_1^p + ΔP \right] - \int_{r_\Gamma}^{r} \left[ \frac{Q_{inj}}{r_\Gamma 2πk_l h} + 2S_\sigma γ \right] \frac{dr'}{r_\Gamma^2} \right] \]  \hspace{1cm} (9)

\[ σ_{θθ} = -ΔP(r) - 2S_\sigma γ + γ σ_1' \]  \hspace{1cm} (10)

The strain in the plastic zone consists of an elastic and a plastic part:

\[ δε_{ij} = δε_{ij}^p + δε_{ij}^P \]  \hspace{1cm} (11)
For a non-associated flow rule with dilation angle $\psi$ and the definition of $\beta = \frac{1+\sin \psi}{1-\sin \psi}$, a differential equation for the radial displacement can be written with a source function $f(r)$ that depends on the elastic strain only:

$$\frac{\partial \delta u}{\partial r} + \beta \frac{\delta u}{r} = f(r)$$  \hspace{1cm} (12)

The solution of the displacement differential equation is

$$\delta u(r) = u_A \left(\frac{r}{r_A}\right)^{-\beta} + r^{-\beta} \int_{r_A}^{r} \rho^\beta f(\rho) d\rho$$  \hspace{1cm} (13)

Every result obtained from each time step will always be the initial input for the next time step. Also, the permeability field will be updated at every timestep.

3. RESULTS AND DISCUSSION

The present study focuses on capturing the transient behavior of wells due to production and injection using a semi-analytical approach of poro-thermo-elastic-plastic coupled model. Due to production or injection, the pressure around the well changes. Then the effect of this is mechanical changes in the formation, which are described by linear poro-elasticity if they are in the elastic regime. But if a failure criterion is exceeded, the failure will occur in the formation. Then is important for geothermal applications with a focus on wellbore stability, induced seismicity, and well stimulation such as thermal fracturing.

Therefore, this paper presents a synthetic case of the mechanical response of injection in a geothermal well in a hydrothermal volcanic system. The Wayang Windu field in Indonesia is such a geothermal field in a hydrothermal volcanic system. So, we have adopted Wayang Windu field conditions in the present synthetic case. The geothermal system is assumed to have homogeneous rock, single porosity dominated by fractures both for flow and storage. The simulation is conducted in a radial system with isotropic far field horizontal stress. Water of 250°C is injected into a high-temperature steam reservoir, 300°C, of 700 m reservoir thickness. The reservoir has a permeability of 2.5x10^{-13} m² and a porosity of 0.15. The injection fluid has a viscosity of 0.10x10³ Pa.s and is injected at a rate of 0.116 m³/s for 30 days. The relevant parameters for the fluid flow and the mechanics parameter are represented in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus Young</td>
<td>0.8 x 10¹⁰</td>
<td>Pa</td>
</tr>
<tr>
<td>Rock bulk modulus</td>
<td>15.0 x 10⁹</td>
<td>Pa</td>
</tr>
<tr>
<td>Fluid bulk modulus</td>
<td>2.15 x 10⁹</td>
<td>Pa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.23</td>
<td></td>
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<tr>
<td>Wellbore radius</td>
<td>0.2</td>
<td>m</td>
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<tr>
<td>Maximum radius</td>
<td>40.</td>
<td>m</td>
</tr>
<tr>
<td>Reservoir thickness</td>
<td>700</td>
<td>m</td>
</tr>
<tr>
<td>Injection rate</td>
<td>0.116</td>
<td>m³/s</td>
</tr>
<tr>
<td>Matrix thermal expansion coefficient</td>
<td>2 x 10⁻⁵</td>
<td>1/°C</td>
</tr>
<tr>
<td>Reservoir temperature</td>
<td>300</td>
<td>°C</td>
</tr>
<tr>
<td>Injection fluid temperature</td>
<td>250</td>
<td>°C</td>
</tr>
<tr>
<td>Reservoir viscosity</td>
<td>0.13 x 10⁻⁴</td>
<td>Pa.s</td>
</tr>
<tr>
<td>Fluid injection viscosity</td>
<td>0.10 x 10⁻³</td>
<td>Pa/s</td>
</tr>
<tr>
<td>Permeability</td>
<td>1.0 x 10⁻¹³</td>
<td>m²</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.15</td>
<td></td>
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<tr>
<td>Biot’s effective stress coefficient</td>
<td>1.0</td>
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<tr>
<td>Injection period</td>
<td>2.59 x 10⁶</td>
<td>s</td>
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<tr>
<td>Initial reservoir pressure</td>
<td>40 x 10³</td>
<td>Pa</td>
</tr>
<tr>
<td>Far-field horizontal stress</td>
<td>-40. x 10⁶</td>
<td>Pa</td>
</tr>
<tr>
<td>Far-field vertical stress</td>
<td>-50. x 10⁶</td>
<td>Pa</td>
</tr>
<tr>
<td>MC friction coefficient</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>MC cohesion</td>
<td>1.0 x 10⁻¹⁰ (elastic) / 1.0 x 10⁸ (plastic)</td>
<td>Pa</td>
</tr>
</tbody>
</table>

The simulation results from THYMA (Thermo-Hydro-Mechanic Analysis) are provided in the form of pressure distribution, stresses, effective stress, strain, criticality, mobility, displacements, and stress path. Pressure distributions are obtained based on mobility, injection rate, and pressure influence radius. Meanwhile the stresses, strains and displacements are calculated based on elastic and plastic laws and the actual pressure and temperature distribution. The mobility field is updated every timestep, depending on the strain and the temperature. The radii of plastic-elastic transition are determined based on MC criterion after calculating the increment of the elastic stress.

3.1 The elastic zone

The elastic solutions have been constructed by increasing the cohesion to unphysically high values. The results are shown in Figures 1 and 2. During the injection process, there is a connection between the formation mechanical response and the fluid flow within the
porous medium. The increase of pressure from the beginning of the injection process results in a decline in effective stresses. This interaction results in a time-dependent behavior. The injection starts from \( t = 0 \)s (the blue line) until \( t = 30 \)days at the red line. The development of the pressure distribution is also influenced by the viscosity contrast between cold water and hot water in the reservoir. The large difference in viscosity causes the pressure distribution as shown in Figure 1a with the change in slope at the front of the cooled zone. The differences in stresses for subsequent timesteps are dominated by the progressive cooling of the reservoir. The Figures show discontinuity in stresses at the cooling front; parts of the curves that are on the same temperature overlap. Apparently, the permeability of the current case is so large that the pressure hardly influences the stress curves. After the well has been constructed, stimulation in these cases would originate solely from thermal effects.

At the initial injection, the stress curve follows the elastic solution for isotropic far-field stress. The compressive tangential stress is significantly increased in the near wellbore (the values become more negative towards the wellbore). With progressive cooling due to the injection process, the compressive tangential stresses increase even further, up to the position of the cooling front. Although the value of tangential stress decreases, the shape of the curve still follows the elastic stress solution curve.

![Figure 1: Elastic solutions; (a) Pressures, (b) Stresses, (c) Effective stresses, and (d) Strains.](image)

The temperature is characterized by a constant value of 250°C up to the cooling front; 300°C beyond it. The temperature difference also makes criticality to rise significantly within the cooled zone. Criticality remains to approach zero for the area further away from the wellbore. But the value increase also causes increased mobility capabilities of fluid flow in the area around the wellbore. In the present simulation, however, this effect is completely masked by the large decrease in mobility due to the increased fluid viscosity at reduced temperature. The stress paths, represented as normal effective – shear stress pairs versus time at selected positions, experience a jump to larger values of both at the moment of passage of the cooling front.
3.2 The plastic zone

Results for the calculations including plastic behavior are represented in Figs 3 and 4. A failure in the formation will occur if the failure criterion is exceeded. In Mohr-Coulomb criterion, the formation will fail when the shear stress exceeds a linearly increasing function of the normal stress. After the construction of the well (t = 0), there is already a plastic region around it. After injection starts, the pressure distribution around the wellbore changes: the pressure is increasing. The associated stress immediately around the well slightly moves away from the Mohr-Coulomb envelope. A thin region around the wellbore stabilizes. Further away, plastic behavior continues. This behavior is caused by the combined effect of pressure and temperature: due to the cooling, the radius of the plastic-elastic transition moves into the reservoir.

The plastic strain causes the possibility of stimulation to occur. The strains and displacements were determined using the plastic flow rule. A significant amount of criticality develops in areas away from the wellbore. The presence of failure in the plastic zone results in increased permeability – higher than in the elastic zone. However, the effect of increased viscosity in the cooled zone is larger than the effect of stimulation in the present calculations, causing much smaller mobility values in the cooled part of the reservoir than outside it.
Figure 3: Plastic solutions; (a) Pressures, (b) Stresses, (c) Effective stresses, and (d) Strains.

Figure 4: Plastic solutions; (a) Criticality, (b) Mobility, (c) Displacement, and (d) Stress path.
4. CONCLUSIONS

Water injection in a geothermal reservoir will cause an increase in the pressure, a decrease in temperature and an associated change in the stress values. As permeability is stress dependent, this affects the fluid flow capability. In our case the fluid flow capability is significantly increased, especially with the appearance of failure. Therefore, it can be seen that injecting fluid into a formation accompanied by the appearance of failure can stimulate an increase in fluid flow rate.

The current implementation of the software tool employs a step function for the temperature solution. This is suboptimal. Future developments need to incorporate the effect of thermal conduction as well. Conduction will cause a smoothing of the thermal front, but it will also facilitate cooling of overlying and underlying layers (Candela et al., 2018). Further, for the failure a simple Mohr-Coulomb criterion was used. The extension to other models will enhance the applicability of the tool (Singh, Wassing and Fokker, 2020).

We applied the new tool on a synthetic case based on the Wayang Windu field properties. For the current parameters the study resulted in a larger effect of the temperature-dependent viscosity than of the pressure-dependent stress and permeability changes. The effect of temperature therefore requires attention. Also, the effect of additional stresses on the permeability need to be critically reviewed: we here used a fracture network of which the effective permeability depends on the total strain. The foundation of this model and the parameters describing the functional relationships must be critically reviewed.

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