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## Numerical Modeling Approaches for Mitigating Induced Seismicity in Geothermal Reservoirs

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### Summary

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Geothermal energy offers a sustainable source of heat and electricity but alters reservoir pressure and temperature, affecting in-situ stress and potentially triggering fault reactivation and induced seismicity. Deep geothermal reservoirs are valuable for their high temperatures but pose challenges like low permeability and fracture-dominated flow, increasing the risk of fault instability.

This study explores two approaches to assess stress changes: a semi-analytical geomechanical proxy and a fully-coupled Thermo-Hydro-Mechanical (THM) model using open-DARTS. The THM model simulates coupled thermal, hydraulic, and mechanical processes in complex rock formations, while the proxy method approximates displacements and stress changes using reservoir simulation outputs and homogeneous geomechanical rock properties assumptions.

The proxy model has been applied to matrix- and fault-dominated systems, including the Brugge dataset. Results include pressure, temperature, displacements, stress changes predictions over 30 years. Fault stability is evaluated using Mohr-Coulomb criteria with a constant friction coefficient.

In fracture-dominated systems, faults often control flow but. Discrete Fracture Model (DFM) has been used for flow modelling.

Combining proxy and THM models can optimize the balance between accuracy and computational cost. The study emphasizes the differing impacts of pressure and temperature on fault stability during geothermal operations.

## Numerical Modelling Approaches for Mitigating Induced Seismicity in Geothermal Reservoirs

### Introduction

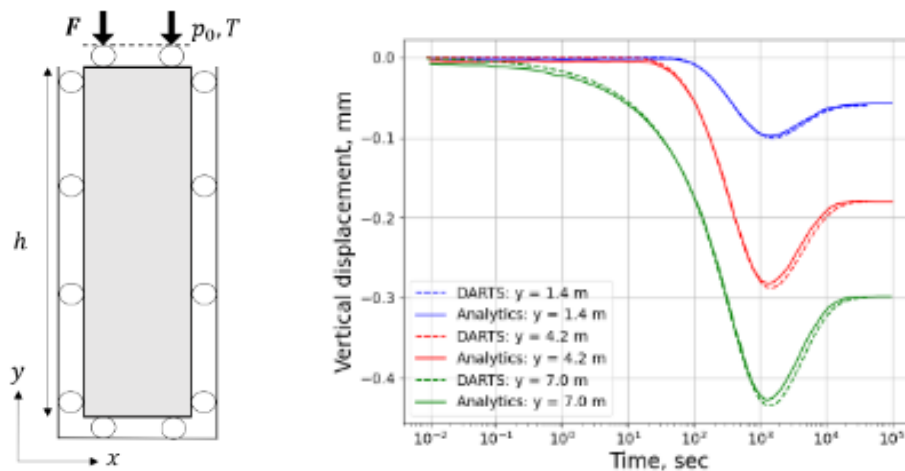
Geothermal energy production plays an important role in the energy transition by providing a green and reliable source of heating and electricity. Pressure and temperature alterations in the reservoir during geothermal energy operations impact the in-situ stress. These changes introduce the risk of reactivating existing faults and subsequent induced seismicity, which in turn, might lead to the temporary suspension, as happened in Mol (Kinscher et al. 2023) or even cessation of the reservoir development, as was the case for the geothermal projects at Pohang (Kim et al. 2022), and Californië (Muntendam-Bos et al. 2022).

Deep geothermal reservoirs are of high interest due to their higher temperatures. At the same time, they might pose a number of challenges, such as low rock permeability with a fracture-dominated flow. While low permeability results in higher injection pressures, cold liquid injection causes a temperature drop near the injection zone, leading to thermal contraction of the surrounding rock. Both of these factors undermine fault stability, and its numerical evaluation can help in induced seismicity risk mitigation in critically stressed fault cases.

In this study, we describe a few approaches for stress change evaluation: a semi-analytical geomechanical proxy method and a fully-coupled Thermo-Hydro-Mechanical (THM) solver developed in our group. We applied them to conceptual models with matrix-dominated and fault-dominated flow in the reservoir.

### THM model

The fully-coupled thermo-hydro-mechanical solver implemented in open-DARTS (Voskov et al. 2024), uses a collocated Fully Implicit multi-point discretization scheme (Novikov et al. 2025). Based on the Finite Volume Method, it treats mass, energy, and momentum fluxes in a unified formulation. The framework can be used to simulate the coupled processes in thermoporoelastic rocks on unstructured polyhedral meshes. The solver has been validated against analytic solutions. For instance, Figure 1 illustrates the thermoporoelastic consolidation setup described in Novikov et al. (2025). Notice that the response of this setup demonstrates an inverse behaviour of the reservoir near the injection well in geothermal applications.



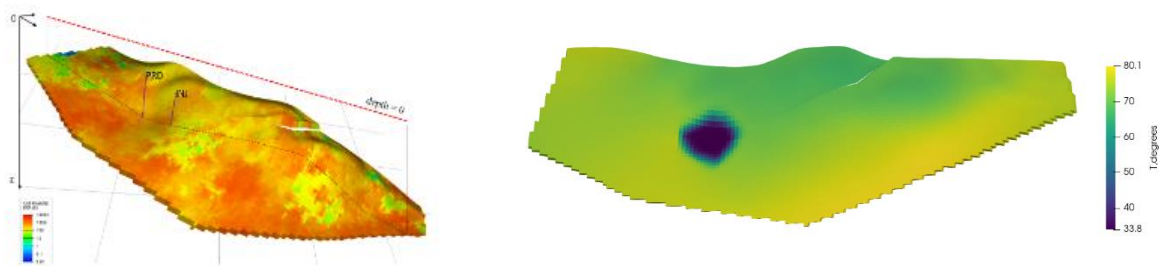
**Figure 1** The setup for uniaxial thermoporoelastic consolidation test (Gao and Ghassemi, 2020) (left) and vertical displacement over time at three points in space with semi-analytical solution method and THM simulation with open-DARTS.

## Geomechanical proxy model

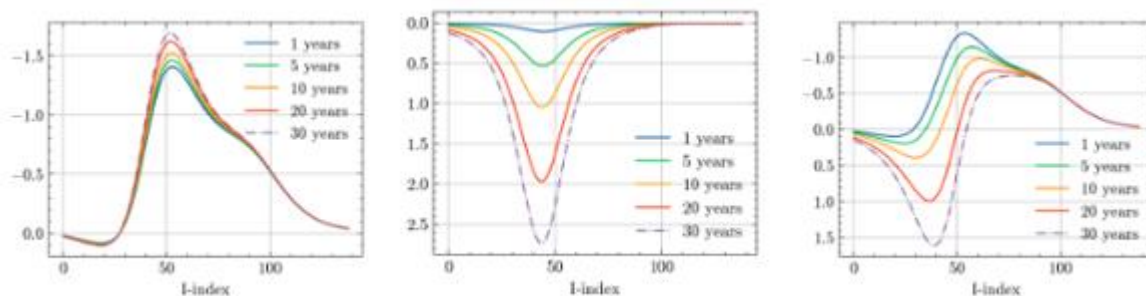
The fully-coupled THM simulation is generally computationally expensive, and it is also challenging to build geomechanical models, especially with multiple faults. For these purposes, we propose an alternative model for an approximate geomechanical state evaluation based on one-way flow coupling. While this model cannot provide an accurate response for complex heterogeneous reservoirs, it can still be a useful and computationally cheap approximation of reservoir response when calibrated to an accurate THM modelling and real observations.

The geomechanical proxy model is based on the nucleus of strain method and assumes homogeneous geomechanical properties of the reservoir rock and linear elasticity. The inputs are cell geometries, pressure and temperature changes in each cell, which can be computed with a reservoir simulator, in our case open-DARTS. Initially implemented for a geometry with rectangular prism cells in isothermal assumptions (Barbosa et al. 2022), it was extended to account for rock thermoelastic response and more complex meshes (Saifullin et al. 2024). This approach was implemented in C++ with parallelization for higher performance and with Python interface allowing easy in-memory link with open-DARTS reservoir simulator.

Although the model allows setting heterogeneous porosity and permeability, it assumes homogeneous rock geomechanical properties due to the analytical solution behind the approach. One of the benefits of this model is that it is not necessary to extend the computational mesh, which is usually the case for THM models. We have applied this geomechanical proxy model to the Brugge dataset (following the same geometry and permeability) with a geothermal doublet described in Saifullin et al. (2024). The permeability and temperature distribution after 30 years are shown in Figure 2, and corresponding displacements shown in Figure 3, which demonstrate different time-scale of pressure and temperature effect.



**Figure 2** The permeability for Brugge dataset (left, taken from Saifullin et al. (2024)) and the temperature distribution at 30 years (right).



**Figure 3** Vertical displacements (in meters) at the surface along the line shown in Figure 1a, computed by only pressure changes (left), only temperature changes (middle) and both (right), taken from Saifullin et al. (2024).

## Fault stability

Given the initial reservoir stresses, and stresses change at a particular time, one can easily compute normal ( $\sigma_n$ ) shear ( $\tau$ ) stresses at the fault plane. In our study, we use Mohr-Coulomb fault slip criteria:

$$SC = C + \tau - \mu(\sigma_n - p),$$

Where  $C$  is the cohesion, which is generally assumed to be zero,  $\mu$  is the friction coefficient of the fault, and  $p$  is the reservoir pore pressure.

Note, that this criteria for slip does not necessarily mean that a seismic event (rapid fault movement) will occur as slow fault aseismic slip can also take place. One of the useful parameters in fault stability analysis is the fault slip potential:

$$FSP = \frac{\tau}{\sigma_n - p},$$

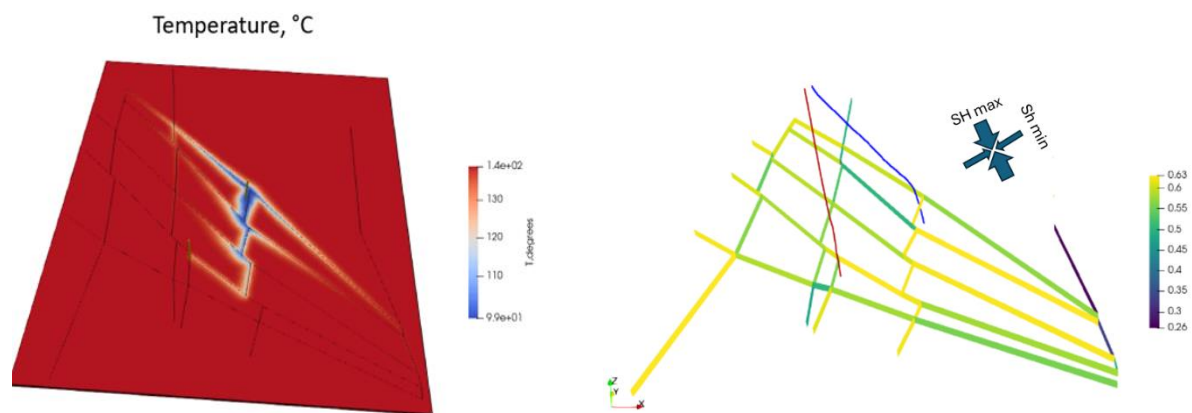
which indicates the potential of a fault to (a)seismic slip in the dimension of the friction coefficient.

### Fault dominated flow

In the case of low rock matrix permeability, the flow can be conducted by faults (or a fracture network) which is often the case in carbonates. Wells, therefore, are drilled into the faults to make use of the permeability in the (near) fault damage zone for fluid flow, but at the same time increases seismicity risk and is therefore generally better avoided..

From a numerical modelling perspective, the incorporation of flow in faults is introduced in our study through the use of a Discrete Fracture Model (DFM). This model can impose meshing challenges, especially in 3D cases. This could be circumvented by using the Embedded DFM which supports independent meshing of matrix and faults/fractures. This approach simplifies the model development, but it requires a very high resolution in the vicinity of the fault to properly account for the stress intensity around the faults (Novikov et al. 2025). In our approach, faults are approximated as a planar surface, and the fault permeability is computed using the power law from a given aperture.

The same geomechanical proxy model was applied to a fracture-dominated geothermal reservoir with vertical faults inspired by VITO geothermal project (Kinscher et al. 2023). The principal horizontal stresses are 83 MPa and 49 MPa correspondingly leading to a strike-slip regime. The temperature distribution from the numerical simulation is shown in Figure 4 (left). Faults, experiencing slip conditions according to the simulation, are marked red in Figure 4 (right), where the injection well is indicated by the dark blue line and the production well by the red line.



**Figure 4** Numerical simulation results of a fracture-dominated reservoir: the temperature distribution at 30 years (left), faults slip condition and wells (right).

Faults can be categorized by aforementioned FSP value into next groups:

- $FSP \geq 0.7$  – a fault is most likely unstable
- $0.5 < FSP < 0.7$  – a fault is possibly unstable
- $0.2 < FSP < 0.5$  – a fault is probably stable
- $FSP \leq 0.2$  – a fault is most likely stable

## Conclusions

The developed geomechanical proxy model was applied to geothermal reservoirs with either matrix-dominated or fault-dominated flow to evaluate the geomechanical state of the field, including the fault slip potential. It can further be used for a fault reactivation study within a particular set of model parameters, such as permeability distribution, geomechanical properties, fault dip angle, initial stresses, juxtaposition, well locations and various flow regimes. One of the interesting applications could be a combination of the geomechanical proxy and the THM models in order to find a balance between accuracy and performance.

Both thermoelastic and poroelastic rock responses are important in the case of geothermal reservoirs, although they have different propagation speeds and distances. The pressure propagation is faster and becomes stationary as well flow rates are maintained constant. The temperature plume expands more slowly and exhibits a transient effect on fault stability during the geothermal energy production. In case of the fracture dominated reservoirs, the temperature plume is also clearly constrained to and following the fracture network, which emphasizes the physical cause of the increased seismic potential of these geothermal systems.

## Acknowledgments (Optional)

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