THERMO-HYDRO-MECHANICAL SIMULATION OF GEOTHERMAL RESERVOIR STIMULATION

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Abstract. *In general terms, induced seismicity occurs when the isotropically effective stress reduction, due to the fluid pressure increase caused by fluid injection, is high enough to produce failure conditions. The objective of the simulation is to test the conjecture that cold water injection produces mechanical instability not only due to hydraulic effects, but also due to coupled thermal effects. Hydro mechanical (HM) and thermo hydro mechanical (THM) numerical simulations have been performed on a very simplified geometry of a horizontal fracture in order to analyze the processes involved in geothermal reservoir stimulation. The results confirm that indeed THM effective stresses are consistently more unstable (closer to a hypothetical yield surface) than HM effective stresses.*

1 INTRODUCTION

Deep hot rocks represent a source of renewable energy. Geothermal energy production can be simply achieved by drilling two wells into a hot deep rock, injecting cold water into one of them and recovering hot water/steam from the other one. This enables to produce electricity and/or heat.

To improve the economic efficiency of the heat exchange, high permeability rock is necessary. Generally, naturally fractured hot rock are intercepted by the wells and their permeability is improved by hydraulic stimulation, obtaining “Enhanced Geothermal Systems” (EGS). In fact, water injection produces overpressure that reduces the effective stresses. If failure conditions are reached, slip occurs, leading to fracture opening due to dilatancy. These processes trigger microseismic events, that should end when injection stop. Nevertheless, it has been observed that microseismic events are still induced once injection is stopped. Parotidis *et al.*[1] assumed that pore-pressure diffusion is the main triggering mechanism for these post-injection events. However, the fact that the largest seismic events can occur after the end of injection, like occurred in Basel (Switzerland)[2], cannot be explained by pressure diffusion alone, because its magnitude decreases with time.

Actually, both at Basel and Soultz[3], the injected water was cold. The temperature contrast between the reservoir (190 ºC at 5000 m deep)[4] and the injected water (at atmospheric conditions at surface) was large. This produces an additional reduction in effective stresses due to thermal strain[5,6] that enhances the seismic potential. Hence, coupled thermo-hydro-mechanical analyses are needed to fully understand the process involved in geothermal reservoir stimulation.

To study the effect of the cooling front caused by cold water injection on thermoelastic strain, coupled hydro-mechanical (HM) and thermo-hydro-mechanical (THM) numerical simulations are performed, simulating water injection into a simplified geometry.

2 PROBLEM SET-UP

The geometry taken into account considers a horizontal 1 m-thick fractured zone underlain and overlaid by a 250 m-thick low-permeability matrix. The model extends laterally 2000 m and is axisymmetric around the vertical well axis, simulating a 2D vertical section of the formation. The top of the fracture filling is located at a depth of 4250 m.

The fracture filling is considered like a continuous porous medium, with intrinsic permeability k=10^{-13} m^2 and porosity ϕ=0.5; the low permeability matrix has intrinsic permeability k=10^{-18} m^2 and porosity ϕ=0.01. A linear elastic constitutive model is assumed with a Young's modulus of E=100 MPa for the fracture filling and of E=10000 MPa for the matrix. Poisson's ratio is assumed to be ν=0.3 for both materials.

Initial conditions correspond to hydrostatic pressure, uniform temperature gradient and lithostatic normal stress. The stress regime is considered axisymmetric and the vertical stress is assumed greater than the horizontal stress with $\sigma_h' = 0.75\sigma_v'$.

A constant pressure boundary condition of 40 MPa, which corresponds to the hydrostatic pressure at the top of the model, is imposed at the top of the outer boundary. An overburden equal to 92 MPa, which corresponds to the lithostatic vertical stress, is imposed at the upper boundary. A mechanical condition of no displacement perpendicular to the boundary is imposed in the other boundaries. The injection flow rate is of 3 kg/s and is uniformly distributed along the contact between the well, with a radius of 0.5 m, and the fracture filling. Water injection lasts for 10 days.

Additionally, thermal conditions are imposed for the thermo-hydro-mechanical model: a temperature of 140 ºC is imposed at the top of the outer boundary, which corresponds to a surface temperature of 5 ºC and a geothermal gradient of 34 ºC/km. Water is injected at 60 ºC, which is a much lower temperature than that of the fracture.

A structured mesh with 8925 quadrilateral elements is used. The mesh is refined close to the injection well, in the fracture filling and close to it. Simulations are performed using the finite element numerical code CODE_BRIGHT[7,8].

3 RESULTS

Water injection in a porous or fractured medium produces an overpressure that reduces the effective stresses, which tends to open the fracture. Furthermore, if water is injected colder than the formation, the decrease in temperature causes two additional hydro-mechanical effects: increase in fluid viscosity and thermal contraction. The temperature increase in liquid viscosity causes a decrease in hydraulic conductivity. Thus, injection of cold water produces a larger overpressure than injection of warm water.

In the THM simulation, the cooling front propagates within the first 20 m of the fracture in the longitudinal direction and penetrates 1 m in the matrix in the transverse direction after 10 days of cold water injection. Thus, two slopes can be observed when plotting pressure as a function of distance from the well (Fig. 1): in the first 20 meters, affected by the cold front, the pressure curve displays a greater slope than in the rest of the fractured zone affected by fluid injection.

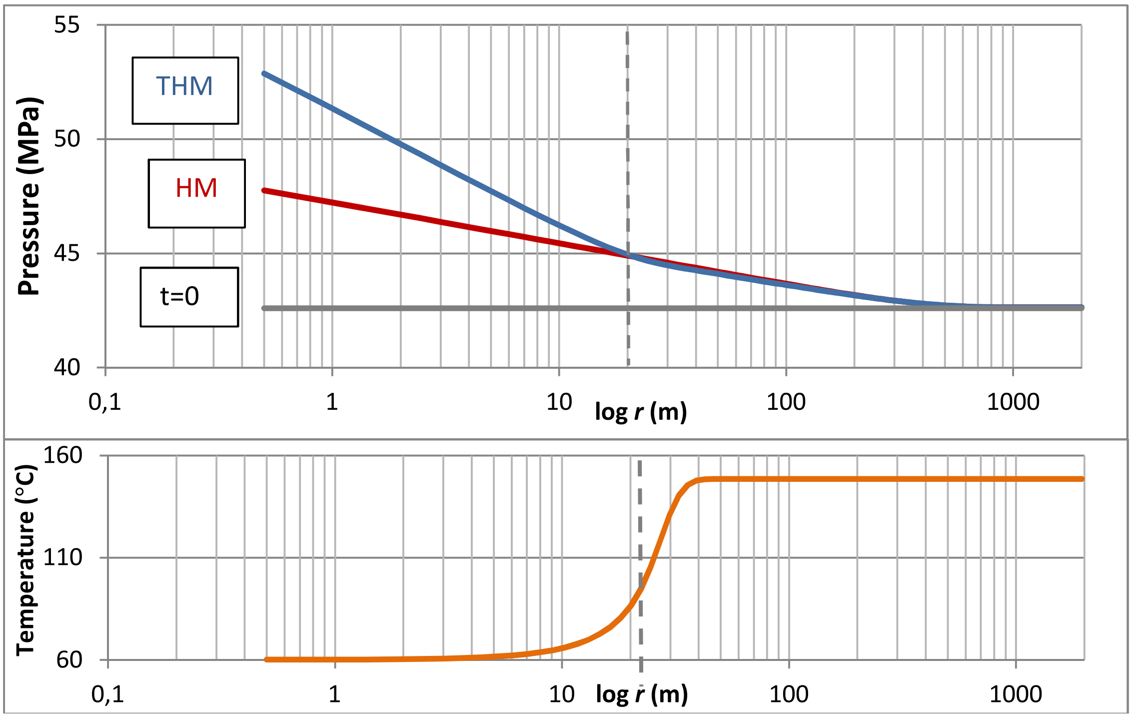

Figure 1. Pressure and temperature inside the fracture filling vs distance from the injection well after 10 days of injection.

Regarding stresses and strains, the cooling front causes thermal contractions of the rock. The effect of this contraction is non-trivial. While the contraction of the fracture filling tends to close it (competing against the expansion caused by overpressure), the contraction of the matrix that is cooled tends to open the fractured zone. The magnitude of the thermal effect is proportional to the temperature drop and to the rock stiffness.

In the studied case, with a fracture filling having E=100 MPa, the thermal contraction of the fracture filling partly compensates the additional expansion caused by the greater overpressure. As a result, inside the fracture, stability is comparable to that of the isothermal case (Table1). Fractured zone expansion causes mechanical contraction of the matrix. Furthermore the matrix affected by the temperature decrease undergoes an additional contraction, opening the fractured zone even more (Fig. 2).

This behavior results in a significant reduction of the stability at the fracture-matrix contact when accounting for cold water injection (Table 1).

Table 1: Mobilized friction angle after 10 days of injection of water in thermal equilibrium with the fracture (HM) and cold water (THM).

Mobilized friction angle	HM	THM
fracture-matrix contact	8.0	11.7
inside fracture	7.9	7.8

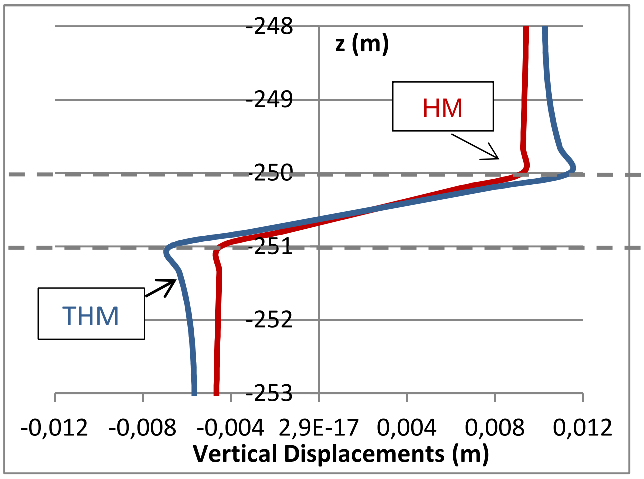

Figure 2: Vertical displacements vs depth for a section placed 3 m away from the injection well - detail of the 2 m above and below the fractured zone (placed between the dashed lines).

4 CONCLUSIONS

The numerical simulations show the influence of thermal effects in the processes of deformation involved in the geothermal hydraulic stimulations. Cold water injection produces a higher overpressure than warm water injection. Thus, a greater effective stress reduction and a larger fracture opening tendency occur. However, cold temperature causes thermal strains of the rock: contraction of the fracture filling tends to compensate hydraulic expansion; but cooling of the matrix close to the fracture acts opening the fracture. These opposing trends lead to more unstable conditions at the fracture edges. Therefore, induced seismicity is likely to be triggered when injecting cold water.

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