Fracture instability caused by cold water injection

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1. Introduction

Deep fluid injection produces fluid overpressure that perturbs the *in situ* stress state. If effective stress reduction is high enough to reach failure conditions, slip occurs and fractures open due to dilatancy, inducing microseismic events.

In enhanced geothermal stimulation, the temperature contrast between the deep hot reservoir and the injected water is very large. This produces an additional reduction in effective stresses due to thermal stresses (Segall and Fitzgerald, 1998; Ghassemi *et al.*, 2007) that enhances the mechanical instability and that can not be neglected.

To better understand the effect of the thermal stress on the rock stability, numerical simulations of thermo-hydro-mechanical coupling are performed on a very simplified geometry. We present here the comparison between isothermal water injection and cold water injection into a fractured medium.

2. Model Set Up

A fractured zone with horizontal orientation is treated as a continuous porous medium. We use a linear elastic constitutive model. Water is injected in it through a vertical well. Water injection lasts for 10 days with a constant flow rate of 3 kg/s. Water temperature is in equilibrium with the medium (150°C) for the isothermal water injection simulation and is injected at 60°C for the cold water injection simulation.

Simulations are performed using the finite element numerical code CODE_BRIGHT (Olivella *et al.*, 1996).

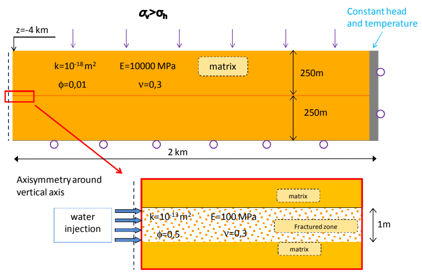

Fig. 1 – Model geometry and boundary conditions.

3. THM coupling

Hooke's law (linear thermoporoelasticity)

$$\Delta\boldsymbol{\sigma}' = K\varepsilon_v \mathbf{I} + 2G\left(\boldsymbol{\varepsilon} - \frac{\varepsilon_v}{3}\mathbf{I} - \frac{1+\nu}{1-2\nu}\alpha_T \Delta T \mathbf{I}\right)$$

$\boldsymbol{\sigma}'$=Effective stress tensor; $\boldsymbol{\varepsilon}$= Elastic strain; ε_v= Volumetric strain ; K=Bulk modulus=$E/(3(1\text{-}2\nu))$; G=Shear modulus=$E/(2(1+\nu))$; E= Young's modulus; ν=Poisson ratio; α_T=linear thermal expansion coefficient; T=temperature

4. Results

Temperature affects the liquid overpressure caused by water injection (Fig. 2). This results in a greater effective stress reduction and in a larger deformation of the fracture filling. However, cold water also contracts the rock (Fig. 3) and changes the stress field (Fig. 4). The magnitude of the thermal effect is proportional to the temperature drop and to the rock stiffness, so the effective stress reduction is greater in the portion of the cooled matrix than in the fracture filling, where the hydraulic effect dominates the thermal effect (Fig. 6- Volumetric strains). Furthermore, thermal contraction in the matrix reduces horizontal stresses more than vertical stresses (Fig. 4).

The initial stress regime controls the stability. In the case of $\sigma_v > \sigma_h$, warm water injection shifts the Mohr's circle to the left, but it reduces its size due to lateral confinement, so the instability is partly compensated. Cold water injection induce a significant reduction of the stability not due to the greater overpressure, but to the thermal processes: at the fracture-matrix contact the Mohr's circle becomes dramatically greater in size because thermal contraction reduces horizontal stresses much more than vertical stresses (Fig. 5).

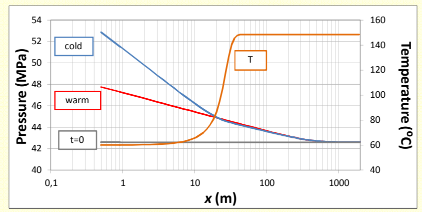

Fig. 2 – Liquid pressure and temperature vs distance from injection well in the fracture filling after 10 days of warm/cold water injection. Overpressure results greater when accounting for cold water because the temperature drop reduces the hydraulic conductivity. Note the change in the slope of the overpressure coinciding with the cooling front in the cold water injection simulation. Note also the difference in hydraulic and thermal response time.

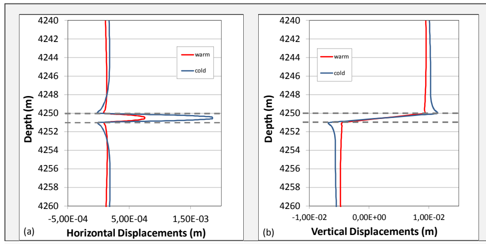

Fig. 3 – Horizontal Displacements (a) and Vertical Displacements (b) vs depth after 10 days of warm/cold water injection. In the fracture filling (dashed lines) hydraulic expansion displaces it away from the well in the horizontal direction (positive values) and push it upwards in its upper side (positive vertical displacements) and downwards in its lower side (negative vertical displacements), which tends to open it. The zone of the matrix close to the fractured zone (two meters above and below) is affected by thermal contraction that reduces the horizontal and the vertical displacements. Note that the deformation perpendicular to the fracture filling is an order of magnitude larger than in its direction because of the lateral confinement.

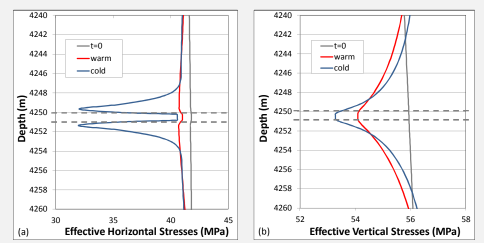

Fig. 4 – Horizontal Effective Stresses (a) and Vertical Effective Stresses (b) vs depth after 10 days of warm/cold water injection. Effective stresses decrease as water pressure increases. Since confinement is largest in the direction of the fractured zone, the decrease in vertical effective stress, caused by isothermal fluid injection, is larger than in horizontal effective stress. When accounting for cold water injection, thermal stresses are sensitive to the rock stiffness, thus they are greater in the matrix. However, as thermal contraction of the matrix acts reducing vertical displacements, the reduction in vertical effective stresses in the matrix results smaller than in the fracture filling. This results in a horizontal stress drop significantly greater than the vertical one .

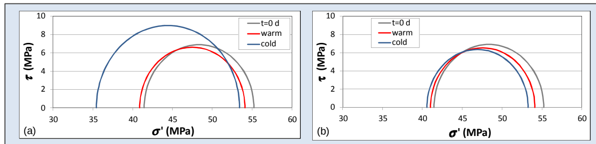

Fig. 5 - Stress state at the contact with the matrix (a) and inside the fractured zone (b) at 3 m away from the injection well. After 10 days of cold water injection, stability is significantly reduced at the fracture-matrix contact, while inside the fracture it is comparable to that of the isothermal case.

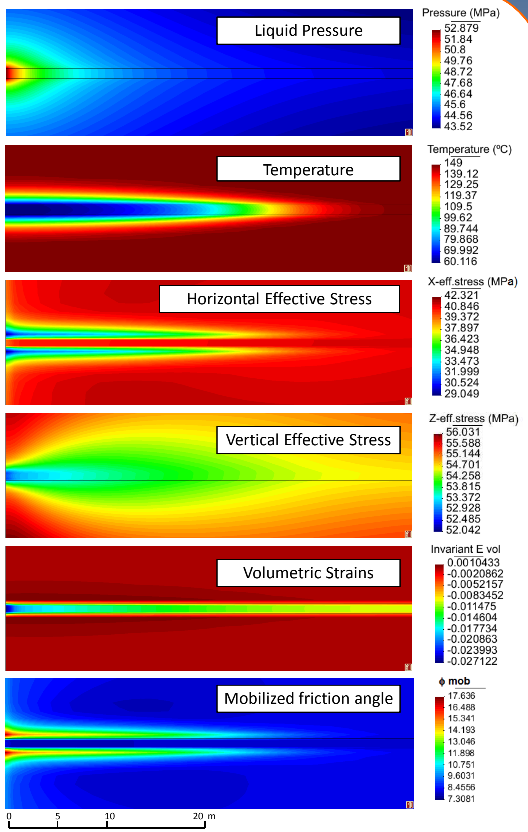

Fig. 6 - Effects of 10 days of cold water injection. Detail of the area near the fractured zone. Overpressure propagates much further in the fractured zone than in the matrix due to the permeability contrast between them. Temperature drop affects the first 20 m of the fracture filling and penetrates 3 m in the matrix. Horizontal effective stresses are very affected by thermal effects at the fracture-matrix contact. Vertical effective stresses are more influenced by overpressure than by temperature drop. Volumetric strains results affected by overpressure in the fractured filling, that expands (negative values), and by temperature decrease in the matrix, that contracts (positive values). Variations of the horizontal effective stresses control the mobilized friction angle, that increases at the fracture edge.

5. Conclusions

The numerical simulations show the influence of thermal effects in the processes of deformation involved in geothermal stimulations. Cold water injection can lead to a more unstable situation at the fracture edge, which may trigger microseismic events.

Stability is controlled by the problem geometry and the initial stress state. Furthermore, the stress changes induced by pressure and temperature variations are very sensitive to problem settings (stiffness and thickness of the fractured zone and boundary conditions).

The differences in hydraulic, mechanical and thermal response times makes it clear that thermal effects will last long after injection stops. The zone where stability is improved by the hydraulic effect, are likely to become unstable once injection stops.

References

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