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# Comparison of two approaches for modelling fracture opening due to cold water injection in geothermal reservoir

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Heat and electricity production from deep hot reservoirs through hydrothermal or petrothermal system requires to inject cold fluid in a naturally or artificially fractured medium. Cold water injection in a hot reservoirs causes thermo-hydro-mechanical (THM) coupled processes that may have several influences on operations and long term production [1]. Cold water has a higher viscosity, which means injection can become difficult due to higher flow impedance, while thermal diffusion in the rock matrix causes shrinkage and thus an increasing fracture aperture over time that can lead to flow channeling and a reduction of operation time. A deep understanding of the contribution of coupled THM processes to injection into fractured media is thus important to predict the long-term performance of a geothermal power plant. In this study, coupled THM processes in a single fracture are numerically investigated with two different approaches to model the discontinuity.

The first numerical approach proposes modelling an implicit fracture in a fracture zone using solid elements (Fig.1 (a)). The impact of the fracture is introduced by means of a stress dependent fracture aperture, which in turn determines the fracture transmissivity. This function allows recovery of the opening, and thus the model replicates opening and closure of the fracture. Then, an equivalent continuum permeability $k_f$ [m$^2$] is obtained as follows:

$$k_f = \frac{(b_{el})^3}{12} s_f = \frac{(b_r + b_{max} \exp{(\alpha\sigma')})^3}{12} s_f \tag{1}$$

where $b_{el}$ [m] is the elastic opening, $b_r$ and $b_{max}$ [m] are the residual and maximum apertures, respectively, $\alpha$ is the stress dependency coefficient; $\sigma_n'$ [Pa] is effective normal stress, and $s_f$ [m]the fracture spacing. The combination of the continuum elements to model an implicit fracture embedded in a fracture zone and the evolving permeability has been used successfully used to model elastic opening in volcanic rock [2] and granodiorite rock [3, 4].

In the second approach, zero-thickness interface elements are used to explicitly model the opening of an existing fracture (Fig.1 (b)), following the work by Liaudat et al. [5]. A constitutive law that is capable of describing the fracture initiation, propagation, closing and opening is implemented in this approach, considering heat transfer in the discontinuity. In this approach, the cubic law is used to estimate the longitudinal transmissivity $t^l$ [m$^3$] as a function of the normal fracture aperture:

$$t^l = \frac{r_n^3}{12} + t_0^l \tag{2}$$

where $r_n$ [m] is the normal separation and $t_0^l$ [m$^3$] is a constant value which makes it possible to assign an initial longitudinal transmissivity even if the fracture is mechanically closed.


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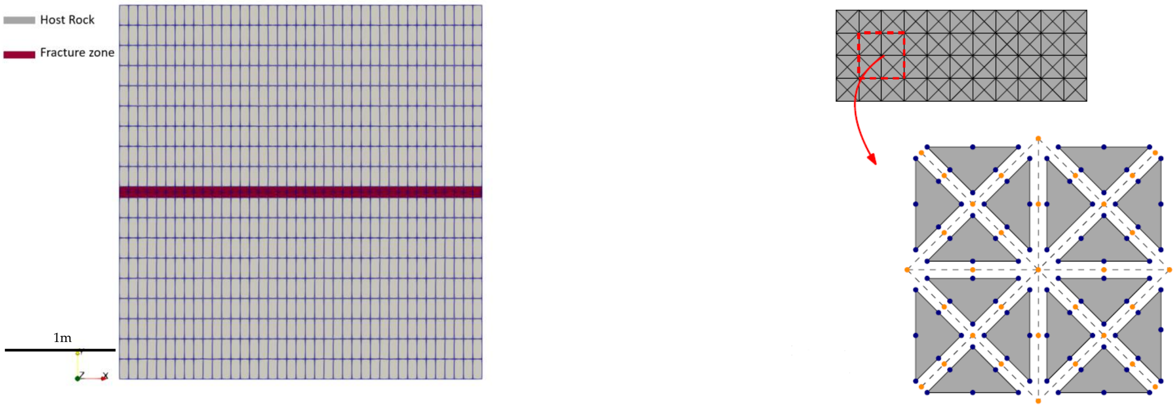
In both approaches, the simulation of cold water injection requires to consider the heat and hydraulic flows in the fracture alongside mechanical behaviour, since changes in pore water pressure and temperature influence the fracture aperture, thus modifying the fracture transmissivity.




(a) via an equivalent continuum (b) via zero-thickness interface elements

**Figure 1: Two approaches for modelling discontinuity**

In order to compare both approaches, a simple synthetic model is studied. The model with its boundary and initial conditions are shown in Fig.2. Water with a temperature of 20 °C and pressure varying from 4 MPa – 10 MPa is injected at the centering point of the fracture. Figure 3 shows the injection pressure profile. Fracture permeability evolution is compared in Fig.4, which shows the two different methods capture different characteristics of the natural fracture behaviour. In the continuum method, the fracture is modelled as a continuum element, thus any pressure or stress change will result in corresponding changes in the fracture permeability, which is reflected in Fig.4 showing that the permeability changes with the injection pressure changing, In contrast, in the interface element, Fig.4 shows only when the injection pressure reaches 10 MPa, the permeability increases sharply from the initial value to the peak value. This is because penalty method is used to allow the small overlapping of the two faces of the discontinuity, thus keeping negligible permeability variation, before it opens. The result in Fig.4 also illustrates the effect of thermal stress on the fracture opening, considering the total vertical stress is 10 MPa while injection pressure is below or equal to 10 MPa.

In conclusion, though the peak permeability predicted from two methods are consistent, both around 1.5 x $10^{-12}$ D, the behaviour before fracture opens in these two approaches are quite different. For the interface method, permeability variations keep negligible before fracture opens, while for the continuum method, permeability changes with corresponding pressure or stress changes without dependence on the opening of the fracture.


(a) fluid/heat flow conditions (b) mechanical conditions

**Figure 2: Synthetic model and its boundary and initial conditions**

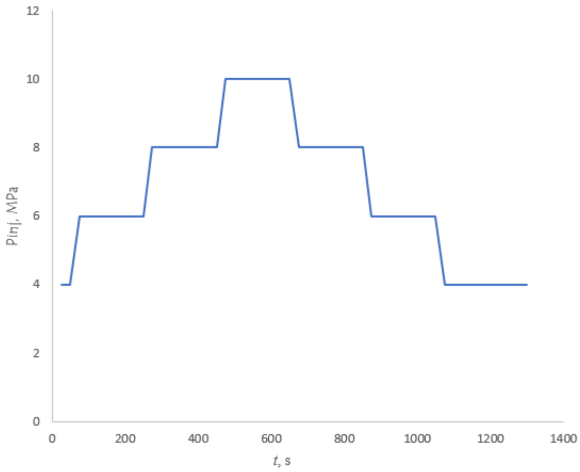



**Figure 3: Injection protocol**

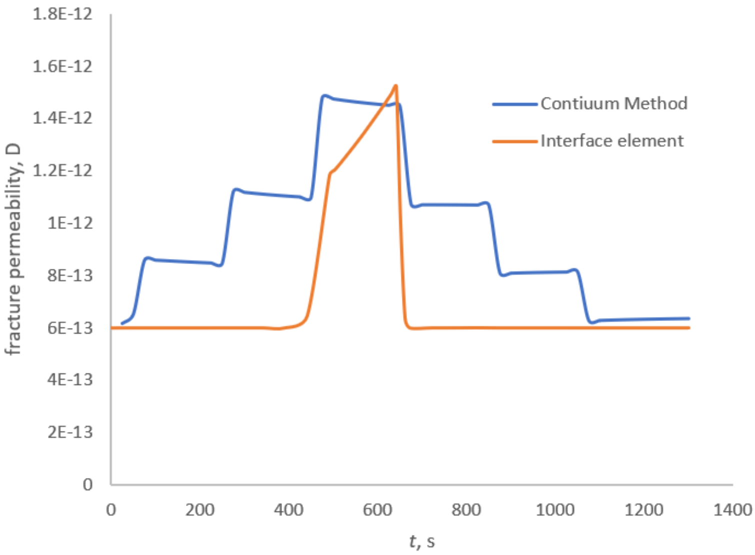



**Fig.4 Comparison of permeability evolution predicted by two approaches**

## Contributor statement

Wen Luo, Josselin Ouf and Kavan Khaledi: conceptualization, investigation, writing-original draft, Phillip Vardon, Reza Jalali, Anne-Catherine Dieudonné, Joaquín Liaudat, Florian Amann: conceptualization, supervision, writing-review & editing.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## References


[1] Luo, W., Kottsova, A., Vardon, P.J., Dieudonné, A.-C., & Brehme, M. (2023). Mechanisms causing injectivity decline and enhancement in geothermal projects. Renewable and Sustainable Energy Reviews, 185, 113623.

[2] Rinaldi, A.P., Rutqvist, J., Sonnenthal, E.L., & Cladouhos, T.T. (2015). Coupled THM modeling of hydroshearing stimulation in tight fractured volcanic rock. *Transport in Porous* Media, 108, 131-150.

[3] Rinaldi, A. P., & Rutqvist, J. (2019). Joint opening or hydroshearing? Analyzing a fracture zone stimulation at Fenton Hill. *Geothermics*, 77, 83-98.

[4] Yoo, H., Park, S., Xie, L., Kim, K.-I., Min, K.-B., Rutqvist, J., & Rinaldi, A. P. (2021). Hydro-mechanical modeling of the first and second hydraulic stimulations in a fractured geothermal reservoir in Pohang, South Korea. *Geothermics*, 89, 101982.

[5] Liaudat, J., Dieudonné, A.-C., & Vardon, P.J. (2023). Modelling gas fracturing in saturated clay samples using triple-node zero-thickness interface elements. *Computers and Geotechnics*, 154, 105128.