Long-term thermal performance of a borehole heat exchanger installed near an open fracture for a range of hydrogeological scenarios

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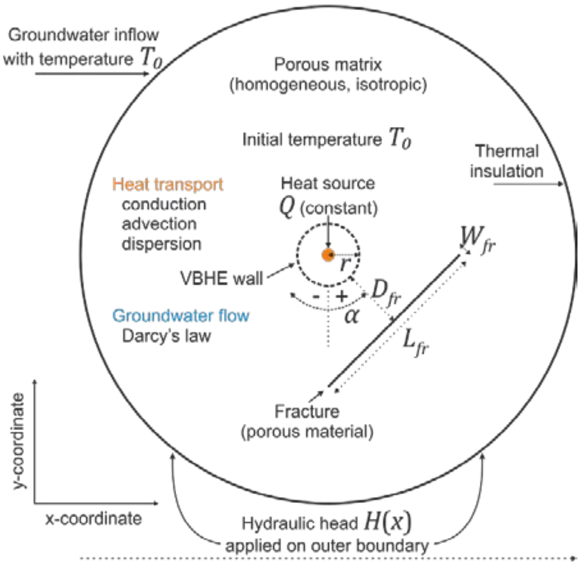
Aim and background

Vertical borehole heat exchangers (VBHEs) are frequently installed in heterogeneous and fractured media which may have groundwater flow (Dehkordi *et al.* 2015). However, currently used models for VBHE performance often assume homogeneous ground conditions. A single open fracture set in a 'matrix' of low hydraulic conductivity increases the apparent thermal conductivity of the ground, thereby improving the estimated thermal performance of VBHE and exacerbating downstream thermal impacts (Gehlin & Hellström 2003; Liebel *et al.* 2012; Dehkordi *et al.* 2015), even if the flowrate of groundwater in such a fracture is low. There is a need for systematic analysis of the effects of open fractures on the long-term performance of VBHEs for a wider range of hydrogeological conditions, including a high hydraulic conductivity in the matrix.

This study uses Monte Carlo (MC) analysis in a 2D numerical model to investigate a range of possible hydrogeological scenarios in which an open fracture may influence the long-term thermal performance of VBHEs. The study addresses the question: "to what extent can the presence of flow in a fracture change the long-term thermal performance of a VBHE, estimated assuming a homogenous host rock?"

Methods

COMSOL Multiphysics was used to set up 2D numerical model (hereafter termed nMILSfr) of a VBHE in an aquifer with a single fracture (Figure 1). Typical hydrogeological and thermal properties for sandstone were set for the matrix material. The Moving Finite Line Source (MILS) analytical solution (Carslaw & Jaeger 1959) was used to validate the nMILSfr model without a fracture. The hydraulic conductivity of the matrix material, K, was calculated using Darcy's Law with a constant hydraulic gradient, B, in the x direction (for a homogenous matrix) to achieve a range of target groundwater velocities in a homogenous matrix. The maximum adjusted value of K was 5.79E-4 m s^{-1}.



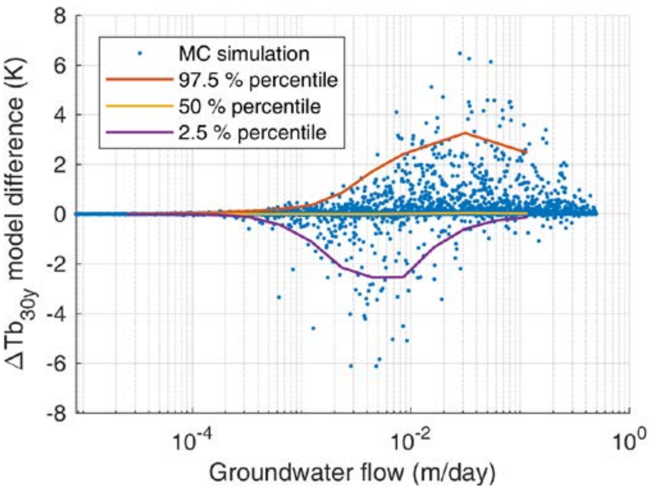
Q – Constant heat source 50 W/m, with radius = 0.02m
Circle model domain of 400m radius
r – radius of vertical borehole heat exchanger (VBHE), 0.05 m
D_{fr} – perpendicular distance from fracture to the VBHE wall, range for MC sampling**: 0.5 m to 40 m**
α - fracture rotation angle relative to x axis direction around VBHE, MC range: **-90 ° to 90 °**
L_{fr} – fracture length, MC range: **1 to 200 m**
W_{fr} – fracture thickness, MC range: **0.1 to 25 mm**
H(x) – fixed hydraulic head at domain boundary based on hydraulic gradient of 0.01 m m^{-1}
Hydraulic conductivity of matrix based on target groundwater flow in homogeneous model, MC range: **8.6E-6 to 0.5 m/day** (Uniformly distributed on a log scale)
Matrix dispersivity in x direction, ***aX***, MC range: **0 to 6 m** with ***aY*** = ***aX*** × 0.1
Re in fracture and matrix for all simulations is <10
Hydraulic conductivity ratio (fracture / matrix) has MC range of **10 to 1E6**
Porosity in matrix 30%, in fracture 60%

Figure 1: Conceptualisation of the nMILSfr model. Not to scale. The hydraulic head on the domain boundary is linearly dependent on the x coordinate, $H(x) = Bx$, where B is a constant hydraulic gradient in the x direction in the case of a homogenous matrix.

Latin hypercube sampling with uniform parameter distributions (see Figure 1 for parameter ranges) was used to generate 5000 MC simulations, which were analysed in MATLAB using the MC toolbox (MCAT) (Wagener & Kollat 2007) for parameter sensitivity analysis. The temperature change at VBHE wall after 30 years was estimated for each set of fracture parameters and for different groundwater flows and matrix dispersivities. An entirely homogenous aquifer (i.e. a matrix without a fracture) was also considered for comparison.

Results

Groundwater flow in the aquifer determines the uncertainty in the temperature at the VBHE wall due to the presence of a fracture (Figure 2). The range of this uncertainty increases with groundwater velocity in the matrix. For medium groundwater flow (between 0.001 m/day and 0.02 m/day) the estimated temperature at the VBHE wall with an uncharacterized single fracture present may be significantly lower than the value estimated assuming homogeneous geology. However, this cooling effect can be more than countered by the slowing of local matrix groundwater velocities (Figure 2, groundwater flow velocity 0.01 m/day to 0.1 m/day). The design of VBHE systems may benefit from an uncertainty analysis to determine useful field measurements and improve risk assessment.



Groundwater flow and matrix dispersivity for each simulation are the same in the two compared numerical models.
Percentiles are moving averages over 20% of data with 70% overlap.

Figure 2: Difference between numerical models with and without a fracture in terms of temperature change at the VBHE wall after 30 years of continuous operation (ΔTb_{30y}), over a range of matrix groundwater flow velocities with varying fracture parameters, sampled using the Monte Carlo (MC) approach.

Key message

Groundwater flow determines the range of uncertainty in the long-term thermal performance of a VBHE due to the presence of fractures. The influence of an open fracture on the thermal performance of a VBHE may be significantly beneficial or unfavorable. This depends on the effectiveness of the fracture in advecting heat and its ability to change groundwater flow velocities local to the VBHE.

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