Groundwater Flow in the Fractured System Surrounding a Nuclear Waste Repository

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Motivation

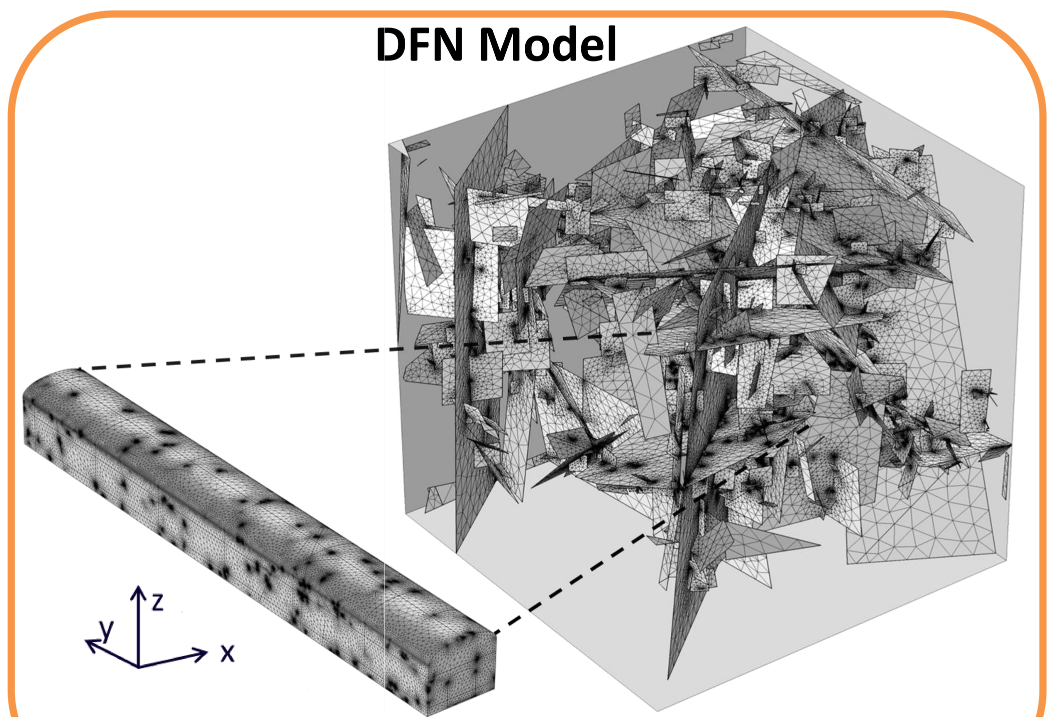
In deep geological repositories for nuclear waste, it is critical to have a clear understanding of groundwater flow at the interface between the storage vault and the fractured rock. Traditional approaches for modelling groundwater often consider both, the geological and engineered structures, as porous media domains [1]. However, there are cases where radionuclide transport in groundwater is controlled by discrete fractures. This work evaluates the influence of fractures in granitic rock on the flow and transport of radionuclides in a storage vault and its surroundings.

The model couples the groundwater flow and mass transport in the host-rock, which is simulated as a discrete fracture network (DFN), and in the vault, simulated as a porous medium. The radionuclide mass transport in the domain considers the effect of advection, diffusion, sorption and radioactive decay. The flow entering the vault and its relationship with the fractures orientation is investigated.

Model concepts

Geometry

DFN Model



Waste vault and fracture geometry and mesh (1,801,850 triangular elements and 1,963,025 tetrahedra) for the DFN model.

Governing equations

Groundwater flow

Porous media

$$\rho S \frac{\partial p_m}{\partial t} + \nabla \rho \left[-\frac{k}{\mu} (\nabla p_m + \rho g \nabla z) \right] = Q_m$$

$$u = -\frac{k}{\mu} (\nabla p_m + \rho g \nabla z)$$

Fractured media

$$d_f \frac{\partial}{\partial t} (\phi_f \rho_f) + \nabla_T (\rho q_f) = d_f Q_f$$

$$q_f = -\frac{k_f}{\mu} d_f (\nabla_T p_f + \rho g \nabla_T z)$$

Coupling term

$$Q_m = -\alpha (p_m - p_f)$$

$$Q_f = -\alpha (p_f - p_m)$$

$$\alpha = \frac{k}{\mu} \cdot \frac{1}{l}$$

Advection-diffusion

Porous media

$$(\phi + \rho_b k_{p,i}) \frac{\partial c_i}{\partial t} + (c_i - \rho_p c_{p,i}) \frac{\partial \phi}{\partial t} + u \nabla c_i = \nabla [(D_d + D_e) \nabla c_i] + J_{m,i}$$

Fractured media

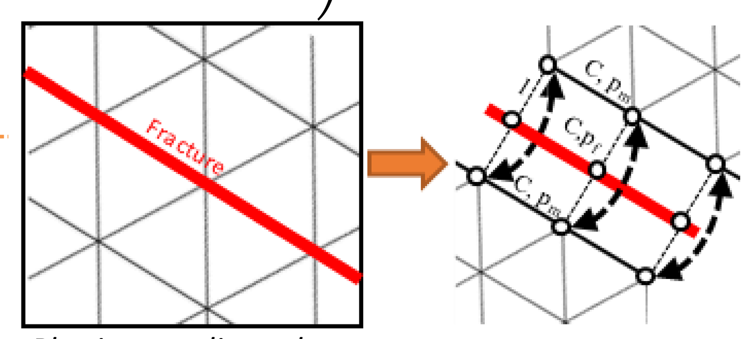
$$d_{fr} \left(\frac{\partial \rho_b c_{p,i}}{\partial t} + \frac{\partial \phi_f c_i}{\partial t} + \nabla_t (D_{e,i} \nabla_t c_i) + u \nabla_t c_i \right) = d_{fr} R_i + J_{f,i}$$

Coupling term

$$J_m = -\beta (c_m - c_f)$$

$$J_f = -\beta (c_f - c_m)$$

$$\beta = D_e \cdot \frac{1}{l}$$



Physics coupling scheme.

The host-rock is an impervious granitic rock crossed by several fractures of high permeability that concentrates most of the groundwater flow. A discrete fracture network of 14,250 fractures and its hydraulic properties based on geological data and a previous Hydro-DFN model [2] was imported to Comsol using an utility app.

A generic storage vault formed by a waste domain surrounded by bentonite is considered. The resolution of the grid is refined at the vault interface and its surroundings.

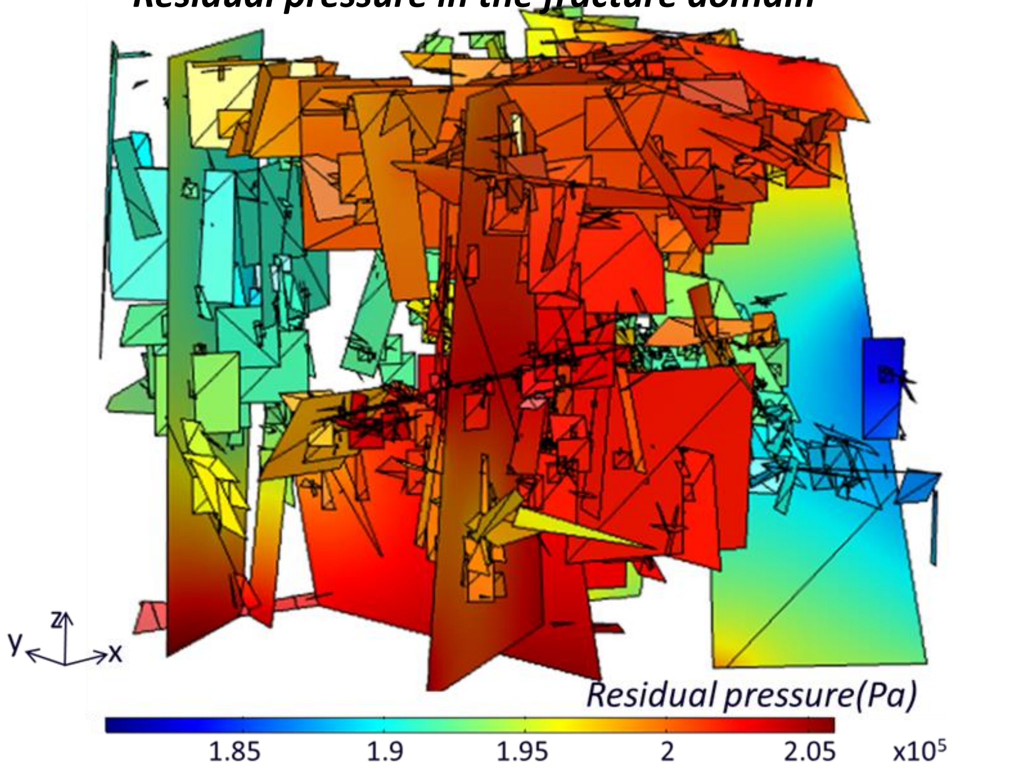
A steady-sate flow simulation is performed using hydrogeological boundary conditions from a regional model [2]. Water density and viscosity are 1000 kg/m^3 and 0.002 Pa·s respectively.

The steady state flow field is used as input for a transient transport simulation of 500k years. 4 chemical species are released from the vault: a conservative tracer and three radionuclides (Cl^{36}, Mo^{93} and Cs^{135}). In addition to the transport process the simulation includes the radioactive decay of the three radionuclides and the linear sorption of cesium.

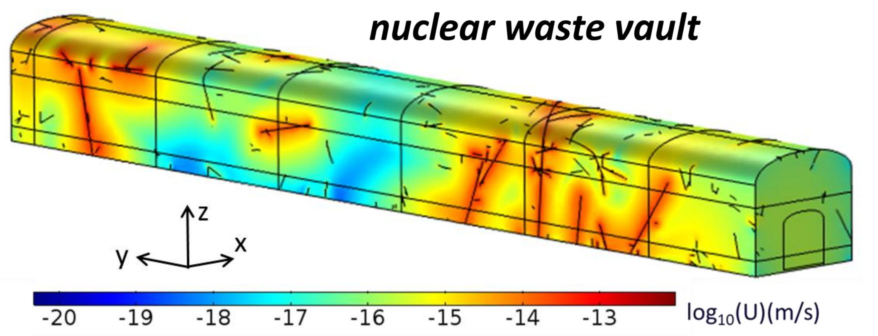
Results

Groundwater flow

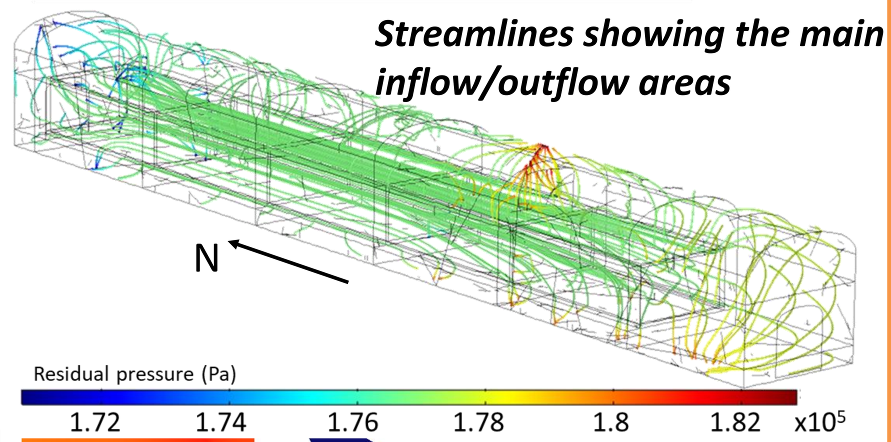
Residual pressure in the fracture domain



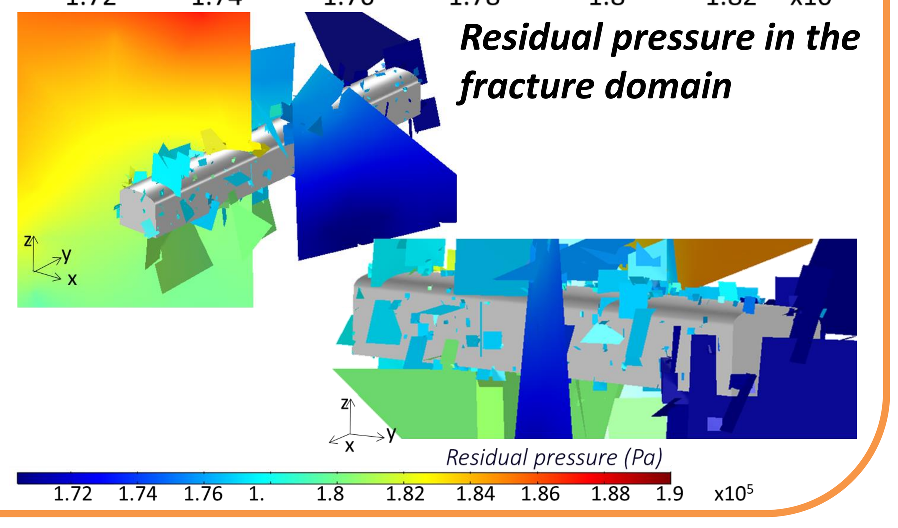
Darcy velocity module in the nuclear waste vault



Streamlines showing the main inflow/outflow areas



Residual pressure in the fracture domain

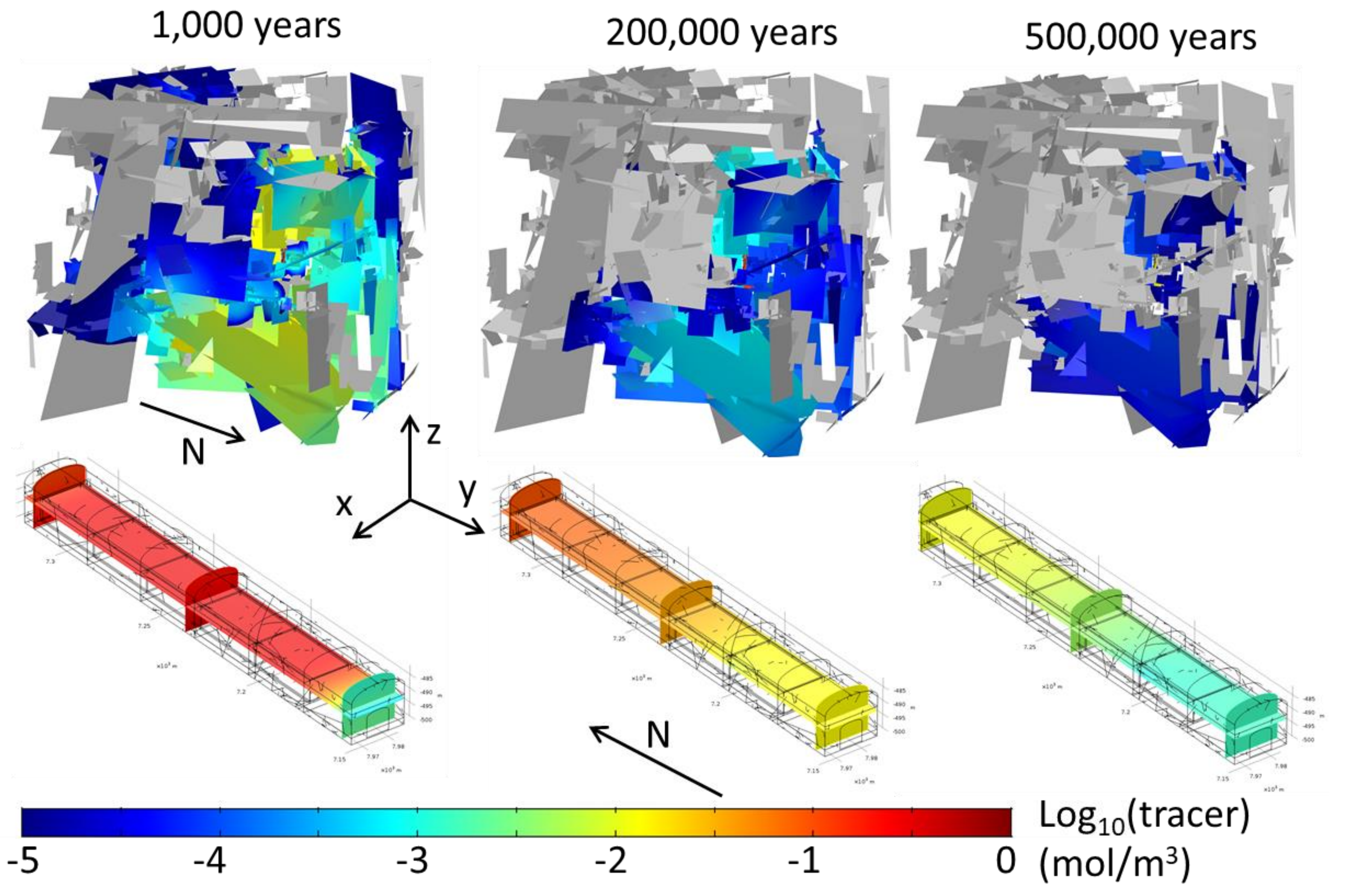


Groundwater enters through the top and bottom boundaries and flows from west to east. However, within the vault, water flows from south to north due to fracture connectivity.

Dead-end fractures intersecting the vault do not affect the groundwater flow field. However, they act as temporal buffers for the radionuclide transport.

Transport considering first order decay and linear sorption

Temporal evolution of a conservative tracer in the model

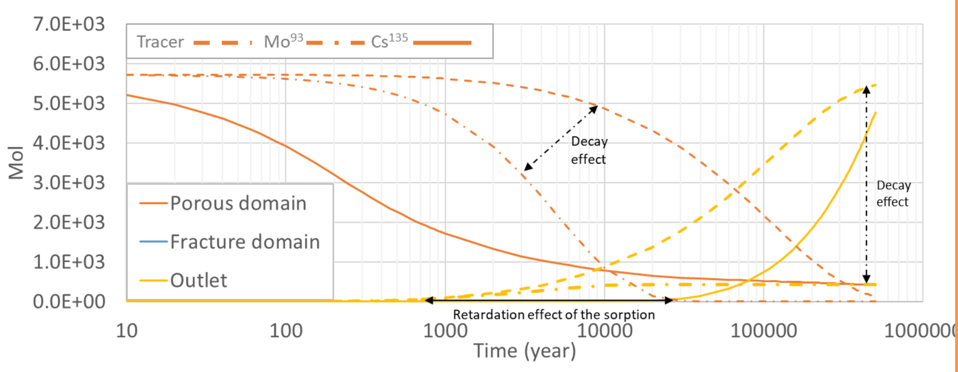


Mass balance at 500,000 y

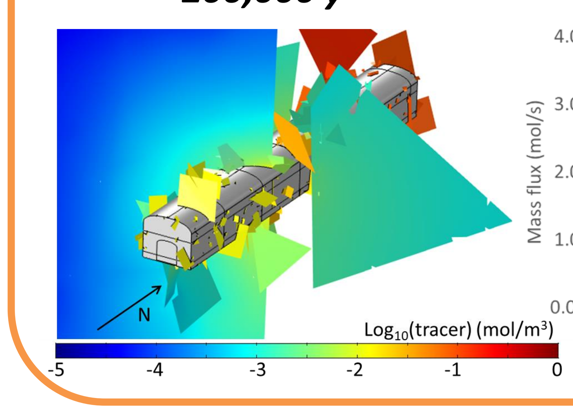
Specie	A	B	C
Tracer	5%	95%	0%
Cl^{36}	1%	77%	22%
Mo^{93}	0%	8%	92%
Cs^{153}	0/83%*	3%	14%

A= Model B = Outlet C = Decay
** Dissolved/Sorbed*

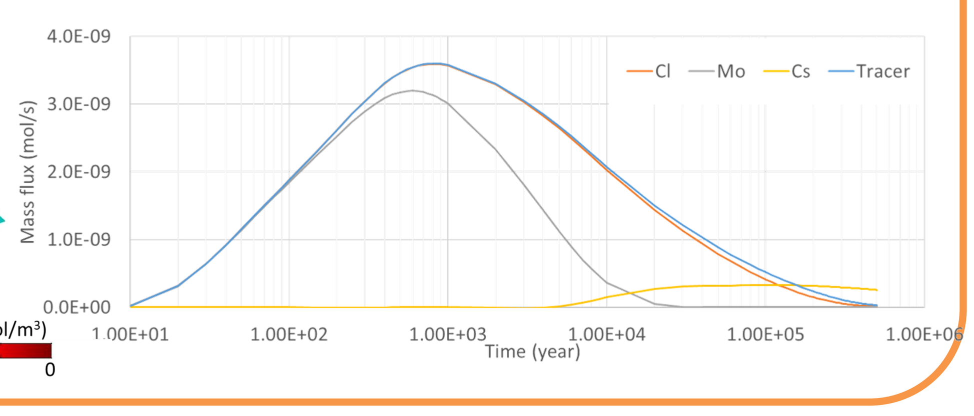
Temporal evolution of the radionuclides.



Tracer concentration at 200,000 y



Breakthrough curves at the vault/fracture interface



Concluding remarks

- The groundwater flow direction near the vault is controlled by the connectivity and orientation of the fractures rather than for the regional groundwater flow field.
- The residence time of the radionuclides in the fractures is smaller than in the vault.
- Dead-end fractures intersecting the vault can have a significant effect in the release of radionuclides although they do not affect the groundwater flow.
- The low half-life of the Mo^{93} reduces significantly the mass that leaves the vault.
- Sorption and decay reduce significantly the amount of Cs^{153} that leaves the vault.

References

[1] Abarca, E., Sampietro, D., Miret, M., 2016. Initial modelling of the near-field hydrogeology – Exploring the influence of host rock characteristics and barrier properties – Report for the safety evaluation SE-SFL. No. R-16-02. SKB , Svensk Kärnbränslehantering AB.

[2] Joyce S, Simpson T, Hartley L, Applegate D, Hoek J, Jackson P, Roberts D, Swan, D, Gylling B, Marsic N, Rhén I, 2010. Groundwater flow modelling of periods with temperate climate conditions - Laxemar. SKB R-09-24, Svensk Kärnbränslehantering AB.