Groundwater flow in the fractured system surrounding a nuclear waste repository

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Geometry & Hydraulic/Transport properties

- The model considers a generic nuclear waste vault imbedded in the centre of a Discrete fracture network formed by 7,200 fractures.

- The domain is a cube of 400 meters length.

- The waste vault is formed by two materials: An homogenised waste surrounded by a low permeable backfill.

- The FEM used in the simulations is formed by 1,801,850 triangular elements and 1,963,025 tetrahedra.

<table>
<thead>
<tr>
<th>Description</th>
<th>Material</th>
<th>K (m/s)</th>
<th>De (m²/s)</th>
<th>φ</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste domain</td>
<td>Homogenized</td>
<td>1.0⋅10⁻⁷</td>
<td>3.5⋅10⁻¹⁰</td>
<td>0.30</td>
<td>(SKB 2014)</td>
</tr>
<tr>
<td>BHA vault backfill</td>
<td>Bentonite</td>
<td>1.0⋅10⁻¹³</td>
<td>1.4⋅10⁻¹⁰</td>
<td>0.43</td>
<td>(SKB 2010)</td>
</tr>
</tbody>
</table>
The discrete fracture network (DFN) form part of a regional characterization of the host-rock that was generated using Connectflow (Hartley L and Holton D, 2003). The fracture network generated is characterized by heterogeneous hydraulic and transport properties such as transmissivity, storativity and aperture. The DFN is imported in Comsol using a custom utility app.
### Governing equations

#### Groundwater flow

\[
\begin{align*}
\rho S \frac{\partial p_m}{\partial t} + \nabla \rho \left[ -\frac{k}{\mu} (\nabla p_m + \rho g \nabla z) \right] &= Q_m \\
u &= -\frac{k}{\mu} (\nabla p_m + \rho g \nabla z) \\
\end{align*}
\]

\[
\begin{align*}
d_f \frac{\partial}{\partial t} \left( \phi_f \rho_f \right) + \nabla_T (\rho q_f) &= d_f Q_m \\
q_f &= -\frac{k_f}{\mu} d_f (\nabla_T p_f + \rho g \nabla_T z) \\
\end{align*}
\]

- The coupling between both equations is carried out by a source/sink term with the following form:

\[
\begin{align*}
Q_m &= -\alpha (p_m - p_f) \\
Q_f &= -\alpha (p_f - p_m)
\end{align*}
\]

where \( \alpha = \frac{k}{\mu} \cdot \frac{1}{l} \)

- \( \alpha \) is a parameter that evaluates the connection between the two domains (matrix and fracture).
- Groundwater flow is solved in steady state by imposing the fluid pressure coming from a regional hydro model in the external boundaries.
**Governing equations**

*Conservative transport*

The coupling between both domains is analogous to the flow coupling.

- Two transport equations:

  - **Porous media**
    \[
    (\phi + \rho_b k_{p,i}) \frac{\partial c_i}{\partial t} + (c_i - \rho_p c_{p,i}) \frac{\partial \phi}{\partial t} + u \nabla c_i = \nabla [(D_d + D_e) \nabla c_i] + R_i
    \]

  - **Fracture media**
    \[
    d_f R \left( \frac{\partial \rho_b c_{p,i}}{\partial t} + \frac{\partial \phi f c_i}{\partial t} + \nabla \left(D_{e,i} \nabla_c c_i\right) + u \nabla c_i \right) = d_f R_i + n_o
    \]

- The coupling between both equations is carried out by a source/sink term with the following form:

  \[
  \begin{aligned}
  Q_m &= -\beta (C_m - C_f) \\
  Q_f &= -\beta (C_f - C_m)
  \end{aligned}
  \]

  where \( \beta = D_e \cdot \frac{1}{l} \)

- The transport is solved in a transient simulation of 500 k years.

- The simulation considers an initial release of 1 mol/m³ in the waste domain.
Governing equations

First order decay

The simulation considers one conservative tracer and three different radionuclides that are affected by first order decay and linear sorption.

Exponential decay equation:

\[ c(t) = c_0 e^{-\lambda t} \]

Partial derivative form of the decay term:

\[ \frac{\partial c}{\partial t} = -\lambda c \]

First order decay and transport parameters

Three radionuclide are considered:

- Cl\textsuperscript{36}: Small decay and no-sorption.
- Mo\textsuperscript{93}: Quick decay and no-sorption.
- Cs\textsuperscript{135}: Small decay and high sorption.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Kd m\textsuperscript{3}/kg</th>
<th>Half life (y) T\textsubscript{1/2}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Backfill</td>
<td>Bedrock</td>
</tr>
<tr>
<td>Cl\textsuperscript{36}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mo\textsuperscript{93}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cs\textsuperscript{135}</td>
<td>1.10E-01</td>
<td>0</td>
</tr>
</tbody>
</table>
Groundwater flow

Water pressure field coming from a regional hydrogeological model is imposed over the edges of the boundaries. The groundwater flow field is solved in steady state. Regional groundwater flow streams from West to East.
Groundwater flow

Regional groundwater flow streams from West to East. However, the groundwater through the vault is from South to North due to the local connectivity of the fractures.
Tracer evolution in the fractures.
Tracer evolution in the vault.
Mass flow at fracture/backfill interface.

\[ \log_{10} (\beta \cdot (c_{\text{fracture}} - c_{\text{porous}})) \text{ mol/(m}^3\text{s)} \]
• Maximum release of tracer is observed at 8,000 years of simulation.

• The decay has an important effect in the release of Mollydenum whereas it is not important in the case of the Chloride.

• The higher Cesium sorption capacity produces a delay in the release of around 7000 years.
Temporal evolution of the dissolved tracer in the different domains

- Temporal evolution of the dissolved mass in the different domains

- The tracer spends around 1000 years to cross the backfill.

- The residence time in the fractures is very small due to the high velocities of the groundwater.

- All the tracer released leaves the modelled domain after 500,000 years.
Temporal evolution of the dissolved Molybdenum in the different domains

- Temporal evolution of the dissolved mass in the different domains

- The tracer spends around 1000 years to cross the backfill.

- The residence time in the fractures is very small due to the high velocities of the groundwater.

- All the tracer released leaves the modelled domain or has been decayed after 500,000 years.

- The higher half-life of the Molybdenum almost decay all the mass before leaving the domain.
Temporal evolution of the dissolved Cesium in the different domains

- Temporal evolution of the dissolved mass in the different domains

- The tracer spends around 1000 years to cross the backfill.

- The residence time in the fractures is very small due to the high velocities of the groundwater.

- After 500,000 years there is still Cesium sorbed in the backfill.

- The sorption retards around 30,000 years the first arrival of cesium to the model boundaries.
Concluding remarks

• Local groundwater flow crossing the repository is controlled by the connectivity of the fractures.

• The transport of radionuclides in the vault is governed by diffusion and convection whereas the transport in fractures is governed mainly by convection.

• The isolated fractures in contact with the repository doesn’t have effect over the groundwater flow system whereas they have an storage effect over the release of radionuclides from the waste through the biosphere.

• The main effective barrier to the movement of the radionuclides is the bentonite backfill. The conservative tracer spends 1,000 years in begin to leave the backfill.

• The residence time of the radionuclides in the fracture domain is very small compared with the one in the backfill.

• The decay of radionuclides decreases the amount of dissolved radionuclides leaving the domain and also decrease the maximum mass flow release in the breakthrough curves evaluated at the fracture/interface.

• The sorption of Cesium retards the first release of Cesium from the vault 30,000 years.
Thanks for your attention
Any question?
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References


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