Hydro-mechanical modelling of gas migration in host rocks for nuclear waste repositories

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Outline

1. Introduction

2. Double porosity approach

3. Governing equations

4. Model validation

5. Conclusions
Introduction

➢ Nuclear power

Current installed energy capacity in Ontario (from 18-Months Outlook)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Capacity</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>13,009 MW</td>
<td>35%</td>
</tr>
<tr>
<td>Gas/Oil</td>
<td>10,277 MW</td>
<td>28%</td>
</tr>
<tr>
<td>Hydro</td>
<td>8,499 MW</td>
<td>23%</td>
</tr>
<tr>
<td>Wind</td>
<td>4,486 MW</td>
<td>12%</td>
</tr>
<tr>
<td>Biofuel</td>
<td>295 MW</td>
<td>1%</td>
</tr>
<tr>
<td>Solar</td>
<td>424 MW</td>
<td>1%</td>
</tr>
</tbody>
</table>
## Nuclear waste disposal

<table>
<thead>
<tr>
<th>Waste types</th>
<th>Option</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLW and short-lived ILW</td>
<td>Near-surface disposal, or in caverns below ground level (at depths of tens of meters)</td>
<td>Implemented in Finland and Sweden.</td>
</tr>
<tr>
<td>Long-lived ILW and HLW</td>
<td>Deep geological repository (DGR) at depths 250-1000 m, or deeper boreholes</td>
<td>DGR is being investigated or constructed.</td>
</tr>
</tbody>
</table>
The concept of DGR

Scale figure


Source: Sanchez, 2005
Gas pathways

Gas pathways: ① EDZ; ② sealing material; ③ host rock: [a] pores [b] existing fractures [c] induced fractures

Source: NAGRA, 2008
Research status

Numerical consideration:

- Hydro-mechanical coupled process
- Unsaturated fluid flow
- Fractures contained in the rock

Gas induced fracturing

Source: Wiseall et al. 2015
Double porosity approach

FPM with double porosity

Porous continuum (PC)

Fractured continuum (FC)

Elementary volume representation

Solid

Water, gas

Source: Zhang et al. 2003

Volume:

\[ V_t = V_{s(p)} + V_p \]

Bulk modulus:

\[ \frac{1}{K} = \frac{1}{K_p} + \frac{1}{K_f} \]

Shear modulus:

\[ \frac{1}{G} = \frac{1}{G_p} + \frac{1}{G_f} \]

Porosity:

\[ \phi_p = \frac{V_p}{V_t} \]

\[ \phi_f = \frac{V_f}{V_t} \]
Main assumptions

① Two phase flow takes place in the FC only.

② The PC is kept fully saturated.

③ The PC and FC are subjected to the same total stress.

④ Fluid flow in each subcontinuum is independent.

⑤ PC is assumed to be volumetrically elastic, FC shows linear elastic behavior.
Coupled variables

Primary variables: $p_{fg}$, $p_{fw}$, $p_{pw}$, $u$, $\phi_p$, $\phi_f$

Mechanics

- Porosity of the PC, $\phi_p$
- Porosity of the FC, $\phi_f$
- Permeability of the FC, $k_f$
- Volumetric strain of PC, $\varepsilon_{pv}$
- Water exchange term, $\Gamma_w = \xi \rho_{fw} (p_{fw} - p_{pw})$
- Permeability alteration
- Pore pressure & effective stress change

Hydraulics

- Volumetric strain of FC, $\varepsilon_{fv}$
- $\frac{\partial \phi_p}{\partial t} = (1 - \frac{K_p}{K_{fp}} - \phi_p) \frac{\dot{p}_p'}{K_p}$
- $\frac{\partial \phi_f}{\partial t} = (1 - \frac{K_f}{K_{f0}} - \phi_f) \frac{\partial \varepsilon_{fv}}{\partial t}$
- $\varepsilon_{pv} = \frac{p'_p}{K_p}$

$k_r = k_{f0} \left( \frac{\phi_f}{\phi_{fo}} \right)^3 \left[ 1 + \exp \left( b_2 \left( 1 - \frac{\phi_f - \phi_{fo}}{\phi_{cr}} \right) \right) \right]^{-1} - b_1 \left[ 1 + \exp(b_2) \right]^{-1} + 1$
Governing equations

Mass balance equations

\[ \rho_{fg} \left( \frac{\phi_f (1 - S_e) M}{\rho_{fg} RT} + \phi_f C_s \right) \frac{\partial p_{fg}}{\partial t} + \nabla \cdot (\rho_{fg} \mathbf{v}_D^{fg}) = \rho_{fg} \phi_f C_s \frac{\partial p_{fw}}{\partial t} - \rho_{fg} (1 - S_e) (1 - \frac{K_f}{K}) \frac{\partial \varepsilon_{fv}}{\partial t} \]

\[ \rho_{fw} \left( \phi_f S_e \mathcal{K}_w + \phi_f C_s \right) \frac{\partial p_{fw}}{\partial t} + \nabla \cdot (\rho_{fw} \mathbf{v}_D^{fw}) = \rho_{fw} \phi_f C_s \frac{\partial p_{fg}}{\partial t} - \rho_{fw} S_e (1 - \frac{K_f}{K}) \frac{\partial \varepsilon_{fv}}{\partial t} + \xi \rho_{fw} (p_{fw} - p_{pw}) \]

\[ \rho_{pw} \phi_p \mathcal{K}_w \frac{\partial p_{pw}}{\partial t} = -\rho_{pw} (1 - \frac{K_p}{K}) \frac{\dot{p}_p}{K_p} - \xi \rho_{fw} (p_{fw} - p_{pw}) \]

Momentum balance equation

\[ \nabla \cdot \mathbf{\dot{s}} + \dot{\mathbf{g}} = 0, \quad \rho = (1 - \phi_f - \phi_p) \rho_s + (\phi_f S_e + \phi_p) \rho_w + \phi_f (1 - S_e) \rho_g \]
Constitutive equations

Mechanical relation

\[ f : (\epsilon - \frac{1}{3} \frac{p_p}{K_p} \mathbf{I}) = \mathbf{\sigma} + \left(1 - \frac{K_f}{K}\right) \left[S_e p_{fw} + (1 - S_e) p_{fg}\right] \mathbf{I} \]

Hydraulic relation

\[ v^D_{f\pi} = -\frac{k k_{rz}^\pi}{\mu_\pi} (\nabla p_{f\pi} - \rho_{\pi} \mathbf{g}) \quad \pi = g, w \quad \rightarrow \quad \text{Darcy’s law} \]

\[ p_c = p_{fg} - p_{fw} \]

\[ S_e = \begin{cases} 
\frac{1}{1-m} \left(1 + \frac{p_c}{p_{gev}}\right)^{1-m} & p_c > 0 \\
1 & p_c \leq 0
\end{cases} \]

\[ k_{rw} = \sqrt{S_e [1 - (1 - S_e)^{1/m}]^2} \]

\[ k_{rg} = (1 - S_e)^3 \quad \rightarrow \quad \text{Relative permeability} \]
Model validation

Gas injection test

\[ \sigma_1 = 12.5 \text{ MPa} \]

Apparatus and results (from Harrington et al. 2017)
Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho_s$</td>
<td>2.31 g/cm$^3$</td>
</tr>
<tr>
<td>Modulus</td>
<td>$G$</td>
<td>769 MPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>$\phi_{f0}$</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>$K_p$</td>
<td>1667 MPa</td>
</tr>
<tr>
<td></td>
<td>$\phi_{p0}$</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>$K_f$</td>
<td>1500 MPa</td>
</tr>
<tr>
<td>Initial strain</td>
<td>$S_{e0}$</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>$b_1$</td>
<td>72</td>
</tr>
<tr>
<td>Initial conductivity</td>
<td>$\kappa_{f0/}$</td>
<td>$3.5 \times 10^{-19}$ m$^2$</td>
</tr>
<tr>
<td></td>
<td>$b_2$</td>
<td>1</td>
</tr>
<tr>
<td>Initial conductivity</td>
<td>$\kappa_{f0/}$</td>
<td>$1.4 \times 10^{-20}$ m$^2$</td>
</tr>
<tr>
<td></td>
<td>$\phi_{cr}$</td>
<td>0.0014</td>
</tr>
<tr>
<td>Pressure</td>
<td>$P_{gev}$</td>
<td>1 MPa</td>
</tr>
<tr>
<td>Conductivity</td>
<td>$\xi$</td>
<td>$3 \times 10^{-13}$ m$^*$/kg</td>
</tr>
<tr>
<td>Exponent</td>
<td>$m$</td>
<td>1/3</td>
</tr>
</tbody>
</table>
Boundary conditions

<table>
<thead>
<tr>
<th>BC No.</th>
<th>Hydraulic BCs</th>
<th>Mechanical BCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Applied</td>
<td>No flow</td>
</tr>
<tr>
<td>2</td>
<td>No flow</td>
<td>No flow</td>
</tr>
<tr>
<td>3</td>
<td>No flow</td>
<td>No flow</td>
</tr>
<tr>
<td>4</td>
<td>No flow</td>
<td>No flow</td>
</tr>
<tr>
<td>5</td>
<td>4.71 MPa</td>
<td>4.5 MPa</td>
</tr>
<tr>
<td>6</td>
<td>4.71 MPa</td>
<td>No flow</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Hydraulic BCs:
- Gas in FC
- Water in FC
- Water in PC

Mechanical BCs:
- Roller
- 12.5 MPa
- 12.5 MPa
Simulated results
Simulated results

Pressure in the IGR

Pressure in the BGR

development of new gas pathway
Conclusions

- To capture the experimental observations of gas induced fracturing, the conventional HM model with single porosity is unsuitable to be used.
- The new developed model with double porosity shows good results compared with the experimental data.
- Further improvements can be made by introducing a 3D model with a non-symmetrical geometry and heterogeneous HM properties.
References

Thank you!

Questions?