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Semi-analytical model of brine leakage through an abandoned plugged well to determine the Area of Review for CO$_2$ geological storages

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Many CO₂ storage projects target deep saline aquifers located in sedimentary basins
• Possible historical oil & gas operations
• Abandoned wells with sometimes unknown plugging records

By leaking through abandoned (plugged) wells, the saline brine risks to leak into overlying fresh water aquifers → wells in the area where this is possible should be reviewed (“Area of review”)
→ This model enables to prioritize the areas to review supposing minimum plug parameters

Example in Alberta, Canada: 508 wells in a 30km x 30 km area. from Bachu and Celia, 2009
Schematic layout of the model

> 1 active injection well

> 1 passive abandoned well, or « Leak »
- \( z_c = z_{L-} \): wellbore only
- \( z_c = z_{L+} \): porous column only
- \( z_{L-} < z_c < z_{L+} \): plug & wellbore
Beginning of CO$_2$ injection

> **Constant CO$_2$ injection flow rate starts** ($Q_0$)

\[ P_{L+} = P_{L+}(t = 0) \]
\[ P_C = P_C(t = 0) \]
\[ P_{L-} = P_{L-}(t = 0) \]

\[ \text{CO}_2 \text{ plume} \]
\[ \text{Drinking water} \]
\[ \text{Storage aq. brine} \]
\[ \text{Wellbore brine} \]
Brine leakage during CO₂ injection

> Dense storage aquifer brine starts filling the leak up to \( z_l \)

> The « wellbore brine » is pushed up

> Pressure increases in the abandonned well
End of the CO₂ injection & « AoR »

> « Area of review » \(d_{AoR}\): Area where the pressure changes due to the injection can drive the reservoir brine up to a shallower aquifer of interest
Equations of the model

> Static pressure equation in the abandoned well

> Pressure under the leak in the storage aquifer

> Pressure over the leak in the overlying aquifer

> Mass conservation

> Darcy flow in the cement plug

> Semi-analytical resolution
Static pressure equation in the abandoned well

> Well bore pressure gradient

\[ \nabla P = \nabla P_{\text{grav}} + \nabla P_{\text{fric}} + \nabla P_{\text{acc}} \]

- « frictional and inertial pressure gradients contributing typically a few percent or less.” (Pruess, 2006, for geothermal wells)

- \[ \nabla P = \nabla P_{\text{grav}} \]

> Thermal equilibrium

(Oldenburg & Rinaldi 2011)
Pressure under the leak in the storage aquifer

\[
P_L(t) - P_L^0 = \frac{\mu_0}{4\pi k h} \left[ Q_0 E_1 \left( \frac{d^2 S_\perp}{4T_\perp t} \right) - \int_0^t \frac{dQ_L}{dt'} E_1 \left( \frac{r_L^2 S_\perp}{4T_\perp (t - t')} \right) dt' \right]
\]
Application to the « PICOREF » sector, Paris basin

\[ P, T, X_S \] correspond to the Paris basin context as presented in Humez et al. (2011).
Brine density profile

Brine density difference: 0.04 MPa pressure increase

Initial salinity gradient

\[ \rho (\text{kg.m}^{-3}) \]

Distance to the surface \( z \) (m)

\[ z_{L_+} = -705 \text{ m} \]

\[ z_{L_-} = -1525 \text{ m} \]

\[ X_s = 0.5 \text{ g.kg}^{-1} \]

\[ X_s = 20 \text{ g.kg}^{-1} \]

\[ X_s = 40 \text{ g.kg}^{-1} \]
Example of brine leakage

- CO₂ injection scenario: 1 Mt/y for 50 years
- D=6.7 km from the injection to the abandoned well
- Cement plug: 10 m high, weak permability of $10^{-13} m^2$
Area to review for a minimum cement plug height on permeability ratio

> **CO₂ injection scenario: 1 Mt/y for 50 years**

Static approach without plug: 146.5 km corresponds to the limit $\frac{h_c}{k_c} \to 0$

Minimum cement plug $\frac{h_c}{k_c} \text{ (m}^{-1}\text{)}$
Prioritization of the wells to review

Adapted from Delmas et al., 2010

\[ d_{\text{AOR}} = \begin{cases} 
2.7 \text{ km for } h_c/k_c = 3 \times 10^{15} \text{ m}^{-1} \\
7.5 \text{ km for } h_c/k_c = 2 \times 10^{15} \text{ m}^{-1} \\
24 \text{ km for } h_c/k_c = 10^{15} \text{ m}^{-1} 
\end{cases} \]
Conclusions

- The model describes the leakage of brine through the leak. Compared to the state of the art (Nordbotten, Celia and co-authors, 2004-2009), it adds the possibility of accounting for density change within the leak due to the incoming of dense brine.

- It shares the advantages (immediate computation) and drawbacks (homogeneous layers) of semi-analytical models.

- Compared to a static approach (Nicot et al., 2009), this dynamic model enables less conservative estimation of the “Area of Review”, by including effects of cement plugs, of brine density differences and of leakage-induced pressure effects.

Next steps

- Inclusion of the CO₂ leakage
- Monte-Carlo analyses
Thanks!

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References

• Bachu, S., M.A. Celia. 2009. Assessing the potential for CO2 leakage, particularly through wells, from geological, storage sites. AGU 2008