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Comparing (Semi-) Analytic Solutions used to Model the Impact of deep Carbon Injection on the Displacement and Pressurization of the Resident Brine

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ABSTRACT

Injection of carbon dioxide into deep saline formations is seen as one possible technology for mitigating carbon emissions from utilities. The focus of this study is on the changes in resident brine pressure due to the injection of large volumes of carbon dioxide into the subsurface. The applicability of several semi-analytic solutions to the problem of brine pressurization is determined. The goal is to find ranges of formation parameters for which simplifying assumption are justifiable. The process involves a solution hierarchy from the most complex solution down to the basic Theis solution.

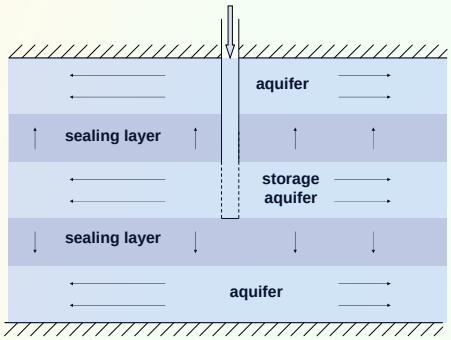
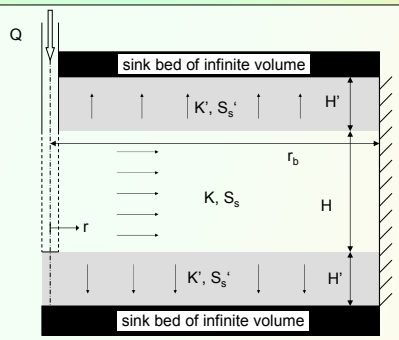


Figure 1): Cross-section of conceptual model of single layer injection

CONCEPTUAL MODEL ASSUMPTIONS

- single-phase flow (valid at distances beyond CO_2 plume extent)
- radial-symmetric domain
- aquifer / sealing layer properties are homogeneous and isotropic in each aquifer / sealing layer
- horizontal layering
- constant aquifer / sealing layer thickness
- piecewise constant volumetric injection rate
- purely horizontal flow in aquifers; purely vertical flow in leaky layers
- constant head in overlying and underlying aquifer



Q: volumetric injection rate [L^3/T]
K: horizontal hydraulic conductivity of aquifer [L/T]
H: aquifer thickness [L]
S_s: specific storage of aquifer [1/L]
K': vertical hydraulic conductivity of sealing layers [L/T]
H': aquifer thickness [L]
S_s': specific storage of sealing layers [1/L]
r_b: distance to radial boundary [L]
r_w: injection well radius [L]

Figure 2) Cross-sectional view of bounded domain with single-phase flow

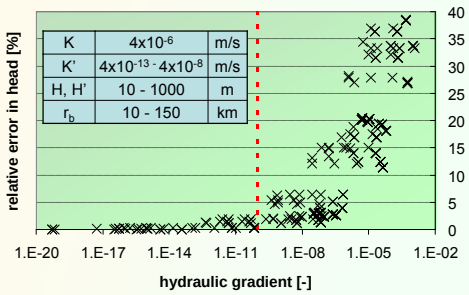


Figure 3) Relative error in head at a radial distance of 0.9 * r_b introduced by neglecting lateral flow boundary

LATERAL BOUNDARY

- assumes radial-symmetric boundary centered on the injection well
- derived by Q. Zhou of LBNL (Zhou et al., 2009)
- Laplace transformed dimensionless head is given as:

$$\overline{h_D} = \frac{2}{p\, r_{Dw}\Psi} \frac{K_1(r_{Db}\Psi) I_0(r_{Db}\Psi) + K_0(r_D\Psi) I_1(r_{Db}\Psi)}{K_1(r_{Dw}\Psi) I_1(r_{Db}\Psi) - K_1(r_{Db}\Psi) I_1(r_{Dw}\Psi)}$$

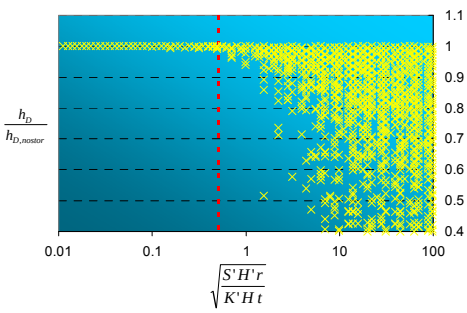
$$\Psi^2 = p + 2\sqrt{\frac{K'H\,S'}{K\,H'S}}\, p \coth\left(\sqrt{\frac{K\,H'S'}{K'H\,S}}\, p\right)$$

where p is the Laplace variable, and r_D, r_{Dw}, r_{Db} are the dimensionless radius, well radius and boundary radius, and I_0, I_1, K_0, and K_1 are the modified Bessel Functions of the first and second kind

- The influence of the lateral boundary is found by evaluating the Laplace transformed head gradient at the boundary radius in an infinite domain.

$$\bar{i} = \frac{Q}{2\pi K H^2} \frac{\Psi}{p} K_1(r_{Db}\Psi)$$

- A gradient close to zero means no influence by the lateral boundary.
- Numerical experiments suggest gradients lower than 10^{-10} lead to head errors of less than 5% (Fig. 3)



	aquifer	leaky layers	
K	$4x10^{-6}$	$4x10^{-13}$ - $4x10^{-8}$	m/s
H	10 - 100	25 - 500	m
S_s	10^{-10} - 10^{-6}	0 - 10^{-4}	1/m

Figure 4) Impact of neglecting storage in sealing layers (h_D = dimensionless head including sealing layer storage, $h_{D,nostor}$ = dimensionless head neglecting sealing layer storage)

HANTUSH-JACOB SOLUTION

- Two additional assumptions ($r_w \to 0$, S'=0) lead to the Hantush-Jacob solution (1955)

$$\overline{h_D} = \frac{2}{p} K_0\left(r_D\sqrt{p + 2\frac{K'H}{K\,H'}}\right)$$

- Numerical experiments (Fig. 4) suggest that the assumption S'=0 is valid when

$$\sqrt{\frac{S'H'r}{K'H\,t}} < 0.5$$

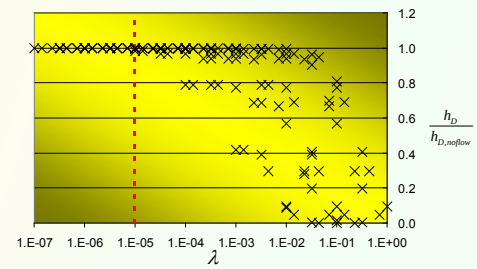


Figure 5) Impact of neglecting flow through sealing layers (h_D = dimensionless head including sealing layer flow, $h_{D,noflow}$ = dimensionless head neglecting sealing layer flow)

THEIS SOLUTION

- Assuming no flow through the sealing layers leads to the Theis solution (1935)

$$\overline{h_D} = \frac{2}{p} K_0\left(r_D\sqrt{p}\right)$$

- This assumption is valid for small leakage factors λ

$$\lambda = \sqrt{\frac{K'H}{K\,H'}}$$

- Numerical experiments suggest a threshold of about 10^{-5}

CONCLUSIONS

- Lateral boundaries can be neglected for Laplace transformed head gradients of about 1e-10
- Storage in leaky layer can be neglected for

$$\sqrt{\frac{S'H'r}{K'H\,t}} < 0.5$$

- Flow through leaky layers can be neglected for $\lambda < 10^{-5}$

FUTURE RESEARCH

- multiple aquifers
- comparison to numerical simulators

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