Analysis of boundary conditions in numerical simulations of geological CO_2 storage

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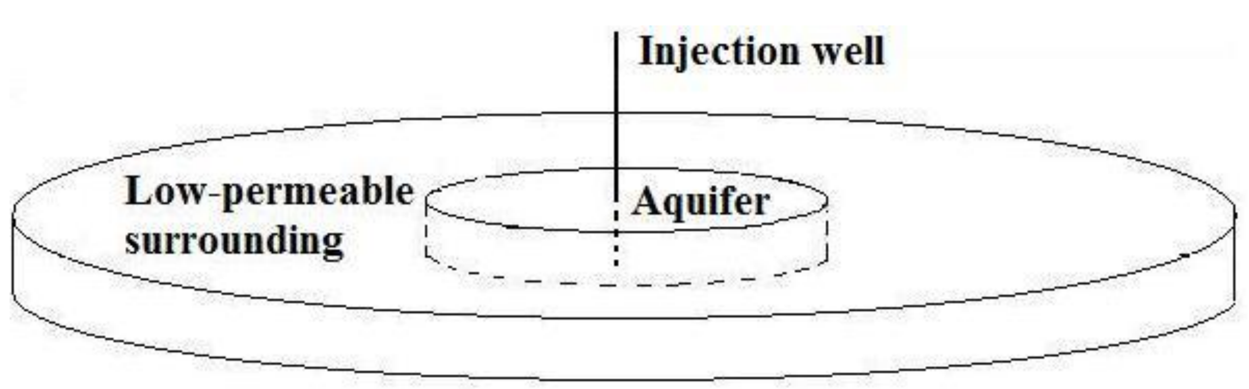
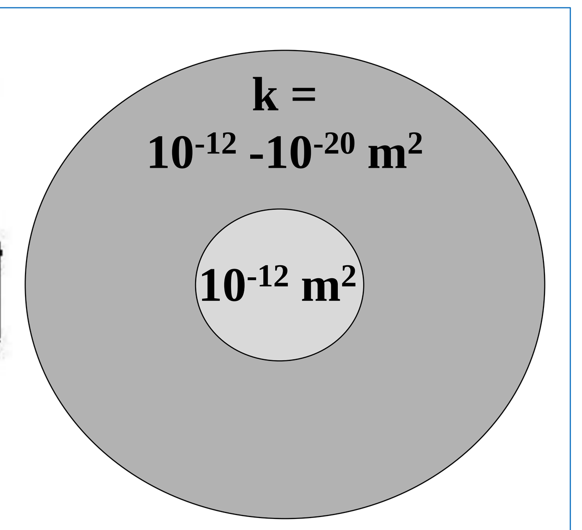
ABSTRACT

Simulations of CO2 injection and subsequent migration and reactions can improve our understanding of the long-term fate of the injected CO2 and potentially displaced formation fluids. Particularly, numerical simulations constitute an important tool in the evaluation and planning of geological CO_2 storage (GCS) projects, where they can provide an estimates of the storage capacity of given target formations. However, well-defined boundaries for such simulations may be difficult to identify and uncertainty in the nature of the boundaries to deep storage formations typically exists. Furthermore, the choice of boundary conditions potentially has a very strong influence on model predictions, and accordingly, there is an ongoing debate on which boundary conditions (BCs) are most appropriate. Particularly the appropriateness of Dirichlet (open) BCs compared to homogeneous Neumann (closed) BCs has recently been discussed. In this work we perform numerical simulations of CO2 storage in deep saline aquifers surrounded by formations of lower permeability. By including the surrounding media in our simulations we analyze the conditions at the storage formation boundaries. We show that for the case of our study, the appropriate BC is in general neither fully open nor closed, but rather a mixed BC which can be expressed as a relationship between pressure gradient and pressure at the boundary. This type of BC appears to be critical for accurate prediction of the displacement of fluids across the boundary. While it cannot predict fluid displacement, the closed Neumann BC can still reasonably predict the pressure buildup during injection, given that the surrounding medium has lower permeability than the storage formation. The Dirichlet (open) BC is not adequate for this scenario and is also shown to be inadequate for simulation of an infinite storage formation.

MODEL AND BACKGROUND

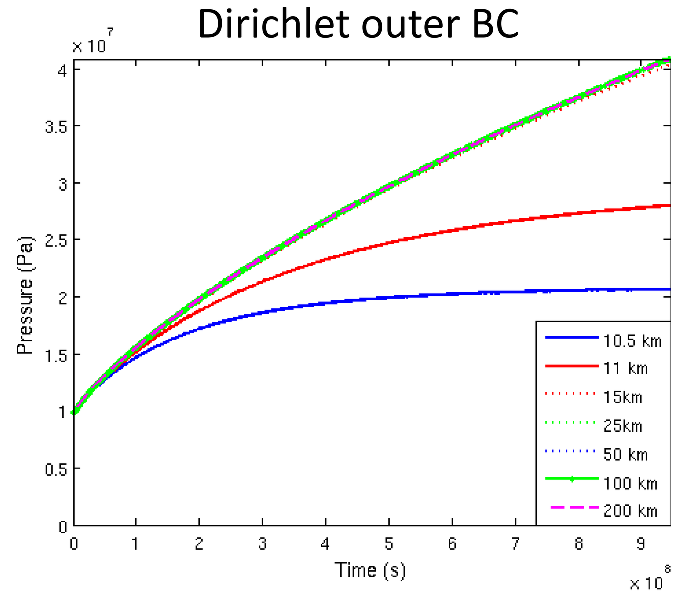




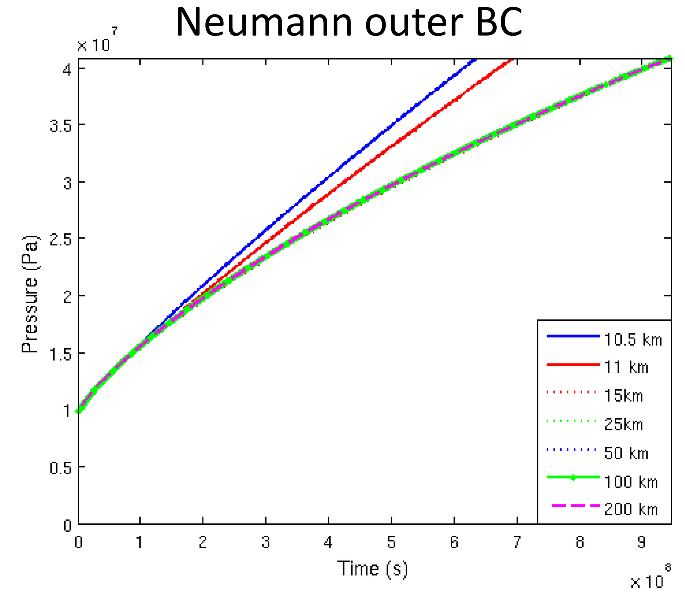
Model setup: the storage formation is surrounded formations of lower permeability

- ❑ By modeling the aquifer together with its surroundings we analyze conditions at the aquifer boundaries
- ❑ Many potential CO2 storage reservoirs are surrounded by materials of lower permeability than the storage unit
- ❑Test-case saline aquifer is of 10 km radius and 50m thickness, at 1 km depth
- ❑ Using large enough surroundings, the outer boundary conditions do not affect the aquifer boundaries

Dirichlet outer BC



Neumann outer BC

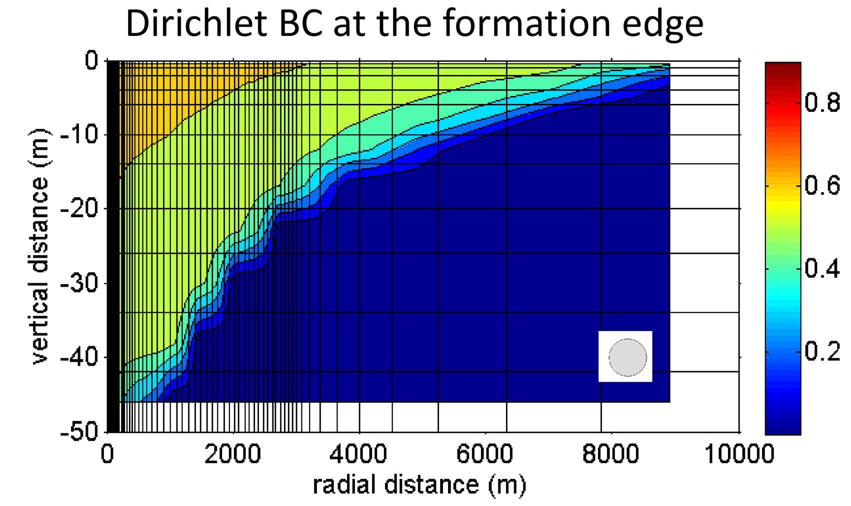


Testing the effect of size of surrounding media for an open (Dirichlet) or closed (Neumann) outer boundary condition. Outer k = 10^{-15} m^2.

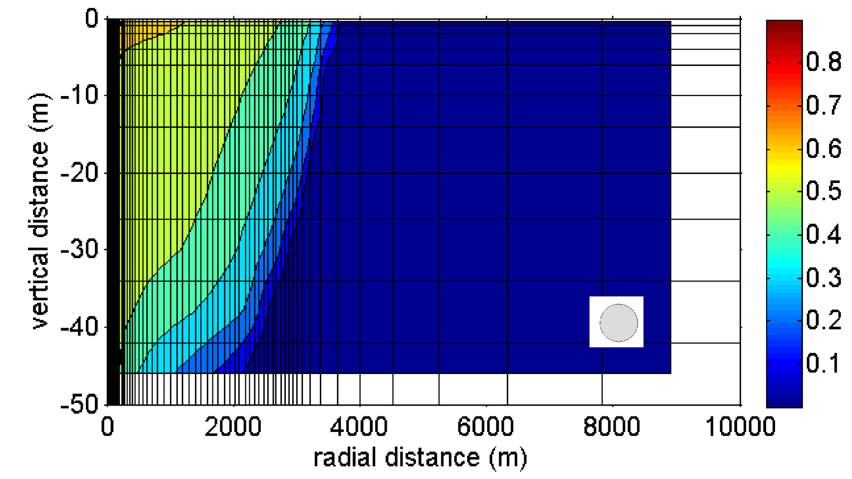
RESULTS

Spreading of supercritical CO_2

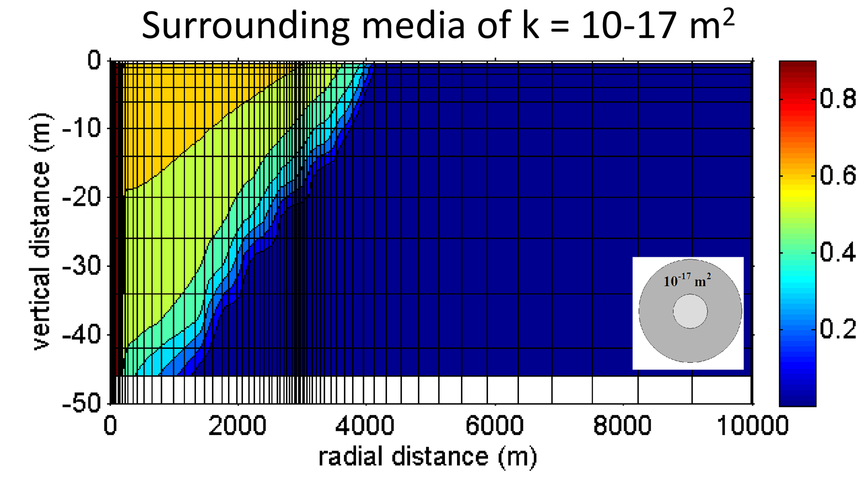
Dirichlet BC at the formation edge



NeumannBC at the formation edge



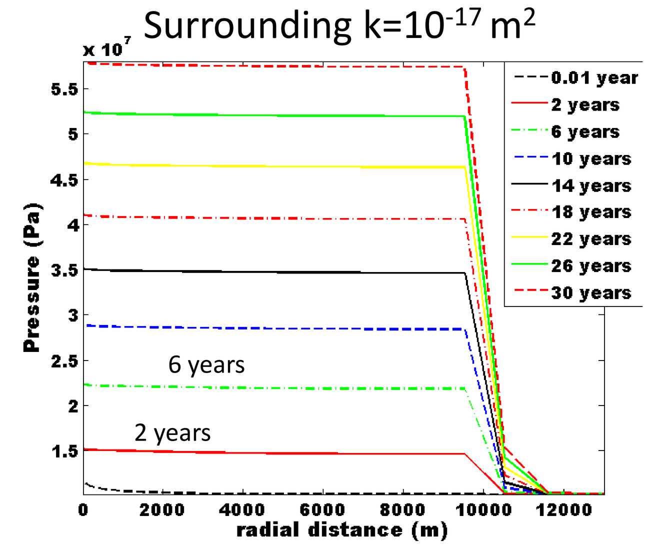
Surrounding media of k = 10-17 m^2



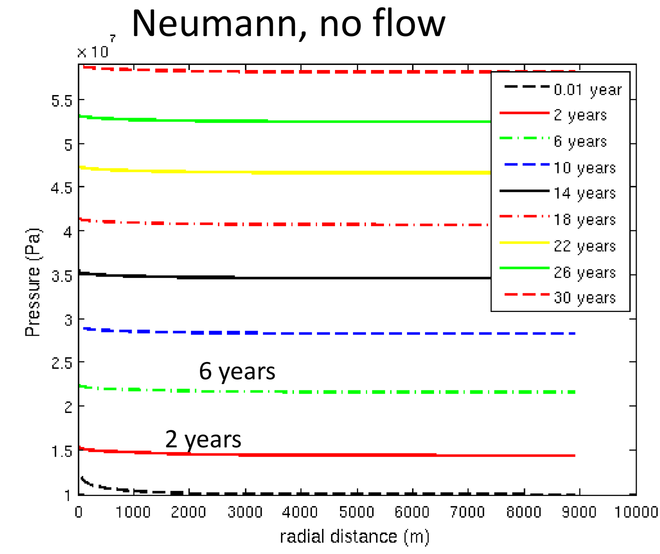
Distribution of $scCO_2$ for different formation boundaries after 30 years of CO_2 injection at 100 kg/s

Pressure evolution in storage formation

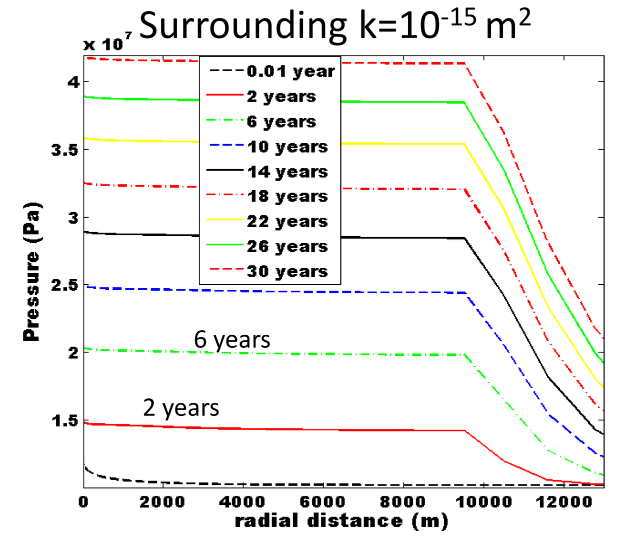
Surrounding k=10^{-17} m^2



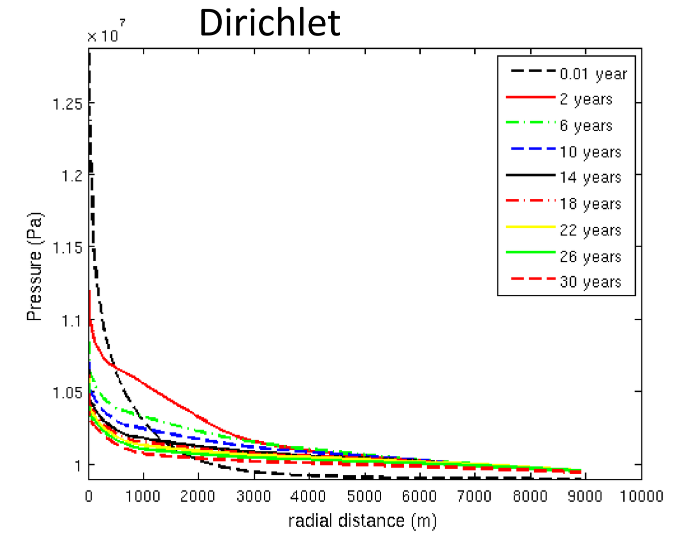
Neumann, no flow



Surrounding k=10^{-15} m^2



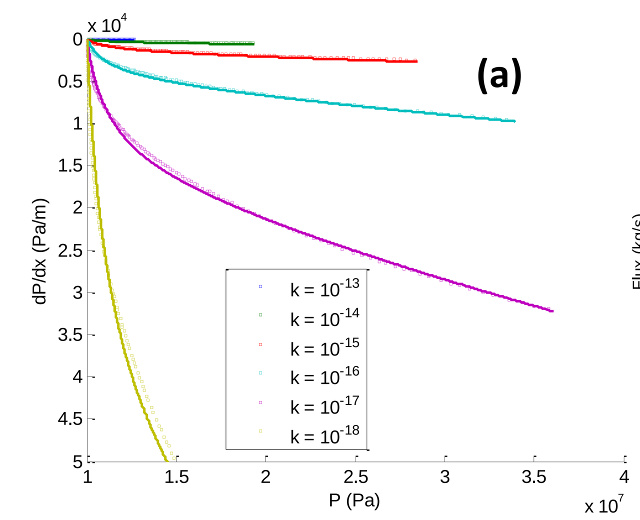
Dirichlet



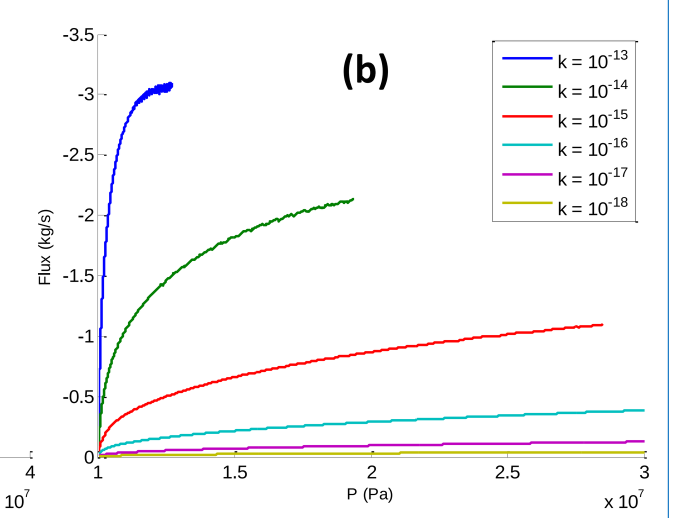
- ❑ The distribution of injected CO2 strongly depends on the boundary condition
- ❑ A low permeability surrounding produces a scCO2 distribution similar to that for a homogeneous Neumann (no flow) BC
- ❑ For the low permeability surrounding, also the pressure distribution over time is similar to that for the Neumann BC
- ❑ For an infinite aquifer, the pressure does not become constant at a hypothetical boundary at 10 km from the injection well during the entire 30 year injection period

Pressure gradient and flux at the boundary

grad(P) – P relationship (Simulated and fitted)



Flux – pressure relationship (Simulation results)

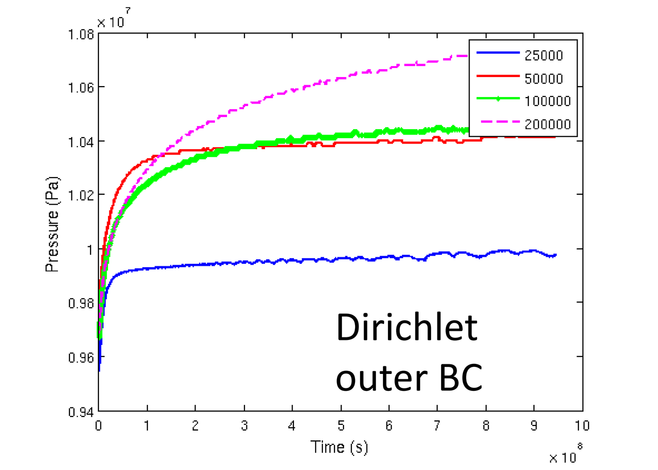


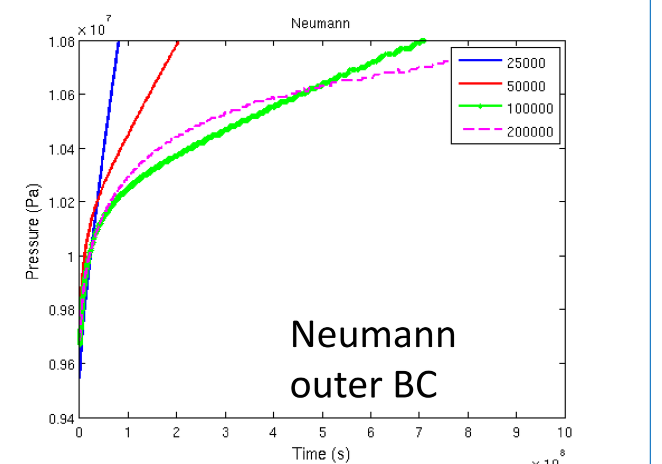
***(a)** Symbols show the relationship between pressure gradient and pressure at the formation boundary as simulated on a fine grid. Lines show the fitted function:*

$$\nabla P = \frac{(P-P_{initial})}{\sqrt{\frac{k_{formation}}{k_{surroundings}}}\left[a\ln\left(\frac{P}{P_{initial}}\right)+1\right]b}$$

For the fitting parameters a and b

Boundary condition for an infinite aquifer ?





Pressure evolution at a hypothetical boundary at 10 km distance from the injection well, for open and closed outer BCs and different total domain sizes

CONCLUSIONS

- ❑ By including the storage formation surroundings in test simulations, the conditions at its boundaries could be examined.
- ❑ A Neumann, no flow, BC obviously cannot predict cross-boundary leakage, but reasonably predicts pressure buildup in the formation.
- ❑ A Dirichlet BC cannot simulate a low-k surrounding, nor can it simulate an infinite aquifer.
- ❑An accurate description of the boundary is necessary to accurately simulate displacement of fluids (e.g. brine) out of the formation.
- ❑ The grad(P) – P relationship at the boundary is non-linear. We have tested a functional form showing good fit over a range of permeability contrasts.

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