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A pseudo-vertical equilibrium model for slow gravity drainage dynamics

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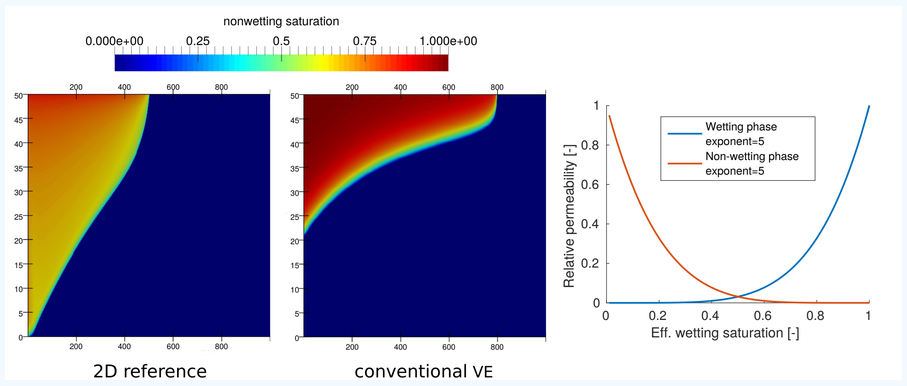
1. Introduction

Vertical equilibrium (VE) models are computationally efficient. However, the assumption of instant gravity segregation may not be valid for all systems. Especially very non-linear relative permeability functions cause slow gravity drainage.



Gas injection into a brine-filled confined aquifer with a relative permeability function with large exponent.

Here, we present a pseudo-VE model that:

- relaxes the assumption of instant gravity segregation,
- applies a pseudo-residual wetting phase saturation inside the plume which declines over time.

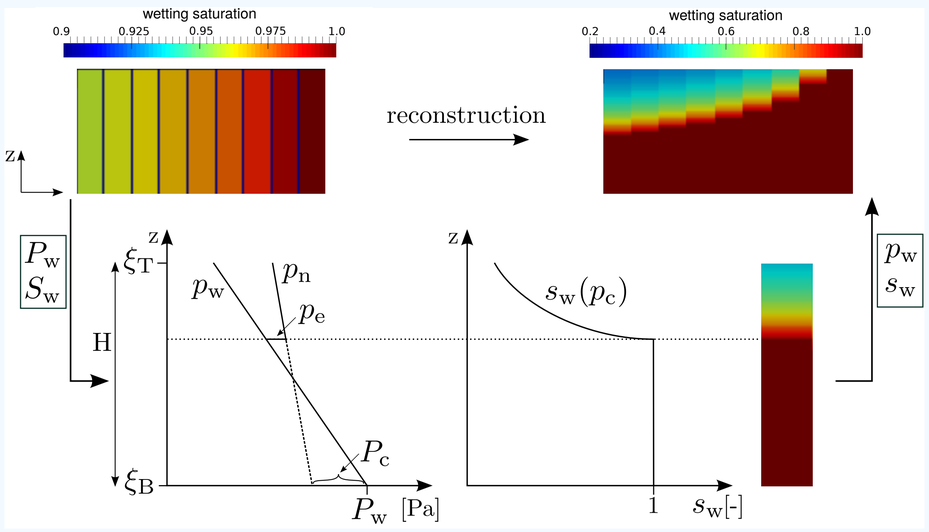
The pseudo-VE model:

- has a much wider applicability than conventional VE models,
- maintains the computational benefit of conventional VE models.

2. Conventional VE model

- Mass balance equation: $\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla_{||} \cdot (\varrho_\alpha \mathbf{U}_\alpha) = \varrho_\alpha \Psi^\alpha$,
- Darcy's law: $\mathbf{U}_\alpha = -\mathbf{K}\Lambda_\alpha(\nabla_{||} P_\alpha - \varrho_\alpha \mathbf{G})$,

  with vertically integrated variables and reference pressure.

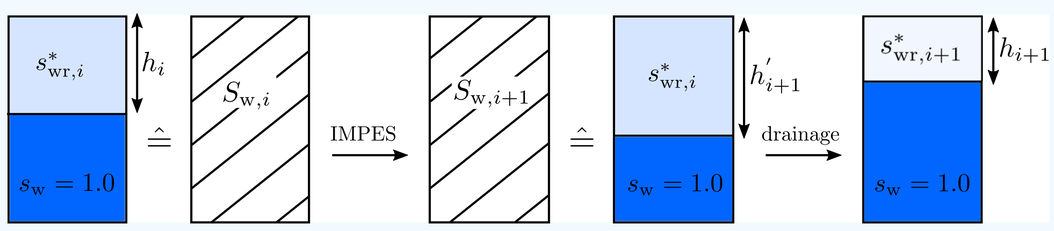


Reconstruction of fine-scale solution in vertical direction.

3. Pseudo-VE model

We apply a pseudo-residual wetting phase saturation inside the plume that declines over time due to drainage.

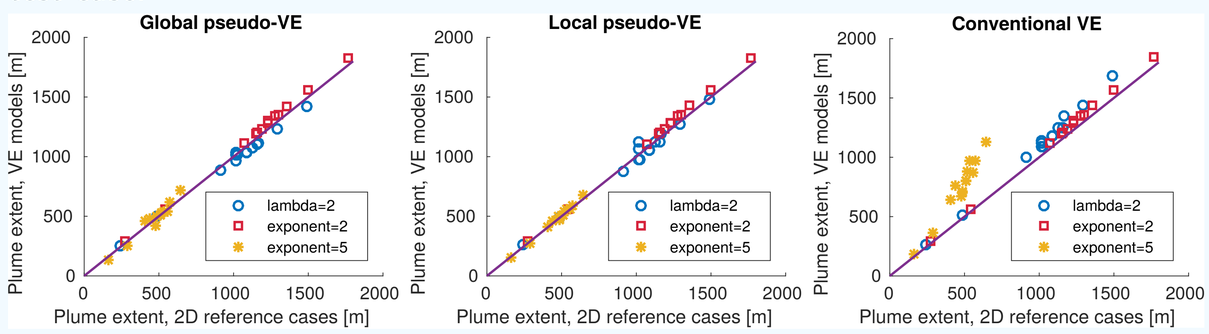
- Global pseudo-VE model: Drainage is calculated as average for the entire plume → uniform pseudo-residual saturation in plume.
- Local pseudo-VE model: Drainage is calculated separately for each grid column → varying pseudo-residual saturation along horizontal direction in plume.



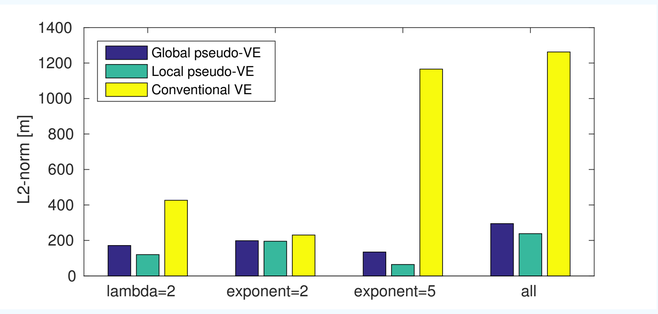
Sequence of calculation of the pseudo-residual wetting phase saturation for the local pseudo-VE model.

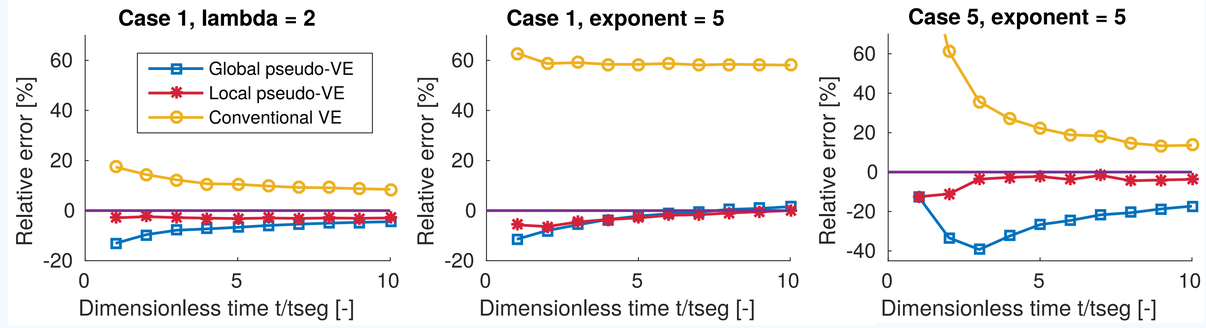
4. Results

We design 15 test cases of gas injection (CO_2, CH_4) into an aquifer filled with brine, changing e.g. inflow rate, permeability and entry pressure. Three different relative permeability functions (low to high non-linearity) are applied to every test case.

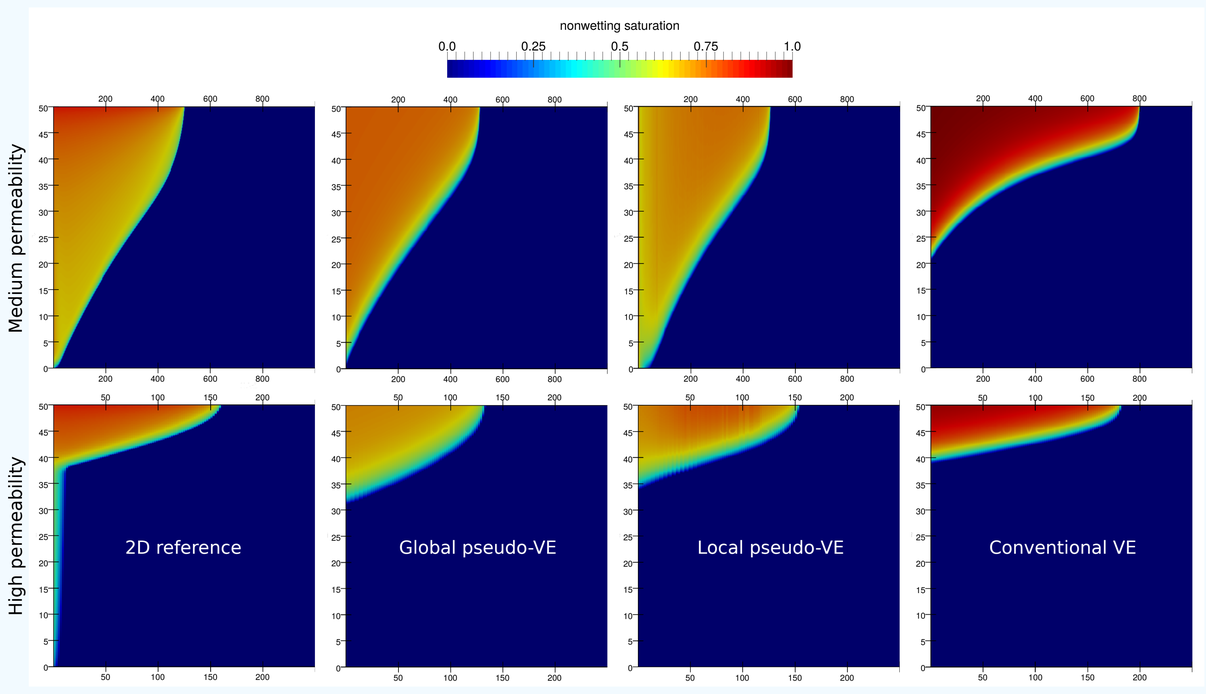


For all relative permeability functions both pseudo-VE models predict the horizontal plume extent far more precise (or equally as precise in case of low non-linearity) than the conventional VE model.





Evolution of relative error over time for two different cases. Case 1: medium permeability, case 5: high permeability.



Plume shapes after $\mathbf{t} = \mathbf{10} \times \mathbf{t}_{\mathrm{seg}}$ *for non-linear relative permeability function.*

5. Outlook

- Include concept into coupled multi-dimensional/VE model.
- Test concept for field scale case of underground energy storage.

Literature

[1] Ackermann, S., Beck, M., Becker, B., Class, H., Fetzer, T., Flemisch, B., Gläser, D., Grüninger, C., Heck, K., Helmig, R., Hommel, J., Kissinger, A., Koch, T., Schneider, M., Seitz, G., and Weishaupt, K. (2017). DuMu^x 2.11.0.

[2] Nordbotten, J. and Celia, M. (2011). *Geological Storage of CO2*. John Wiley and Sons, New York.