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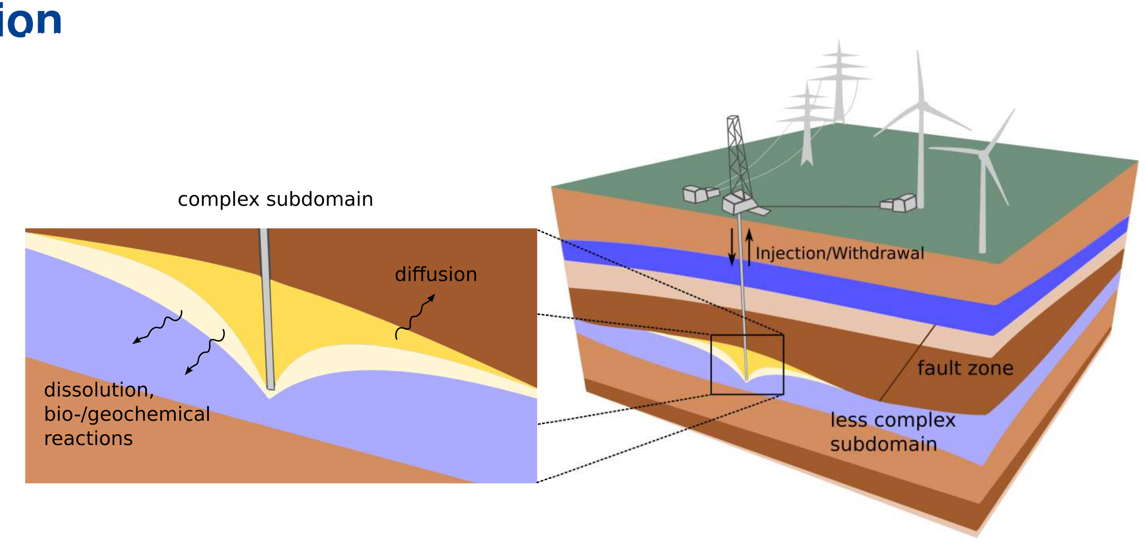
Adaptive Coupling of a Full-Dimensional Model with a Vertical Equilibrium Model

Motivation



Underground storage system

Modeling challenges:

- large domains and limited data,
- locally complex processes,
- dynamic boundary conditions.

Here, we present a coupled model that adaptively applies:

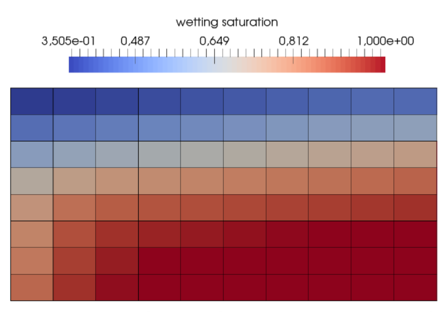
- a full-dimensional model in regions of higher complexity and where the vertical equilibrium assumption does not hold,
- a vertical equilibrium model in the rest of the domain.

State of current work

1. Models

1.1 Full-dimensional 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: $\mathbf{u}_\alpha = -\frac{\mathbf{k} k_{r\alpha}}{\mu_\alpha}(\nabla p_\alpha - \varrho_\alpha \mathbf{g})$,

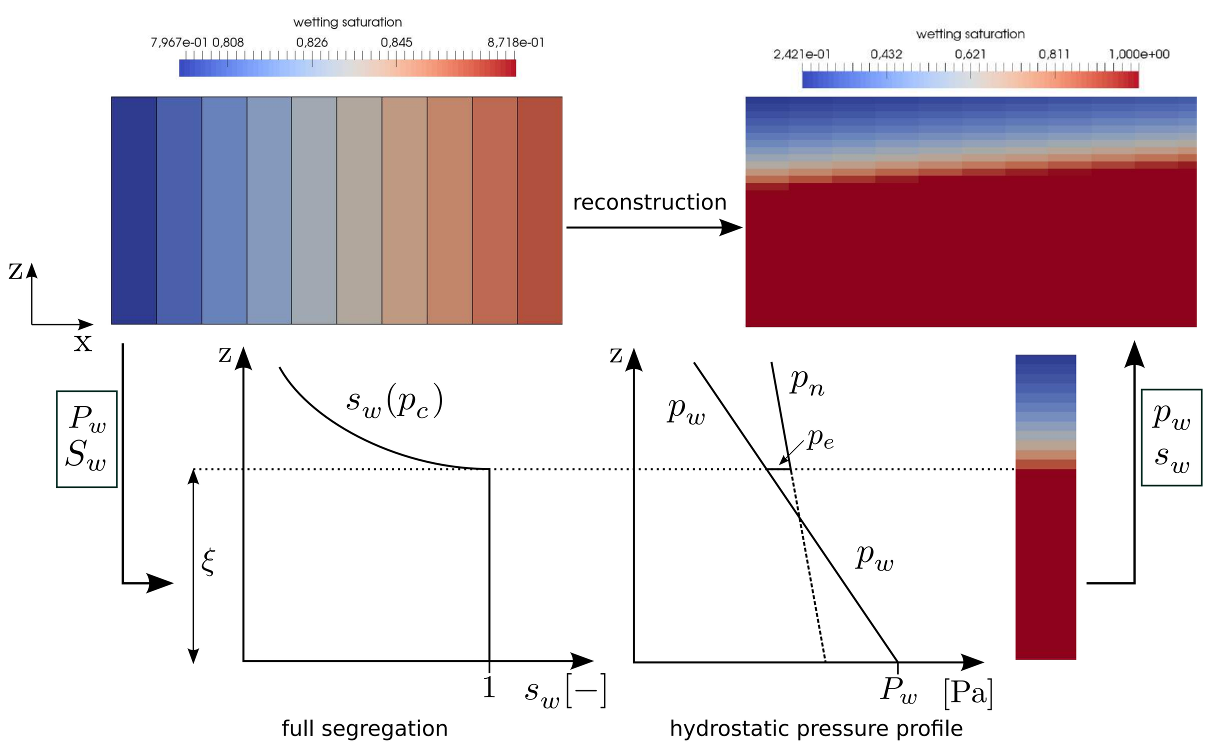


with wetting/non-wetting phase α, saturation s, pressure p, density ϱ_α, porosity ϕ, permeability tensor k, relative permeability $k_{r\alpha}$ viscosity μ_α, sink/source ψ^α.

1.2 Vertical equilibrium model:

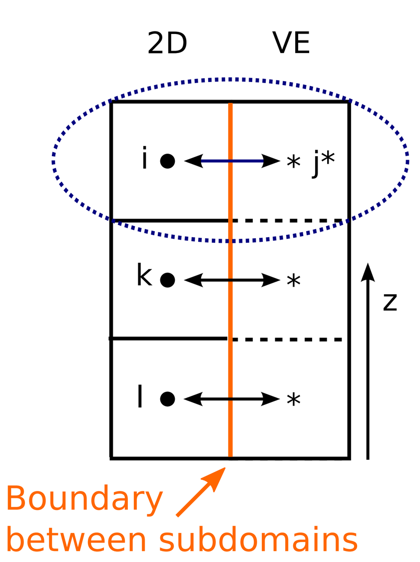
- Mass balance equation: $\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla_{\shortparallel} \cdot (\varrho_\alpha \mathbf{U}_\alpha) = \varrho_\alpha \Psi^\alpha$,
- Darcy's law: $\mathbf{U}_\alpha = -\mathbf{K}\Lambda_\alpha(\nabla_{\shortparallel} P_\alpha - \varrho_\alpha \mathbf{G})$,

with vertically integrated variables and reference pressure.



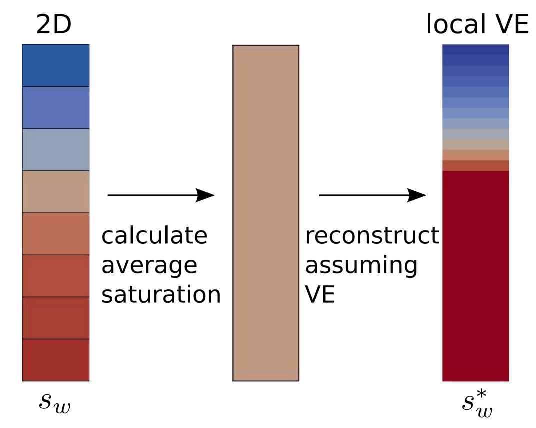
Reconstruction of solution in vertical direction

2. Model coupling

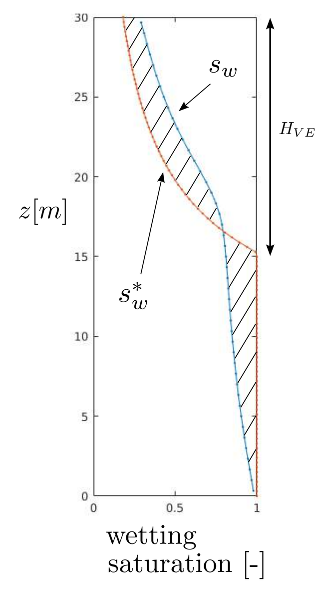


- Discretized mass balance equation (Finite Volume Method): $\sum_j q_{tot,ij} = \sum_j v_{tot,ij} q_{ij} = q_{tot,i}$, with source/sink $q_{tot,i}$.
- Total velocity from VE-cell i to 2D cell j: $v_{tot,ij} = -k\lambda_{tot}\left(\frac{p^*_{wj} - p_{wi}}{\Delta x} + f_n \frac{p^*_{cj} - p_{ci}}{\Delta x}\right)$.
- Reconstructed pressures in VE ghost cells: $p^*_{wj} = P_{wj} - \varrho_w g z$, $p^*_{cj} = p_c(s^*_w)$.
- Calculation of secondary variables in VE ghost cells: Total mobility $\lambda_{tot} = \lambda_w + \lambda_n$ and fractional flow function $f_n = \lambda_n / \lambda_{tot}$ based on averaged saturation in ghost cell saturation $\bar{s}^*_w$.

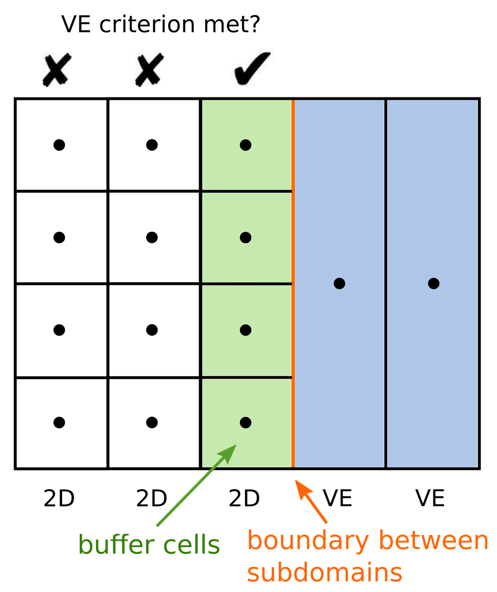
3. Model adaptation



Construction of VE saturation profile



Area between profiles



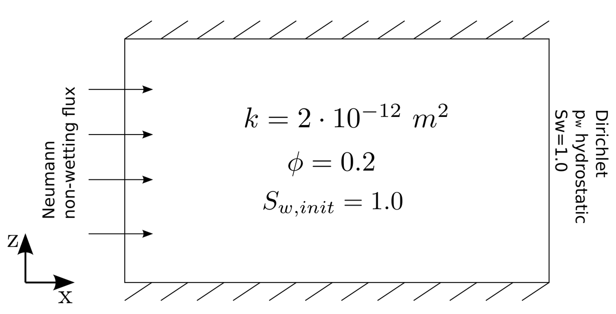
The criterion is normalized by the height H_{VE} of the VE gas plume.

$$c_{sat} = \frac{\int_0^H |s_w - s^*_w| \mathrm{d}z}{H_{VE}} < \epsilon_S,$$

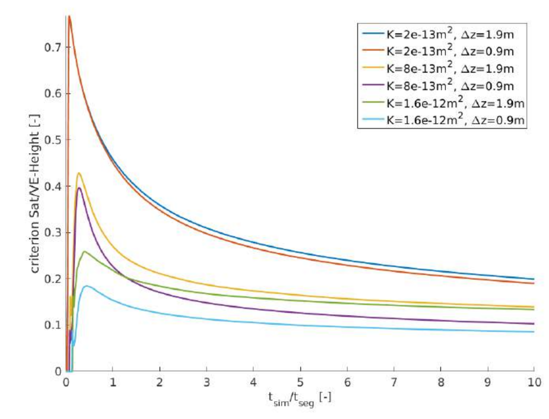
$$c_{relPerm} = \frac{\int_0^H |k_{rw} - k^*_{rw}| \mathrm{d}z}{H_{VE}} < \epsilon_r.$$

A buffer zone is introduced between the subdomains.

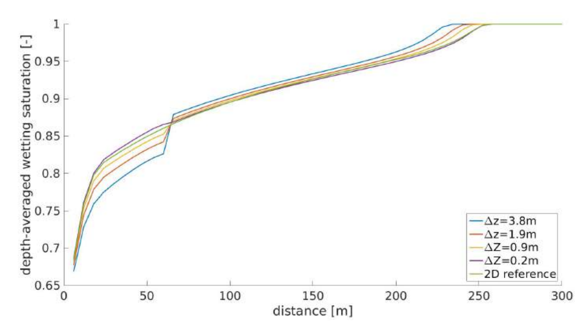
4. Results



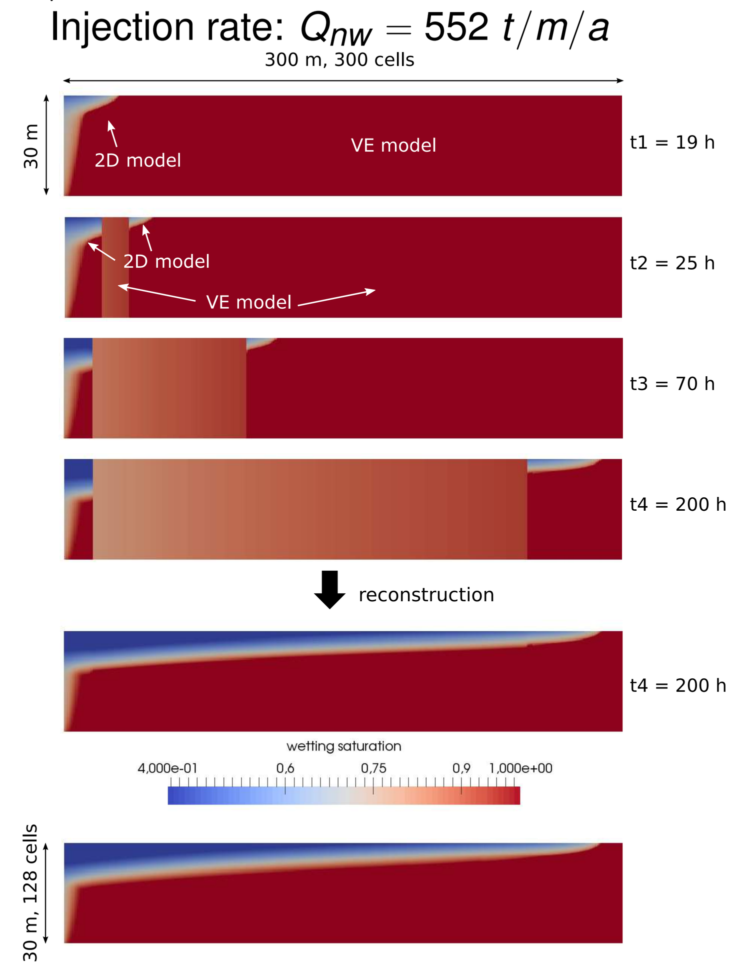
Brooks-Corey cap. pressure:
$\lambda = 2.0$, $p_e = 1\ bar$
Phase properties (CH_4, water):
$\varrho_n = 59.2\ kg/m^3$
$\varrho_w = 991\ kg/m^3$
$\mu_n = 1.2 \cdot 10^{-5}\ Pa\,s$
$\mu_w = 5.2 \cdot 10^{-4}\ Pa\,s$
Injection rate: $Q_{nw} = 552\ t/m/a$



Saturation criterion in one column



Influence of grid size, non-adaptive



Adaptive modelcoupling

5. Outlook

- Analysis of advantages and disadvantages of adaptive concept.
- Include hysteresis in the model.
- Test concept for field scale case of underground energy storage.

References

[1] J.M. Nordbotten and M.A. Celia.
Geological Storage of CO2.
John Wiley and Sons, New York, 2011.

[2] Kilian Weishaupt, Martin Beck, Beatrix Becker, Holger Class, Thomas Fetzer, Bernd Flemisch, Georg Futter, Dennis Gläser, Christoph Grüninger, Johannes Hommel, Alexander Kissinger, Timo Koch, Martin Schneider, Natalie Schröder, Nicolas Schwenck, and Gabriele Seitz.
DuMuX 2.9.0, March 2016.