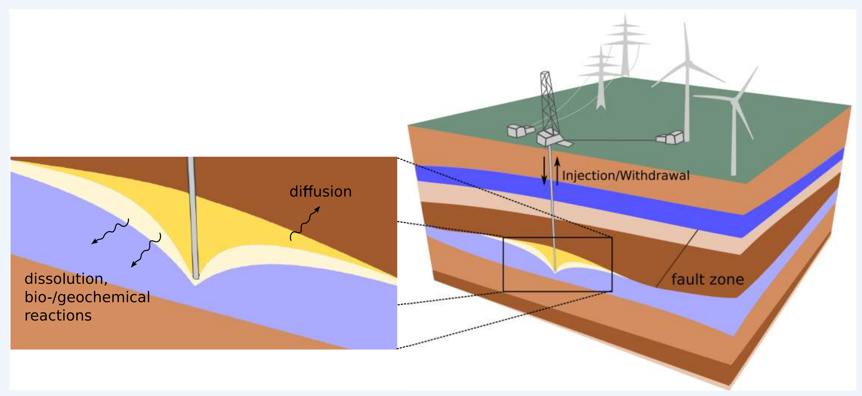
Evaluation of the coupling of a full-dimensional multiphase model to a vertical equilibrium model

Beatrix Becker[1,2], Bo Guo[2], Michael A. Celia[2], Karl W. Bandilla[2], Bernd Flemisch[1], Rainer Helmig[1]
[1]Department of Hydromechanics and Modeling of Hydrosystems, University of Stuttgart, [2]Department of Civil and Environmental Engineering, Princeton University.

1. Introduction

Underground energy storage is the main option for large scale energy storage, apart from pumped-hydro.



Underground storage system

Modeling challenges:

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

Here, we present a coupled model that applies:

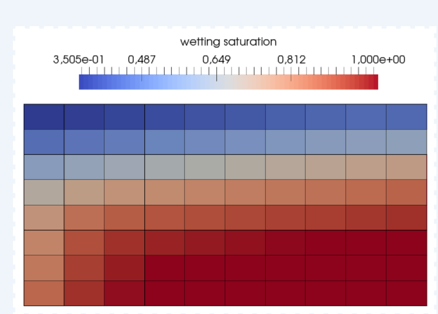
- a full-dimensional model in regions of higher complexity and where the vertical equilibrium assumption does not hold;
- a vertical equilibrium model in the rest of the domain.

2. Existing Models

2.1 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.

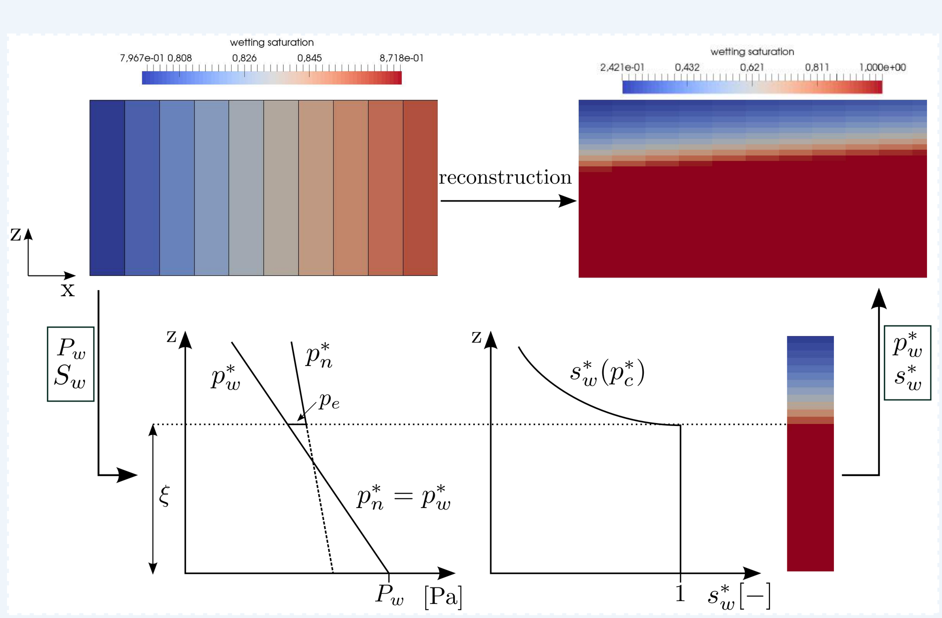


Full-dimensional saturation

2.2 Vertical equilibrium model:

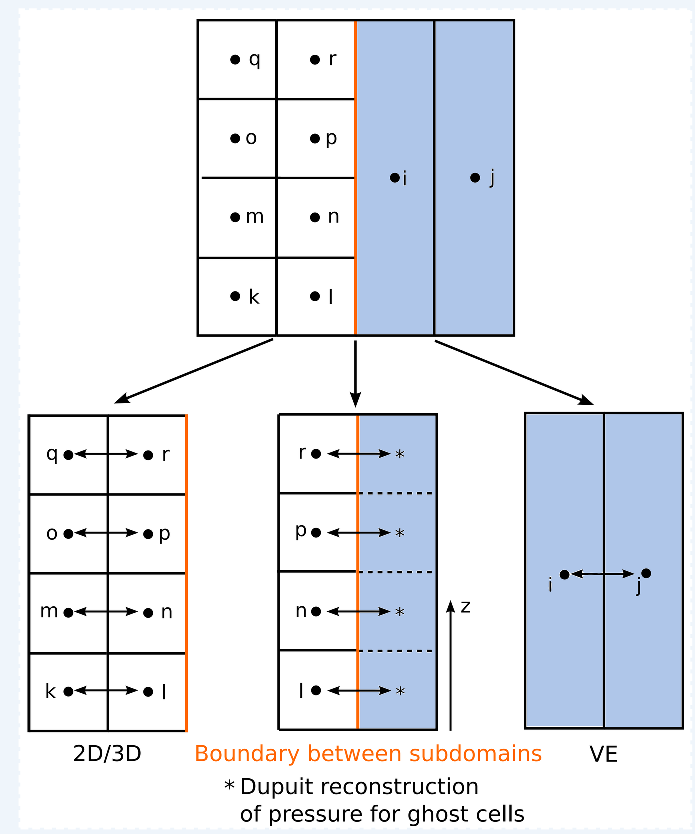
- Mass balance equation: $\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla_{\shortparallel} \cdot (\varrho_\alpha \mathbf{U}_\alpha) = \varrho_\alpha \Psi^\alpha,$
- Darcy's law: $\mathbf{U}_\alpha = -\mathbf{K}\Lambda_\alpha(\nabla_{\shortparallel} P_\alpha - \varrho_\alpha \mathbf{G}),$

with vertically integrated variables and reference pressure.



Reconstruction of solution in vertical direction

3. Model Coupling

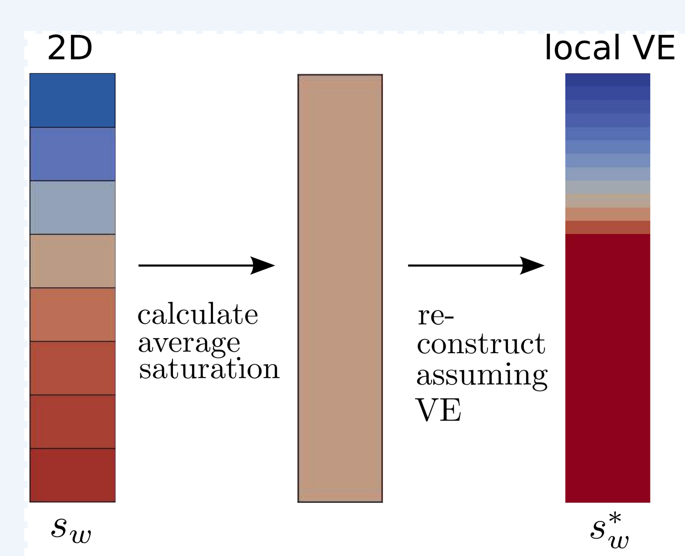


Coupling concept

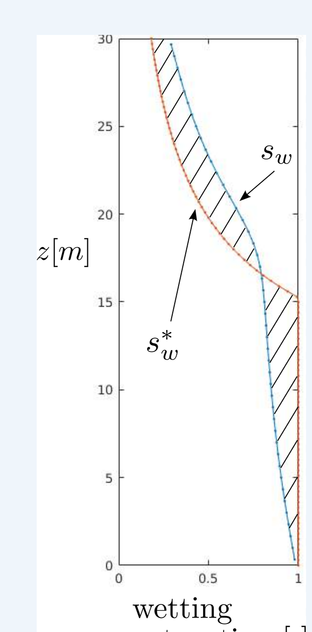
- Discretized mass balance equation (Finite Volume Method):
  $\sum_j q_{tot,ij} = \sum_j v_{tot,ij} a_{ij} = q_{tot,i},$
  with source/sink $q_{tot,i}$.
- Total velocity from VE-cell i to 2D cell j:
  $v_{tot,ij} = -k\lambda_{tot}\left(\frac{p_{wj} - p^*_{wi}}{\Delta x} + f_n \frac{p_{cj} - p^*_{ci}}{\Delta x}\right).$
- Reconstructed pressures in VE ghost cells:
  $p^*_{wi} = P_{wi} - \varrho_w g z,$
  $p^*_{ci} = p_c(S_w).$
- 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 $\bar{s}^*_w$.
- IMPES-algorithm: saturation S_w in VE-cell, reconstructed saturation s^*_w and saturation in ghost cell $\bar{s}^*_w$ based on old time step.

4. Criterion for VE Applicability

- Local criterion to quantify conformity of the full-dimensional solution with the vertical equilibrium assumption.
- Calculated as the area between profiles (saturation or relative permeability) over z for each column.
- Full-dimensional profile determined based on simulation results, VE profile determined based on average saturation in column.



Construction of VE saturation profile



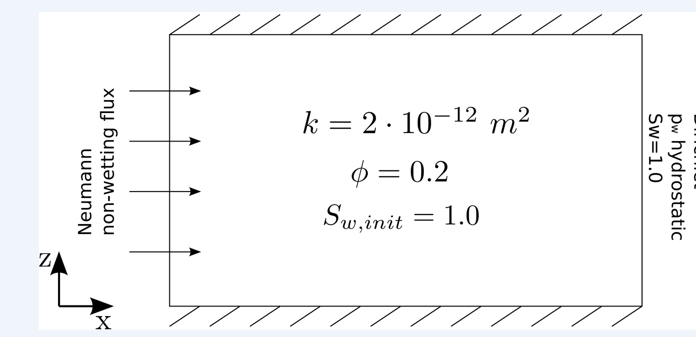
Area between profiles

The criterion is normalized by the aquifer height H:

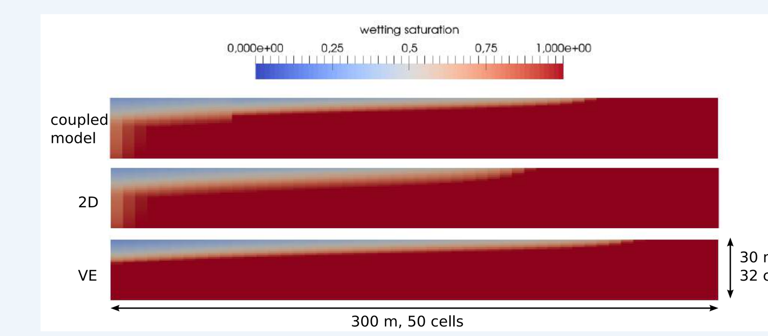
$$c_{sat} = \frac{\int_0^H |s_w - s^*_w| \mathrm{d}z}{H} < \epsilon_S,$$

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

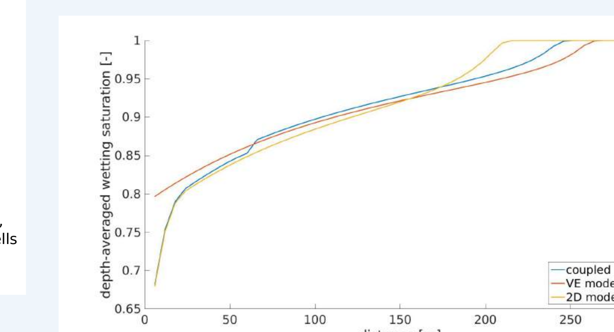
5. Results



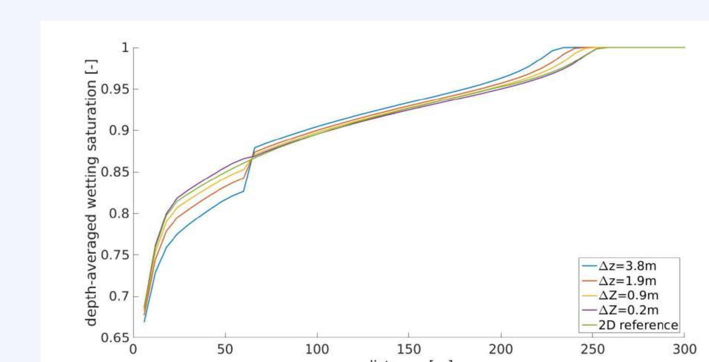
Brooks-Corey cap. pressure:
$\lambda = 2.0$, $p_e = 1 \cdot 10^5\ Pa$
Phase properties (CH_4, water):
$\varrho_n = 59.2\ kg/m^3$
$\varrho_w = 991\ kg/m^3$
$\mu_n = 1.2 \cdot 10^{-5}\ Pa\,s$
$\mu_w = 5.2 \cdot 10^{-4}\ Pa\,s$
Injection rate: $Q_{nw} = 552\ t/m/a$

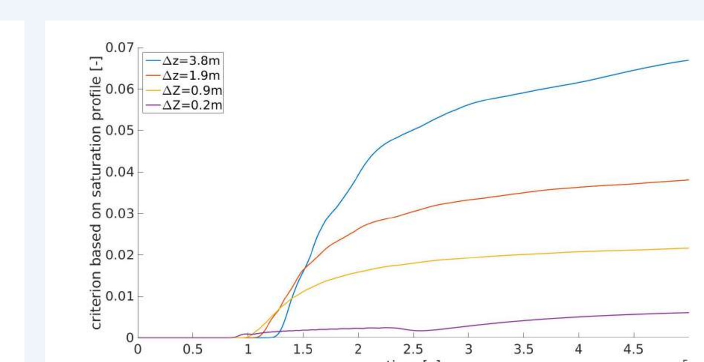


Saturation distribution after 6 days



Influence of grid size:





6. Summary and Outlook

Summary:

- A coupled model of VE and full-dimension is developed.
- A criterion for applicability of the VE model is developed and tested.
- The coupled model reduces computational effort significantly while maintaining accuracy.

Outlook:

- Implement adaptive boundary between model domains. Test adaptation criteria.
- Analysis of advantages and disadvantages of adaptive concept.
- Include hysteresis in the model.
- Test concept for field scale case of underground energy storage.

7. References

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