Modelling gravity-driven fingering in soils having an intrinsic non-zero contact angle (water repellent soils) using the innovative moving-boundary approach

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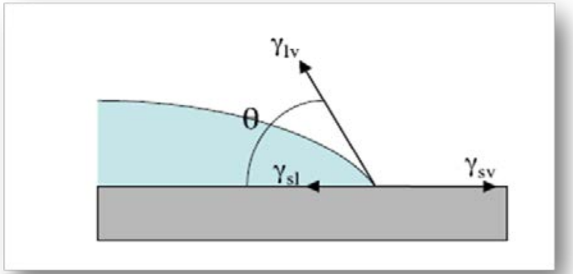
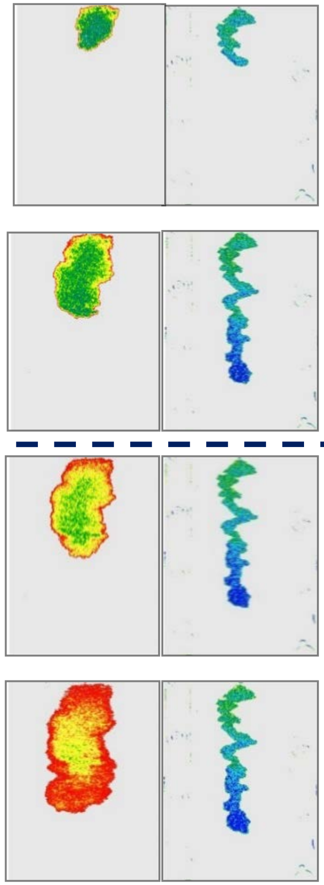
The contact angle was found to influence soil wetting pattern



Q= 1 ml min^{-1}

$\mathbf{CA = 33^0}$ $\mathbf{CA = 75^0}$



Wetting – 2 ml in the soil

Wetting – 5 ml in the soil

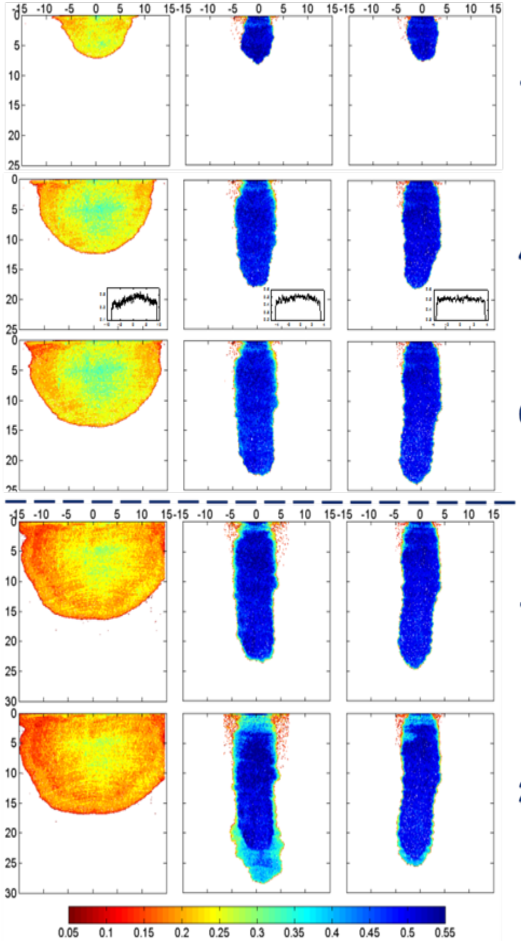
5 min Redistribution

50 min Redistribution

Wallach et al.(2013) WRR

Q = 1 ml min^{-1}

wettable | slightly repellent | strongly repellent



15 min Infiltration

45 min Infiltration

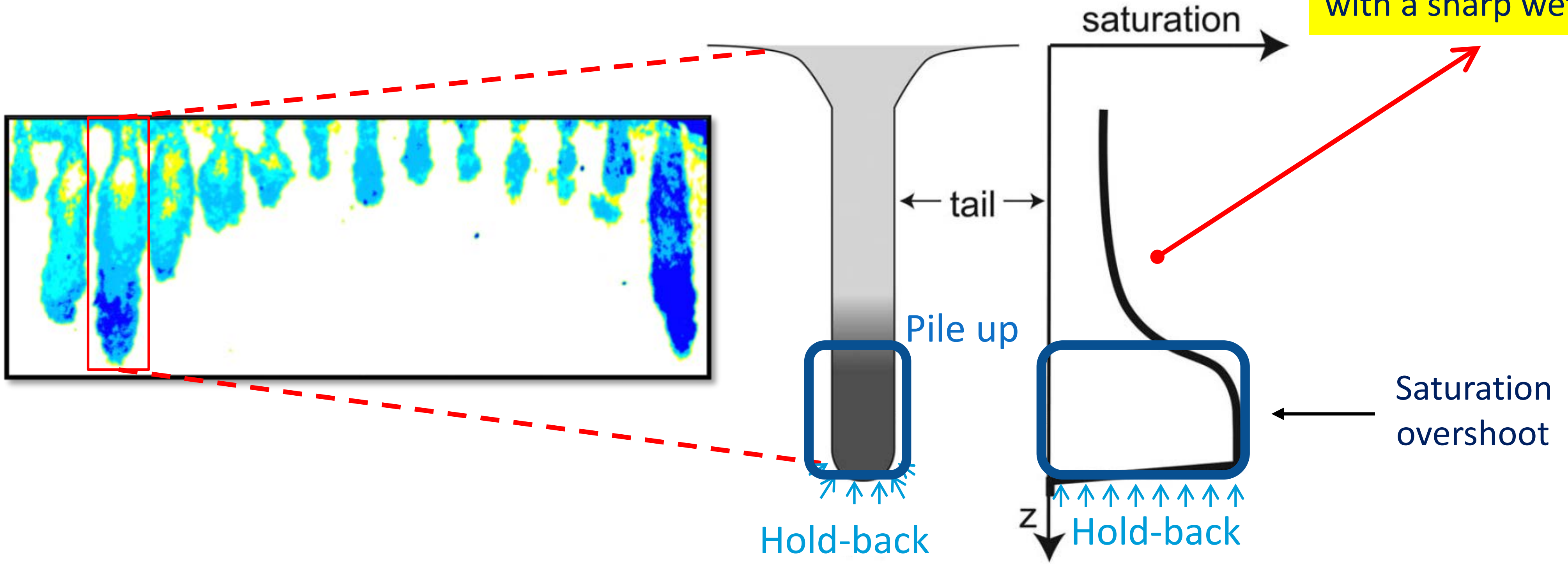
60 min Infiltration

1 h redistribution

2 and 10 h redistribution

Xiong et al.(2011) J. Hydrol.

Saturation overshoot is formed in gravity-driven unstable flow



Can Richards equation predict such non-monotonic water content profile with a sharp wetting front?

No

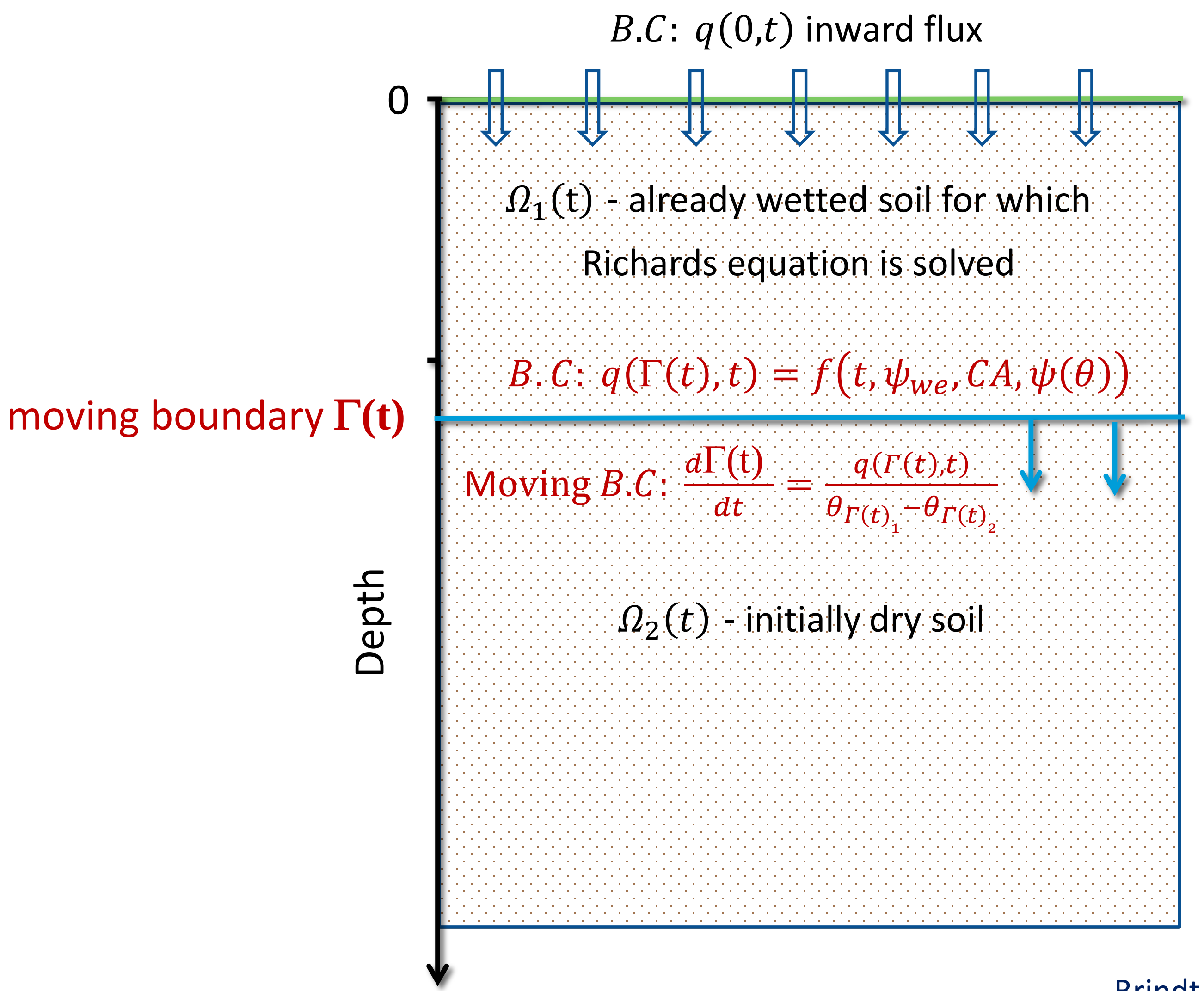
DiCarlo (2004) WRR

The moving – boundary approach to model the wetting front propagation in soils of non-zero contact angle

The moving boundary approach divides the flow domain into two sub-domains:

1) **$\Omega_1(\mathrm{t})$ - Above the moving wetting front, Γ(t)** , where Richards equation is solved for the upper boundary condition and a non-stationary wetting front.
2) **$\Omega_2(\mathrm{t})$** - **Below the moving wetting front, Γ(t)** .

The moving boundary (wetting front) location, Γ(**t**), is determined as part of the simultaneous solution for both domains.



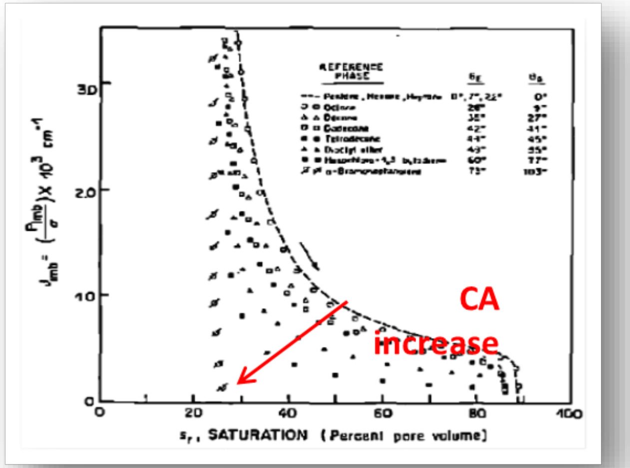
Brindt and Wallach, *WRR* 2017, 2020

The pressure-saturation relationship dependence on the CA and water flux

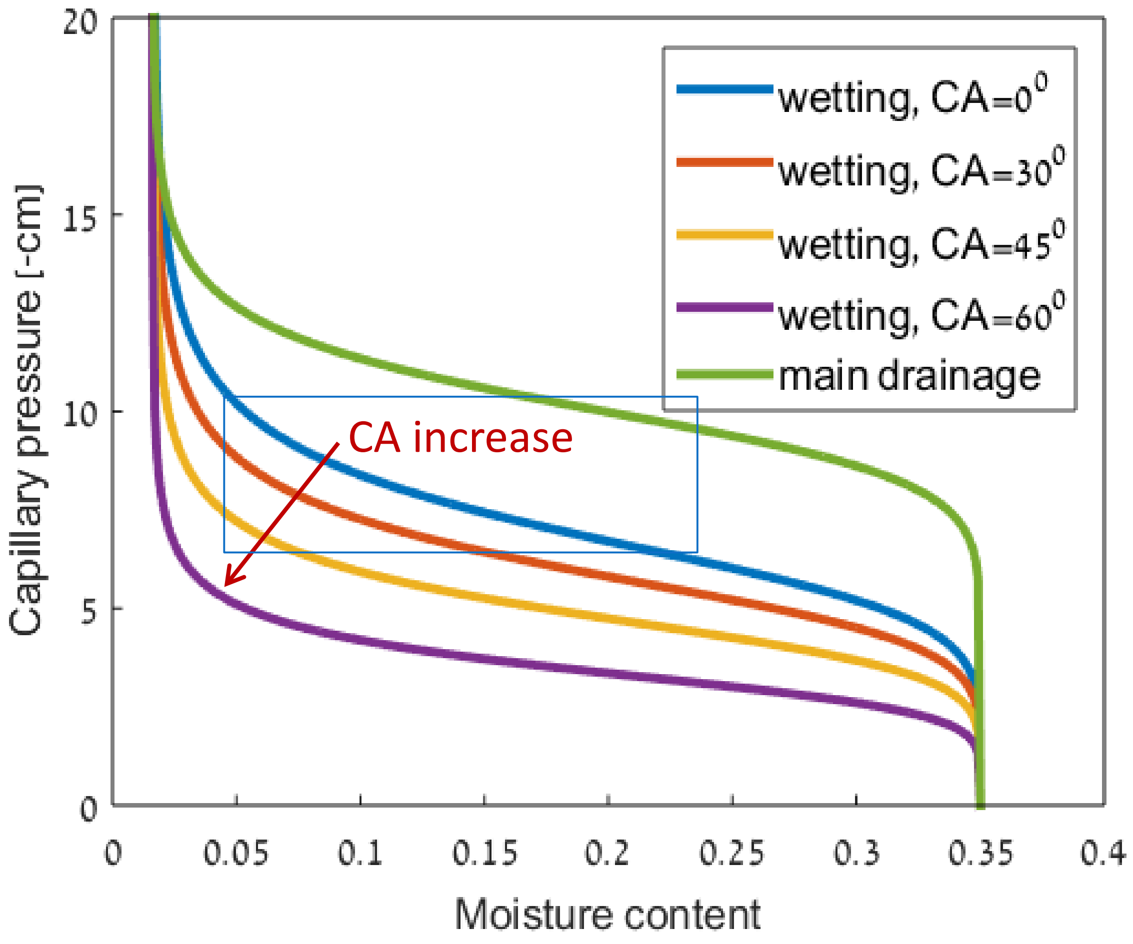
Incorporating the CA into VG model

(Bachman et al., [2007]:

$$\theta = \theta_r \frac{\theta_S - \theta_r}{\left(1+\left|\frac{\alpha_w \psi}{\cos(CA^0)}\right|^{n_w}\right)^{m_w}}$$



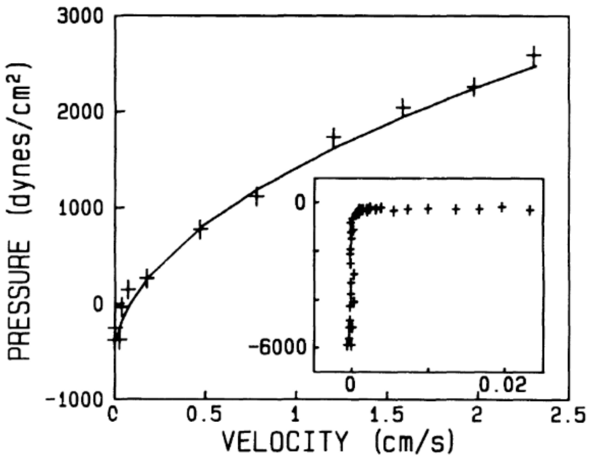
Morrow (1976) J. Can. Pet. Tech

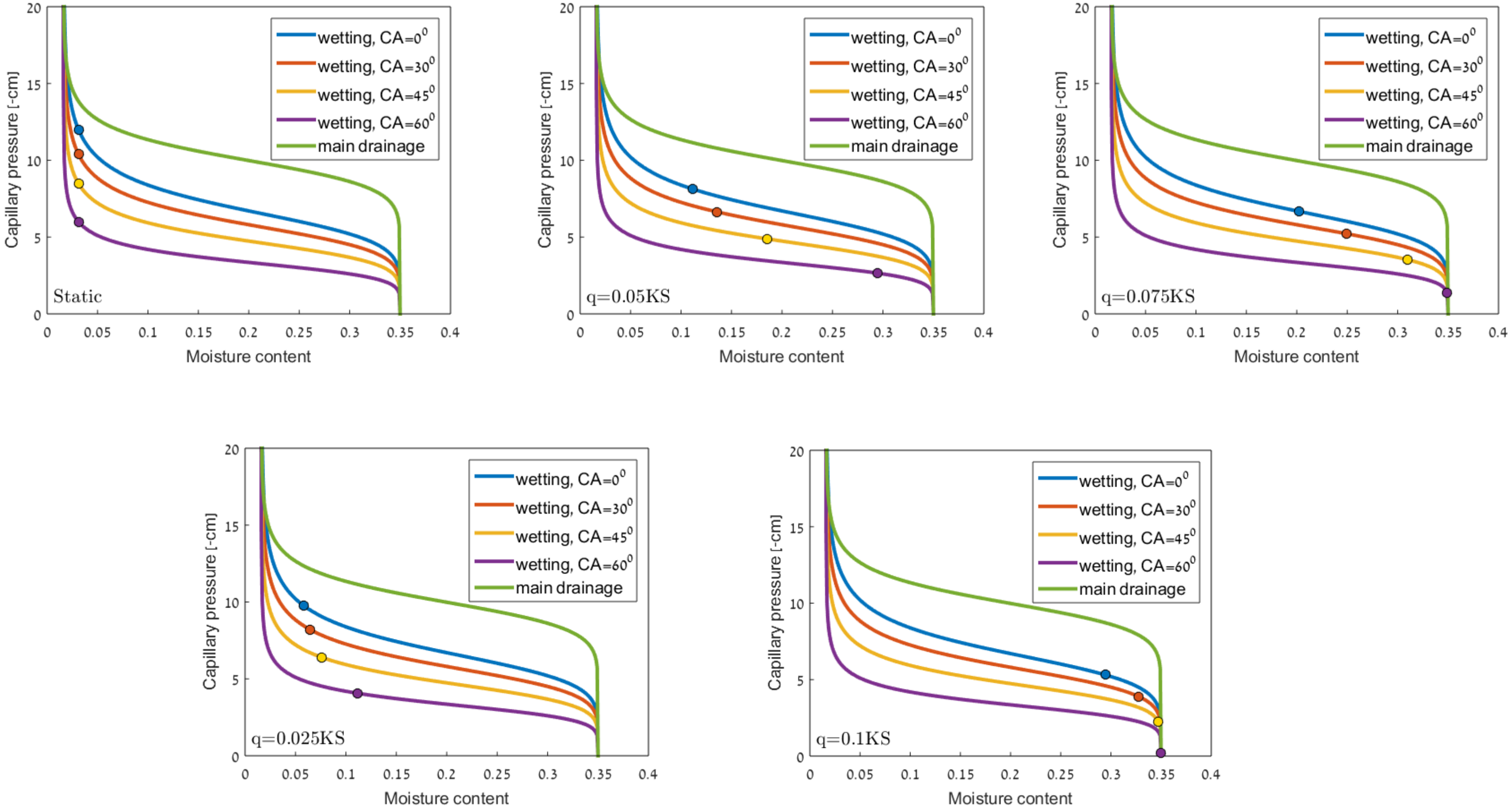


The water flux and CA effect on the pressure-saturation relationship at the moving wetting front

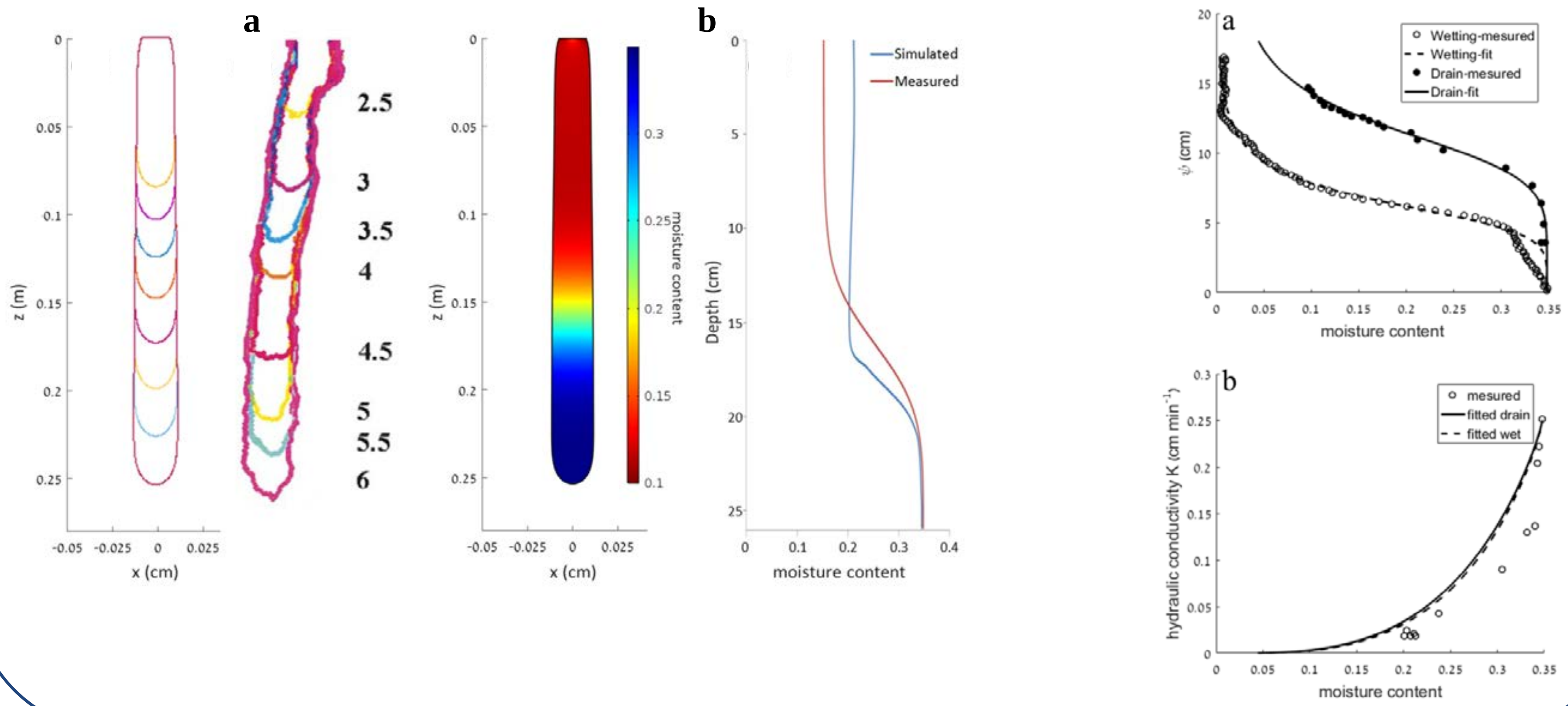
Weitz [1987] model:

$$\psi = \psi_{wa} cos(CA) \left[1 - a \left(\frac{N_{ca}}{cos(CA)} \right)^{\beta} \right]$$





Verification of the moving-boundary model by comparison to the experimental study of Bauters et al. (2000)



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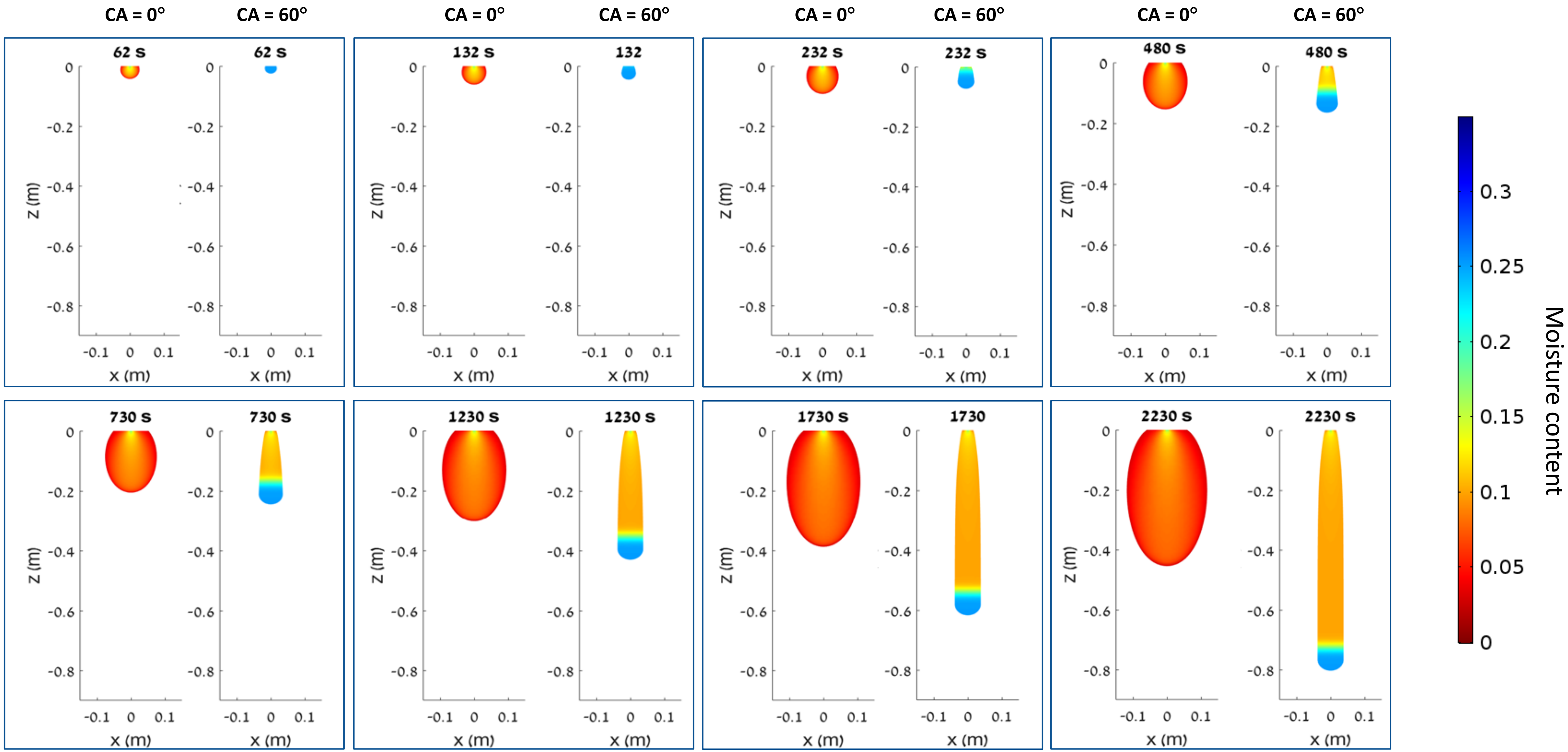
Time course of 2-D plume development in wettable and sub-critical water repellent soils



Plume shape dependence on contact angle, θ, and inlet dimensionless water fluxes (q/Ks)

- Unstable flow can be formed for low Ca’s and high fluxes
- As CA increases, unstable flow is formed for lower flux
- Stable flow was formed even for CA = 60°, but under a very low flux of q/KS = 0.1

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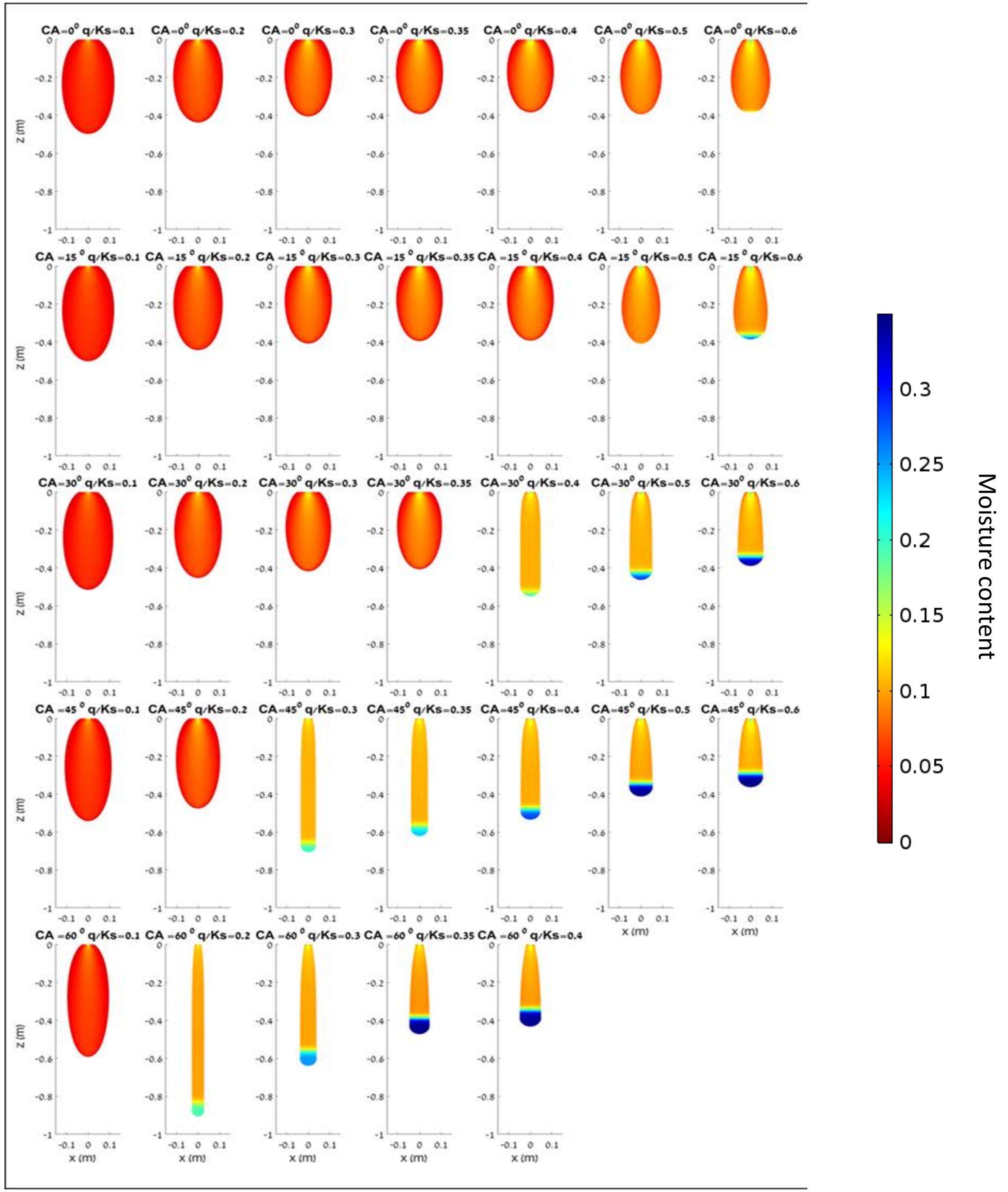
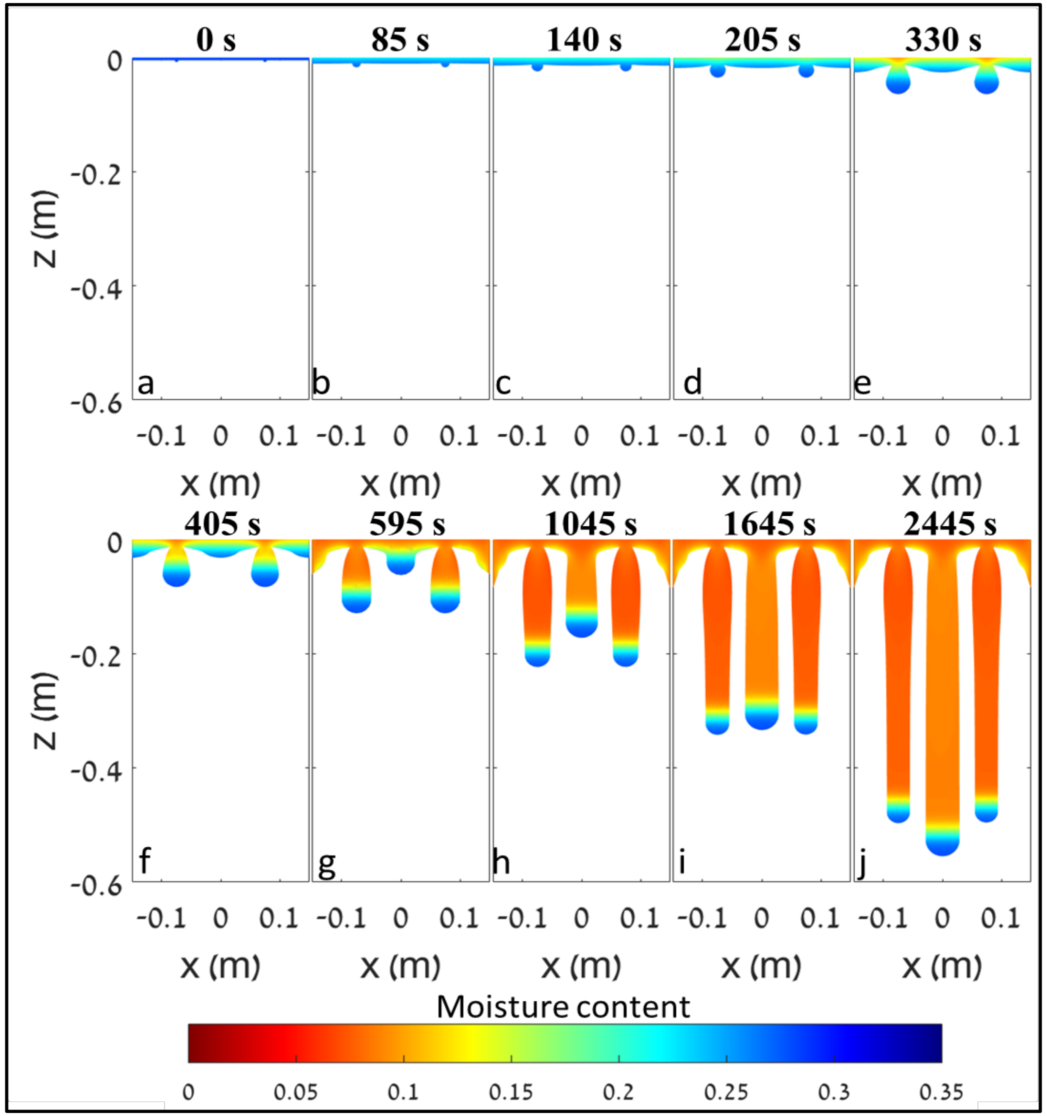


Formation of secondary fingers – moving boundary modelling approach

Simulated moisture-content distribution profiles for gravity-driven fingers generation from a nearly horizontal wetting front. The dimensionless flux at the surface was 0.06. The pressure–saturation relationship for $\theta = 45^{o}$ was used in the moving-boundary model.

While flow above the perturbation converges into the two growing fingers, the wetting flow propagation at the fingers vicinity decreases, and an area of high water content is gradually developing between the two fingers. This area spontaneously develops into a local perturbation that progressively turns into a new gravity-induced finger that includes a saturation overshoot at its front.



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Conclusions

- 2-D gravity-driven fingers are simulated using physically-based equations that follow the moving-boundary approach.
- The moving-boundary approach, after verification with experimental studies, was used to model stable and gravity-driven unstable flow alike in wettable and sub-critically water repellent soils.
- The moving-boundary simulations of non-zero contact angles verify the assumption that the latter is the cause for the "hold-back" through its effect on the static and dynamic water-entry value
- The model predicts, similar to observed results, saturation overshoot and a sharp wetting front for1D and 2D flow that depend on the CA and income water flux.
- To the first time a model determines the dependence of finger dimension and internal water-content distribution on the combined effect of contact angle and influx.
- A spontaneously generated a new perturbation between the already formed fingers forms a new gravity-induced finger having a larger width and that propagates faster than the original fingers.

Thanks

Questions are welcome