On wettability and unstable flow in porous media

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It is well known that flow in water-repellent soils ($\theta \geq 90^0$) takes place in distinct preferential flow pathways.

Fingering due to unstable flow were also observed in wettable soils.

The contact angle in wettable soils is normally assumed zero and so do models used to simulate flow in wettable soils.
Preferential flow in water-repellent soils

Irrigated orchard – ERT measurements

Tap water irrigation – wettable soil

Effluent irrigation – water repellent soil

Wessolek et al., 2008, EJSS
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Moisture content visualization of finger formation and persistence in a sand slab (Glass et al., 1989).

Wetting front taken at different times (a–f) during redistribution in dry sand and (g–l) during second cycle of redistribution with fingers in the sand (Wang et al., 2003).
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Fingering due to unstable flow were also observed in wettable soils.

Contact angles in wettable soils are normally assumed zero and so do models used to simulate flow in these soils.
Ensuing questions

- Does finger generation and persistence controlled by the contact angle $0^\circ < \theta < 90^\circ$ between the water and soil (sub-critical repellent soils)?
- If yes, how do fingers formed and expand in these media?
Materials

- Model substrates: modified and un-modified 0.3-0.5 mm quartz dune sand. The modification of the quartz particles was obtained by silylation which induces stable contact angles of varying degrees (S100 – 35°, S450 – 48°, S1000 – 56°, and S1500 – 73°).

- Sandy soil from Safariya Citrus Orchard (sieved to <0.5 mm) that rendered water repellent by prolonged irrigation with treated wastewater
Flow chamber and a CCD camera

- Transparent flow chamber, 25-cm high, 15-cm wide, and 0.5-cm thick (inner dimensions) for the quartz runs and 32.5-cm high, 30-cm wide, and 0.8-cm thick (inner dimensions) for the repellent soil runs.
- CCD camera (1920 × 1080 pixels, 8 fps).
- Water was applied at different rates to the soil surface as a point source; 5 ml for the quartz and 60 ml for the repellent soil.
Flow chamber runs

1 ml/min

S100

S1500
Wetting – 2 ml in the soil

Wetting – 5 ml in the soil

Redistribution – 5 min

Redistribution – 50 min

S-100 ($\theta \approx 33^0$)
Wetting – 2 ml in the soil

Wetting – 5 ml in the soil

Redistribution – 5 min

Redistribution – 50 min

S-1500 (θ ≈ 75°)
### S-100 ($\theta \approx 30^0$) and S-1500 ($\theta \approx 75^0$)

<table>
<thead>
<tr>
<th></th>
<th>S100 Q=1 ml/min</th>
<th>S1500 Q=1 ml/min</th>
<th>S100 Q=15 ml/min</th>
<th>S1500 Q=15 ml/min</th>
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</thead>
<tbody>
<tr>
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<td><img src="wetting_s1500.png" alt="Image" /></td>
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<td>- 2 ml in soil</td>
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<tr>
<td>- 5 ml in soil</td>
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<tr>
<td>Redistribution</td>
<td><img src="redist_s100.png" alt="Image" /></td>
<td><img src="redist_s1500.png" alt="Image" /></td>
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<td><img src="redist_s1500_15ml_50min.png" alt="Image" /></td>
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</tbody>
</table>
Infiltration to wettable and water repellent soils
Flow chamber study for wettable and water repellent soils (Xiong, Furman, Wallach, 2012)

**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

**Q = 5 ml min⁻¹**
- wettable
- slightly repellent

3 min Infiltration

9 min Infiltration

12 min Infiltration

1 h redistribution

2 and 10 h redistribution
Vertical cross-section along the plumes’ center

- **S100 1ml/min**
  - Depth (pixels): 0, 100, 200, 300, 400, 500, 600, 700
  - Volumetric water content (-): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5
  - Graph showing end of wetting (5 min) and 50-min redistribution

- **S100 10 ml/min**
  - Depth (pixels): 0, 100, 200, 300, 400, 500, 600, 700
  - Volumetric water content (-): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5
  - Graph showing end of wetting (0.5 min) and 50-min redistribution

- **S1500 1ml/min**
  - Depth (pixels): 0, 100, 200, 300, 400, 500, 600, 700
  - Volumetric water content (-): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5
  - Graph showing end of wetting (5 min) and 50-min redistribution

- **S1500 10 ml/min**
  - Depth (pixels): 0, 100, 200, 300, 400, 500, 600, 700
  - Volumetric water content (-): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5
  - Graph showing end of wetting (0.5 min) and 50 min redistribution
Vertical cross-section along the plumes’ center

S100 1ml/min

Volumetric water content (-)

Depth (pixels)

S100 10 ml/min

Volumetric water content (-)

Depth (pixels)

S1500 1ml/min

Volumetric water content (-)

Depth (pixels)

S1500 10 ml/min

Volumetric water content (-)

Depth (pixels)

Cartoon of a preferential flow path and the associated saturation within the flow path. Saturation overshoot occurs when the tip saturation is greater than the tail saturation.
Vertical cross-section along the plumes’ center
Plumes elongation during wetting and redistribution
S-450 ($\theta \approx 48^0$) and S-1000; $\theta \approx 56^0$
(b) Contact angle hysteresis at a rough surface

**FIGURE 3** — Values of advancing ($\theta_A$) and receding ($\theta_R$) contact angles observed at rough surfaces, versus intrinsic contact angle, $\theta_E$. From: Morrow, 1976
(c) Hysteresis in capillary rise due to contact angle hysteresis.

(a) Hysteresis in capillary rise with interaction of contact angle and pore geometry in absence of contact angle hysteresis.

FIGURE 4 — Effect of contact angle on capillary pressure, core No. 1.

FIGURE 5 — Effect of contact angle on capillary pressure, core No. 2.

Morrow, 1976
The “bundle of capillaries” model

Editor’s note: Equations removed at request of author.
Hysteresis due to capillary wetting and dewetting - geometry and CA effects

\[ \theta = 0^0 \]

\[ \theta = 35^0 \]

\[ R(z) = R_0 \left[ 1 + A \sin \left( \frac{2\pi z}{BR_0} \right) \right] \]
The use of the capillary-bundle model for water flow in soil

- Capillary pressure $\psi$ (cm)
  - $n=4$
  - $n=2$
  - $n=1.5$

- Volumetric water content $\theta$
  - $n=4$
  - $n=2$
  - $n=1.5$

- Conductivity $K$ (cm/s)
  - $n=4$
  - $n=2$
  - $n=1.5$

- Wetting front position (cm)

- Time (sec)
Pore geometry and contact angle effects on the wetting front deceleration

Infiltration in bundle of sinusoidal capillaries at θ=0°
Pore geometry and contact angle effects on the wetting front deceleration
Pore geometry and contact angle effects on the wetting front deceleration
Pore geometry and contact angle effects on the wetting front deceleration
Saturation overshoot

20/30 Sand

Volumetric Water Saturation

Figure 5. Snapshots of the saturation profile versus depth for six different applied fluxes in initially dry 20/30 sand (Accusand) measured using light transmission. At the highest (11.8 cm/min) and lowest (7.9 × 10^{-4} cm/min) fluxes the profiles are monotonic with distance and no saturation overshoot is observed, while all of the intermediate fluxes exhibit saturation overshoot.

DiCarlo et al, 2010
Conclusions

Does finger generation and persistence controlled by the contact angle $0^\circ < \theta < 90^\circ$ between the water and soil (sub-critical repellent soils)?

Yes. The plumes turned to be narrow and longer with saturation overshoot behind the wetting front as contact angle increases.

If yes, how do fingers formed and expand in these media?

Contact angles increase the water entry value along the finger perimeter which hinders plume’s spontaneous propagation. As such, water accumulates behind the wetting front owing to a negative balance between the hindered wetting front propagation and the continuing water influx. Pressure is building up behind the wetting front and increases the wetting front velocity until a balance between the out- and influx is reached yielding a constant propagation velocity.

Higher application rates increase the pressure at the lateral wetting front of the plume which extends its expansion (dynamic water entry value).
Contribution: Michal Margolis
Qiuling Wang
Dr. Yunwu Xiong
Dr. Ellen Graber

Thanks