SANDY SOILS GLOBAL CONFERENCE
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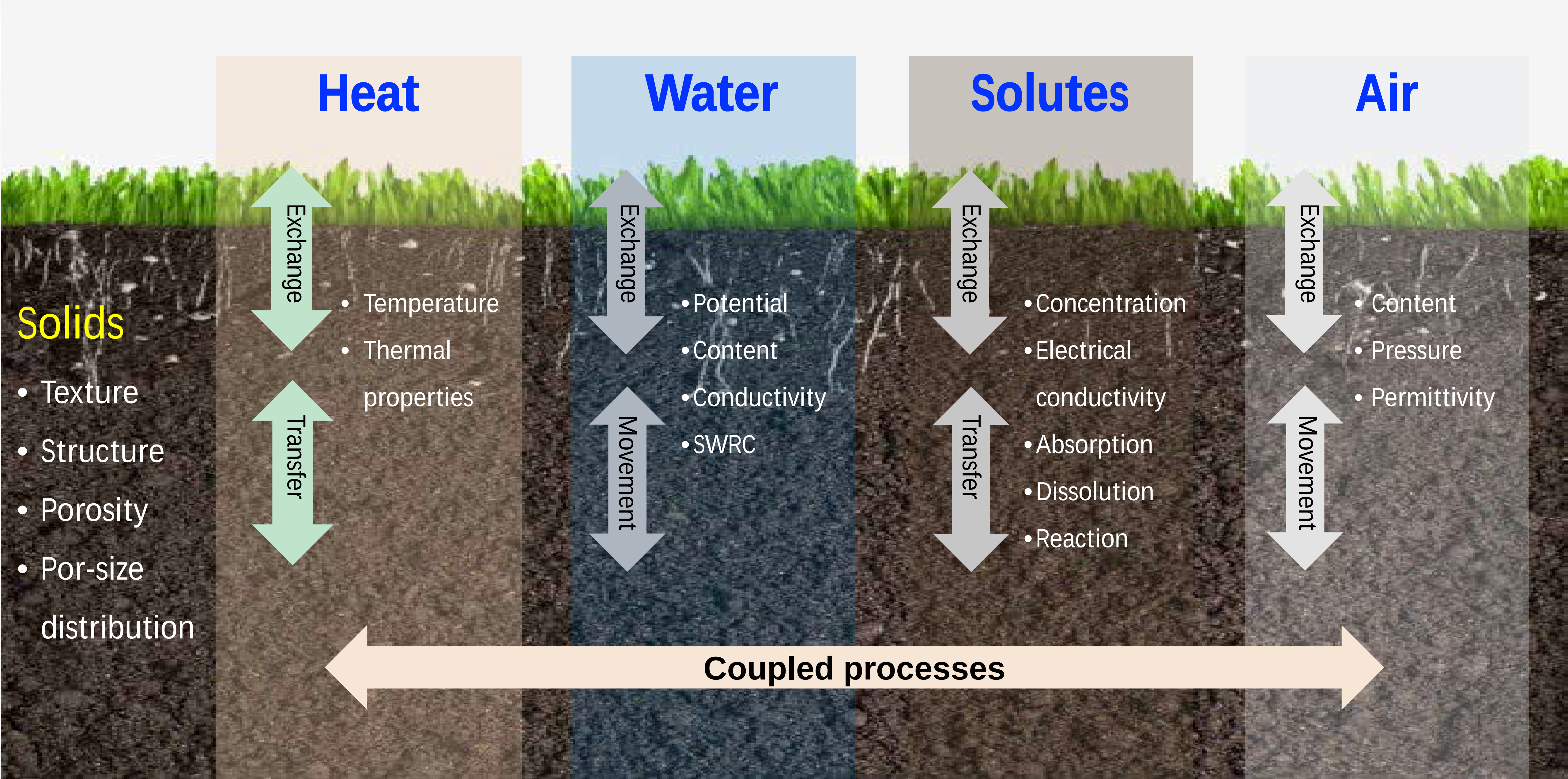
中国農業大學
China Agricultural University

A thermo-TDR approach for simultaneous determination of transport parameters of sandy soils

Lin Liu, Yili Lu, Tusheng Ren
China Agricultural University

Robert Horton
Iowa State University

Soil Physical Properties & Processes



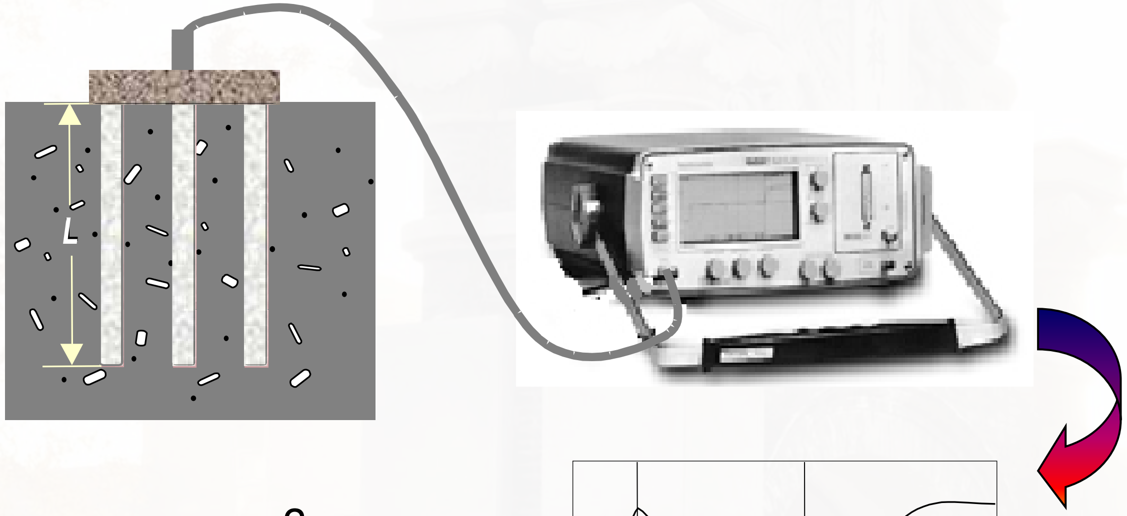
ü **Thermo-TDR technology**

ü **Thermo-TDR approach for monitoring soil water retention and gas diffusivity**

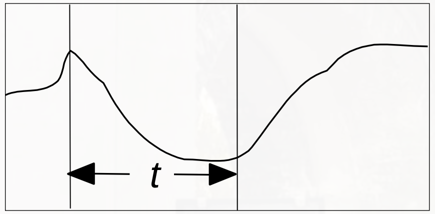
- **Theory**
- **Validation**

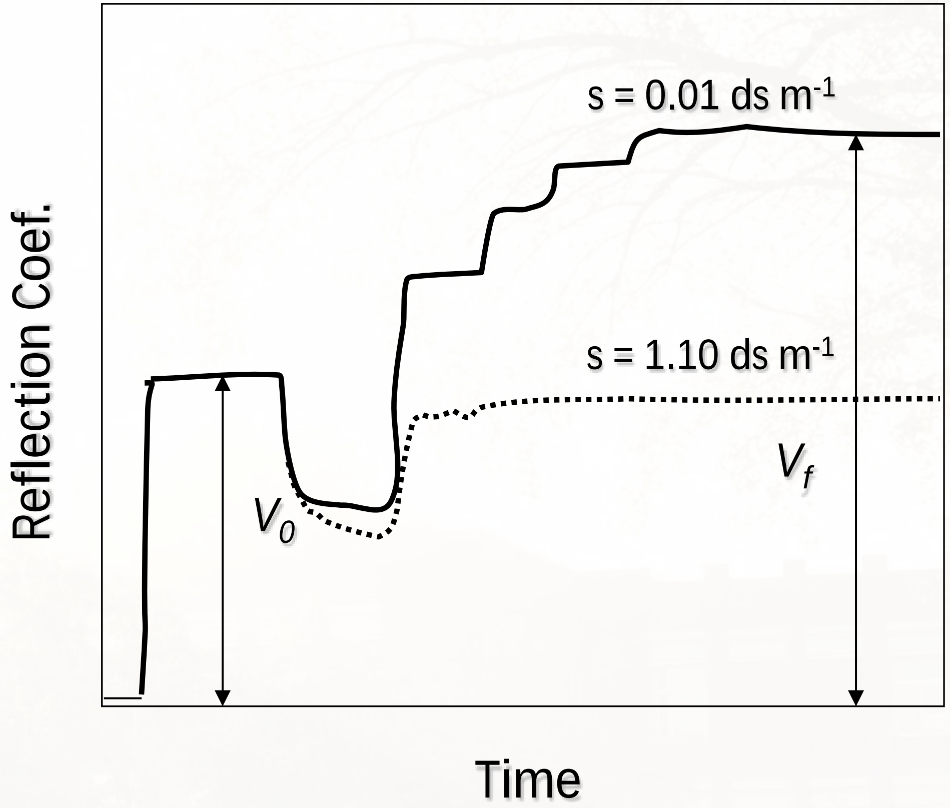
Thermo-TDR technology

TDR: monitoring soil water content and electrical conductivity



$$K_a = \left(\frac{ct}{2L}\right)^2$$





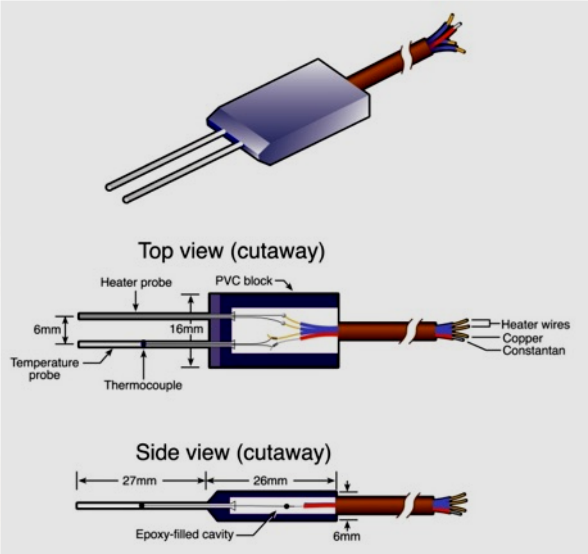
$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3$$

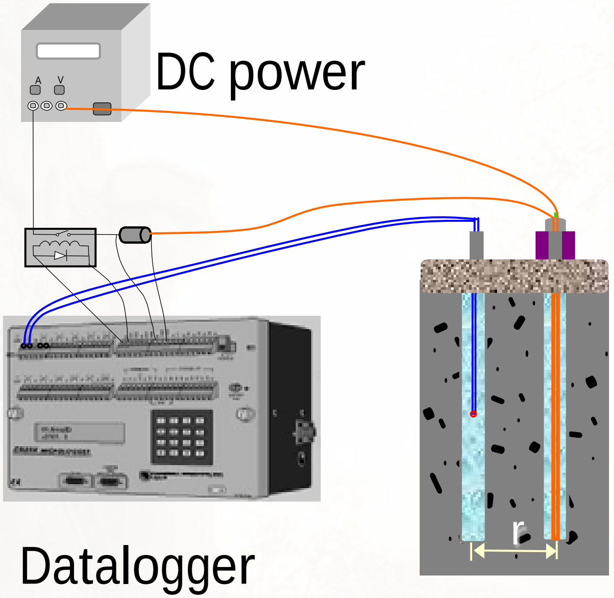
$$\sigma = \frac{K_a}{Z_u}\left[\frac{2V_0}{V_f} - 1\right]$$

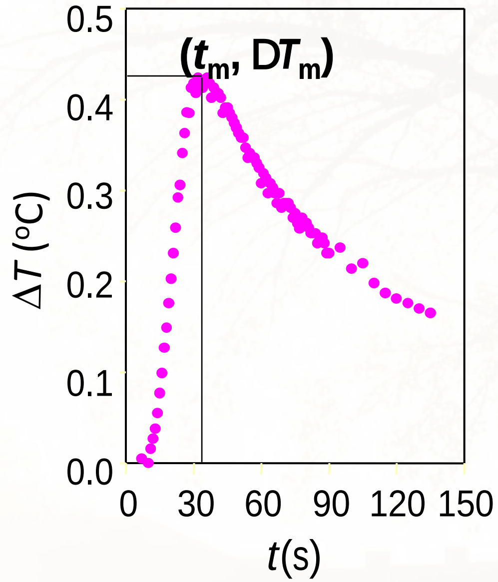
Topp et al. 1980. WRR. 16:579-582

Dalton et al. 1984. Science. 224:989-990

Heat pulse method: measuring soil thermal properties







$$C = \frac{q}{4\pi\alpha T_m}\left[Ei\left(\frac{-r^2}{4\alpha(t_m - t_0)}\right) - Ei\left(\frac{-r^2}{4\alpha t_m}\right)\right]$$

$$\alpha = \frac{r^2}{4}\left[\frac{1}{(t_m - t_0)} - \frac{1}{t_m}\right] \Big/ \ln\left[\frac{t_m}{(t_m - t_0)}\right]$$

$$\lambda = \alpha \times C$$

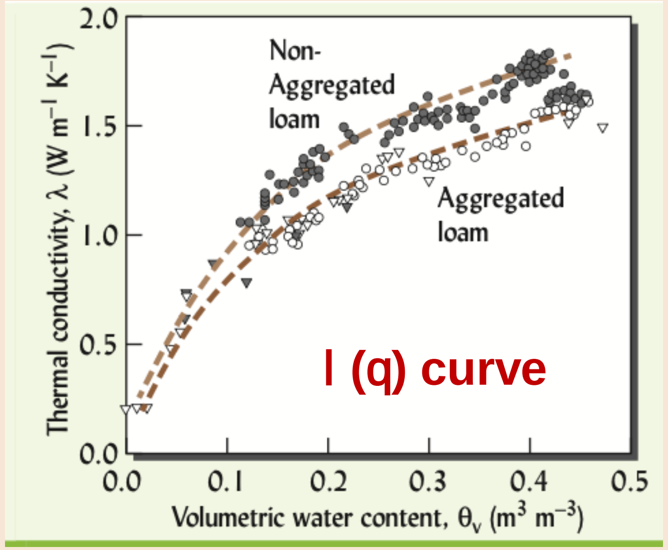
C: Volumetric heat capacity

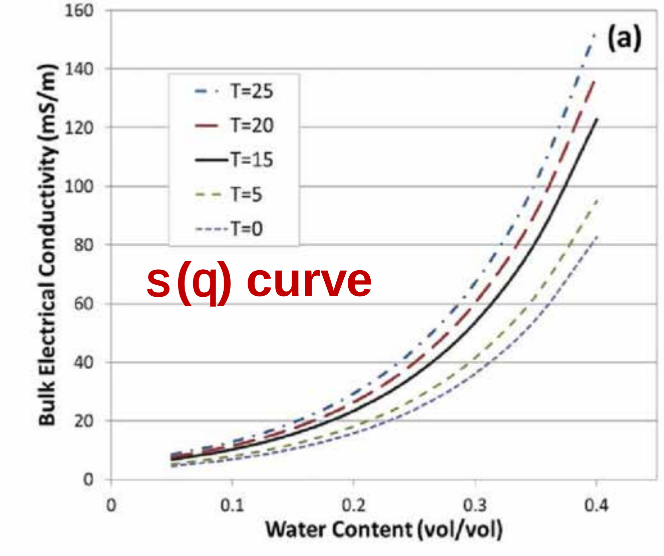
α: Thermal diffusivity

λ : Thermal conductivity

Campbell et al. (1991), Kluitenberg et al. (1993), Bristow et al. (1994)

Thermo-TDR technology: combining two units into one

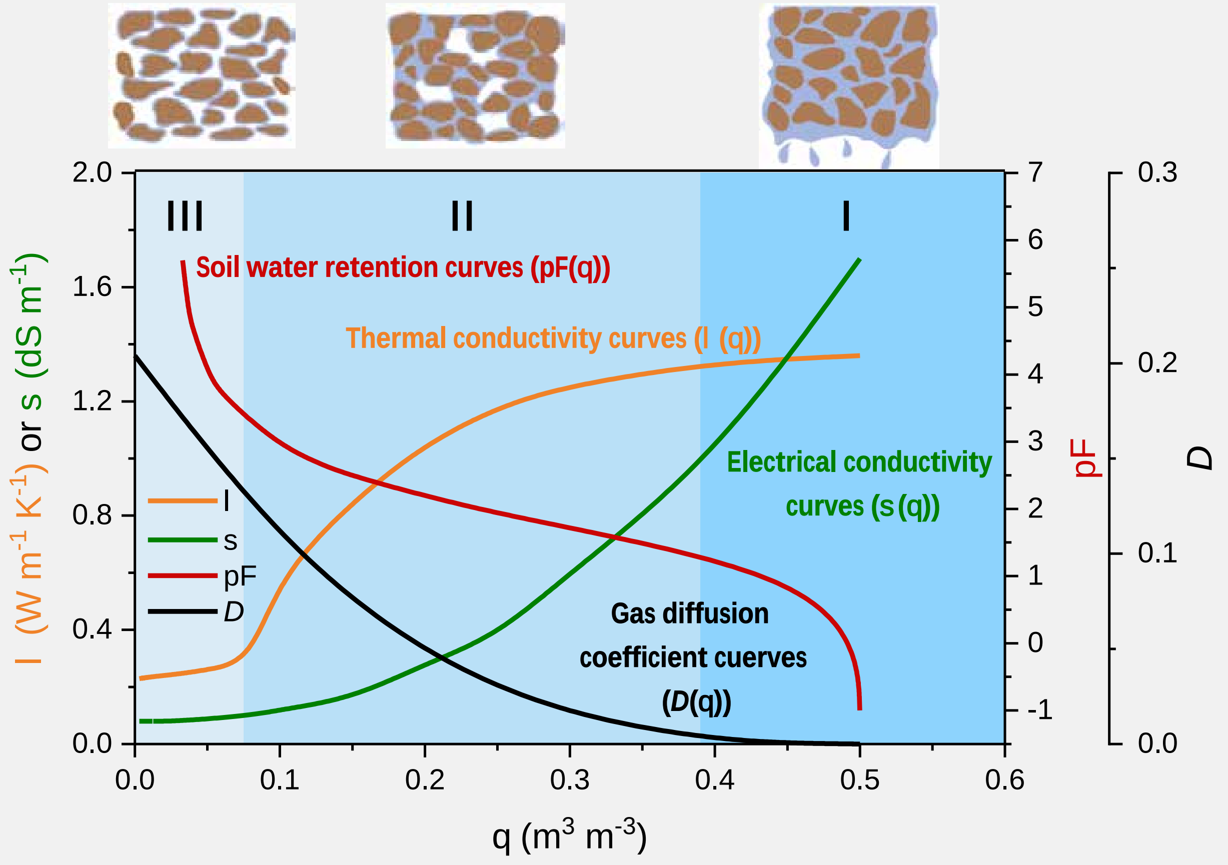




Ren et al (1999), Lu et al (2024)

Determining soil water retention and gas diffusivity: theory

Similarities between soil transport parameters



- The parameters have similarities in curve shapes;
- All curves are governed by water content and pore traits (determined by texture and bulk density).

ü **Measuring pF(q) & *D* (q):**

- Time and labor consuming
- Difficult to monitor in the field

ü **Measuring l (q) & s (q):**

- Relatively quick and simple
- In-situ monitored is possible with thermo-TDR sensors.

? How are the four curves correlated with each other?

? Is it possible to determine pF(q) and *D*(q) curves indirectly from easily measured l (q) and s (q) curves?

From l (q) curve to pF(q) curve

van Genuchten (1980)
Soil Sci Soc Am J

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + (\alpha pF)^{1/(1-m)}\right]^{-m}$$

θ_s: saturated water content
θ_r: residual water content
α, m: Soil specific parameters

Inputs

- Texture
- Bulk density: r_b
- Particle density: r_s
- Measured l (q) curve
- Field capacity (pF_{fc}, q_{fc})

q_s $\theta_s = 1 - r_b / r_s$

q_r $$\frac{\lambda - \lambda_{dry}}{\lambda_{sat} - \lambda_{dry}} = 1 - \left[1 + \left(\frac{\theta}{\theta_f}\right)^{1/(1-p)}\right]^{-p}$$

Lu & Dong et al (2015)
J Geotech Geoenviron Eng

a, *m* $$\frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r} = \left[1 + a(pF_{fc})^{1/(1-m)}\right]^{-m}$$

Liu et al (2024)
Soil & Till Res

From *h*(q) curve to *D* (q) curve

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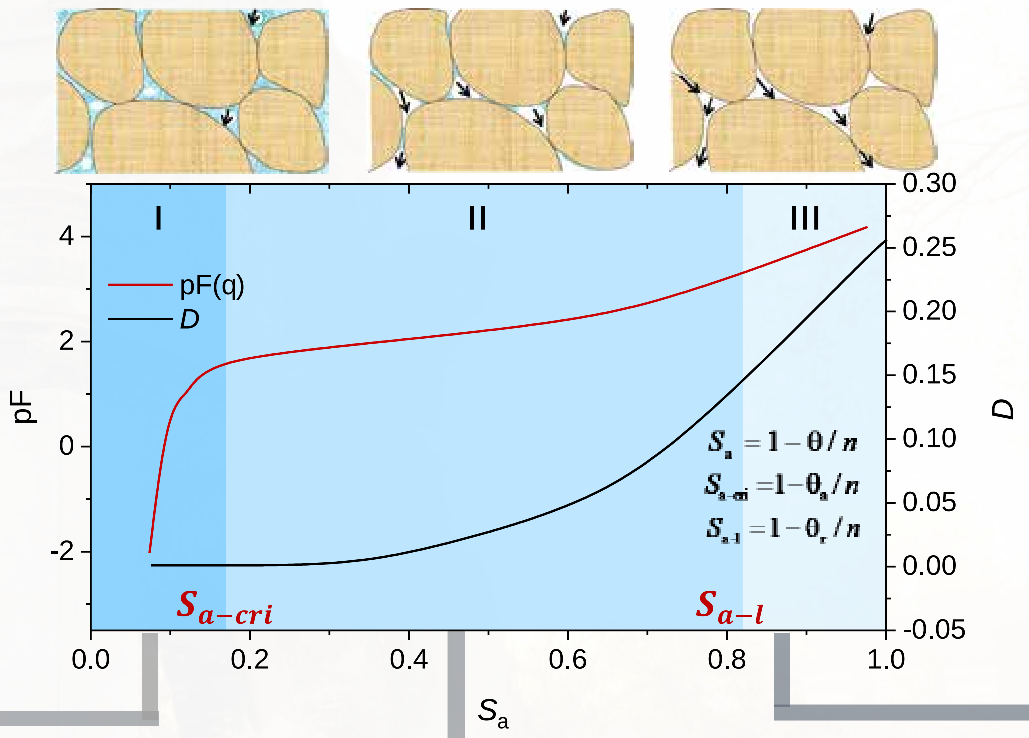

Section I ($0 < S_a \le S_{a-cri}$):

- pF increases dramatically with S_a
- Air diffusion strongly restricted in limited pore space

$D = 0.0001$ (very low, constant)

Section II ($S_{a-cri} < S_a < S_{a-l}$):

- More space for air diffusion
- pF, D increases exponentially with S_a

$$D = D_{dry} - b(1 - S_{a-l})\left(\frac{S_a - S_{a-cri}}{S_{a-l} - S_{a-cri}}\right)^c$$

Section III ($S_a \ge S_{a-l}$):

- Most pore space for air diffusion
- pF & D increases linearly with S_a

$$D = D_{dry} - b(1 - S_a)$$

Determination of model parameters

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$$D = \begin{cases} 0.0001 & \text{Section I} \\ \left[D_{dry} - b(1 - S_{a-l})\right]\left(\dfrac{S_a - S_{a-cri}}{S_{a-l} - S_{a-cri}}\right)^{c} & \text{Section II} \\ D_{dry} - b(1 - S_a) & \text{Section III} \end{cases}$$

Dividing points of degree of air saturation:

$$S_{a-cri} = 1 - {}^{\theta_a}/_{n}$$

$$S_{a-l} = 1 - {}^{\theta_r}/_{n}$$

Air-entry water content (q_a) and residue water content (q_r) are determined from the pF(q) curve.

Diffusion coefficient of dry soils D_{dry}:

$$D_{dry} = n^{X_{dry}}$$

X_{dry} is the particle shape factor, estimated by fitting the D_{dry} model to measured (n, D_{dry}) data.

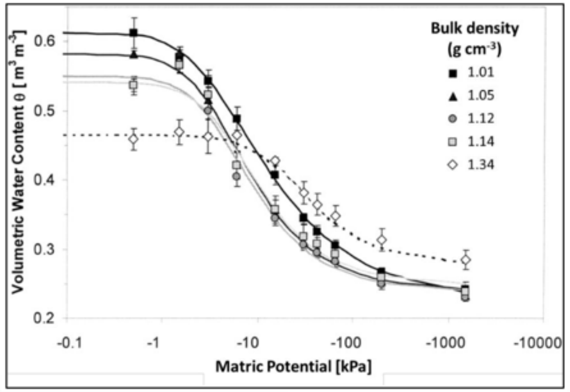
Parameters b and c:

Determined by fitting the above D(q) model to measured (S_a, D) data.

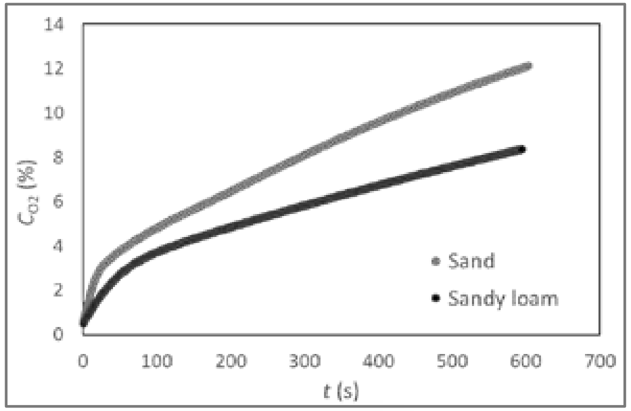
Determining soil water retention and gas diffusivity: validation

Measurement on repacked soil columns

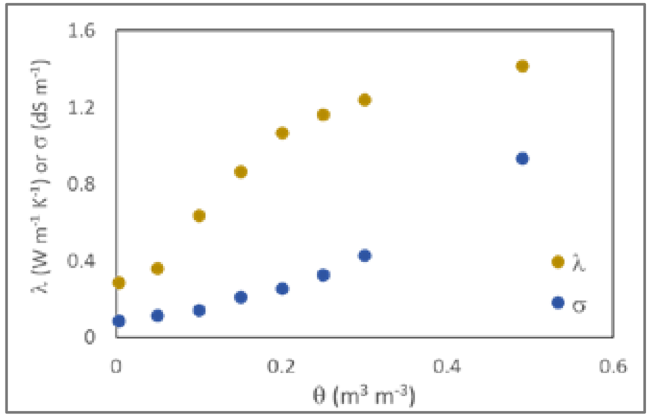
Sand:	sand - 94%, clay - 5%	r_{b}: 1.40, 1.50, 1.60 Mg m^{-3}
Sandy loam:	sand - 39%, clay - 1%	r_{b}: 1.35, 1.45, 1.55 Mg m^{-3}

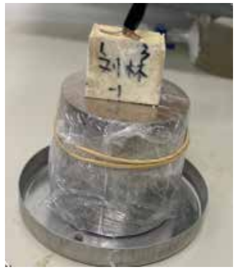


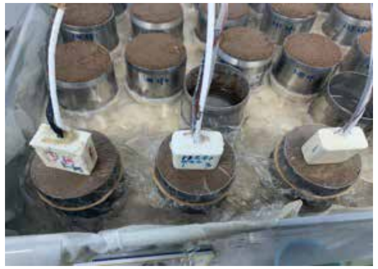
h(q)
Sand box, pressure plate



***D* (q)**
One-chamber method







l (q), s (q)
Thermo-TDR technology

Results: thermo-TDR Measured l (q), pF(q), *D* (q) curves

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ü **Thermal conductivity curve: l (q)**

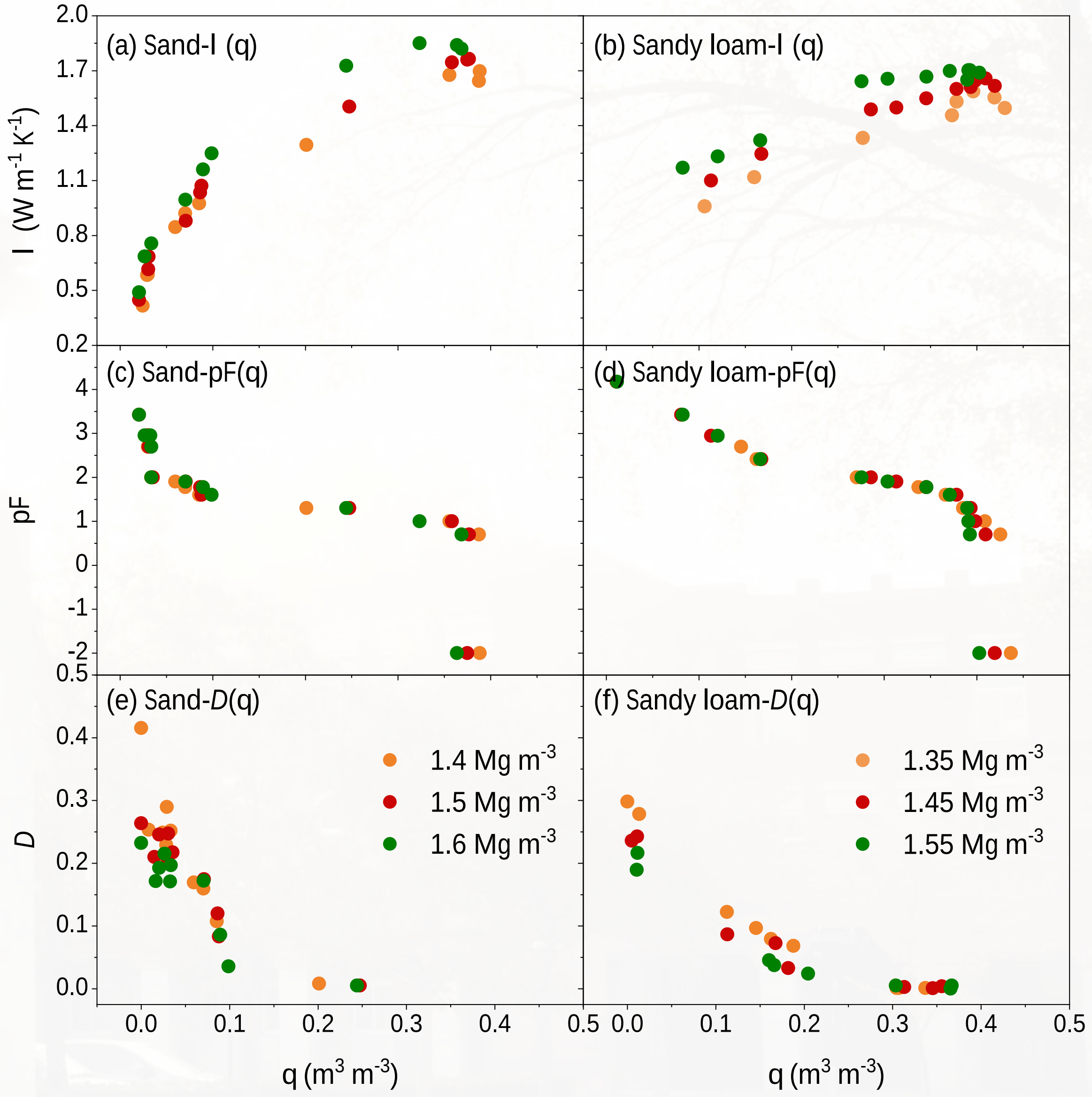
- l increases with both sand content and r_b
- At equivalent q, $l_{sand} > l_{sandy\ loam}$

ü **Water retention curve: pF(q)**

- Sand shows lower water retention capacity;
- r_b: slightly improves water retention, more pronounced in sandy loam.

ü **Gas Diffusivity: *D*(q)**

- Sand requires higher air content (lower q) to activate dominant air-phase diffusion;
- *D* decreases at greater r_b values, more severe in sandy loam.



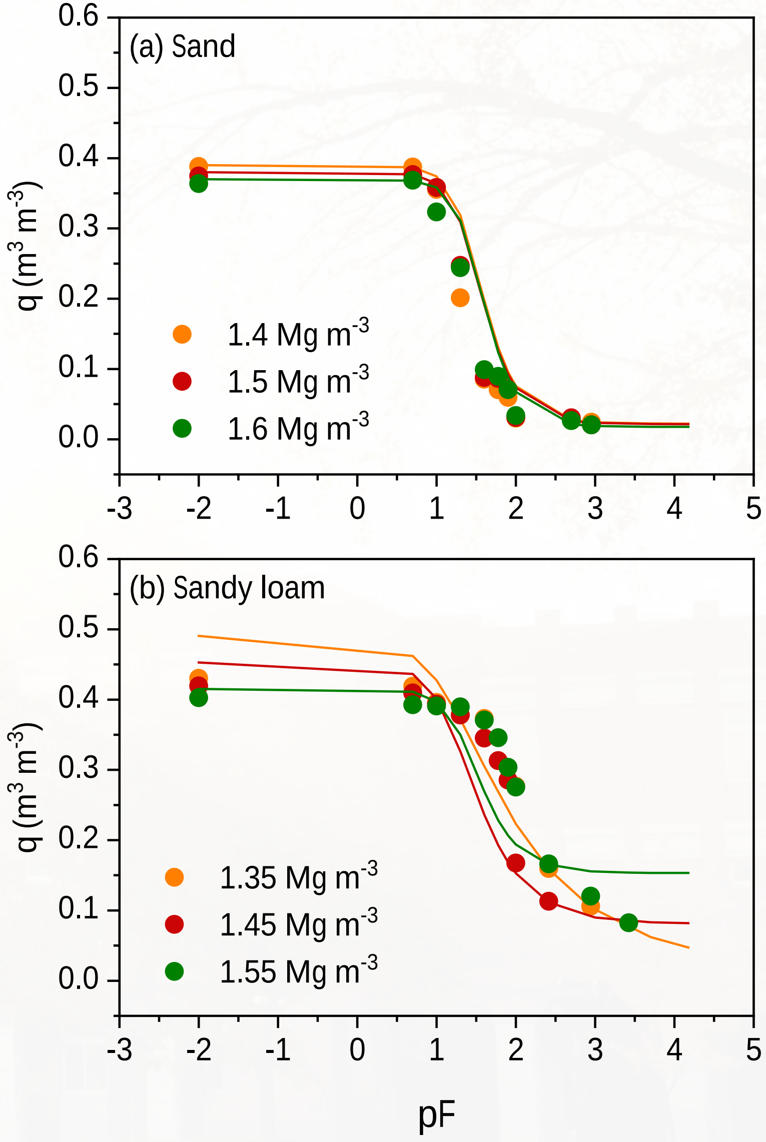
Results: pF(q) curve derived from l (q) curve

ü Model performance:

- Model fits the measured data well for both soils;
- Model is applicable for predicting water retention behavior under various bulk density and texture scenarios.

ü Model errors:

- Acceptable: RMSEs in estimated q: < 0.055 m^3 m^{-3};
- Slight overestimation near saturation.



Results: *D*(q) curve derived from pF(q) curve

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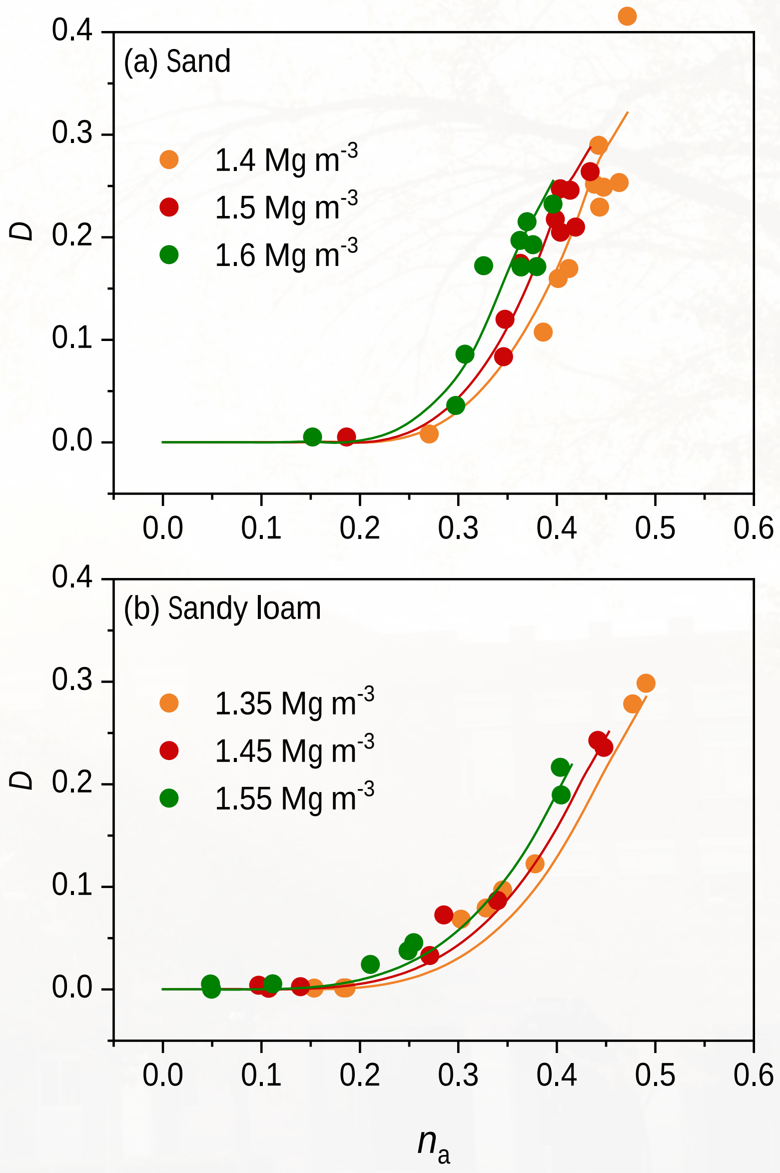
- **Performance:** Worked well for both soils across full range of air-filled porosities.
- **Errors:** RMSE of estimated *D* is low: 0.034 for sand and 0.017 for sandy loam.
- **Robustness:** Accurately captured the effect of bulk density on air diffusivity, as evidenced by the consistent downward shift of the curves with increasing bulk density.



Summary

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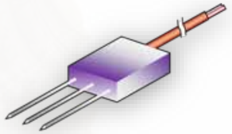
Thermo-TDR technique



State variables

T, q, K_a

Thermal & electrical properties

l (q), a(q), C(q), K_a(q), $\boldsymbol{s}$(q)

Fractions of solid, water, air

r $_b$, V_s, n_a, S

Soil processes

- Heat transfer
- Water movement
- Water evaporation
- Air movement
- Heat-water-solute-air processes

In situ soil properties

l (q), $\boldsymbol{s}$ (q) ⟶ pF(q), D(q)

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