Gas Diffusion-Derived Tortuosity Governs Saturated Hydraulic Conductivity of Sandy Soils

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Introduction

- Saturated hydraulic conductivity (K_{sat}, cm min^{-1}) is used in hydrological models to characterize water infiltration, surface run-off and to assess contaminant leaching.
- Gas diffusivity (D_p/D_0, where D_p and D_0 (cm^2 s^{-1}) are gas diffusion coefficients in soil and free air, respectively) is an accurate transport parameter representing pore tortuosity and connectivity, with potential for prediction of soil hydraulic properties.

Objectives

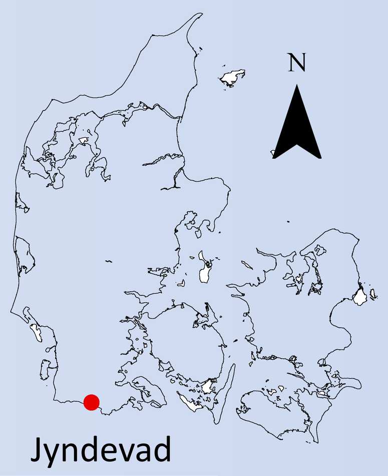
- To examine potential relationships between D_p/D_0 and K_{sat} from measurements on a high number of intact soil samples from a coarse sandy field.
- To quantify K_{sat}- D_p/D_0 descriptive model parameters as a function of matric potential condition for D_p/D_0 measurements.
- To evaluate the contribution of basic pore-network tortuosity (derived from D_p/D_0) to the overall cementation exponent (m) in classical K_{sat} predictive models.

Methods

Sampling

100 cm³

1. Top layer (0-20 cm)
2. 88 sampling points in a 15 x 15 m Grid



Particle size analysis on bulk soil

Sieving sizes:

90, 180, 250, 500, 1000, 2000 μm

Jyndevad	Mean	SD (%)	Min	Max
Clay (<2 μm, kg kg^{-1})	0.043	9.3	0.037	0.052
Silt (2-20 μm, kg kg^{-1})	0.049	10.2	0.040	0.060
Sand (50-2000 μm, kg kg^{-1})	0.908	0.55	0.878	0.919
d_{10} (μm)	0.908	0.6	0.878	0.919
d_{50} (μm)	158.1	11	105.7	187.1
d_{80} (μm)	547.5	6	467.6	638.0
OM (kg kg^{-1})	0.031	0.13	0.024	0.043
Total porosity (ϕ, Mg kg^{-1})	0.466	4	0.405	0.513
ε - pF 2.0 (cm^3 cm^{-3})	0.30	10	0.20	0.37
D_p/D_0 (pF 2.0)	0.074	5	0.027	0.101
K_{sat} (cm min^{-1})	0.47	36	0.13	1.07

Soil matric potential (Ψ = -30, - 100, -300, -1000 cm H_2O) on 100 cm³ soil cores

- Air-filled porosity (ε) at different pF
- pF= Log (- matric potential in cm H_2O)

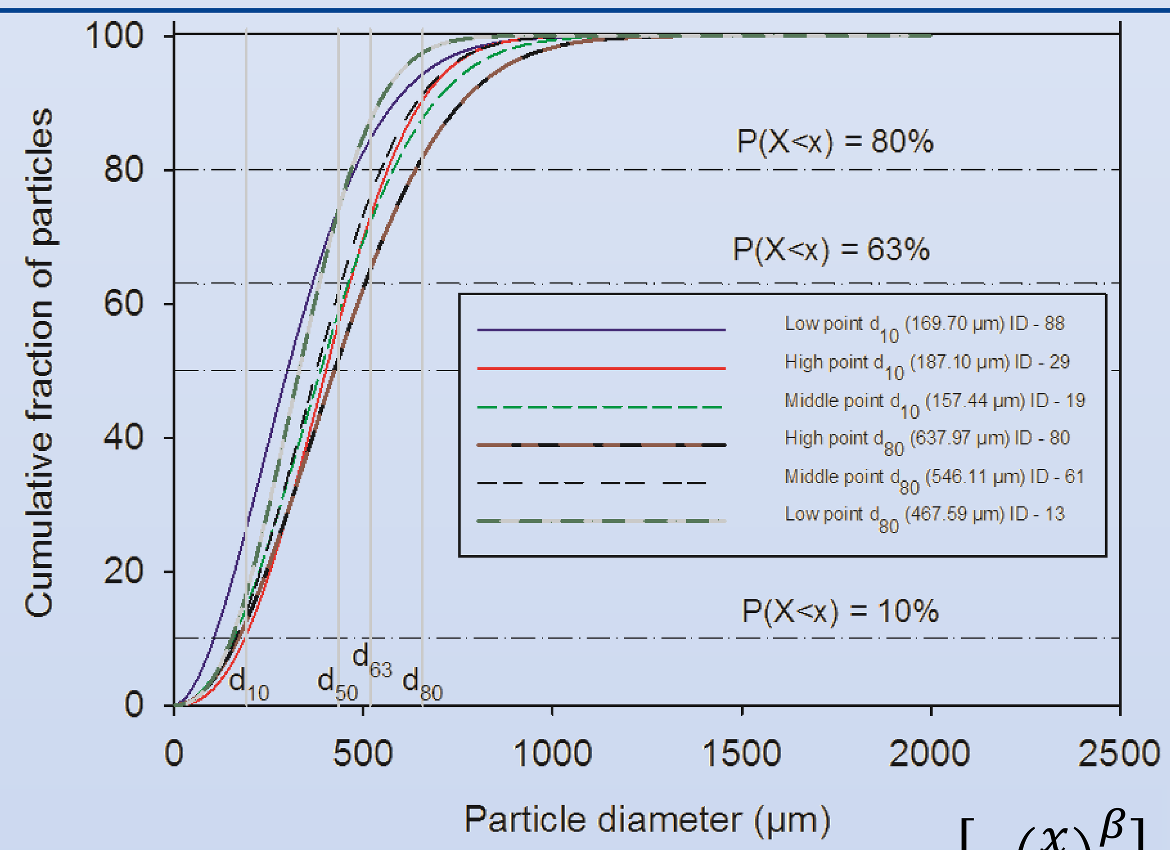
Soil gas diffusivity D_p/D_o analysis on the 100 cm³ soil cores (pF 1.5-3.0) – one-chamber method.

K_{sat} (Ψ ≈ 0 cm H_2O), with the constant head method on the 100 cm³ soil cores.

Models

$$K_{sat} = \frac{d^2 \phi^{3m}}{24} \cdot F_w$$

(d_{50}, d_{63})
$(m_{50}=2.9;\ m_{63}=3.0)$

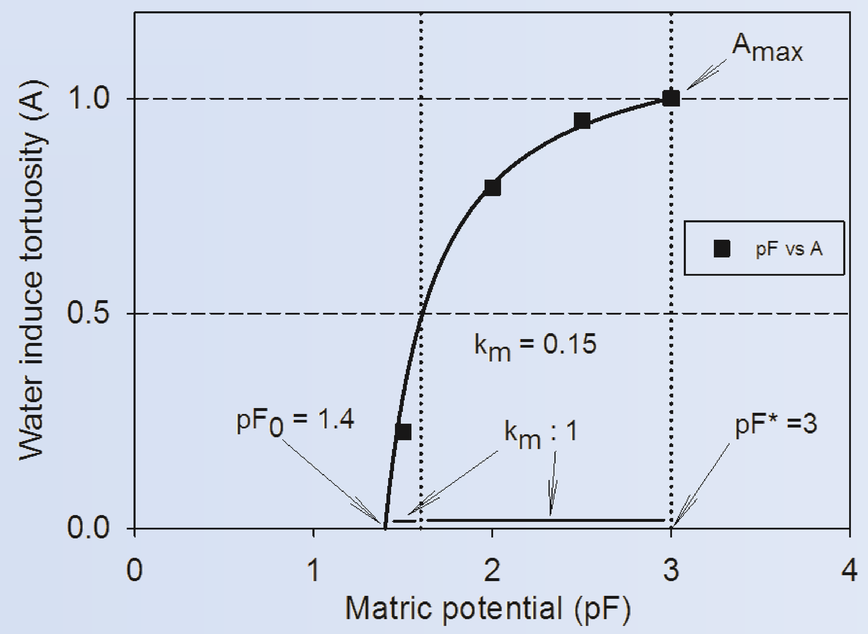


$$P(X<x)\% = 100 - 100\, e^{\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]}$$

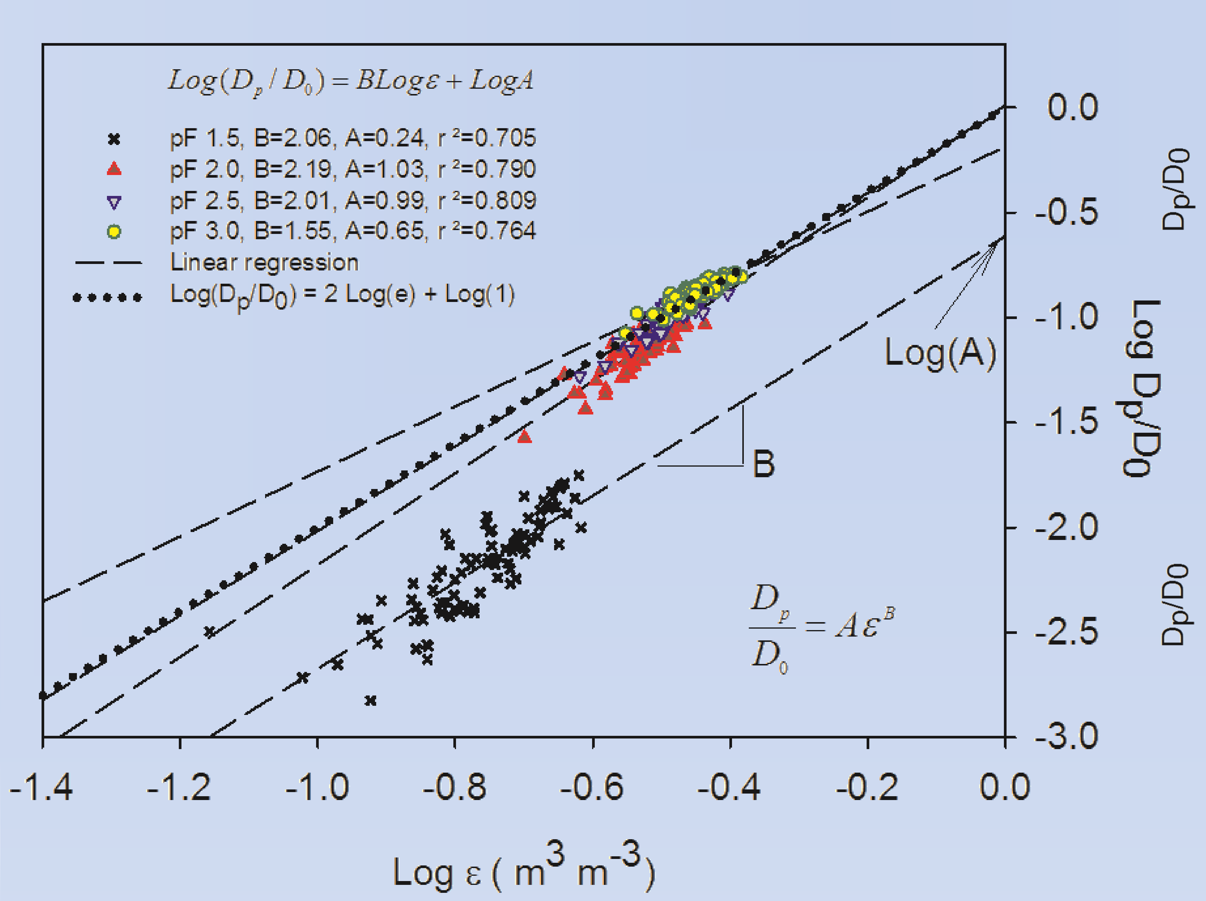
$$D_p/D_0 = A\varepsilon^B$$
$$K_{sat} = \lambda\left(D_p/D_0\right)^{\sigma}$$
$$K_{sat} = \lambda(A\varepsilon^B)^{\sigma}$$
$$K_{sat} = (\lambda A^{\sigma})\varepsilon^{(B\sigma)} = P_1\varepsilon^{P_2}$$

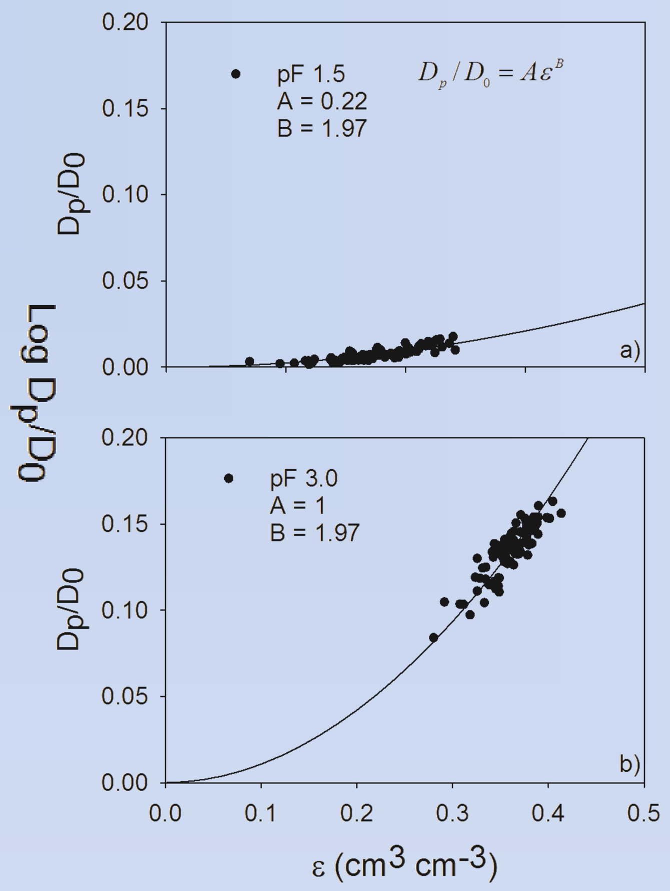
$$K_{sat} = P_1 \phi_e^{\,P_2}$$
$(\phi_e=\varepsilon)$

$$A(pF) = A_{max}\left[\frac{\left(\frac{pF-pF_o}{pF^*-pF_o}\right)}{k_m + (1-k_m)\left(\frac{pF-pF_o}{pF^*-pF_o}\right)}\right]$$

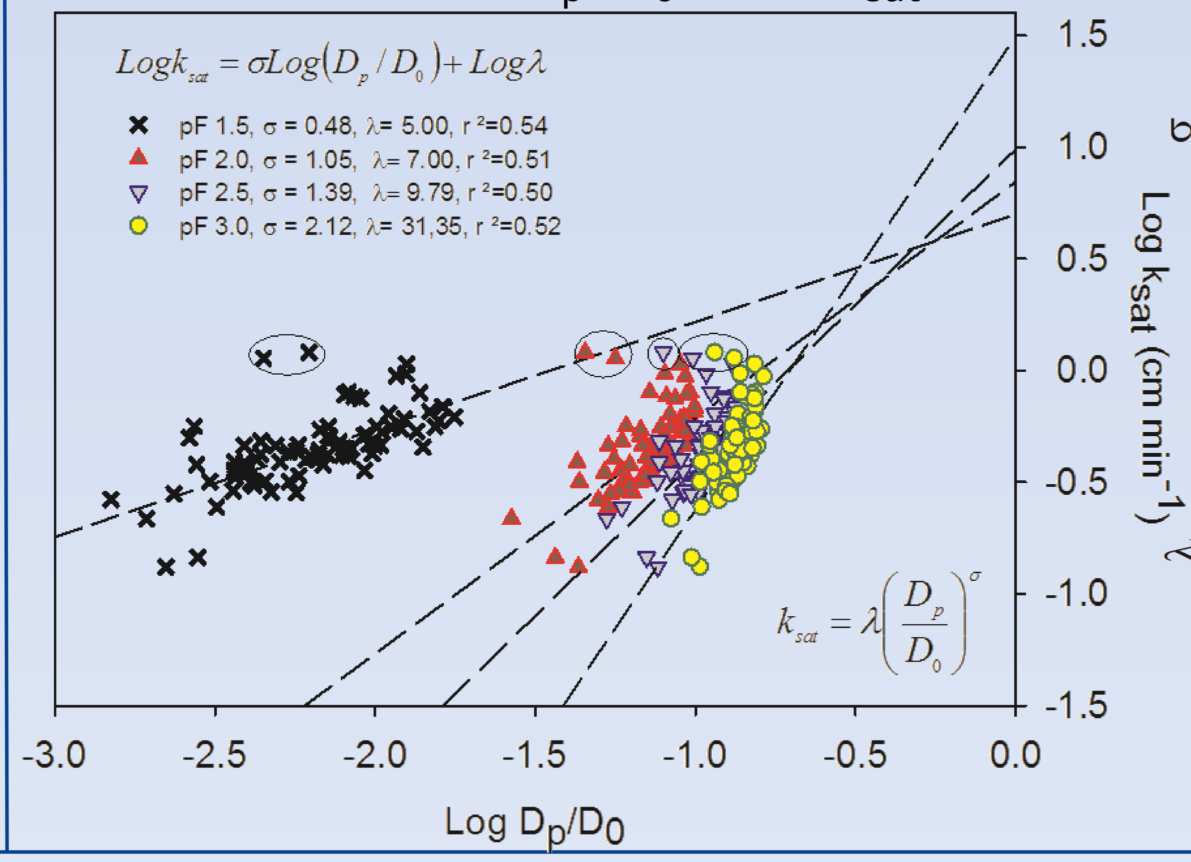


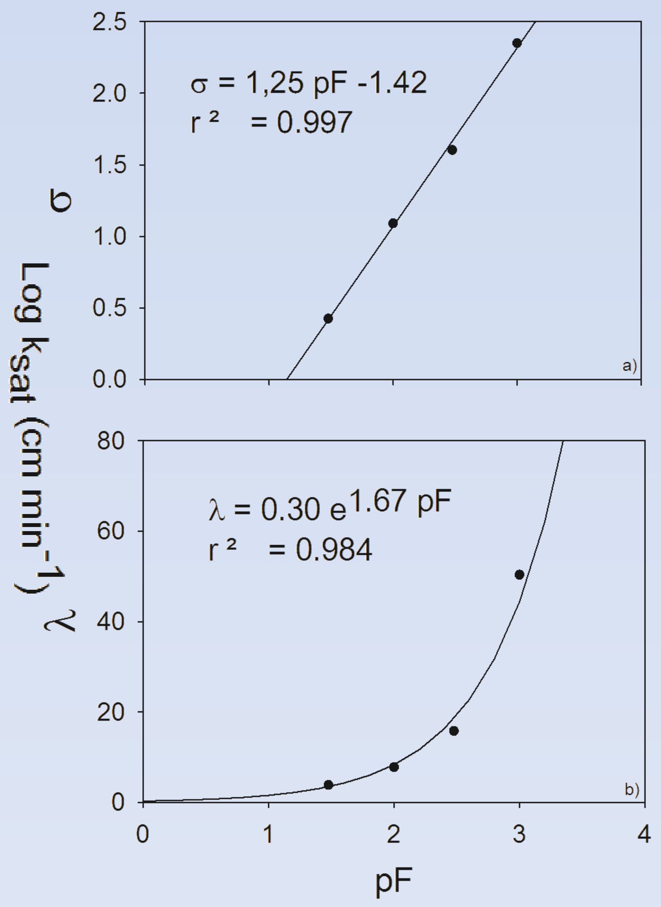
Results





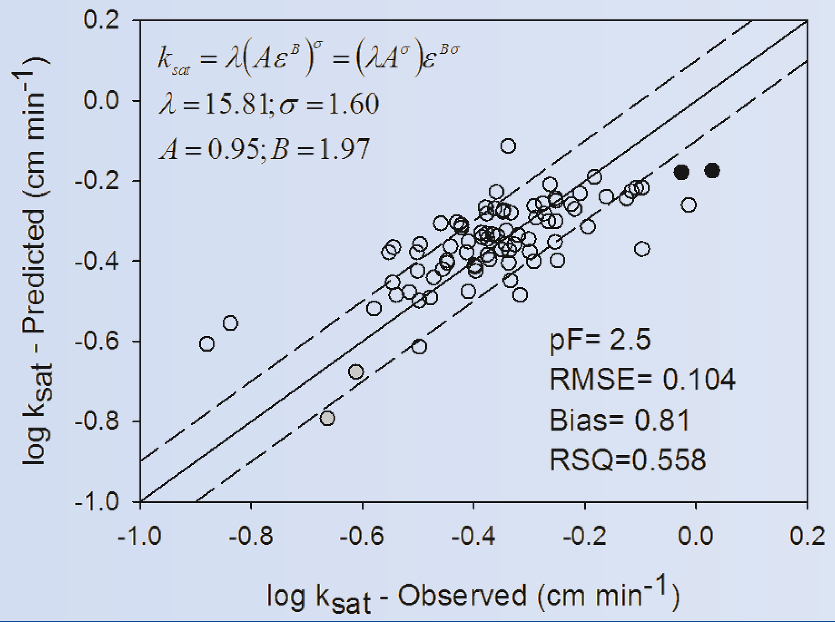
Link between D_p/D_o and K_{sat}





K_{sat} prediction

	D_p/D_0 – ε approach		K_{sat} – D_p/D_0 relationship		K_{sat} – ε relationship	
pF	$D_p/D_0 = A\,\varepsilon^B$		$K_{sat} = \lambda\,(D_p/D_0)^{\sigma}$		$K_{sat} = P_1\,(\varepsilon)^{P2}$	
	A	B	λ	σ	P_1	P_2
1.5	0.22	1.97	3.85	0.43	2.00	0.85
2.0	0.79	1.97	7.79	1.09	6.02	2.15
2.5	0.95	1.97	15.81	1.60	14.56	3.15
3.0	1.0	1.97	50.37	2.35	50.37	4.63



Conclusions

- The found K_{sat}-D_p/D_0 relationship was shown to be a mathematically analogue to the generalized Kozeny-Carman-type K_{sat} model, implying a high dependence on the soil effective porosity.
- All the parameter inherent in the new relations, including water induced tortuosity (A) and the new parameters (λ,σ) showed strong but different relations with pF.
- The pore-network tortuosity exponent (around 2, average of 1.97) derived from D_p/D_0. was a significant part of the total Revil-Cathles cementation exponents (m) for K_{sat}. Thus, pore-network tortuosity and connectivity will play a major role for saturated and unsaturated water flow in this coarse sandy soil.

Perspectives

- Further studies on heterogeneous soils with wider ranges of porosity, higher content of fine particles and difference of K_{sat}.
- Space-time studies should to be considered in order to validate the output data of the new model suggested.

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