Technische Universität Braunschweig

Institut für Geoökologie
Bodenkunde und Bodenphysik

# A physical based model to describe effective hydraulic conductivity of the soil mixtures

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# Introduction

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## A physical based model to describe effective hydraulic conductivity of the soil mixtures

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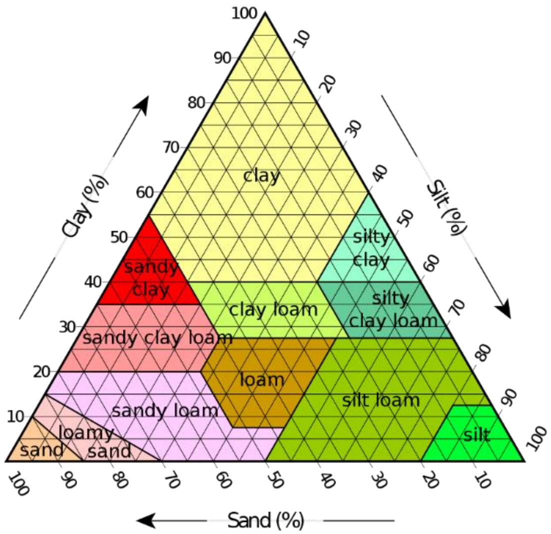
There is a long-lasting interest in obtaining the effective hydraulic conductivity functions of soil mixtures. The few available models to obtain hydraulic conductivity of mixtures are mostly empirical and applicable for saturated conditions. We propose a simple physical model based on the effective medium theory to calculate the effective hydraulic conductivity of soil mixtures with two or more components. The model incorporates the volumetric content of each mixture component and their hydraulic conductivity to calculate the effective conductivity of the mixture. The results of the model were compared with the measured hydraulic conductivity data obtained from the simplified evaporation method using the Hyprop device. Samples were prepared by packing homogeneous mixtures of different soil textures in cylinders with a volume of 250 cm$^3$. Packed soil mixtures were saturated and exposed to evaporation in a climate controlled laboratory with constant air temperature and humidity. The results show an acceptable match between the measured and modeled hydraulic conductivity of the tested soil mixtures. The model can be used as a physical way to describe the effective hydraulic conductivity of mixtures in a wide range of moisture.

# Research needs

✓ Soil by nature is a mixture of three main components: Sand, Silt, and Clay




✓ Soil mixtures may have different constituents such as:

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- Rock fragments
- Plastic particles
- Mulches
- Composts
- Wood chips
- Clay Lense
- Break fragments
- Animal bones
- etc.

✓ All the Components of soil influence its hydraulic properties. However, there is a lack of data and models to describe effective hydraulic properties of soil mixtures

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# Research needs

✓ **Therefore:**

- There is a need for physical or analytical models to estimate hydraulic properties of soil mixtures based on properties of their components.

- Hydraulic behavior of soil mixture still needs to be investigated experimentally in unsaturated conditions.

✓ **Some theories try to explain behavior of (soil) mixtures:**

**Mixture theory**

(focuses more on shear strengths and void ratio relations, etc.)

**Effective medium theories**

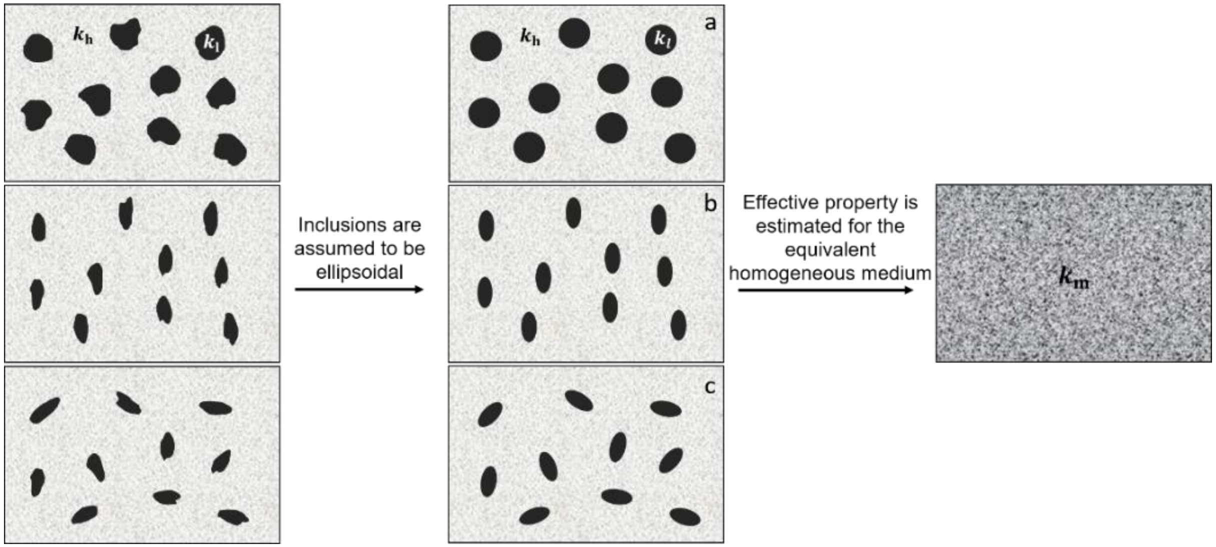
(focus more on electromagnetic conductivities of the mixtures, but there are also some evidence of diffusivity and hydraulic conductivity)

# Purpose

- ✓ To **propose** a physical model based on the general effective medium theory (GEM) to calculate effective unsaturated hydraulic conductivity of soil mixtures.

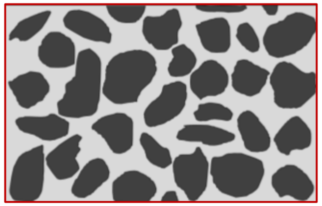
- ✓ To **evaluate** the proposed model using the measured hydraulic conductivity data obtained for packed soil mixtures.

# Effective medium concept

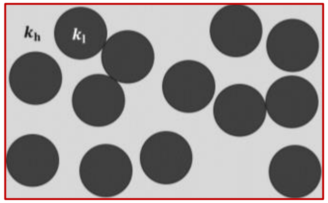



Oriented spheroids

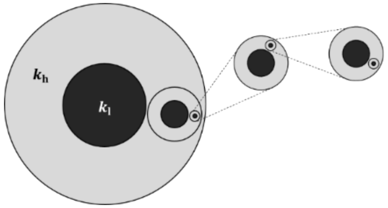
Randomly oriented spheroids



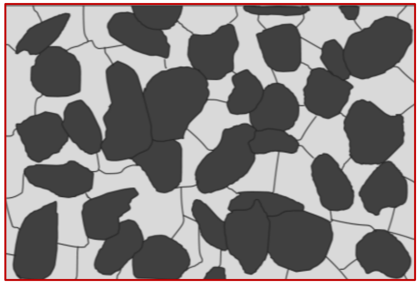
Maxwell




Bruggeman's symmetric (BS) model




Bruggeman's asymmetric (BA) model



**General effective medium (GEM)**

McLachlan (1985 to 1990)

# General effective medium theory (GEM) for (soil) mixtures

Hydraulic conductivity of lower conductive component

Hydraulic conductivity of higher conductive component

$$\boxed{\frac{\boldsymbol{f}\,(\boldsymbol{K}_\mathbf{l}-\boldsymbol{K}_\mathbf{m})}{\boldsymbol{K}_\mathbf{l}+\dfrac{\boldsymbol{f}_\mathbf{c}}{\mathbf{1}-\boldsymbol{f}_\mathbf{c}}\boldsymbol{K}_\mathbf{m}}+\frac{(\mathbf{1}-\boldsymbol{f})(\boldsymbol{K}_\mathbf{h}-\boldsymbol{K}_\mathbf{m})}{\boldsymbol{K}_\mathbf{h}+\dfrac{\boldsymbol{f}_\mathbf{c}}{\mathbf{1}-\boldsymbol{f}_\mathbf{c}}\boldsymbol{K}_\mathbf{m}}=\mathbf{0}}$$

$\boldsymbol{f_c} = \mathbf{0.84} \pm 0.02$ in 3D
Mendelson and Cohen (1982)

Hydraulic conductivity of mixture

$$A=\frac{f_\mathrm{c}}{1-f_\mathrm{c}} \qquad k_r=\frac{k_m}{k_h} \qquad \beta=\frac{k_\mathrm{l}}{k_\mathrm{h}}$$

$$\tau=f\left[A-\beta^{1/t}(1+A)+1\right]-A+\beta^{1/t}$$

Inclusions as oriented spheroids

$$\boxed{t=\frac{f_\mathrm{c}}{1-L}}$$

$L$ = Effective depolarization factor

$$\boxed{\boldsymbol{k}_\mathbf{r}=\left(\frac{-\boldsymbol{\tau}\pm\sqrt{\boldsymbol{\tau}^2+4\boldsymbol{A}\boldsymbol{\beta}^{1/t}}}{2\boldsymbol{A}}\right)^{\boldsymbol{t}}}$$

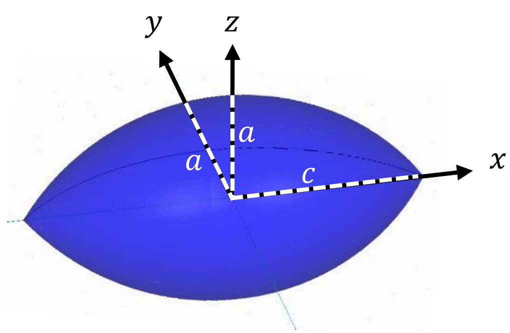
Inclusions as randomly oriented spheroids

$$\boxed{t=m\,f_c}$$

$$m=\frac{5-3L}{3(1-L^2)}$$

# Depolarization factors ($L$) in GEM

**Prolate spheroid** $\boldsymbol{a < c}$

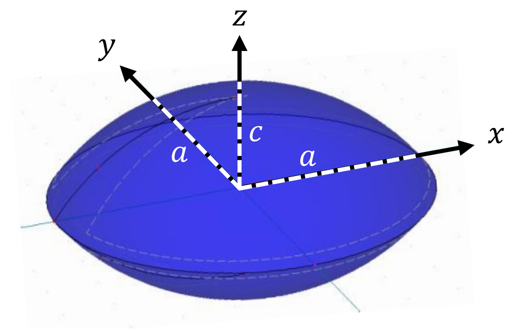



$$L_x = \frac{1-e^2}{2e^3}\left[\ln\left(\frac{1+e}{1-e}\right) - 2e\right]$$

$$L_y = L_z = \frac{1}{2}(1 - L_x)$$

$$e = \sqrt{1 - (^a/_c)^2}$$

**Oblate spheroid** $\boldsymbol{a > c}$

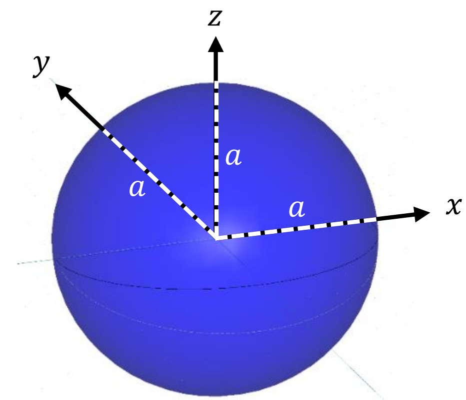



$$L_z = \frac{1+e^2}{e^3}[e - \arctan(e)]$$

$$L_x = L_y = \frac{1}{2}(1 - L_z)$$

$$e = \sqrt{(^a/_c)^2 - 1}$$

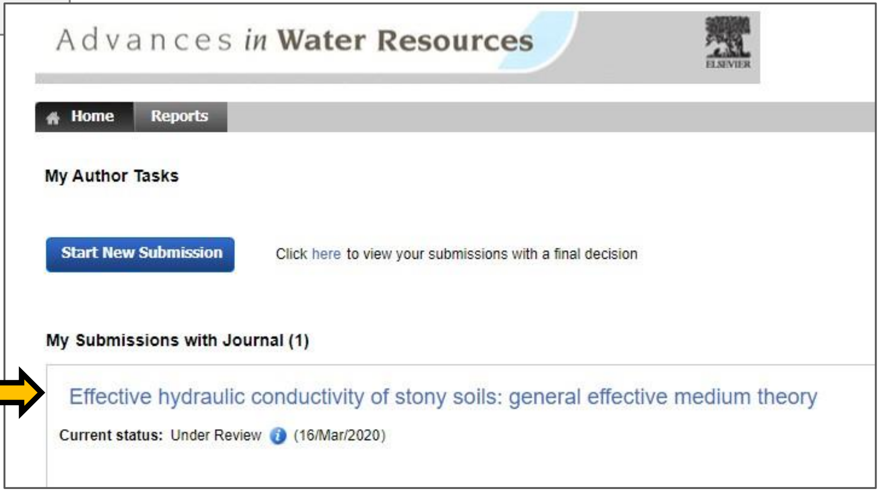
**Sphere**




$$L_x = L_y = L_z = \frac{1}{3}$$

# GEM (more details)

A review of some of the effective medium theories to calculate hydraulic conductivity of stony soils:

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# Two case studies...

✓ **Case study 1** Sandy loam soil mixed with 50 % Clay clods

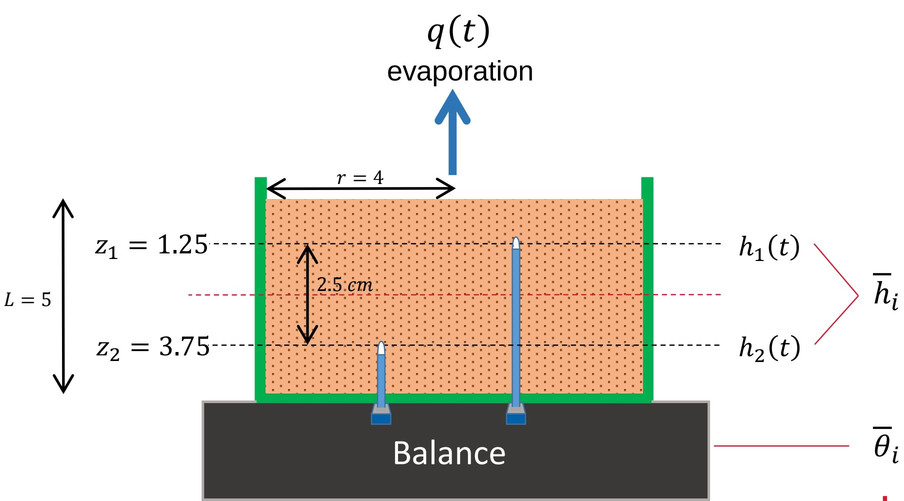
✓ **Case study 2** Sandy loam soil mixed with 50 % Sand

- Soil mixtures were packed according to a volumetric basis of each component.
- A stepwise packing in 250 cm3 cylinders was intended to obtain homogeneous soil mixtures.
- Packed samples were saturated by natural saturation from the bottom using the tap water.
- Experiments were done for two replicates for each soil and mixture (a total of six cylinders in each case).

# Experimental evaluation of GEM
## (Simplified evaporation method, SEM)

Unsaturated hydraulic conductivity of the soil mixtures were measured using the Hyprop device[TM]

## Simplified evaporation method (Peters and Durner, 2008a)




$\theta(h)$

$$\begin{cases} \Delta t_i = t_i - t_{i-1} \\ \Delta\bar{\theta}_i = \bar{\theta}_i - \bar{\theta}_{i-1} \end{cases} \rightarrow \quad q_i = Z_m \frac{\Delta\bar{\theta}_i}{\Delta t_i}$$

$$K_i(\bar{\bar{h}}_i) = -\frac{q_i}{\frac{\Delta h_i}{\Delta z} + 1}$$

(Darcy-Buckingham law)

$$\Delta h_i = \frac{(h_2^{i-1} - h_1^{i-1}) + (h_2^i - h_1^i)}{2}$$

$$\bar{\bar{h}}_i = \frac{h_1^{i-1} + h_2^{i-1} + h_1^i + h_2^i}{4}$$

$K(h)$

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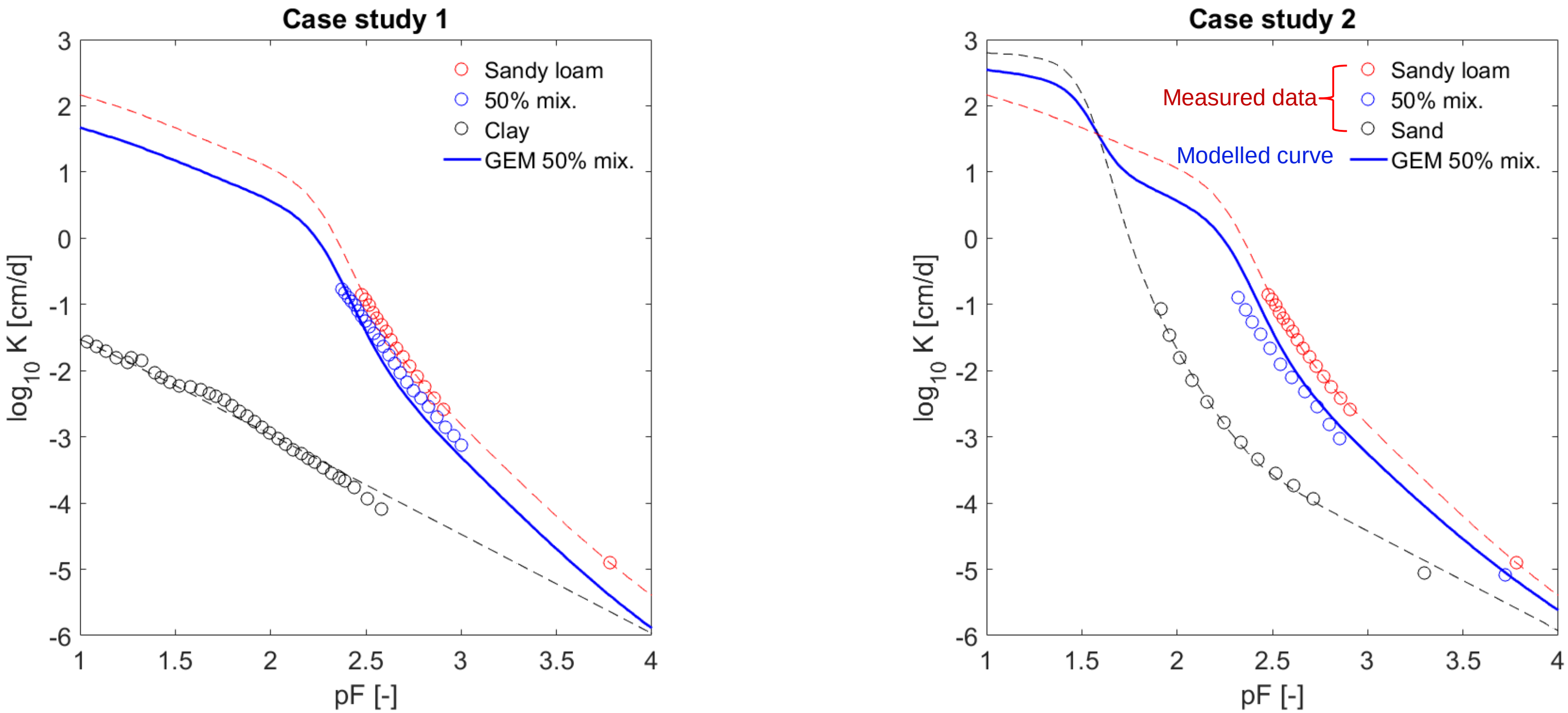
# Results (Hydraulic conductivity of the mixtures)




- ✓ The measured hydraulic conductivity of soil mixtures is dominated by sandy loam in both cases.
- ✓ The modeled conductivity curve by GEM matches reasonably well to the measured conductivity data in both cases.

# Conclusions

- ✓ A model based on the effective medium theory was proposed and evaluated to calculate HCC of soil mixtures based on the volume content and hydraulic conductivity of each constituent.

- ✓ The model is physical based and to the best of our knowledge it is the only model to calculate unsaturated hydraulic conductivity of soil mixtures.

- ✓ The model was evaluated using the measured hydraulic conductivity data of soil mixtures. The results seem reasonable in the considered cases. However, the model needs further improvements to have the best fit to the measured data.