183-7: Saturation-Dependent Hydraulic Conductivity Anisotropy in Unsaturated Soils

University of Houston-Clear Lake
changing futures by degrees

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Introduction

- Large scale soils usually demonstrate different moisture spreading and solute transport behavior at different water saturation (or tension), due to anisotropy.
- While effects of saturation on soil anisotropy in unsaturated soils have been recognized for long time, they have not been fully described conceptually.
- Early models include quantifying saturation-dependent anisotropy of soil formations that consist of many thin layers each with its own hydraulic properties characterized by a uniform density distribution of saturated hydraulic conductivity or soil bulk density.
- Some other approaches have also been developed to study soil anisotropy behavior in dealing with flow and transport problems in saturated and unsaturated soils, such a tensorial connectivity-tortuosity concept which assumed that only soil pore connectivity and/or tortuosity and saturated hydraulic conductivity are anisotropic.
- We are interested in the anisotropy that mainly arises from a combination of both wide range of soil texture variations and within narrow range of texture units due to particle segregation and compaction that typically affect porosity or bulk density.
- We developed a new approach to combine the neural network analysis results with thin layer approach to explore saturation-dependent anisotropy behavior for a wide range of texture and bulk density conditions.

Objective

- To develop hydraulic conductivity models that quantify anisotropy of saturated and unsaturated soils composed of many thin layers distinguished by both texture and bulk density of soil.

Hydraulic Conductivity Functions

- Effective degree of saturation (S_e) and the unsaturated hydraulic conductivity (K) are related to capillary pressure head (ψ) through the van Genuchten function

$$S_e(\psi)=\frac{1}{\left[1+(\alpha_{vG}\psi)^n\right]^m}$$

$$K(\psi)=\frac{K_s\left\{1-(\alpha_{vG}\psi)^{mn}\left[1+(\alpha_{vG}\psi)^n\right]^{-m}\right\}^2}{\left[1+(\alpha_{vG}\psi)^n\right]^{m\ell}}$$

where S_e is the effective degree of saturation, K_s is the saturated hydraulic conductivity, a and l are related to pore-size distributions, m and n are empirical parameters, l is a parameter which accounts for the dependence of the tortuosity, and the correlation factors on the water content estimated to be about 0.5 as an average for many soils.

van Genuchten Parameters vs. Texture and Bulk Density

- Based on results of van Genuchten hydraulic parameters in relation to texture (using mean grain diameter as a surrogate) and bulk density as established by earlier neural network approach, we perform a regression to relate hydraulic properties to two main indicators d_m, the mean grain diameter and the bulk density ρ.
- for each van Genuchten parameter, p, we will establish a functional relationship $p = f_p(d_m, \rho)$, where d_m is the mean grain diameter and ρ the soil bulk density.
- Relationship between van Genuchten hydraulic parameters and dm, ρ. Analysis indicates

log(n) is poorly correlated to either d_m or ρ,

θs decreases slightly with dm and ρ, and largely linearly correlated,

θr poorly correlated to either d_m or ρ.

log(α) is mostly correlated to ρ, and is weakly linearly correlated to d_m.

log(Ks) is poorly correlated to ρ, and is more correlated to d_m

- These linear regression relationships are used to develop anisotropy models
- From the above analysis, we will consider four scenarios: (1) $K_s \sim d_m$, $\alpha \sim d_m$; (2) $K_s \sim d_m$, $\alpha \sim \rho$; (3) $K_s = \langle K_s\rangle$, $\alpha \sim d_m$, and (4) $K_s = \langle K_s\rangle$, $\alpha \sim \rho$.

Anisotropy Model Development

- We consider a soil consisting of a large number of thin, but distinguishable layers of different texture (as indicated by mean grain diameter) and the bulk density.
- Each layer is characterized by its own van Genuchten type hydraulic conductivity function

$$K_h(\psi)=\iint K(\psi,d_m,\rho)f(d_m,\rho)\,dd_m\,d\rho$$

$$K_v(\psi)=\left[\iint\frac{f(d_m,\rho)}{K(\psi,d_m,\rho)}dd_m\,d\rho\right]^{-1}$$

$$A(\psi)=\frac{K_h(\psi)}{K_v(\psi)}$$

$f(d_m, \rho)$ is joint probability density function

$K_h(\psi)$ is the hydraulic conductivity parallel to layering

$K_v(\psi)$ is the hydraulic conductivity perpendicular to the layers

$A(\psi)$ is the anisotropy factor

- two types of probability density functions of dm and ρ, uniform and log-normal distributions, are considered to examine the effect of their distributions.

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Parameter Distributions

- Joint probability density function for two uniformly distributed variables d_m and ρ, if they are independent, is

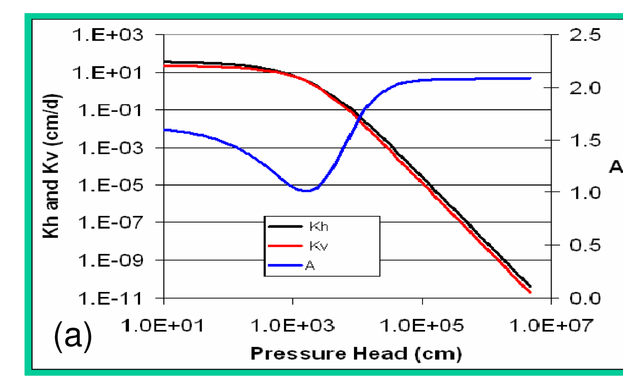
$$f_{dm}(d_m)=\begin{cases}\dfrac{1}{(d_{m\max}-d_{m\min})(\rho_{\max}-\rho_{\min})}, & d_{m\min}\le d_m\le d_{m\max},\ \rho_{\min}\le\rho\le\rho_{\max}\\ 0 & otherwise\end{cases}$$

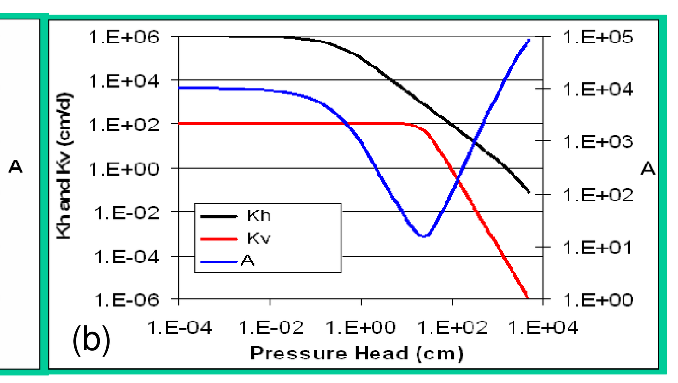
- Joint probability density function for two log-normally distributed variables dm and ρ, if they are independent, is

$$f(d_m,\rho)=\frac{1}{2\pi\sigma_{\ln dm}\sigma_{\ln\rho}d_m\rho}\exp\left\{-\frac{1}{2}\left[\frac{(\ln d_m-\langle\ln d_m\rangle)^2}{\sigma^2_{\ln dm}}+\frac{(\ln\rho-\langle\ln\rho\rangle)^2}{\sigma^2_{\ln\rho}}\right]\right\}$$

Results

(1) Ks ~ dm, α ~ dm



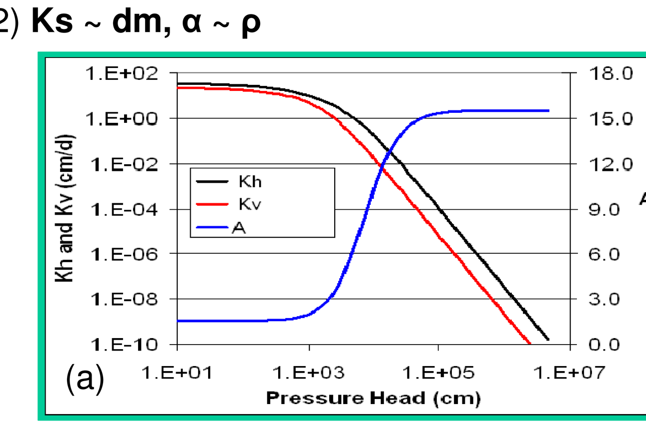


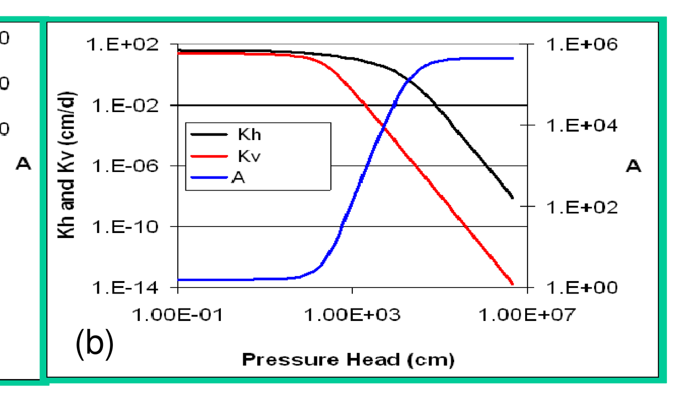
Case (1) Both K_s and α are related to the mean grain diameter d_m through regression relationships.

(a) $d_{m\min}$ = 0.0747 (mm), $d_{m\max}$ = 0.92487 (mm), and n = 1.59.

(b) $d_{m\min}$ = 0.001(mm), $d_{m\max}$ = 5 (mm), and n = 1.59.

(2) Ks ~ dm, α ~ ρ



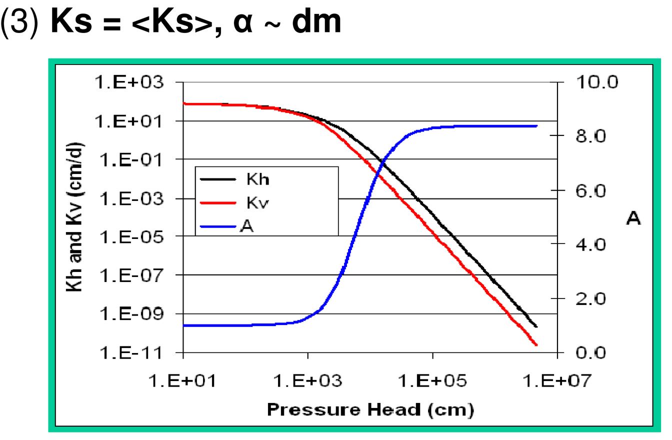


Case (2) K_s is related to the mean grain diameter dm, and α is related to the bulk density, ρ, through regression relationships.

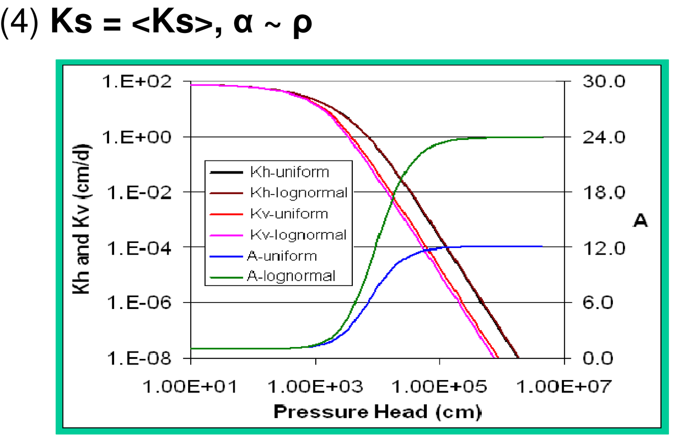
(a) $d_{m\min}$ = 0.0747 (mm), $d_{m\max}$ = 0.92487 (mm), $\rho_{\min}$ = 1.28 (g/cm^3), $\rho_{\max}$ = 1.59 (g/cm^3), and n = 1.59.

(b) $d_{m\min}$ = 0.0747 (mm), $d_{m\max}$ = 0.92487 (mm), $\rho_{\min}$ = 1.0 (g/cm^3), $\rho_{\max}$ = 2.0 (g/cm^3), and n = 1.59.

(3) Ks = <Ks>, α ~ dm



(4) Ks = <Ks>, α ~ ρ



Case (3) K_s is assumed to be constant equal to the mean value, and α is related to the mean grain diameter d_m. $d_{m\min}$ = 0.0747 (mm), $d_{m\max}$ = 0.92487 (mm), and n = 1.59.

Case (4) K_s is assumed to be constant equal to the mean value, and α is related to ρ. $\rho_{\min}$ = 1.28 (g/cm^3), and $\rho_{\max}$ = 1.59 (g/cm^3), and n = 1.59.

Main Conclusions

- When both Ks and α are correlated to the grain diameter, the anisotropy factor exhibits a minimum in the middle range of pressure head. In the middle range of saturation, the formation behaves similarly to isotropic case.
- When only one hydraulic parameter is related to the grain diameter or when both are not related to the grain diameter, the medium anisotropy decreases with increasing saturation.
- The anisotropy is stronger when hydraulic parameters are log-normally distributed than when they are uniformly distributed.