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In Situ Estimation of Soil Hydraulic Properties with the Cone Permeameter

Molly M. Gribb, PhD

Associate Professor

and

Sondra E. Ordway and Steven C. Anderson

PhD and BS student, respectively

Department of Civil & Environmental Engineering

University of South Carolina, Columbia SC

with

Jirka Simunek, PhD

Assistant Researcher, US Salinity Lab, ARS, USDA

Riverside, CA

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Presentation Overview

- **Cone Permeameter:** New method for estimating K(h) and ?(h)
- **Inverse Solution:** Numerical simulation coupled with nonlinear optimization of hydraulic parameter inputs
- **Results:** Cone flow data and resulting soil hydraulic properties

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The Cone Permeameter for Soil Hydraulic Property Estimation:

- An in situ method developed for use with cone penetration testing equipment
- Injection of water into the subsurface and measurement of increasing pore water pressures and injected volume with time
- Analysis via inverse modeling
- Laboratory and field tests have confirmed its performance
- Development of a second generation prototype is underway

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Field Testing of the Cone Permeameter

- **Location:** Poinsett State Park, South Carolina
  - Interbedded, unconsolidated sands and clays of the Atlantic Coastal Plain
  - Sites with soils of differing bulk density, fines content, porosity, and flow behaviors
- **Testing protocol:**
  - Barrel sampler pushed to testing depth to obtain initial moisture content data
  - Cone permeameter installed to a depth of 50 cm
  - Applied water pressure heads of 30 cm & 50 cm (or 21 & 80 cm, or 21 & 108 cm)

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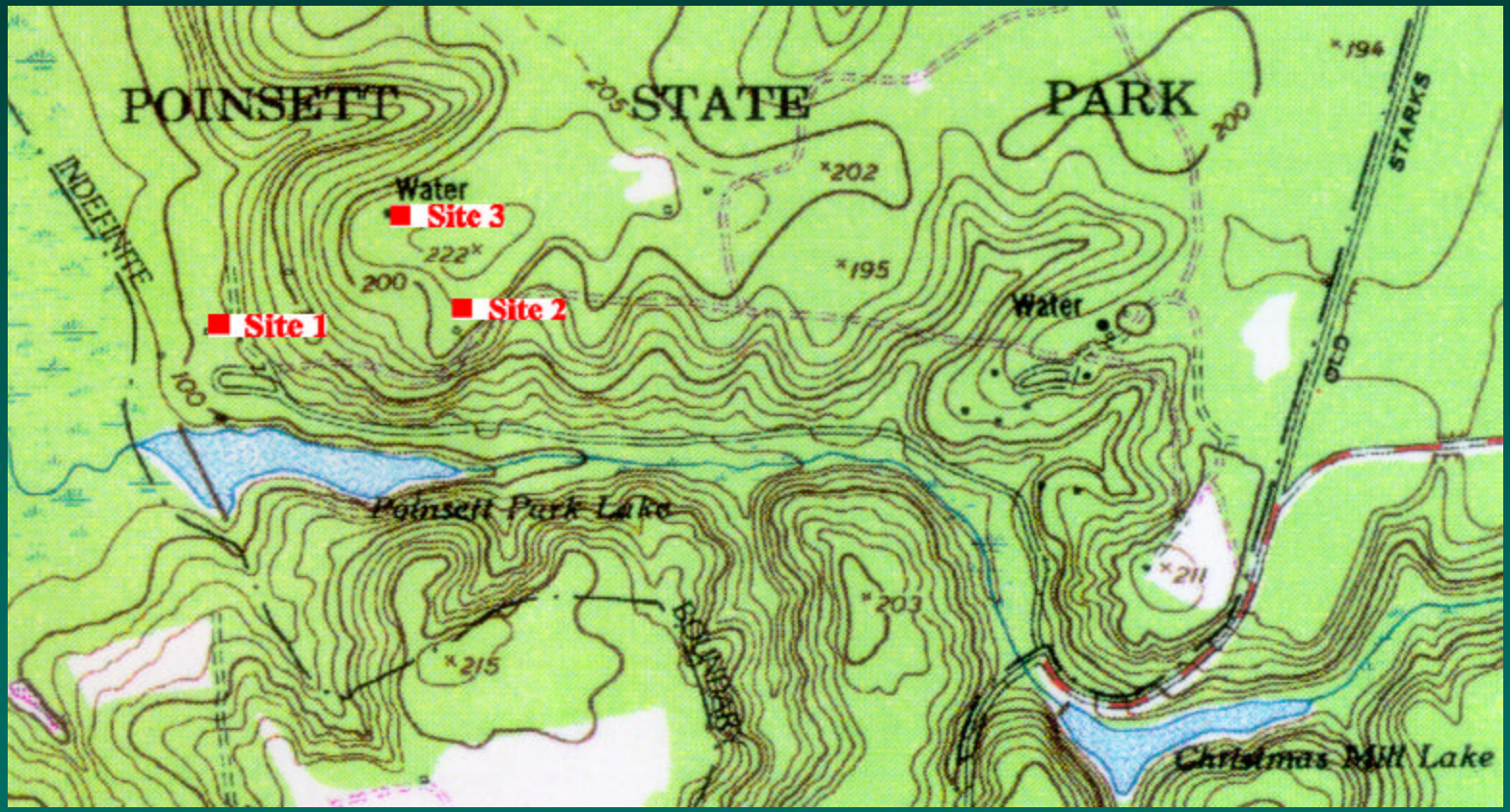
Poinsett State Park testing locations



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The Guelph Permeameter for K_s Measurement

- The GP is an in situ method for predicting the saturated hydraulic conductivity of an unsaturated soil (Reynolds & Elrick, 1986).
- A constant head of 5 and/or 10 cm is supplied to the borehole.
- The quasi-steady state inflow rate is input to a semi-analytical solution to find K_s.

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Cone Permeameter Test Procedure

- After GP tests are run, soil anchors are placed into the Guelph test holes and the frame was secured. The core sampler is inserted.
- Samples of known volume are removed and volumetric moisture contents are paired with initial permeameter tensiometer readings and used in the inversion as known points of ?(h).

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Cone Permeameter Test Procedure, cont.

- The cone permeameter is assembled in the field. Tensiometer rings located 5 and 10 cm above the screened section measure pore pressures as water is injected through the screened section.
- Insertion in the sampler hole is accomplished using a rack jack assembly (Geonor Inc).

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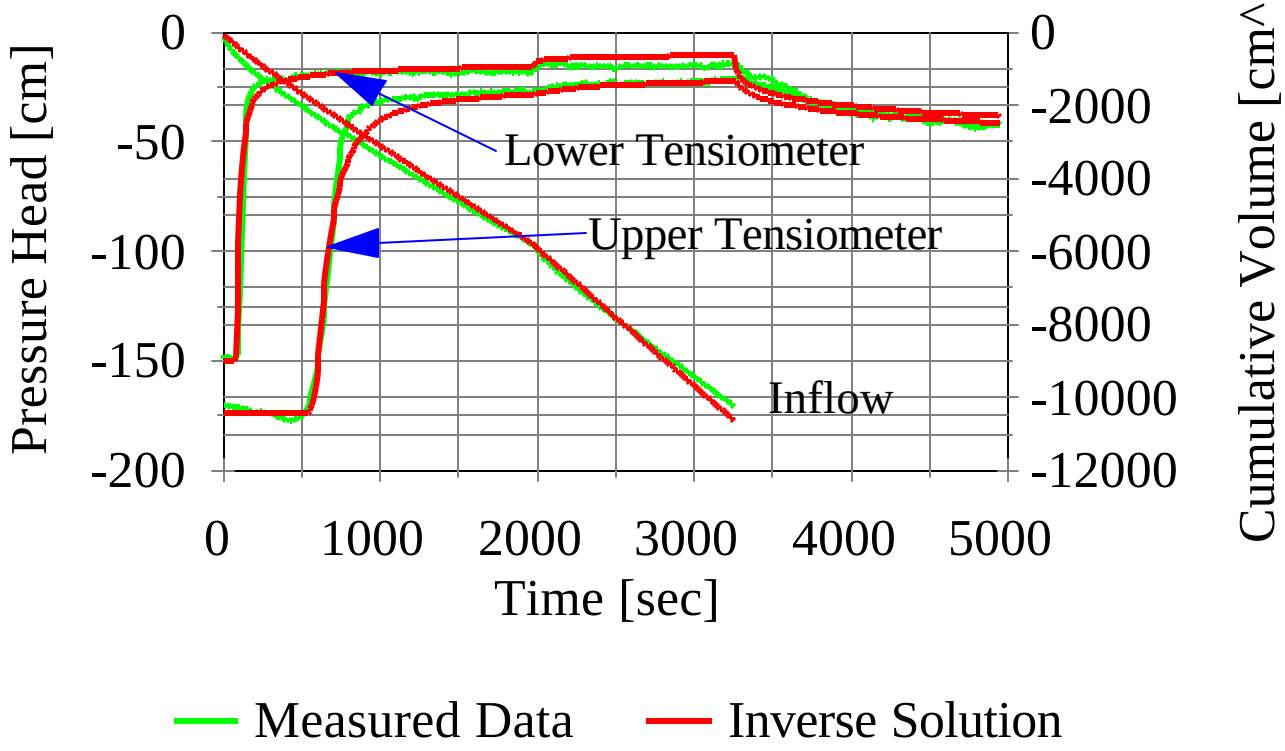
Example Cone Permeameter Data

Applied heads of 30 and 50 cm at Site 1



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Cone Permeameter Test Procedure, cont.

- Following a test, the permeameter is excavated. Excellent contact between the device and the soil is evident from the photo.
- Lab tests are performed on soil samples taken near the permeameter to obtain soil hydraulic properties for comparison.

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What is the Inverse Method?

Solution of the inverse problem requires determining unknown causes, based on observations of their effects.

This is in contrast to the corresponding direct problem, whose solution involves finding effects based on a complete description of their causes.

-Alifanov

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Applications of Inverse Parameter Estimation for Soil Hydraulic Properties

- Laboratory one-step and multi-step outflow tests, with or without pressure head measurements; evaporation method; multi-fluid multi-step outflow tests.
- Field instantaneous profile tests; ponded infiltration tests; multi-step soil water extraction tests.
- Cone permeameter and tension disk infiltrometer tests.

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Inverse Solution Method

The governing flow equation for radially symmetric, Darcian flow in an isotropic, rigid porous medium (Richards, 1931) is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\left(\frac{\partial h}{\partial z} + 1\right)\right) = \frac{\partial \theta}{\partial t}$$

r = radial coordinate, z = vertical coordinate (positive upward), t = time, h = pore water pressure head, and K and θ = hydraulic conductivity and volumetric moisture content, respectively.

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The van Genuchten (1980) expressions for ?(h) and K(?):

$$\theta_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + |\alpha h|^n\right]^m} \qquad h < 0$$

$$\theta_e = 1, \qquad h \geq 0$$

$$K(\theta) = K_s \, \theta_e^{0.5} \left[1 - \left(1 - \theta_e^{1/m}\right)^m\right]^2 \qquad h < 0$$

$$K(\theta) = K_s \qquad h \geq 0$$

θ_e = effective moisture content, K_s = sat. hydraulic conductivity, θ_r and θ_s = residual and sat. moisture contents, respectively, ?, n and m (= 1 - 1/n) = empirical parameters. The five unknown parameters are K_s, θ_r, θ_s, ? and n.

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An objective function, ?, expressing differences between flow responses measured with the permeameter and those predicted numerically with hydraulic parameter inputs, is minimized:

$$?(\mathbf{b}, q, p) = ? \; v_j \; ? \; w_{ij}[q^*_j(x, t_i) - q_j(x, t_i, \mathbf{b})]^2$$

$$+ ? \; v_j \; ? \; w_{ij}\,[p^*_j(?_i) - p_j(?, \mathbf{b})]^2$$

where the 1st term represents deviations between measured and predicted flow variables, represented by $q_j^*(x, t_i)$, and $q_j(x, t_i, \mathbf{b})$, respectively; **b** is the vector of input parameters ($?_r$, $?_s$, ?, n, K_s); v_j and $w_{i,j}$ are weighting factors. The 2nd term represents differences between independently measured and predicted soil hydraulic properties (e.g., ?(h), K(?) or K(h) data), while the terms $p_j^*(q_i)$, $p_j(q_i, \mathbf{b})$, v_j and $w_{i,j}$ are weighting factors for the soil hydraulic properties.

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Inputs to the Inverse Problem for the Cone Permeameter

- Measurements of pore pressure heads at tensiometer rings for the duration of the test.
- Measurements of cumulative inflow volume injected into the soil as a function of time.
- Independent measurement of the initial moisture content in the soil.

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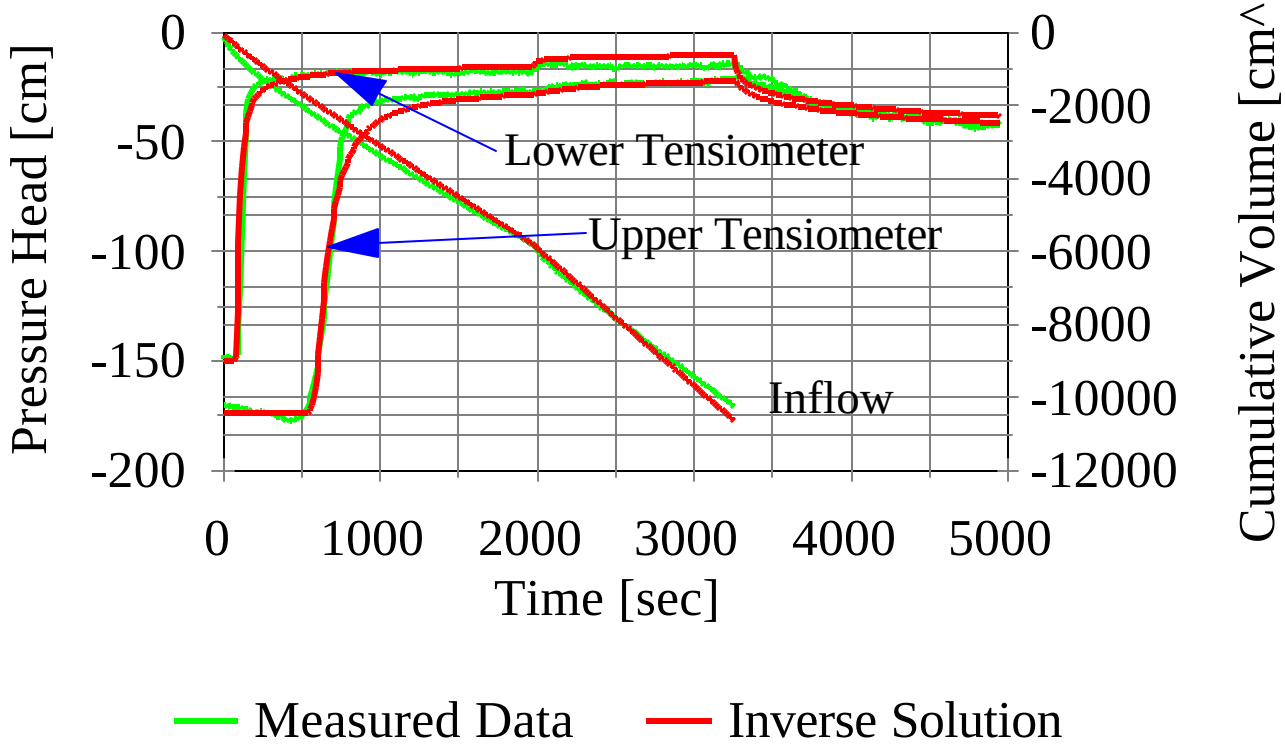
Example Cone Permeameter Data

Applied heads of 30 and 50 cm



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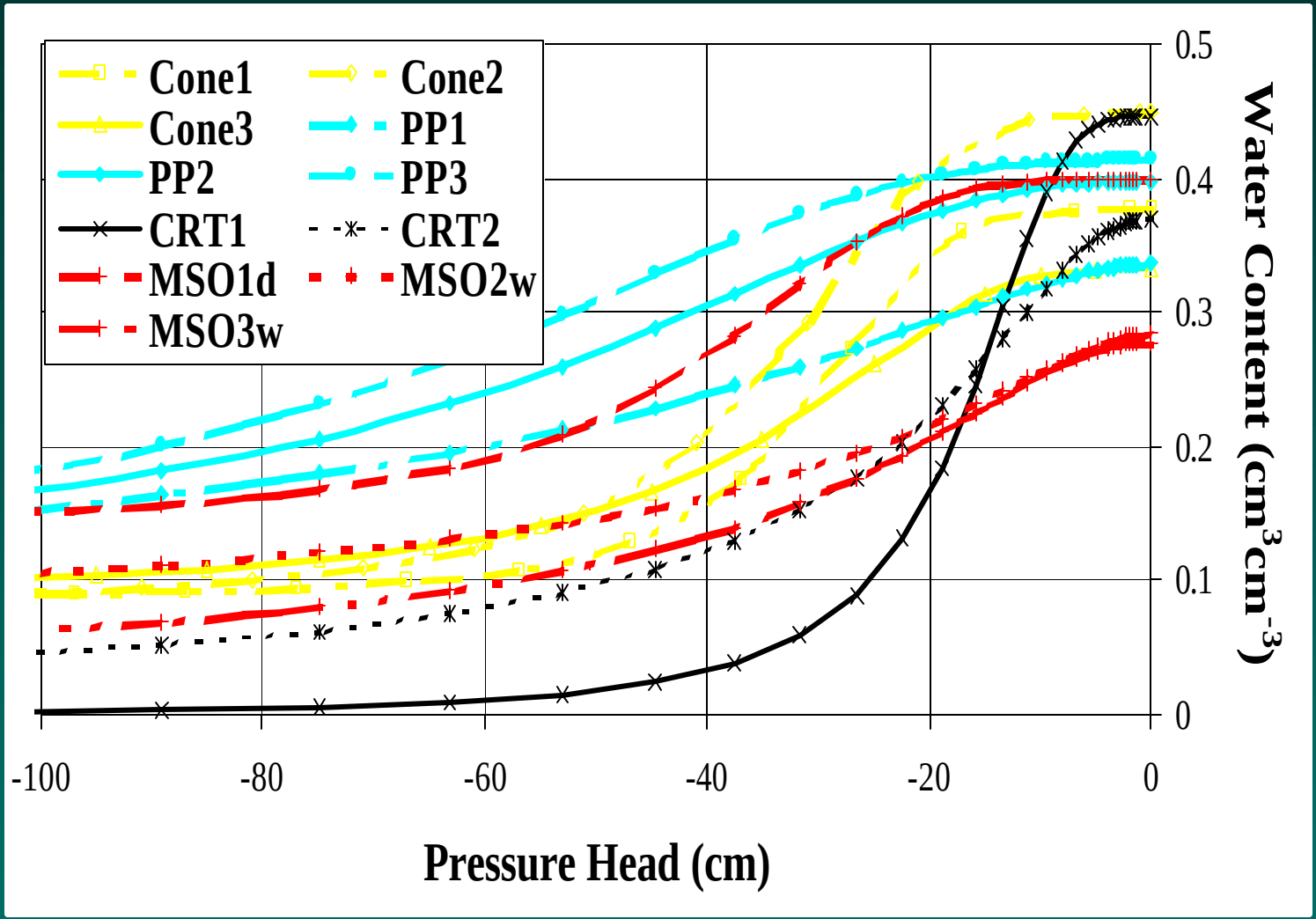
Moisture Retention Curves



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K_s from Cone Permeameter and Other Tests

Test Method	**K_s** (cm/sec)
MSO Tests (2)	0.0012 - 0.0027
GP Tests (6)	0.0025 - 0.0039
FH Tests (9)	0.0013 - 0.0044
CP Test A: h_0 = 30, 50 cm	0.0016
CP Test B: h_0 = 30, 50 cm, & redistribution	0.0016
CP Test C: h_0 = 30, 50 cm	0.0011
CP Test D: h_0 = 21, 108 cm	0.0036
CP Test E: h_0 = 21, 80 cm, & redistribution	0.0010

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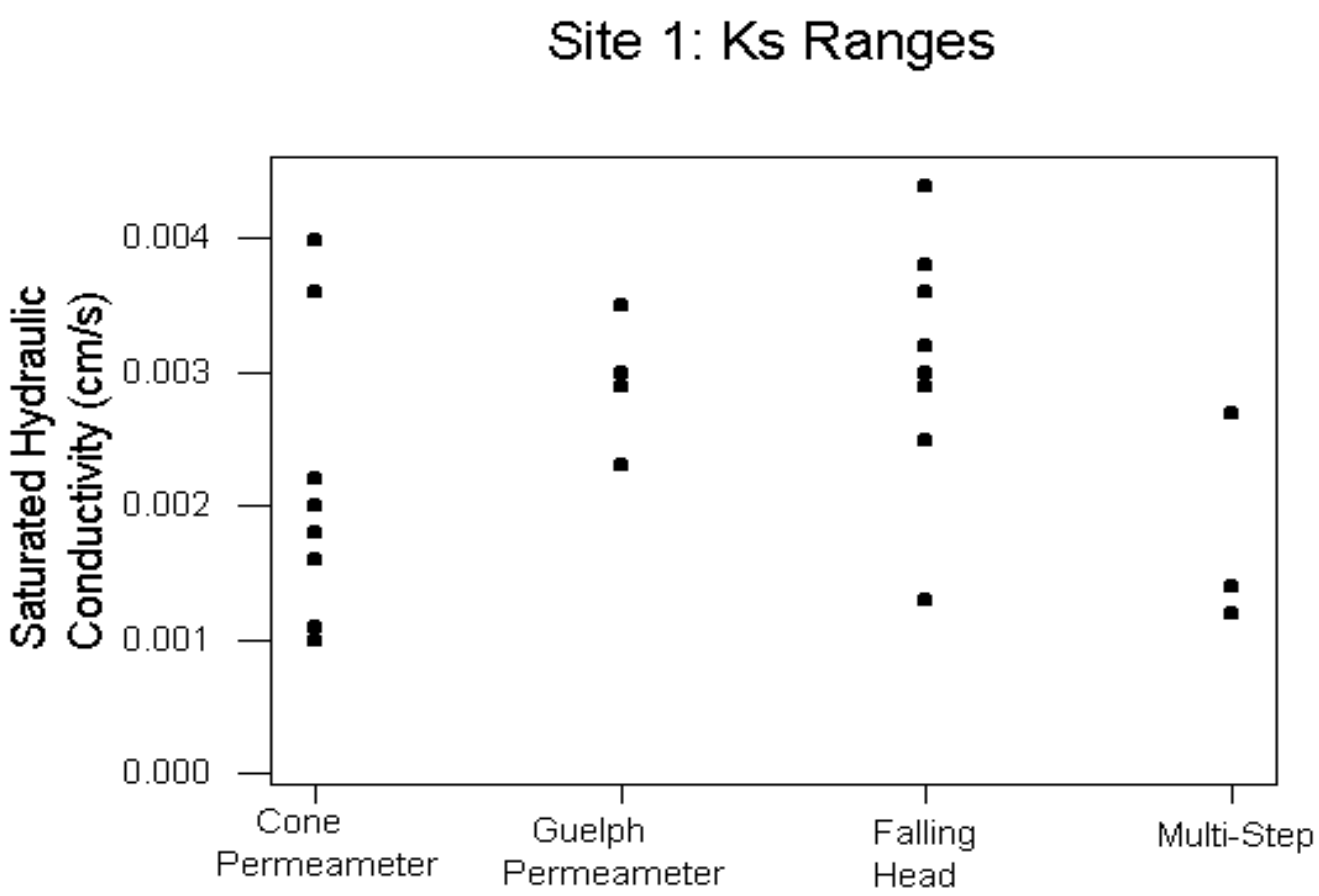
Distribution of K_s Values



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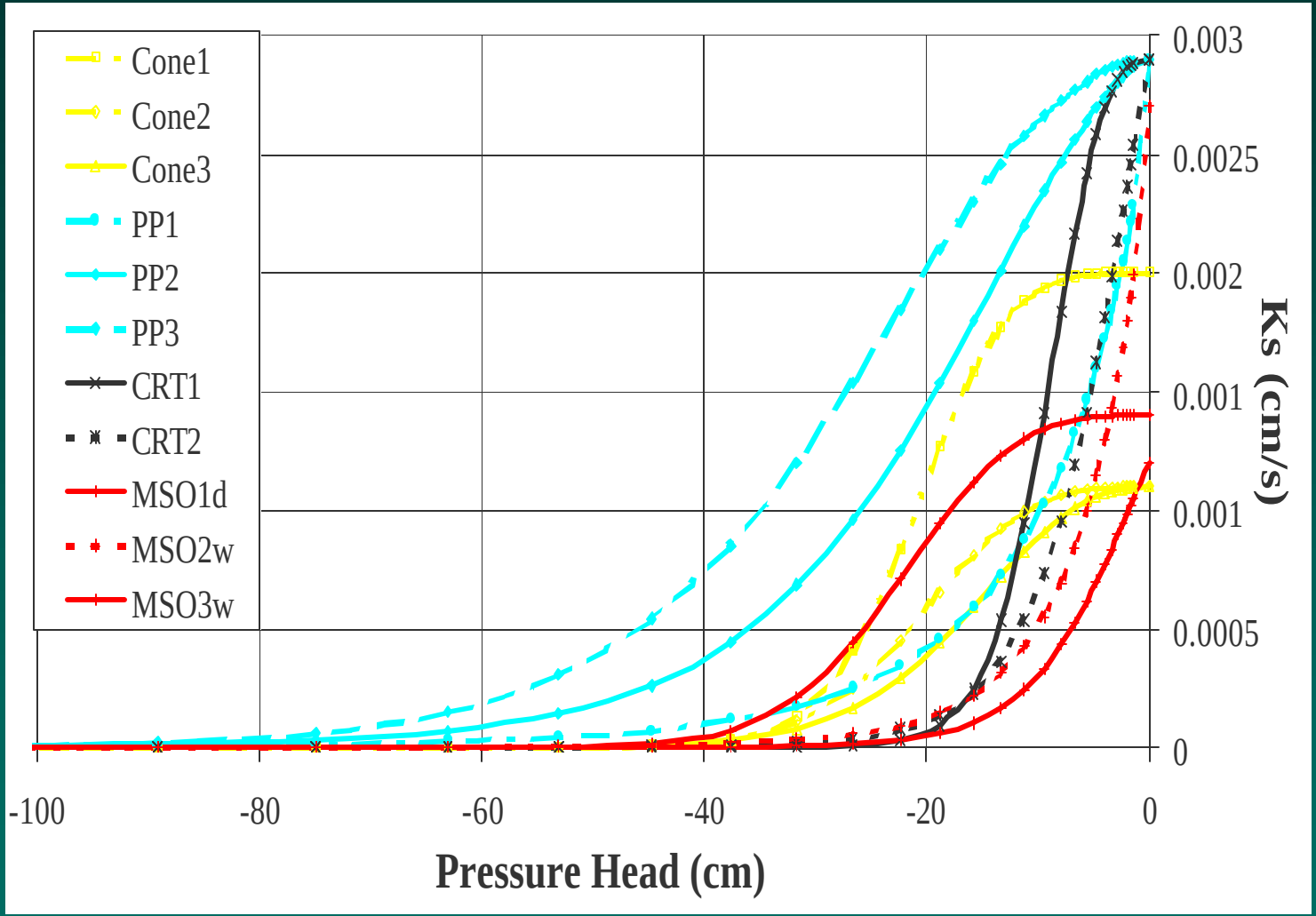
Hydraulic Conductivity Curves



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Benefits of the Cone Permeameter and Inverse Modeling Approach

- Consistency: Hydraulic properties estimated from transient data can be used to predict/simulate transient flow conditions.
- Efficiency: Use of transient flow measurements provides relatively fast results.
- Completeness: Possibility for obtaining the wetting and drying K(h) and ?(h) curves simultaneously from analysis of a single experiment.

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Current Limitations of the Cone Permeameter and Inverse Solution

- Parameters are only valid for the range of experimental conditions experienced.
- Measurement of initial moisture content required to obtain realistic values of $?_s$ and $?_r$.
- Requires accurate experimental procedures and advanced numerical modeling skills.
- A new prototype must be constructed to allow for testing at depth.
- The effects of disturbance on soil hydraulic properties obtained have not been fully investigated.

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Potential for Use at the Hanford Site

- The cone permeameter method is minimally intrusive and well suited for use at contaminated sites.
- Inverse methodology is well accepted and commonly used in the analysis of soil samples in the lab (one-step, multi-step outflow tests).
- A new prototype is under construction to allow for use with standard cone penetration push technology.
- Potential cost savings over traditional measurement methods for determination of soil hydraulic properties.