Project ID: **55109**

Project Title: **New Permeameters for in situ Characterization of Unsaturated Heterogeneous Permeability**

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Project Title
New Permeameters for *in situ* Characterization of Unsaturated Heterogeneous Permeability: Development, Design, Testing, and Application

Publication Date
June 15, 1999

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Progress Report

RESEARCH OBJECTIVES

Thick unsaturated zones underlie many Department of Energy (DOE) landfills, industrial areas, and waste storage sites in the western United States and are the primary pathway for contaminants to migrate into underlying aquifers. The spatial variability of unsaturated hydraulic properties in these heterogeneous geologic materials directly influences the movement of water and non-aqueous phase liquids (NAPL's). Poor characterization of heterogeneity may lead to ineffective remedial designs and increased risk, requiring subsequent additional remedial actions at increased cost and time. Remedial design can be improved using probabilistic risk-based decision analysis, which requires a large number of hydraulic property observations. Laboratory methods for estimating the unsaturated permeability are expensive, time-consuming, and may not yield results representative of heterogeneous field conditions. Simple and rapid field methods for estimating *in situ* unsaturated permeability are appealing and potentially cost-effective.

The primary objective of our EMSP research is to design, develop, and test new permeameters for use in spatial variability studies. We have established a series of permeameter design criteria, including: 1) measurements should be relatively rapid, 2) the total cost per data point should be low, 3) results would accurately reflect the variation of unsaturated hydraulic properties between sampled locations, 4) the volume sampled (measurement support) would be small, and 5) useful range would be relevant to the range of soil moisture conditions encountered at DOE sites.

RESEARCH PROGRESS AND IMPLICATIONS

This report summarizes work after year three of a three year project. We have requested a one year no-cost extension. In past years we have reported our activities related to development and testing of techniques for inverting permeameter data, development of numerical tools for data inversion, error evaluation for permeameter design, and permeameter component design. This year, however, the results of our error evaluation for permeameter design have caused us to redirect our research, and we focus on the results of these studies and their implications for our research. We now believe that it is not possible, given our current mathematical models for unsaturated flow and the range of possible instruments, to reliably estimate, from *in situ* measurements, the spatial statistics of parameters that describe the slope of the pressure-saturation and relative-permeability curves.

We evaluated the effect of error on the uncertainty of estimated spatial statistics to improve permeameter designs. Hydraulic properties (e.g., hydraulic conductivity) are estimated using an observed system response to invert a mathematical model of an experiment. Errors in estimates of hydraulic properties (property-estimation errors) arise from both measurement and inversion-model errors. Because property-estimation errors are correlated with the sampled hydraulic property and are not mean-zero, estimated spatial statistics of hydraulic properties are biased and uncertain.

Measurement errors result from erroneous, direct observation of system or device states (e.g., pressure, flow rate, and the location of observation points) and are non-linearly propagated through the inverse solution for the hydraulic property. Because measurement errors are a function the hydraulic response of the sampled system and the "true" value of the hydraulic property, estimation errors are likely to be correlated with the true hydraulic-property.

Inversion model error results when the fundamental assumptions of the inversion model are invalid. This type of error can result from an incorrect mathematical model, an inappropriate parametric model, sub-sample-scale heterogeneity, scaling-effects, boundary condition errors, and other unresolved or ill-described physics. Most inversion-model errors introduce systematic errors in the estimated hydraulic property and can be correlated with the true values of the sampled field.

We evaluated bias and uncertainty in the spatial statistics of unsaturated hydraulic properties estimated with a tension infiltrometer, a field device commonly used for examining the spatial variability of unsaturated hydraulic properties. We considered only small measurement errors affecting the observed flux-rate from the device, small measurement errors in the applied device pressure, and an error in the contact between the device and the sampled medium. We neglected other, more serious, forms of inversion-model error, including: hysterisis, air entrapment, sub-sample-scale heterogeneity, and fluid-viscosity changes. We used a Monte Carlo approach to propagate our simple errors through steady-state, analytical inversions for hydraulic properties, and we evaluated the bias and uncertainty in spatial statistics of our estimated hydraulic properties. In the hydraulic property range of materials likely to be encountered at DOE sites, estimated hydraulic properties were strongly biased, and their spatial statistics reflected this bias and were highly uncertain. Bias and uncertainty increased when boundary-condition error was also considered. Because the tension infiltrometer performed very poorly under nearly ideal conditions, we concluded that the tension infiltrometer cannot reliably estimate hydraulic properties for spatial variability studies. Other approaches for estimating unsaturated permeability (e.g., transient methods) require more complicated inversion models, which are likely to be more sensitive to measurement and inversion-model errors.

Because the tension permeameter performed so poorly for estimating the spatial statistics of *in situ* unsaturated hydraulic properties, we evaluated property-estimation errors inherent to laboratory methods for estimating unsaturated hydraulic properties and their impact on estimates of spatial statistics. In principle, laboratory methods provide the most accurate estimates of unsaturated hydraulic properties, because inversion models are simple and subject to fewer sources of error. We directly evaluated, using Monte Carlo methods, the influence of property-estimation errors on spatial statistics for parameters that describe the moisture-retention curve and unsaturated hydraulic conductivity. Our results indicate that very small amounts of measurement error introduce little bias or additional uncertainty in estimated spatial statistics for hydraulic properties that scale the unsaturated hydraulic conductivity and moisture-retention curves (saturated hydraulic conductivity, porosity, and air entry value). Spatial statistics for parameters related to the slope of the relative permeability and pressure-saturation curves, however, are moderately to very strongly biased by property-estimation errors and are substantially more uncertain. Our results represent a "best" case, as the measurement errors used were very small and a variety of errors (air entrapment, alteration of sample properties during removal and experiments, etc.) were neglected. We conclude that laboratory methods may not be capable of generating reliable estimates of spatial statistics for model parameters that describe the slope of the relative permeability and moisture-retention curves, especially in the presence of more realistic errors.

We now believe that the spatial statistics of parameters that describe the slopes of the pressure-saturation and relative permeability curves cannot be reliably estimated using either field or laboratory methods, even under nearly ideal conditions. As a result, we have shifted the focus of our research and placed emphasis on estimating those parameters that scale the pressure-saturation and relative permeability curves (saturated hydraulic conductivity and air-entry pressure) and surrogate methods for estimating the slope parameters. Preliminary error analysis of direct methods for estimating the saturated hydraulic conductivity (air permeameter) and air-entry pressure (air-entry permeameter) indicate that spatial statistics for these parameters can be reliably estimated in the field. Surrogate methods for estimating the slope of the pressure-saturation and relative permeability curves from these data appear to perform worse than laboratory methods but much better than *in situ* measurement techniques (e.g., the tension infiltrometer).

Our preliminary permeameter design now consists of a modification of the air mini-permeameter device with a water-flow apparatus for saturating the sampled area. The air permeability is measured, the sample area is saturated, and the air-entry pressure is measured. Preliminary laboratory testing of an air-entry permeameter have been successful.

PLANNED ACTIVITIES

We will continue to refine and finalize our permeameter design and construct a field prototype. Measurement errors for our device will be quantified based upon laboratory testing. Using the statistics of our measurement errors, we will evaluate bias and uncertainty affecting spatial statistics of unsaturated hydraulic properties estimated with our device. This will serve to identify the material types where our device will yield accurate estimate spatial statistics of unsaturated hydraulic properties. Our final activity will be a field demonstration of the final permeameter design. A field test site has already been selected, and permeameter testing will be performed at a U.S. DOE EMSP project site (A Hybrid Hydrogeologic - Geophysical Inverse Technique for the Characterization, Monitoring, and Risk Assessment of Leachates in the Vadose Zone) in Socorro, New Mexico.