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Permeameters for In-Situ Characterization of Unsaturated Heterogeneous Permeability

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Research Objective

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 two of a 3-year project. We report our activities to date 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.

Analytical Inversion Techniques: We evaluated, developed, and verified parameter estimation methods for inverting steady-state permeameter data, including a variety of boundary conditions and source geometries. Several analytical and quasi-analytical techniques for inverting steady-state permeameter data yield estimates of unsaturated hydraulic conductivity at specific tensions that are independent of parametric models. This represents an advantage over numerical estimation techniques, because numerical estimation yields parametric-model-specific parameter values. Because the time-scales required to reach steady state are large, however, steady-state permeameter methods are inconsistent with our first design criterion.

Numerical Simulations: Numerical simulations of permeameter performance are an integral part of our approach to permeameter design. We evaluated a variety of unsaturated flow codes, but found that they were computationally inefficient, did not preserve the required precision, did not implement necessary iterative schemes, or lacked other required options (e.g., types of source). Because modification of these codes was not practical, we developed and verified a flexible, axisymetric, 2-D, Richard's equation, saturated/unsaturated flow code based on the Galerkin formulation of weighted residuals for finite elements with Newton iteration to handle the non-linearity. This code will be extended for 3-D problems.

Error Evaluation: We are evaluating the effect of error on the uncertainty of estimated spatial statistics to improve permeameter designs. Four types of error affect hydraulic property estimates: 1) measurement errors within the device, 2) boundary condition and flow geometry errors, 3) improper

model specification (e.g., hydraulic properties are not consistent with the parametric model used in inversion), and 4) systematic errors in data inversion. In addition, estimated spatial statistics may be biased by measurement-support-scale heterogeneity.

We have evaluated the effect of small measurement errors on estimated spatial statistics determined from permeameter data. We analyzed the tension permeameter because it is frequently used for estimating spatial statistics of unsaturated hydraulic conductivity. We considered only pressure transducer measurement error within the tension permeameter device and neglected all other sources of errors, and used a Monte Carlo approach for the error analysis . Our preliminary results suggest that small amounts of measurement error can potentially lead to very large uncertainties in estimated spatial statistics, especially for correlation length. We suspect that including the other sources of error will further increase the uncertainty in estimated spatial statistics. If the uncertainty in estimated spatial statistics is high, it may not be possible to directly measure some unsaturated hydraulic properties for use in spatial analysis.

Effect of Measurement Scale Heterogeneity: We hypothesize that measurement-scale heterogeneity will introduce additional uncertainty in estimated spatial statistics for unsaturated hydraulic properties. As a result, we are developing adjoint sensitivity analysis techniques to quantify the impact of measurement scale heterogeneity on hydraulic parameters estimated with various permeameter designs. This approach yields a quantitative measure of the sensitivity of a measured effective property to the heterogeneities present within the measurement support. We have successfully applied this approach to the air permeameter, an instrument that measures saturated hydraulic conductivity in air dry sediments.

Independent Estimates of Scaling Variables: We believe that independent estimates of scaling variables, saturated hydraulic conductivity and the air entry value, may be subject to less error, therefore, providing better estimates of spatial statistics. Both of these variables can be estimated with a modification of the air mini-permeameter device. We are currently validating this approach.

Device Design: We have completed preliminary permeameter component designs. The basic permeameter design is modular consisting of a water-source package, a hybrid air mini-permeameter, and an instrument package. Development of each package is proceeding independently, allowing for flexibility in specific permeameter configuration.

Planned Activities

We believe that measurement error and bias, caused by systematic errors and measurement-scale heterogeneity, can substantially increase the uncertainty in estimated spatial statistics for unsaturated hydraulic properties. We will, therefore, continue to investigate the effects of these errors and biases with emphasis on minimizing their effect in final permeameter designs. We will specifically examine: boundary condition and flow geometry errors, the effects of improper model specification, data inversion error, and the influence of measurement-scale heterogeneity on effective property bias.

Based upon these results, we will continue to refine and finalize permeameter component designs. Prototype components will be constructed, and their performance verified in the laboratory before field testing. Our final activity will be a field test 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 (project: A Hybrid Hydrogeologic - Geophysical Inverse Technique for the Characterization, Monitoring, and Risk Assessment of Leachates in the Vadose Zone) in Socorro, New Mexico.

We plan to request a no-cost extension for the present project. Little work was accomplished in the first year due to difficulties implementing a subcontract, and because the senior PI was on sabbatical.