Investigation of Scale and Heterogeneity Effects on Flow and Transport in Multiphase Systems

Cass T. Miller

Dept. of Environmental Sciences and Engineering
University of North Carolina
CB #7400, 104 Rosenau Hall
Chapel Hill NC 27599

U. S. Army Research Office
F. O. Box 12211
Research Triangle Park, NC 27709-2211

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Contamination of the subsurface environment by fluids that are immiscible with water is recognized as a commonplace occurrence. Subsurface systems that include immiscible fluids are multiphase systems; the phases present may include a solid, an aqueous, an immiscible organic, and a vapor. Fundamental processes that govern the behavior of such systems are complex. Several crucial questions remain to be answered for multiphase subsurface systems before a mature level of understanding is achieved. Among the most important of these unresolved issues are the effects of measurement scale, system dimensionality, and media heterogeneity on fundamental fluid flow and interphase mass transfer processes.

Work performed on this project was aimed at investigating scale effects in homogeneous and heterogeneous multiphase porous media systems. Important scale effects were shown in experimental and theoretical work, showing that continuum-based approaches have severe limitations for multiphase porous media systems. A powerful x-ray method was developed, which offers significant advancements in precision and accuracy for measuring fluid saturations in small- to intermediate-scale experiments when compared to conventional dual-gamma methods. Intermediate-scale experiments have shown the profound influence of moderate heterogeneity on multiphase flow and transport processes, which has implications for the appropriate form of constitutive relations and application of continuum-based approaches.
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Final Report

Cass T. Miller, Principal Investigator

16 March 1995

U.S. Army Research Office

Grant Number: DAAL03-91-G-0155

The University of North Carolina-Chapel Hill
Department of Environmental Sciences and Engineering

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Statement of Problem Studied

Contamination of the subsurface environment by fluids that are immiscible with water is recognized as a commonplace occurrence. Subsurface systems that include immiscible fluids are multiphase systems; the phases present may include a solid, an aqueous, an immiscible organic, and a vapor. Fundamental processes that govern the behavior of such systems are complex. Several crucial questions remain to be answered for multiphase subsurface systems before a mature level of understanding is achieved. Among the most important of these unresolved issues are the effects of measurement scale, system dimensionality, and media heterogeneity on fundamental fluid flow and interphase mass transfer processes.

Most multiphase research to date has relied upon small-scale measurement of constitutive relations, assumptions of local equilibrium for solute distribution among phases, and the assumption of a homogeneous porous media. The purpose of this project was to investigate multiphase flow and interphase mass transfer processes as a function of scale in both homogeneous and heterogeneous porous media systems.
Summary of Most Important Results

A significant amount of new information has resulted from the work performed during this project, as is evidenced by the publications that have been attributed to this project. Some additional work is in process and I expect two or three additional papers from work completed on this project. Rather than discuss all aspects of this work, a few of the high points are summarized below.

1. Significant work was accomplished to elucidate the nonaqueous phase to aqueous phase dissolution process. This has included experimental and theoretical work that has shown that the size of a representative elementary volume (REV) for NAPL residual is relatively large compared to other properties such as porosity and grows rapidly with media heterogeneity (Mayer and Miller, 1992). The importance of this is that significant errors are expected if one uses continuum models, which are based on the assumption of the existence of an REV, for heterogeneous systems. It may well be that only stochastic approaches are reasonable for such systems, however essentially all work performed to date for multiphase systems is continuum based. This is fertile ground for continuing work that likely will be of far-ranging significance.

2. Putting the issues raised in item 1 aside, it is clear that NAPL-aqueous phase dissolution is fast for regions that are at residual saturation. Two aspects of this problem are worthy of further concern: dissolution to low concentrations typical of health-based standards, and dissolution from pools that result from subsurface heterogeneity. Partial insights into these issues are addressed in Mayer and Miller (1995), which is currently being revised and will be resubmitted in the near future.

3. It is now clear that mass transfer in the unsaturated zone is an extremely complex phenomena that is influenced by moisture characteristic history (Szatkowski et al., 1995). What we have found by examining data collected in our lab and others is that the majority of gas flow occurs through channels of large pores, which leads to diffusion-limited mass transfer resistance that is a function of moisture state and history.

4. X-ray methods developed in this project have been shown to offer an order of magnitude improvement in precision and accuracy compared to traditional dual-gamma approaches. These methods offer an exciting new approach, which is resulting in the production of data sets of a quality that can not be achieved using competing methods.

5. One application of the x-ray methods mentioned in item 4 has shown that mild heterogeneities in porous media systems exert a profound impact on fluid flow and species transport in multiphase systems. A set of intermediate-scale experiments fully describing these observations will be completed in the coming months. This finding is of profound significance, suggesting that small-scale variations can importantly effect appropriate constitutive relationships at larger scales—reinforcing the findings mentioned in item 1 for example. We will continue to explore this area in future work.
Publications and Technical Reports

Journals


Proceedings and Book Chapters


Published Abstracts and National Meeting Presentations


**PhD Dissertations and MS Technical Reports**


Participating Scientific Personnel

1. PI: Cass T. Miller at 25% effort.

Dissertations, theses, and reports that are credited in part to this project are annotated above. Note there is not a one-to-one correspondence between the students supported and the dissertation, theses, and report list. In some cases, students contributed to the project, but work on the project did not overlap with their dissertation or thesis. In other cases, the PI contributed significantly to work presented in a dissertation or thesis that was considered part of this project, but for which the student had other sources of support (e.g., fellowship).
Reports or Inventions

Patents will not be sought on any experimental or mathematical model developments accomplished in this work. All details of experimental procedures and computer codes have been or will be published and are considered to be in the public domain.