

Project 87003 - Advanced Conceptual Models for Unsaturated and Two-Phase Flow in Fractured Rock

Michael J. Nicholl - University of Idaho

Robert J. Glass - Flow Visualization and Processes Laboratory, Sandia National Laboratories

Harihar Rajaram - University of Colorado

Thomas R. Wood - Idaho National Engineering and Environmental Laboratory

Research Objective: The Department of Energy Environmental Management Program is faced with two major issues involving two-phase flow in fractured rock; specifically, transport of dissolved contaminants in the Vadose Zone, and the fate of Dense Nonaqueous Phase Liquids (DNAPLs) below the water table. Conceptual models currently used to address these problems do not correctly include the influence of the fractures, thus leading to erroneous predictions. Recent work has shown that it is crucial to understand the topology, or 'structure' of the fluid phases (air/water or water/DNAPL) within the subsurface. It has also been shown that even under steady boundary conditions, the influence of fractures can lead to complex and dynamic phase structure that controls system behavior, with or without the presence of a porous rock matrix. Complicated phase structures within the fracture network can facilitate rapid transport, and lead to a sparsely populated and widespread distribution of concentrated contaminants; these qualities are highly difficult to describe with current conceptual models.

We are working to develop advanced conceptual models for two-phase flow in fractured rock. Preliminary experiments have shown that behavior at fracture intersections is key, thus we are employing systematic experimentation to identify and classify behavior at intersections. Understanding gained at the scale of intersections will be used to augment a Modified Invasion Percolation Model (MIP) that has shown significant promise in predicting flow through fracture networks. Development of the MIP model will be iterative, in that we will use numerical simulations to design critical physical experiments at the network scale which will challenge the model. The augmented, and fully tested MIP model will be exercised on realistic fracture networks for the purpose of understanding large-scale development of phase structure. Networks will be generated using algorithms conditioned to field data collected at DOE sites (e.g., INEEL, Nevada Test Site, Oak Ridge). Results of the large-scale network simulations will be abstracted so that critical features may be included in conceptual models used by the Environmental Management Program.

Research Progress and Implications:

This report summarizes the first eight months of effort on a new project initiated in FY03. As of June 2003, we have accomplished the following:

- 1) We conducted a more detailed evaluation of the preliminary experiments used to develop our investigative approach. In those experiments, water was invaded at a variety of flow rates into an air-filled, two-dimensional analog fracture network. Results demonstrated the critical control that fracture intersections place on two-phase flow in fracture networks. At low flows, capillary and gravitational forces combined to create a narrow pulsing flow structure that spanned the system vertically. At higher flows, viscous forces acted to remove the pulsation. Results were prepared as a journal article, and submitted to *Water Resources Research* [Glass et al., in review].
- 2) We initiated a collaborative relationship with a research group at Seoul National University. This group, which is led by Dr. Kang-Kun Lee is using a combined experimental-numerical approach to consider DNAPL migration in fracture networks. They are particularly interested in the influence of ambient groundwater flows, making their work complementary to ours. The first fruit of that collaboration is an article demonstrating that modification of an Invasion Percolation algorithm to include gravity, and the first-order effects of viscous forces shows good agreement with physical experiments in a simplistic fracture network. Results were published in *Geophysical Research Letters* [Ji et al., 2003].
- 3) We carried out an extensive review of models for fracture networks. These include models developed from observations of networks on outcrops at several scales and stochastic models that are prevalent in the literature from the 1980s to very recent developments. The results of this review were included as part of a review paper co-authored by Rajaram, which was submitted to *Reviews in Geophysics* [Molz et al., in review].
- 4) We prepared a manuscript based on previous work that will be used to support the development of our new conceptual model(s) of transport in fractured rock. Eight experiments were conducted to evaluate the repeatability of flow under nearly identical conditions and to characterize general patterns in flow behavior. Collected data revealed that flow generally converged to a single fracture in the bottom row of blocks. Periods of pathway switching were observed to be more common than periods with steady, constant flow pathways. We noted the importance of fracture intersections for integrating uniform flow and discharging a “fluid cascade”, where water advances rapidly to the next capillary barrier creating a stop and start advance of water through the network. The results of this simple experiment suggest that the interaction of multiple fracture intersections in a network creates flow behavior not generally recognized in popular conceptual and numerical models. The manuscript was submitted to the *Vadose Zone Journal* [Wood, et al., in review].

5) M.J. Nicholl helped to evaluate a well completion technique developed by investigators at the INEEL (J.M. Hubbell, J.B. Sisson). Their design significantly reduces the deleterious effects of barometric fluctuations on water level measurements. Thus providing a means to more accurately predict water table gradients in fractured rock, such as is found at the INEEL. A journal article documenting the design and testing of this well completion technique was submitted to the Vadose Zone Journal [Hubbell et al., in review].

6) We presented an overview of our project at the EMSP Principal Investigator Workshop in Richland, WA on May 6-7, 2003.

7) M.J. Nicholl gave invited presentations regarding experimental investigation of flow through unsaturated fracture networks at: North Dakota State University (1/31/03), Tufts University (2/11/03), University of Alabama (2/18/03), University of Massachusetts (3/10/03), University of California at San Diego (3/20/03), and University of Nevada at Las Vegas (3/28/03).

8) In collaboration with ongoing unsaturated fractured rock research at INEEL, we evaluated unit processes active at the scale of individual intersections that may explain dynamical behavior observed in experiments at the network scale (see 1 and 4 above). The competition between capillarity, gravitational, viscous, and in some cases inertial forces results in unstable pooling of fluid above intersections. The release of fluid from the pools was seen to be sensitive to intersection geometry. Three basic types of intersections were identified: 1) strong integrating capillary barriers with large uniform storage volumes; 2) weak capillary barriers with small storage volumes; and 3) flow limiting capillary bridges. A manuscript is in preparation for Water Resources Research [Wood et al., in preparation].

Planned Activities:

For the remainder of calendar year 2003, we plan the following tasks on this project.

1) A Graduate Research Assistant working at the University of Colorado with Rajaram is engaged in developing computer codes for the generation and visualization of fracture networks. The initial focus is on two-dimensional networks. This effort will be continued to generate three-dimensional networks, and populate individual fractures within the network with variable apertures. These generated networks will become the focus for simulations of two-phase flow using the MIP model. The proposed MIP model simulations will cover a wide range of fracture network parameters (e.g. connectivity and coordination number) to evaluate the range of behavior expected in two-phase flow phenomena in fracture networks.

2) M.J. Nicholl is planning to spend July-September, 2003 at Sandia National Laboratories collaborating directly with R.J. Glass on network scale simulations, and supervising experimental efforts to understand behavior in single intersections.

3) Enhance our collaboration with Dr. Lee's group at Seoul National University. We hope to bring one member of their research team to the US during the September-December, 2003 time frame to participate in our experimental efforts and coordinate numerical simulations.

4) We will expand upon our understanding of the unit processes active at individual intersections by conducting a series of experiments utilizing a small number of fracture intersections in a single vertical fracture.

5) M.J. Nicholl will continue collaborations with J.M. Hubbell and J.B. Sisson at the INEEL to evaluate field data collected from thick sequences of unsaturated fractured basalt.

Information Access:

Glass, R.J., M.J. Nicholl, H. Rajaram, and T.R. Wood, Unsaturated flow through fracture networks: Evolution of liquid phase structure, dynamics, and the critical importance of fracture intersections, *Water Resources Research*, in review, 2003.

Hubbell, J.M., J.B. Sisson, M.J. Nicholl, and R.G. Taylor, Well design to reduce barometric pressure effects on water level data in unconfined aquifers, *Vadose Zone Journal*, in review, 2003.

Ji, S.H., I.W. Yeo, K.K. Lee, and R.J. Glass, Influence of ambient groundwater flow on DNAPL migration in a fracture network: Experiments and simulations, *Geophys. Res. Lett.*, 30(10), 11-1 to 11-4, doi:10.1029/2003GL017064, 2003.

Molz, F. J., H. Rajaram, and S. Lu, Fractal concepts in subsurface hydrology: Origins, applications and future developments, *Reviews of Geophysics*, in review, 2003.

Nicholl, M.J., R.J. Glass, H. Rajaram, and T.R. Wood, Advanced conceptual models for unsaturated and two-phase flow in fractured rock, presented at the EMSP Principal Investigator Workshop, Richland, May 6-7, 2003, www.pnl.gov/emsp/presentations.stm.

Wood, T.R., R.J. Glass, R.A. Laviolette, D.L. Stoner, T.R. McJunkin, R.K. Podgorney, K.S. Noah, R.C. Starr and K.E. Baker, Unsaturated flow through a small fracture-matrix network: Part 1, Experimental observations, in review, *Vadose Zone Journal*, May 2003.