H71A-0789 0830h POSTER

Relative Importance of Dispersive and Diffusional Processes in Aquifers Containing a Connected High-conductivity Network: Assessment of the Relative Conductivity Peclet Number Criterion

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Recent studies of solute transport in highly heterogeneous aquifers have revealed the importance of well-connected networks of high-conductivity materials on solute transport. Despite comprising only a small percentage of an aquifers volume, connected high-conductivity channels have been demonstrated to control the behavior of solute plumes and sometimes, produce greatly asymmetric, non-Gaussian plume patterns with near-source peaks and extensive spreading in low-concentration regions. Such plume patterns can be caused by diffusional mass transfer into and out of high-conductivity channels, and cannot be described adequately by classical advection-dispersion theory. This study is aimed at quantifying the relative importance of diffusional mass transfer versus classical dispersion in flow fields controlled by connected high-conductivity networks. The ultimate goal is to develop guidance for selecting the most appropriate model, either diffusional or dispersive, for a given set of field conditions. In 2-D and 3-D numerical experiments three end-member high-conductivity network configurations are investigated, i.e., low-conductivity matrix containing straight high-conductivity channels parallel to the dominant flow direction, low-conductivity matrix containing straight high-conductivity channels perpendicular to the dominant flow direction, and low-conductivity matrix containing hypothetical but geologically plausible high-conductivity channels generated using invasion percolation theory. In all three cases, systematically increased conductivity ratios are assigned to the low-conductivity matrix versus high-conductivity channels. The effects on plume development of different solute source sizes and shapes (relative to the interchannel spacing) are investigated. A Relative Conductivity Peclet Number (RCPN) is suggested as a useful criterion to quantify the relative importance of diffusional mass transfer versus spreading due to dispersion. The RCPN criterion takes into consideration the matrix versus channel conductivity contrast, the geometry of channel network, and the magnitudes of molecular diffusion and local dispersion. As the RCPN becomes small, plumes appear Gaussian. As the RCPN becomes large the plumes are asymmetric, exhibit tailing, and their shapes are controlled by local relative preferred pathways. A series of simulation experiments suggest that the RCPN criterion is capable of providing a good quantitative measure of plume behavior and thus provides some guidance for model selection.

H71A-0790 0830h POSTER

An Explanation of 03Anomalous03 Specific Yield in Unconfined Aquifers

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Interpretations of pumping tests in unconfined aquifers using the theories of Dagan (1967) and Neuman (1974) systematically result in unrealistically low values of specific yield. Addition of Boulton0304s empirical fitting parameter resulted in a partial improvement of specific yield estimates and a better fit of observed data near the water table in few cases (Moench, 1997).

However, in was proven that the unsaturated zone does not play an important role in the processes below the water table, and the empirical fitting parameter does not have clear physical meaning. Analysis of numerous sites indicates that data were collected in alluvial aquifers. Such aquifers exhibit a major geological condition that is not represented by neither of above mentioned three existing models- deviation of the aquifer base from aquiclude conditions. This aquifer base can be represented as an aquitard that is capable of vertical water movement inside the aquitard and water release to the upper unit.

We present a more realistic model of alluvial aquifer with the aquitard at the base. For typical parameters of the alluvial sand/gravel aquifer and clay aquitard, the piezometer responses differ from the responses predicted by Neuman0304s (1974) model at intermediate times and only at the later times these responses have similar asymptotic behavior.

Using this unconfined aquifer/aquitard (AA) model, we investigate the aquitard effect on effective parameter values. Results indicate that (1) presence of the aquitard may strongly affect the aquifer response and data interpretation; (2) use of the contrast in hydraulic conductivity for discriminating aquifer and aquitard units in the steady-state conditions should be replaced with the hydraulic diffusivities, defined as the ratio of the hydraulic conductivity to the specific storage.

H71B MCC: Hall C Sunday 0830h

Fundamental Advances in Understanding of Pore-Scale Transport Phenomena in Porous Medium Systems II Posters

Presiding: **M Hilpert,** Johns Hopkins University**; D Zhang,** Los Alamos National Laboratory

H71B-0791 0830h POSTER

Liquid Vapor Interfacial Stability Under Slow Laminar Flow in Microchannels

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We address the question of whether liquid-vapor interfaces in microchannels remain stable under slow laminar flow conditions. This is an important issue for development of constitutive relationships for hydraulic conductivity of unsaturated porous media based on liquid configuration under equilibrium conditions. We controlled water flow rates and matric potentials in glass capillary channels of square and triangular cross sections. Video microscope imagery was used to deduce liquid-vapor radii of curvature and liquid velocity at different locations within a channel. Preliminary results show remarkable stability of the liquid vapor-interface under slow laminar flows (capillary number $= 3.71\times10^{-8}$). Measured velocities were in excellent agreement with model predictions assuming steady and equilibrium conditions. Ongoing work focuses on identification of limits of the assumption of stable interfaces based on energy dissipation considerations.

H71B-0792 0830h POSTER

The Impact of Two-Phase Saturation History on Three-Phase Flow Characteristics of Sediments: A Pore-Scale Model

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Predictive field-scale models of the concurrent movements of three fluids require accurate predictions of macroscopic three-phase flow properties such as relative permeabilities and capillary pressures. Since direct experimental measurements of such properties are very difficult and empirical correlations are often not reliable, the use of physically-based three-phase pore-scale models has become an appealing alternative. In this paper, we describe the features of our advanced three-phase quasi-static pore network model which integrates a realistic representation of pore connectivity and morphology, a realistic description of fluid displacement mechanisms, and a sound representation of wetting properties of the rock. The model works with three-dimensional, disordered networks of cylindrical ducts with triangular, rectangular, and circular cross-sections obtained directly from the analysis of micro-CT images of rock samples. This approximation allows one to capture the flow of water in filaments along the pore corners, NAPL in intermediate layers, and gas in the pore center. All pore-level displacement mechanisms: piston-type, snap-off, cooperative pore-body filling, and double-displacements are considered with arbitrary wettability and spreading. Permeabilities of the phases are computed with accurate expressions of the hydraulic conductance of each phase in the network elements for different pore geometries and phases configurations. The model is used to simulate gas injection processes into porous media that initially contain water and NAPL after a two-phase drainage or imbibition processes. The gas injection is performed using a *cluster-based invasion percolation algorithm with trapping.* The profound effects of two-phase saturation history on describing three-phase transport properties of a porous medium are illustrated by performing a series of gas injection processes using different initial water/NAPL saturations and configurations.

H71B-0793 0830h POSTER

Predicted Disappearance of Saturation Hysteresis in Coarse Granular Media Based on Capillary and Gravity Scaling, and Experimental Tests

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Since the classic work of W. B. Haines (1930), hysteresis in the relation between matric (capillary) potential versus water content has been recognized as a basic aspect of interactions between water and variably saturated porous media. This lack of unique correspondence between potential and saturation has well-recognized consequences for equilibrium, flow, and transport. Although hysteresis in moisture characteristic relations has several causes, the existence of different pore-sizes within porous media (the "ink bottle" effect) is primary. This capillarity-dependent phenomenon has a grain-size limit imposed by the influence of gravity, and more generally by the relations between surface and body forces, and length scales. Above this limit, capillary hysteresis vanishes. The grain-size associated with vanishing of capillary hysteresis was predicted in two ways; first with a simple pore-size model, and second by Miller-Miller scaling. Both methods predict that hysteresis vanishes when characteristic grain-sizes exceed about 8 mm, when the water-air surface tension is 72 mN/m, and when the body force is due to ordinary gravity. More generally, capillary hysteresis is predicted to disappear when the Haines Number (dependent on grain-size, surface tension, the body force, density difference between immiscible fluids) exceeds 8. The predicted critical grain-size was experimentally supported through measurements of drainage and wetting curves of sands and gravels, with grain-sizes ranging from 0.2 up to 11 mm. We also consider effects of interfacial tension variation (surfactants), variation of the body force (centrifugal field), and capillarity associated with grain-surface roughness.

H71B-0794 0830h POSTER

Simulation of Flow and Transport in a Single Fracture Using the Reynolds Equation: Macroscopic Effects of Underestimating Local Head Loss

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Fluid flow in a single fracture is commonly simulated using the Reynolds equation. Recent work suggests that this depth-averaged approach underestimates head loss in regions of changing aperture. Implementing an ad hoc correction in the numerical formulation of the Reynolds equation allows us to modify local head loss, and calibrate simulation results to existing experimental data. Calibrated flow fields provide an improved estimate of longitudinal dispersivity, demonstrating the importance of adequately describing local head loss.

H71B-0795 0830h POSTER

Parallel Two-phase Flow Simulation and Representative Elementary Volume

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Two-phase flow simulation using the Lattice-Boltzmann method has drawn great attention, as it can simulate a variety of two-fluid flow situations that are difficult in laboratory. The capability to use the real pore structure geometry is a particular strength of the model, compared to the more widely used pore network simulators. We have already shown that two-phase flow simulation can replicate physical two-phase fluid flow in the realistic and complex pore structure in the previous works. However, this computation-intensive simulation is very time consuming even with modern computers. In addition, we need to resolve two interfaces grain/pore boundary and the boundary between wetting and non-wetting fluids. This requires a finer grid structure in a digital rock sample, which makes the problem size bigger. Since parallel machines are now widely available and most parts of the Lattice-Boltzmann algorithm are local operations, a parallel implementation is a good candidate for resolving these issues. We developed a parallel two-phase flow simulator that has several optimizations customized for the Lattice-Boltzmann algorithm. With the optimizations, our code could achieve a speedup of 12 with 14 processors, while a non-optimized code is only 4 times faster with 14 processors than a serial code. With the help of the efficient parallel simulator, we could explore the representative elementary volume (REV) of two-phase fluid flow. We found that the REV for two-phase flow is bigger than one for porosity or absolute permeability. In order to represent various situations of two phase flow in complex pore geometry, the size of a digital rock sample should be greater than 20 times of mean pore size in length scale (1D). This size is about twice bigger than one for single-phase flow simulations. Thus the REV (3D) for two-phase flow simulation is eight times bigger than the REV of single-phase flow. Our parallel simulator efficiently and successfully calculated the relative permeability of these large size problems, which are almost prohibitive to run on serial machines. Our efficient parallel simulator can also be used for more complicated applications with two-phase fluid flow in porous media, such as capillary pressure curve simulation, relative permeability estimation from thin sections and diagenetic modeling related to two-phase fluid flow.

H71B-0796 0830h POSTER

Characterization of the Mass Flux to Groundwater from DNAPL Trapped in Low Conductivity Zones

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Dense nonaqueous phase liquids (DNAPLs) have caused significant groundwater contamination at many hazardous waste sites. Due to heterogeneity in the subsurface, DNAPL may be trapped in high both high and low conductivity zones. The objective of this study is to quantify the impact of low conductivity zones on the mass flux to groundwater in heterogeneous systems. Pore-scale DNAPL dissolution was investigated in a 2-dimensional etched silicon pore network with different conductivity zones parallel to the flow direction (i.e., a high conductivity zone bounded by two low conductivity zones). Fluorescence microscopy and digital image analysis were used to determine the mass flux to water and the specific surface area during dissolution. The average linear velocity in each zone was also quantified. In the high conductivity zone, the Peclet Number ($Pe = vd/D$; $v =$ average linear velocity, $d =$ grain diameter, $D =$ molecular diffusion coefficient) was ~ 100 and dissolution was controlled by advection. In the low conductivity zones, however, Pe ~ 1 and dissolution was controlled by both advection and diffusion. Mass transfer in the high conductivity zone was described with a 1-D advection-1^{st} order dissolution equation, whereas mass transfer in the low conductivity zones was described with a 2-D advection-dispersion-1^{st} order dissolution equation. Mass transfer coefficients for each zone were obtained by fitting mass flux results. It was determined that the mass flux to water flowing from the low conductivity zones was less than 1 % of the mass flux to water from the high conductivity zone. Further efforts are being made to determine how the dimension and permeability values of low conductivity zones affects the mass flux to groundwater relative to high conductivity zones.

H71B-0797 0830h POSTER

A Pore Scale Study of Permeability Reduction Caused by Biofilm Growth

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A pore-scale numerical model was developed to study mechanisms of permeability reduction caused by biofilm growth in porous media. The model determines water flow, transport and reaction of solutes and microbes, and biofilm growth in a porous medium at length scale of millimeters to centimeters. Model biofilms are collections of connected grid cells that contain microbes. Model biofilms are impermeable to water flow and reduce solute diffusion coefficients linearly with increasing microbe concentration. The lattice Boltzmann method with bounce-back boundary conditions is used to calculate local fluid velocity driven by a constant pressure gradient. An implicit finite difference algorithm is used to solve transport and metabolic reactions of aqueous solutes with microbes. Finally, a rules-based scheme governs biofilm expansion. Flow field development is assumed to occur instantaneously with respect to changes in biofilm configuration. Model results compare favorably to previously published work. Factors that affect permeability reduction include type of porous medium heterogeneity, flow rate, and limiting substrate concentration. In heterogeneous porous media, preferential flow paths provide more substrate that enables greater biofilm growth rates there. Subsequent growth and clogging of pores causes flow to be diverted to smaller pores. Bulk flow rates impact shear rates at the water-biofilm interface and limit extent of biofilm growth. The limiting substrate concentration and the requirement that microbes located deep within biofilms obtain sufficient substrate together determine the maximum biofilm thickness.

H71B-0798 0830h POSTER

Pore-Scale Investigation of Immiscible Displacement Fronts Under the Influence of a Gradient

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Understanding the behavior and geometry of two-phase immiscible displacement fronts is critical in the fields of environmental restoration, geologic hazardous waste storage, and petroleum engineering (*e.g.* air sparging, NAPL infiltration, and secondary recovery of petroleum by water flooding). Depending on the flow conditions, the presence of gradients, such as those caused by gravity forces, viscous forces or permeability gradients, can variously lead to either stabilized (*e.g.* piston-like) or to unstable (*e.g.* gravity or viscous fingering) displacement fronts.

Previous studies have found that the resulting displacement fronts may have patterns with percolation, or fractal, characteristics which cannot be adequately described by continuum equations [Chaouche *et al.*, 1994; Glass & Yarrington, 1996; and, Zhang *et al.*, 2000]. Numerical pore-network models which incorporate the appropriate physics provide a framework in which to study these characteristics.

We present results of numerical simulations on regular two-dimensional rectangular lattices which are based on the method of invasion percolation in a gradient (IPG). Special attention is given to the characterizing the fractal-like geometry of the displacement fronts, and identifying scaling laws. Attempts are made to provide a methodology for upscaling the pore-scale results to intermediate scales.

H71B-0799 0830h POSTER

Interfacial Area per Volumie for Multiple Fluid Phases in Sandstone undergoing Imbibtion

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Recent experimental investigations on micro-models and theoretical developments suggest that interfacial area per volume (IAV) for multiple phases in a porous medium plays an important role in specifying the state of a porous medium system. It is well known that capillary pressure and saturation do not uniquely specify the state of the system because a single value of relative volume saturation can correspond to infinitely different distributions of two phases within the volume. However, compared with other parameters like porosity, permeability etc., IAV is difficult to measure in opaque material such as rock because it involves measuring the interfaces between a wetting phase, a non-wetting phase and rock.

We have used a Wood's metal injection technique to determine IAV in sandstone undergoing imbibition. Measurements were performed on sandstone samples measuring 52 mm in diameter and ranging from 25 mm to 100 mm in length. Wood's metal was used to represent a non-wetting fluid and ethylene glycol (EG) was used to represent a wetting phase fluid. The imbibition experiments were performed for pressure drops ranging from 0 MPa to 0.68 MPa. To determine the IAV for a sample injected with Woods metal, images of the Woods-metal-injected core were taken with a Scanning Electron Microscope (SEM). A custom computer code was used to analyze each SEM image to isolate the rock phase, the wetting phase (EG) and the non-wetting phase, and to calculate the interface between each of the two phases. Analysis of the images of the metal-injected sample found that interfacial length per area (ILA) values for the sandstone ranged from 0 to 150 per cm for the rock-metal interface and decreased from 680 to 20 per cm for the ethylene glycol rock interface for pressures that ranged from 0 MPa to 0.68 MPa. For the metal-ethylene glycol interface, ILA values ranged from 0 to 7.5 per cm for the same pressure range. The investigation also found a break-though pressure between 0.027 and 0.034 MPa where metal saturation increased rapidly. Drainage and scanning drainage experiments are currently underway.

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H71B-0800 0830h POSTER

Interfacial Area Measurements for Unsaturated Flow Through a Porous Medium

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Fluid-fluid interfaces play a key role in the dynamics of multiphase flow and contaminant transport in subsurface systems. For example, interfacial area is directly related to the dissolution rate, and therefore impacts the clean-up process, for non-aqueous phase liquids (NAPLs) present in the subsurface. In addition, recent theoretical work based on conservation laws and the second law of thermodynamics has demonstrated the need for incorporation of quantitative measures of both interfacial area and curvature into multiphase flow models. It has also been hypothesized that traditional, hysteretic, capillary pressure-saturation curves are actually a two-dimensional projection of a multi-dimensional capillary pressure-saturation-interfacial area surface. To provide experimental support for these theoretical developments, we have used the GSECARS microtomography beamline at the Advanced Photon Source to produce three-dimensional pore-scale images of unsaturated flow through a porous medium. Analysis of images obtained at a resolution of 17 microns per pixel allows computation of interfacial area, curvature, and saturation. Corresponding pressure measurements are made during the course of the experiments. Presented here are plots of capillary pressure as a function of experimentally measured fluid-fluid interfacial area and saturation, as well as preliminary data on the curvature of the interfaces.

Use of the Advanced Photon Source was supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under Contract No. W-31-109-Eng-38.

H71B-0801 0830h POSTER

Quantitative Constrained Imaging of Dissolution and Precipitation in a Natural Fracture

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Flow-through tests are completed on a natural fracture in novaculite at temperatures of 200C, 800C, 1200C, and 1500C. Measurements of fluid and dissolved mass fluxes, and concurrent X-ray CT imaging are used to constrain the progress of dissolution and its effect on transport properties. An increase in sample temperature results in a transient closure of the fracture to an equilibrium set, that evolves over approximately 25 h. Successive temperature increases develop sequential closure, the incremental closure decreasing in magnitude with an increase in temperature. The initial differential pressure drop across the fracture increases by two orders of magnitude through the 900 h duration of the test, representing a reduction in hydraulic aperture from 50 to 10 microns. Net dissolution prevails throughout the test. Observed changes in permeability are consistent with the dissolution of contacting stressed asperities; measured solid mass balances match hydraulically measured changes in aperture for a nominal contact area of 15%. Visual identification of dissolution is at the 37 micron resolution of the imaging method, but conforms to the hydraulic and mass balance observations.

H71B-0802 0830h POSTER

Mechanisms for Hysteresis in a Horizontal Unsaturated Fracture with Matric Imbibition

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Within porous media, macroscopic hysteretic pressure-saturation relations have long been thought to be the result of microscopic effects such as phase invasion within local ink bottle geometry, phase trapping or accessibility, and differences between solid-liquid-liquid contact angles for wetting and nonwetting invasion. Here we consider the mechanisms for hysteresis within a horizontal rough-walled fracture. An analogue horizontal rough-walled fracture (10 cm x 15 cm) was formed by placing a piece of transparent textured glass against a water saturated, flat porous plate. Water could enter and leave the fracture via the porous plate while air entered or left via the fracture edges. The evolution of wetted structure within the fracture was recorded with digital images taken through the transparent side as the tension in the porous plate was raised and lowered. Following a sequence of such invasion experiments, the porous plate was replaced with a piece of flat glass and the aperture field was measured using a light transmission technique. Analysis of digital images taken during displacement demonstrated that the macroscopic hysteresis in pressure-saturation curves resulted primarily from the underlying microscopic mechanisms of ink bottle and phase trapping accessibility. Additionally, we found the wetted structure within the fracture to become connected and form a satiated (0 tension) structure containing complex entrapped air structures (volumetric saturation 0.5) thus greatly reducing permeability at 0 tension. The pressure at which this structure formed on wetting and fragmented on drainage also showed significant hysteresis.

H71B-0803 0830h POSTER

Experimentally Derived Collision Efficiencies of Microparticles Using Atomic Force Microscopy: Toward a Better Understanding of Particle Transport in Porous Media

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Collision efficiencies (α) represent the probability of attachment of a particle to a collector and are determined by the forces of attraction and repulsion between these surfaces at the nanoscale. In this study collision efficiencies of micron-sized particles were derived from force versus distance data collected using atomic force microscopy (AFM).

Individual latex spheres measuring 1 μm in diameter were attached to the ends of silicon nitride cantilevers and brought into contact with glass beads measuring between 30 and 50 μm in diameter in aqueous solution. The surfaces were translated toward each other at a rate of approximately 3 μm/sec, which is consistent with typical pore water velocities. Contact-mode AFM was used to measure forces of repulsion and attraction with picoNewton resolution as the surfaces were moved together and subsequently separated. Intersurface potential energies were determined by integrating force data with respect to distance. Collision efficiencies are calculated from potential energy using Spielman and Friedlanders (1974) method that describes deposition of Brownian particles by convective diffusion.

Using the AFM technique, collision efficiencies can be determined directly from measurable forces of interaction between the transported species and the collector. This direct method may more accurately describe the transport of microparticles in porous media by including the forces involved in both attachment and detachment. In the future, collision efficiencies of live bacterial cells will be measured and column experiments will be performed to verify the accuracy of these collision efficiencies.

H71B-0804 0830h POSTER

Colloid-Facilitated Cesium Transport in the Vadose Zone at the Hanford Site

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Transport of ^{137}Cs and colloids through a Hanford sediment column under unsaturated conditions was investigated. The movement of cesium and colloids followed the convective-dispersive solute transport equation and the mass transfer processes governing colloid-facilitated cesium transport were colloidal deposition, cesium sorption to the medium, and cesium sorption to colloids. It was found that cesium was strongly adsorbed to Hanford sediments and only colloid-bound cesium could breakthrough. Cesium experienced a greater facilitated transport at higher saturation than at low saturation and the migration of cesium was more a function of the behavior of colloids than of dissolved cesium. A two-region model was used in describing colloid-facilitated cesium migration and the influence of the system saturation was examined by relating to the variation of simulated model parameters. Hanford native colloids, i.e., *in-situ* colloids from the Hanford site, and modified colloids, i.e., *in-situ* colloids subject to chemical treatment, were used as model colloids to study facilitated cesium transport in this research. The results of this study will be of help in understanding the response of colloid-facilitated cesium migration to variation of saturation at the Hanford site.

Key words: cesium; colloid; facilitated transport; saturation; and Hanford sediment.

H71B-0805 0830h POSTER

Critical Phenomena of Nonwetting Fluid Infiltration, Redistribution, and Immobilization in Saturated Porous Media

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This study presents a capillary pressure-relative permeability-saturation (Pc-kr-S) constitutive model that incorporates the key characteristics necessary for simulating the infiltration, redistribution, and immobilization of nonwetting fluid in a saturated porous medium. To develop a model validation data set, the migration of a dense, nonaqueous phase liquid (DNAPL) pool within a one-dimensional, 1 m tall, saturated sandpack was monitored under alternating drainage and imbibition conditions. A light transmission/image analysis system measured the evolution of the interface between mobile and residual DNAPL as well as providing a continuous sequence of fluid saturation profiles. The terminal pressure is demonstrated to be the minimum sustainable capillary pressure for imbibing nonwetting fluid, below which continuity cannot be sustained and complete residual is formed. A ratio of terminal to entry pressure of approximately 0.6 is found to apply at both bench and macroscopic scales, and to be independent of porous media and fluid properties. Numerical simulations of the bench-scale experiments, using model parameters obtained independently from measured local scale Pc-kr-S hysteretic curves, predict, within measurement uncertainty, the observed equilibrium pool heights and rates of DNAPL migration and immobilization. Constitutive models that do not incorporate both an entry and a terminal capillary pressure, such as those based upon the standard van Genuchten function, are unable to reproduce the observed equilibrium pool heights. Constitutive models that do not properly incorporate nonwetting phase relative permeability hysteresis, including appropriate function curvature and the abrupt extinction of relative permeability at the terminal pressure, are unable to reproduce the observed rates of DNAPL migration and immobilization.

H71B-0806 0830h POSTER

A Model for Predicting Residual NAPL in the Vadose Zone

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A constitutive model for relative permeability-saturation-pressure relationships is outlined for predicting free, trapped, and residual NAPL in the vadose zone. Residual NAPL is commonly defined as that NAPL which does not drain from the pore spaces under gravity. We conceptualize residual NAPL to be NAPL that becomes immobile after filling small pore wedges or spaces and after forming thin films or lenses on water and solid surfaces. As such, the residual NAPL can be continuous and/or discontinuous in the pore spaces. Because the residual NAPL is immobile, it does not contribute to free NAPL advection, regardless whether NAPL is draining from or imbibing into pore spaces. Trapped NAPL differs from residual NAPL because it is always discontinuous and occluded by water. The mechanisms for the formation of residual and trapped NAPL are different. We model residual NAPL using similar concepts as those used to model residual water. Using the hysteretic constitutive model, the water and NAPL (free, trapped, and residual) saturations are predicted from the capillary pressures in an air-NAPL-water fluid system and the water and total-liquid saturation-path histories. Water and free-NAPL relative permeabilities are predicted from integral expressions. When all of the NAPL will be in residual form, the free-NAPL relative permeability will be zero. The model can be easily incorporated in multifluid numerical flow codes. As a preliminary test of the model, the water and NAPL saturations and relative permeabilities are predicted from simulated air-NAPL and NAPL-water capillary pressures involving a scenario where a slug of NAPL infiltrates into a sandy porous medium and drains later to its residual value. The results are shown and discussed. The model can be used in numerical codes for more accurately predicting the behavior of NAPL in the subsurface. Modeling residual NAPL in the vadose zone is important because it is a long-term source for groundwater contamination.

H71B-0807 0830h POSTER

Measurement of Flow and Transport in Macroporous Soils

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Preferential flow in agricultural regions poses a serious environmental threat by allowing chemicals to bypass the soil matrix and to be channeled into ground water. Although a long-known phenomenon, our understanding of and ability to predict macropore flow and transport remain far from complete. To analyze the processes that control macropore flow in soil, we have built large (25 cm diam., 80 cm length) repacked soil columns with different macropore/matrix domain configurations: (i) In column I, multiple macropores were created in one-half cross-section. Water flow and chloride transport experiments were performed for macropores open to the atmosphere and buried-macropores. Measurements at the bottom boundary as well as across the profile consistently revealed the higher degree of preferential flow in open macropores as compared to the buried macropores. (ii) In column II, a single cylindrical macropore was located in the center of the surrounding soil matrix. We conducted experiments of water flow and solute transport using KBr as a conservative tracer. In the soil matrix, TDR-probes measure soil water content and solute concentration, and mini-tensiometers register matric potential. In and adjacent to the macropore-system, TDR-coil probes (diam. 0.3 cm, length of copper coil 1.5 cm) and mini-tensiometers (ceramic cup diam. 0.1-0.2 cm) monitored macropore flow and provided information to quantify inter-region water transfer. Bromide specific electrodes measured the bromide concentration in the effluent of the macropore region and of the matrix region as well as directly inside the soil matrix. The experimental setup seems promising for analyzing basic flow and transport processes in macroporous soils. In future experimental analyses, the complexity of the macropore configuration will be systematically increased in terms of macropore number, geometry, continuity, and physical properties of macropore walls.

H71B-0808 0830h POSTER

Mobile-Immobile Model Simulation of Non-equilibrium Tracer Transport through Undisturbed Soil Columns under Transient Flow Conditions

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Physical non-equilibrium transport processes in soil may lead to preferential leaching of contaminants into the ground water system. The application of dual- and multi-permeability models to analyze preferential transport still remains difficult due to the large number of model parameters required that can only be determined with a high level of uncertainty. Mobile-Immobile Models (MIM) require fewer parameters and have been frequently used for simulating non-equilibrium transport under steady-state flow conditions. In this study, we utilize a single region transport model (SRM) and a modified MIM to simulate several tracer transport experiments under transient flow conditions in undisturbed soil columns. Analyses of the transient experiments were performed using inverse parameter estimation algorithm of modified HYDRUS (Simunek et al. 2002). Bulk soil water contents, pressure heads at discrete depths, cumulative outflow and effluent solute concentrations were included into the objective function. The results revealed that for mild non-equilibrium transport in columns of Ap and Bv-horizons, the MIM performed only slightly better than the SRM. For transport under highly non-equilibrium preferential flow conditions (Ah columns), the MIM generally performed better than the SRM. An important observation in our study is that the MIM could not predict solute transport under transient flow conditions when using parameters obtained from the steady-state experiments. Moreover, simultaneous fitting of water and solute parameters proved to be somewhat better than sequential fitting. Similarly, using a water transfer term based on water content gave better results as compared to using a water transfer term based on pressure head. Overall, the MIM could reproduce physical non-equilibrium transport processes under transient flow conditions satisfactory, except for a tendency to over-estimate the observed cumulative tracer loss.

H71B-0809 0830h POSTER

Upscaling biofilm processes from the pore-scale to the Darcy scale: A report on continuing theoretical and experimental research

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In our continuing research on transport and reaction processes in biofilms in porous media, we report on new theoretical and laboratory results with a focus on upscaling pore-scale processes to the Darcy scale. In particular, we will describe theoretical results, obtained via the method of volume averaging, for predicting the effective dispersion tensor in porous media systems with biofilms under the conditions of local mass equilibrium between the biofilm and fluid phases. We show how the effective dispersion tensor depends upon the intrinsic transport parameters of the biofilm and fluid phases, the velocity field, and the geometry of the two phases. We have observed that, unlike passive dispersion, the component of the dispersion tensors in the longitudinal direction is not necessarily monotonically increasing in time. As a second focus, we will describe new experimental efforts to characterize the geometric structure of biofilms in porous media using nuclear magnetic resonance microscopy, and efforts to relate these sub-pore scale measurements to the effective dispersion tensor that is obtained in the theoretical effort.

H71B-0810 0830h POSTER

Numerical simulation of permeability upscaling as a function of minipermeameter support

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Because of technological limitations, the scale of property heterogeneity that can be represented with a computational model is significantly larger than the scale at which properties are measured by most instruments. Consequently, techniques are needed to upscale and synthesize small scale measurements to infer the larger scale effective properties. Laboratory upscaling experiments were conducted using an automated air minipermeameter system. Repeated permeability measurements on geologic samples showed different but sympathetic patterns of spatial variability at different sample supports and, depending on the rock, different upscaling behavior. We numerically simulate the laboratory measurements using sequential gaussian simulation to generate permeability realizations and the finite difference method for permeameter flow to help explain the experimental observations.

H71B-0811 0830h POSTER

On the Processes Occurring During Infiltration of Brine into Porous Media

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Infiltration of saline solutions and pure water into pre-wetted and air-dried sands was investigated using a light transmission system. Four grades of sand and five solutions were tested. Narrow fingers with a sharp, almost saturated, wetting front were observed in the dry sands for all solutions. The water saturations left behind the "fingertip" of saline solutions was higher than for those of pure water, resulting in a greater lateral expansion of the saline fingers over time. In the dry sand, the rate of lateral expansion scaled with the square root of time, most likely due to classic liquid sorption with the possible addition of water vapor diffusion. Early on, the salty fingers moved faster, but were ultimately overtaken by the pure water fingers. In pre-wetted sand, the wetting fronts were diffuse and never exceeded 26 percent saturation. The elevated surface tension of the brines was the major cause for the observed differences in finger width and velocity, yet appeared to be insignificant in air-dry sand. Additionally, water vapor transport in the vicinity of the infiltrating saline solutions was investigated. Drying around infiltrating brines was observed. The same solutions were applied to layered systems, where two horizontal fine layers were embedded within a coarser matrix, mimicking stratified sedimentary deposits. Water vapor stripping was found to enhance the lateral transport of brine in layered sand, where capillary barrier effects play a major role. Our observations suggest that (1) wetting fronts of infiltrating solutions are significantly different in air-dry and pre-wetted sand; (2) surface tension of the infiltrating solution plays an important role in determining the infiltration rate into pre-wetted sand; and (3) vapor pressure gradients, which develop due to differences in vapor pressure as saline solution infiltrates into pure water or vice versa, drive water vapor transport along them and should therefore be taken into account in places where brine leaks into the vadose zone.

H71B-0812 0830h POSTER

Thermal Transients in Closed, Unsaturated Soil Systems: Model Results

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Soil heat and unsaturated water transport are coupled processes. J.R. Philip and D.A. de Vries developed a theory in the late 1950's which has been widely and successfully applied. However, some aspects of their theory have been questioned in recent literature. This study used computer simulation program SPLaSHWaTr 2.4 by P.C.D. Milly to simulate temperature (T) and moisture transient conditions in closed, 5-cm long sand and silt loam columns. Three T boundary condition types were considered: rise and plateau (r), periodic cycling (p), and transition (t) between steady states. Initial moisture content and T were uniform with r (5 °C) and p (20 °C). At one end T was held fixed, 5 °C for r and 20 °C for p and t. Changing T at the opposite end defined r (linear rise from 5 °C to 35 °C in 2 h), p (triangular wave between 5 and 35 °C with 8 h period for sand and 24 h period for silt loam) and t (linear fall from 35 to 5 °C in 4 h). The initial moisture and T condition for t was the steady-state distribution associated with 35 °C end temperature at the variable T end and 20 °C at the fixed T end. Results of the r boundary condition for silt loam appear similar to experimental data cited in the original publication of the theory. Boundary condition p resulted in a persistent, relatively dry region near the cycled boundary. Steady state was attained in one and six days for sand and loam, respectively, with r, while with t steady state attainment took up to twice as long. Such simulations provide a potential design tool for new experiments which would compare simulated and actual dynamic behavior.

H71B-0813 0830h POSTER

Simultaneous Estimation of Water Flux, Soil Moisture, Solute and Heat Transport Characteristics Using a Multi-functioned Heat Pulse Probe

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Soil water, solute, and heat flow are three major transport mechanisms in soils. As all three transport types are related to each other, obtaining these properties at the same time, location, and measurement volume is essential for the general understanding of transport phenomenon in soils. A small multi-functioned sensor with 6 needles that includes a heater, four thermistors, and a four electrode Wenner array was developed for that purpose. Volumetric heat capacity and diffusivity were obtained by applying a heat pulse along the heater needle and measuring temperature responses at 4 needles, each 6 mm away from the heater. Volumetric water content was estimated from volumetric heat capacity knowing the specific heat of the soil. Bulk soil electrical conductivity (EC) was obtained by the four electrodes of the Wenner array probe, from which the EC of the soil water was estimated using volumetric water content obtained by heat pulse probe. In addition to these properties, water flux could be obtained using thermal responses at upper and down stream thermistors. Unlike traditional methods, this method does not require water potential and hydraulic conductivity measurements, but directly measures water flux at a single point. All soil properties were obtained simultaneously and estimated by parameter optimization. Since the data sets obtained by the multi-functional sensor are interrelated, parameter optimization for simultaneous soil water, solute, and heat transport gives more accurate results than from single property measurements.

H71B-0814 0830h POSTER

Using Advanced Tensiometers to Monitor Temporal Variations in Pore Pressure

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The Savannah River Site has installed a comprehensive vadose zone monitoring system (VZMS) at its low level radioactive waste disposal facility to collect the necessary information to calculate contaminant flux. The VZMS includes water content reflectometers, suction lysimeters, advanced tensiometers (ATs), water flux meters, access ports for neutron probes, and a tipping bucket rain gauge. Forty one ATs were installed from 1999 to 2001 at depths ranging from 2 to 60 feet and have been operated continuously. The installation depths were based on a hydrostatigraphic model developed from core logs, cone penetrometer logs, moisture content profiles, water retention curves model that were obtained during the phased installation of the VZMS. An AT consists of a porous cup installed at a prescribed depth with casing back to the surface and a pressure transducer that is lowered into the casing and connects with the porous cup. The pressure transducer transmits its signal to a datalogger where the data is stored for future retrieval using a cellular phone communications package. Results from the 2 year operating period show that the AT calibrations are stable and t ATs are capable of extended monitoring of pore pressures in the 0 to 300 cm H_2O range. The ATs had sufficient resolution to detect the naturally occurring fluctuations in pore pressure (1 to 100 cm H_2O over 1 to 72 hours) that resulted from infiltration events at the site. The stable performance of the ATs combined with their ability to detect naturally occurring fluctuations in pore pressure make the ATs a useful tool in measuring temporal pore pressure variations for use in calibrating numerical models of fluid flow in variably saturated porous media.

H71B-0815 0830h POSTER

Effects of Variable Rainfall Rate on Soil-water Storage: Column Experiments at Near-zero Pressure Head

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We conducted column irrigation experiments to evaluate flow processes resulting from impulse changes in rainfall rate upon a satiated porous medium. These experiments were designed to emulate the effects of highly variable rainfall rates upon wet soils in order to examine threshold conditions that may initiate preferential flow, and to gauge the effects of wetting and draining history on soil-water storage and redistribution in soils at the near-zero pressure head range. An entire 0.75 m long medium sand column was driven to a quasi-steady pressure head and uniform water content with low intensity irrigation. We then spike increased the irrigation rate by 2-9 times the background intensity but 3-4 orders of magnitude below the saturated hydraulic conductivity, and for various durations. Thereafter the irrigation rate was reduced to the prespike value for 1 hour, and then stopped. Results show that during the post-spike irrigation the pressure head, water content and column storage decreased to values that were lower than those observed during the prespike interval, despite having the same steady irrigation rate. This observation indicates that a rapid decrease in surface flux upon a near-zero pressure head region could lead to enhanced drainage of an unsaturated profile. The conceptual model explaining these observations relies on the release or tearing away of stored soil-water from the bulk soil-water flow.

H71B-0816 0830h POSTER

On the use of Effective Stress in Granular Media

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Effective stress, typically defined as the difference between lithostatic and hydrostatic pressures, has long been used to help explain deformation in experimental and subsurface environments. The correction factors to account for finite grain-to-grain contact areas have been defined (cf. Terzaghi's boundary porosity, as well as Bishop and Eldin 1950-51 and Skempton 1960-61). However, the relationships among finite grain contacts, gravity, and buoyancy have often been poorly explained and the finite contact area corrections are often ignored even when contact areas are large. Force balance on a grain scale can help clarify these issues. For small grain-to-grain contact areas the usual effective stress captures the average stress on a reference plane exerted by the grains, but this is far from the value of the stress between grains. As contact areas increase, there is a shielding of buoyancy forces that normally arise from the vertical gradient of fluid pressure.

New correction factors are derived for average grain-to-grain contact area stresses which should be employed when analyzing data from experimental piston/cylinder devices when grain contact areas within the sample differ from grain contact areas with the piston surfaces. The role of fluid and grain densities, as well as the role of pore pressure and its gradient are self consistent. Although force balance arguments are based on static conditions, implications for dynamics with compaction, pressure solution, and fluid flow modeling in a porous media will also be presented.

H71B-0817 0830h POSTER

Dynamic response of fluid flow through deformable porous media to wave excitation

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A number of field tests and laboratory experiments have indicated that the application of periodic pressure pulsing to fluids in a porous medium subject to a constant external pressure gradient can enhance oil production from depleted reservoirs or non-aqueous-phase liquid (NAPL) extraction from groundwater aquifers. However, the scientific understanding of the fundamental physical mechanisms governing the fluid flow response to compressional wave excitation remains elusive. To address this problem, the Biot model equations were decoupled and solved analytically for a boundary value problem involving a periodic fluid pressure pulse imposed on a constant pressure gradient. The solutions were computed numerically with input data corresponding to recent laboratory experiments on cores with cylindrical geometry. The optimal stimulation frequency required to induce maximum fluid flow was determined theoretically for the first time. Sensitivity analysis showed that it depends on cylinder length, Poisson's ratio, Young's modulus, porosity, and permeability of the core sample. Resonant behavior of the samples occurs in both a frequency range corresponding to in-phase motions of the solid and the fluid and a frequency range wherein opposing phase motions dominate. The numerical results also suggest that stimulation driven by pulsing pore pressure is more effective than that driven by pulsing the total dilatational stress.

H71B-0818 0830h POSTER

Hydraulic and Seismic Properties of Methane-Bearing Coal

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In the last 10 years, coalbed methane (CBM) has transformed from being a coal mine hazard to a low-risk source of long term dry natural gas. The benefit of this clean burning natural gas as an energy source in conjunction with vast amounts stored in coal basins has led to the development of an industry that produces CBM. Reduction of carbon emissions to the atmosphere through carbon dioxide injection into coal has added another benefit to the production of CMB, as carbon dioxide may be used to desorb methane from coal seams. In order to successfully produce CBM, more information is needed on the migration of methane through fractures and cleats and on the replacement of methane by carbon dioxide in the coal seam. Laboratory experiments are underway to address these questions. Tests on core samples are being performed under in-situ pressure to gain insights on processes occurring in CBM extraction and carbon dioxide sequestration. A variety of techniques are being used including measuring physical properties, electrical resistivity, and saturation and phase location using x-ray computed tomography. Simultaneously measurements of seismic waves are performed including P- and S-wave velocities as well as amplitudes of body waves as a function of methane and carbon dioxide concentration in coal. The results can be used to design an experiment to monitor time-lapse changes and thus the production of gas from a coal seam during methane production.

H71B-0819 0830h POSTER

An analysis of the role of fluids in fracture initiation and propagation using direct simulation of the coupled fluid-solid system

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It is well known that pore fluid pressure fundamentally influences a rocks mechanical response to stress. However, most measures of the mechanical behavior of rock (e.g. shear strength, Youngs modulus) do not incorporate, either explicitly or implicitly, pore fluid pressure or transport properties of rock. Current empirical and theoretical criteria that define the amount

of stress a given body of rock can support before fracturing also lack a direct connection between fluid transport and mechanical properties. The research outlined below explores these issues both qualitatively and quantitatively using a novel application of discrete numerical models of coupled fluid and solid physics.

In strongly coupled fluid-solid systems the evolution of the solid framework is influenced by the fluid and vice versa. These couplings often result in changes of the bulk material properties (i.e. permeability and failure strength) with respect to the fluids ability to move through the solid and the solids ability to transmit momentum. Feedbacks between fluid and solid framework ultimately play key roles in understanding the spatial and temporal evolution of the coupled fluid-solid system. Continuum numerical models of these systems attempt to capture these changes by using complicated constitutive relations, simple rules, or choosing to ignore them altogether. This often results in less than acceptable comparisons with observed behaviors. To address these issues discrete numerical models of the coupled systems based on fundamental fluid and solid physics have been developed. These models use direct simulation of fluids and solids to capture the evolving behavior of the system of interest. Our formulation couples the popular discrete element method (DEM) for solid mechanics and the lattice-Boltzmann method (LB) for solving the Navier-Stokes solutions of incompressible fluid flow.

To examine the role of fluids in strongly coupled systems we developed 2-dimensional models of fracture initiation and propagation using the coupled DEM-LB model. Models exploring the rates of propagation and the initiation of fractures were developed to help isolate the role of mechanical and hydrologic heterogeneities on the overall system behavior. Preliminary results indicate that the model captures linear poro-elastic behavior. Comparisons of model results to simple laboratory experiments indicate that the general elastic and in-elastic behavior of the model is quite realistic. Finally, more complicated models of fracture initiation and propagation in saturated media point towards a hydrologic control on fracture development and behavior.

URL: http://www.nmt.edu/~dboutt/AGUFall02/

H71B-0820 0830h POSTER

Fully Determined Fluid Velocity Fields for Complex 2D Media With Multi-Scaled Heterogeneity.

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Numerical schemes for fluid flow in complex rock geometries rely on comparison with existing empirical data for their validation. Such data, when available, are generally limited to non-unique, bulk measurements of properties such as hydraulic conductivity and permeability and are not adequate to fully validate complex numeric schemes.

Here we describe an experimental system which has been developed to fully quantify velocity fields throughout synthetic two-dimensional heterogeneous media. We first create a digital image with the desired combination of matrix and fracture porosity, incorporating detail over several orders of magnitude. This image is then translated into a physical medium using either stereolithography or wire EDM machining. The result is a flow cell comprising two transparent plates with a thin section of material, identical to the digital image of the medium, between them. In order to observe and measure fluid velocity, the flow cell is integrated in a purpose built experimental rig and a controlled flow of fluid, seeded with neutrally dense microparticles, is induced. By illuminating the flow seed and acquiring temporally separated images of sub-areas of the medium, the local velocities can be determined at high-resolution using a particle image velocimetry technique.

The apparatus is currently being used to investigate a range of problems including the importance of nonlinear interactions between matrix and fracture flow, scaling laws in the region of the percolation threshold and the scaling of the velocity flow field relative to the scaling of the material geometry, the latter with a view to identifying potential rules for upscaling of fluid simulations. Simultaneously, the same investigations are conducted using a modified Lattice Boltzmann scheme in order to assess the extent to which the numerical scheme accurately predicts flow.

H71B-0821 0830h POSTER

Measuring Changes in Fracture Aperture During Injection to Estimate Characteristics of Fractured Rock Near a Well

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Fracture networks are critical to ground water flow, but details of the geometry of networks in the subsurface can be difficult to determine with currently available technology. Sheet fractures, or other flat-lying fractures, are an important component of fracture networks in crystalline rock. Using a televiewer, or other borehole geophysical technique, it is possible to determine the depth a sheet fracture intersects a borehole, but it is more difficult to determine the size of the fracture and its connectivity to other fractures in the network. The aperture of a sheet fracture will change in response to pressure changes during a hydraulic well test, and the amount that the aperture changes will depend on both the size of the crack and how it is connected to the network. We are developing a field test that measures changes in aperture during a well test to estimate fracture geometry. The test uses a borehole extensometer between straddle packers to measure changes in aperture, and transducers to measure pressure during and after a hydraulic well test conducted by injecting at a constant flow rate. In general, the fracture opens as pressure increases during injection, and closes as pressure decreases during recovery. A coupled model of deformation and fluid flow is inverted to estimate fracture parameters that best predict the records of aperture and pressure.

Efforts toward developing this test have focused on designing and fabricating instrumentation for acquiring the field measurements, and deriving theoretical analyses for interpreting the results. The borehole extensometer consists of two retractable anchors separated by connecting rods attached to a submersible LVDT. The anchors are designed to lock themselves in place once actuated, thus minimizing creep over time. Another application for this device is to measure long-term changes in fracture aperture due to Earth tide or other effects, so it is important to reduce creep effects. The anchors are deployed on opposite sides of a fracture and they are displaced as the fracture dilates. Lab tests show that the lower limit of resolution is approximately 0.1 micron, and temperature changes both downhole and above ground appear to be a major threat to resolution. The connecting rods are configured to minimize overall length changes of the device owing to downhole temperature changes. Above ground, the data acquisition system is held at a near constant temperature in an insulated container to reduce spurious displacement measurements caused by changing the temperature of the electronics. The system has recently been deployed in the field at shallow depths, and we expect to obtain data after completing the packers and winch system that will be required to deploy the device at working depths (30 to 100 m). Simple analytical models, and a more complete semi-analytical model are being developed to interpret the results of the field tests. The semi-analytical model determines the pressures and aperture changes during injection of water into a flat-lying fracture intersecting a borehole. The solution is obtained by iterating between one analysis for fluid-flow and another for elastic displacements of the fracture using methods developed for modeling hydraulic fracture propagation.

URL: http://www.ces.clemson.edu/~tschwei/prebex/overview.htm

H71B-0822 0830h POSTER

Permeability of 2D Multiscale Fracture Networks

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Modeling fluid transfers in fractured rocks remains one of the main challenge of modern hydrology. Fractures are key structures for the migration of fluids, but their spatial heterogeneity and complexity at all scales make difficult the definition of simplified, but relevant, flow models. A major difficulty comes from the multiple scales involved. Fractures occur at all scales, from micro-cracks up to pluri-kilometric faults. Beyond such a characteristic that implies a large distribution of fracture size, the geometry of fracture networks is also characterized by a wide distribution of orientations, of apertures and by a spatial repartition of fracture densities which may be inhomogeneous.

This complex geometry raises some fundamental issues about the hydraulic characterization and modeling of fractured media. The definition of a representative elementary volume which is basic to classical homogeneous models is in particular questionable in multiscale fracture networks that do not present any apparent characteristic scale. Even the definition of a pertinent scale, or scale range, to describe the geometry of a fracture networks, or to measure the hydraulic properties of the system, is not explicit.

In this paper, we give some insights into the way to deal with two-dimensional multi-scale fracture networks. We especially focus on the consequences of some basic statistical properties of fracture networks : (i) the fracture length distribution, (ii) the spatial correlations between fractures, and (iii) the fracture aperture distribution. Fracture length defines the spatial extent of the heterogeneity that a fracture may potentially induce on flow while fracture aperture defines the intensity of this flow heterogeneity by fixing fracture permeability. On the other hand, spatial correlations may enhance or limit the efficiency of the fracture network to carry flow at the global scale.

We assume in the model that both the spatial distribution and the fracture length distribution are following power laws. Beyond the relevance of this model to natural fracture networks, that we tested on some natural examples, the power-law distribution model has the interesting property to have no characteristic length scale except its endmost limits. Using Monte-Carlo simulations, we first analyzed the consequences of these geometrical features on the connectivity property of stochastic fracture networks. We show that depending on the relative value of the fractal dimension, D, and of the power-law length exponent, a, the connectivity may be controlled either by the smallest or largest fractures. The variations of the connectivity with scale depends also strongly on the relative value of a and D. In term of permeability, we analyzed in particular the definition of a relevant scale, or scale range, for fluid flow, and of the pertinent flow model. We obtain a rich phenomenology when covering the range of all possible fracture distributions. For instance, a large length distribution combined to a large aperture distribution may lead to a great increase of the permeability with scale. On the opposite, the spatial correlation between fractures tends to lead to a decrease of the permeability with scale. Through the analysis of the network equivalent permeability as a function of the fracture network structure, this work allows a better understanding of the relationships between geometrical and hydraulic properties of fracture networks.

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H71C MCC: Hall C Sunday 0830h

Interannual Variability of the Hydrologic Cycle I Posters *(joint with NG, A, B, GC)*

Presiding: **P Kumar,** University of Illinois, Urbana-Champaign**; U Lall,** Columbia University

H71C-0823 0830h POSTER

Long-memory Models for Hydrologic Prediction in the la Plata Basin.

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Long-term fluctuations in both rainfall and runoff in the la Plata drainage basin (area 3.1 million square kilometers) have been widely reported. In the case of the Parana River at Corrientes, meteorologists have detected a "near-decadal" fluctuation from which predictions of runoff have been published with lead-time of ten years. If runoff is predictable to this extent, then it should be possible to predict it by means of statistical models with long memory, of the type ARIMA(p,d,q) with fractional d in the range from zero to 0.5. This paper presents results obtained when models of this type were fitted to the flow records from the Parana at Corrientes and other long-term flow and rainfall records from the South American sub-continent. Methods of model fitting are compared, and predictions are presented together with their confidence intervals.