Fast Flow in Unsaturated Coarse Sediments

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PROBLEM STATEMENT AND RELEVANCE

Although the problem of rapid contaminant migration through very coarse granular sediments is recognized, our understanding of this flow regime remains incomplete. Existing conceptual models for preferential flow through the vadose zone assume that fast flow occurs through saturated or nearly saturated local pathways. However, such highly saturated conditions are often unstable and uncommon in vadose zones comprised of coarse granular sediments. Effective remediation and management of contaminated coarse-grained sediments such as those found at the Hanford Site requires knowledge of unsaturated fast flow. Thus, gaining improved understanding of unsaturated flow in coarse granular sediments is important for scientific and practical concerns. Research on fast flow and transport in thick water films is just now emerging (Figure 1). Fluxes and velocities sustainable by water films in coarse granular sediments have not previously been quantified. Such information is relevant in other areas besides understanding contaminant transport at the Hanford vadose zone. For example, a better understanding of the failure mode for natural and engineered capillary barriers is also needed (Figure 2), and in some cases appears to occur via film flow. This research proposal was developed to improve our understanding of the physics of unsaturated flow in coarse- to very coarse-textured sediments, and through this meet practical needs related to contaminant transport in such vadose environments.

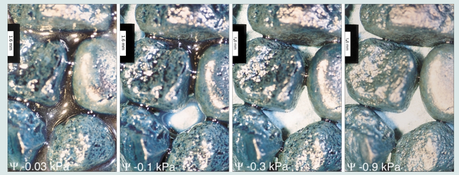

Figure 1. The importance of water films in controlling flow and transport in unsaturated, coarse sediments is illustrated in this series of photographs (3.8 mm average diameter Hanford gravel). The pore-scale distribution of water between pendular rings around grain-grain contact points and films coating grains changes dramatically over a narrow range of near-zero matric potentials [-0.03, -0.1, -0.3, and -0.9 kPa shown in A, B, C, and D, respectively]. When direct pendular ring connectivity is broken [C and D], water films control flow and transport.

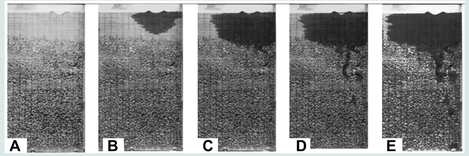

Figure 2. Breakthrough of water from finer to coarser textured sediments (capillary barrier failure). In very coarse textured sediments, water entry can be initiated by film flow, rather than by saturation of pore pathways.

RESEARCH OBJECTIVES

Unsaturated flow in very coarse sediments is a critical research area because it contains important features that are beyond the realm predictable by conventional vadose zone hydrology and classical scaling analysis. We hypothesize that in very coarse-textured (> 1 mm grain-size) high gravity-driven flow rates can be sustained at relatively low saturations, doing so via film flow rather than by flow through an interconnected network of locally saturated pores. Our hypothesized fast, gravity-driven film flow in coarse sediments is fundamentally different from traditionally recognized unsaturated flow in finer textured sediments, including preferential flow processes (macropore flow, finger flow, funnel flow) because it is truly unsaturated at the pore-scale. Our general objectives are (i) to quantify the macroscopic hydraulic properties of very coarse textured sediments in the near-zero (-5 to 0 kPa) matric (capillary) potential region, and (ii) determine the microscale basis for fast unsaturated flow. We will develop appropriate scaling relations for unsaturated flow in coarse-grained sediments based on these direct macroscopic and microscale measurements.

CENTRAL HYPOTHESIS

The main hypothesis to be tested is that water films at near-zero matric potentials enhance flow and transport in unsaturated coarse sediments (Figure 1). Films of sufficient thickness permit significantly faster flow than predicted by classical scaling theory (Figure 3).

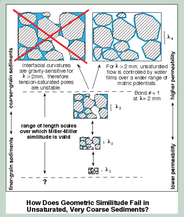

Figure 3. Classical Miller-Miller similitude has an important, unexplored upper scale limit. This limit is encountered for grain-sizes greater than about 2 mm. Above this limit, air-water interfacial curvature is influenced by gravity, and water films control transport processes at near-zero matric potentials.

APPROACHES

In order to pursue our research objectives and test our central hypothesis, studies are being conducted to quantify macroscopic (column scale) and microscopic (grain-film scale) hydraulic properties and processes in coarse sands and gravels (Figure 4). Without direct measurements at these two scales, our theories and models remain untested speculation. In order to obtain results that are directly relevant to the DOE, we are focussing most of our efforts on coarse granular sediments from the Hanford Site (Hanford formation vadose zone, grain-sizes ranging from 0.1 to 50 mm). Tests are also being conducted on quartz sands and gravels for the purpose of obtaining more general results. We are focussed on a critical, narrow (-5 to 0 kPa) matric potential range because (1) it encompasses most of the saturation-desaturation range in coarse-textured media, (2) it permits fast, gravity-driven flow, and (3) it is the energy region associated with capillary barrier failure. Yet this is a difficult energy region to study because of extreme changes in saturation and conductance that result from very small changes in potential, especially in coarser textured media. Some of the established macroscopic methods for measuring unsaturated hydraulic properties of porous media are unsuitable for coarse-grain sediments because they require that variations in saturation over short vertical distances be negligible. As part of this project, we have developed methods that permit acquisition of saturation-potential-conductance relations that are well suited for coarse granular media.

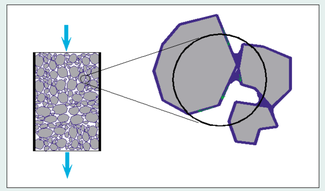

Figure 4. Understanding unsaturated flow and transport requires a combination of direct macroscale and microscale testing. Concepts and measurements at both the column and grain-film scales are the foundation of this project.

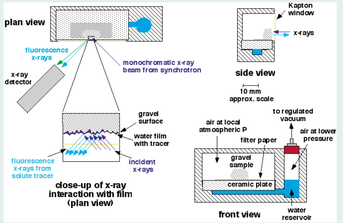

Figure 5. Suction plate apparatus adapted for measuring local average water film thickness on sediment grain surfaces.

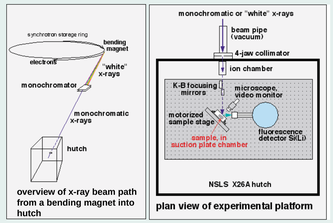

Figure 6. Synchrotron x-ray source, and components of the NSLS x-ray fluorescence microprobe beamline.

EXPERIMENTAL METHODS

Macroscopic Hydraulic Properties

Macroscopic saturation-potential-conductance information is being obtained using equilibrium and steady-state methods. Conventional suction/pressure plate measurements provide potential-saturation data. Measurements of potential and average saturation during steady unsaturated flow provide information on saturation-potential-permeability relations. Recent initial testing of this latter method on Hanford formation gravel was successful.

Microscale (Film) Hydraulic Properties

These measurements build on our previous experience with film flow on roughened quartz glass surfaces that served as model rock fracture surfaces. The method relies on determining average water film thicknesses using x-ray fluorescence of a solute tracer. A Hanford gravel sample is placed in a small suction plate device, and scanned with a defocused synchrotron x-ray microbeam while equilibrating to selected matric potentials (Figure 5). Important differences and complications introduced in the studies on Hanford gravel include a high matrix fluorescence background and greater surface roughness. These x-ray experiments are conducted at beamline X26A (Figure 6) of the National Synchrotron Light Source (Brookhaven National Laboratory). Experiments are conducted in the 0 to –5 kPa matric potential range.

INITIAL RESULTS

Macroscopic Measurements

- Scaled moisture characteristics (saturation versus matric potential) for coarse Hanford sediments are practically similar to those of reference finer grain quartz sands (Figure 7).
- Scaled unsaturated hydraulic conductivities of coarse sediments (including Hanford sediments) show enhanced flow relative to reference finer grain quartz sands (Figure 8).

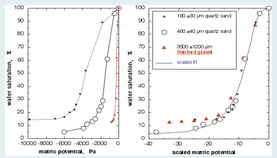

Figure 7. Unscaled and scaled moisture characteristic of a Hanford gravel, compared with those of quartz sands (main drainage curves). Note that Miller-Miller scaled moisture characteristics (lower graph) are practically identical. This reflects the fact that most of the water retention is localized within pendular rings, and that Bond numbers for gravels are not much greater than 1.

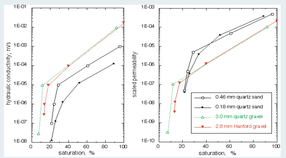

Figure 8. Unscaled and scaled unsaturated hydraulic conductivities of gravels, compared with quartz sands. Note that significantly higher scaled hydraulic conductivities have been measured on the gravels in the low saturation region, indicative of fast film flow. Direct, microscale measurements are needed to test this conjecture.

Microscale Measurements

- Film moisture characteristics on Hanford gravel show that most of the changes in film thickness occur in the –2 to 0 kPa matric potential range (Figure 9).
- Film hydraulic diffusivities can be obtained from transient film thinning measurements (Figure 10).
- Microscale measurements of film hydraulic diffusivities and transmissivities are consistent with macroscopic measurements on unsaturated gravel columns.

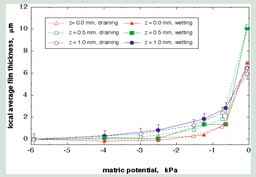

Figure 9. The dependence of local average water film thickness on matric potential, measured directly on a Hanford gravel surface. Note that equilibrium film thickness-potential relations are nonhysteretic, unlike moisture characteristics of bulk porous media.

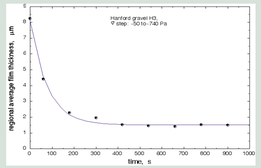

Figure 10. Measurement of transient water film thinning on a Hanford gravel surface, in response to a step change in matric potential. In this case, the initial equilibrium matric potential is -0.05 kPa. At time-zero, the boundary potential was changed to - 0.74 kPa. The film hydraulic diffusivity is calculated from the rate of film thinning.

SUMMARY

- Macroscale (column) and microscale (grain-film) measurements of unsaturated hydraulic properties are being conducted on Hanford vadose zone sediments.
- These tests are showing that film flow at near-zero matric potentials can explain some fast, unsaturated flow in very coarse sediments.
- Such findings identify film flow as another mechanism capable of supporting fast, preferential flow and transport in coarse vadose zone sediments.
- Film flow might be an important failure mode in capillary barriers that contain very coarse sediments.

PLANNED ACTIVITIES

The results to date are still too limited to draw general conclusions. The macroscopic and microscale studies described above will be continued on a range of grain sizes, in both well-sorted and mixed size distributions. The combined data set will permit testing of scaling laws relevant for unsaturated flow in coarse granular sediments. The microscale x-ray fluorescence experiments will continue in conjunction with microtopography measurements. The combined results of macroscopic and microscopic experiments will be used to develop a tested, physical model of unsaturated flow in coarse sediments. Column experiments of well-sorted sediments, and further microscale measurements will be in progress for the remainder of FY2000. Studies on mixtures of grain sizes will be done during FY2001. Implications of these results on capillary barrier performance will be tested during FY 2002.

ACKNOWLEDGMENTS

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RELATED PUBLICATIONS

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