PROCEEDINGS, TOUGH Symposium 2006
Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, 2006

MODELING OF PHYSICAL OBSERVATIONS OF WATER DIVERSION IN A CAPILLARY BARRIER USING A CENTRIFUGE

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ABSTRACT

Water flow behavior in capillary barriers has been primarily investigated using mathematical models, with comparatively few physical experiments conducted. The centrifuge modeling technique for studies of unsaturated flow is receiving attention as a rapid physical observation method. This method was used to conduct a number of capillary barrier experiments in this study to examine the relationship between the infiltration intensity and the diversion length.

The objectives of this study are to demonstrate centrifuge experiments of water movement in a fine-over-coarse layer system in order to gain basic knowledge of capillary barriers and to cross-evaluate the centrifuge technique with TOUGH2 simulations of capillary barriers. Of particular interest in this study were the water diversion length variability associated with the rainfall intensity, and their representation within the TOUGH2 code.

INTRODUCTION

Several studies comparing experimental observations from physical models and numerical simulation results obtained using different TOUGH2 modules have been performed for several purposes including code validation, data analysis and parameter estimation (Moridis and Pruess, 1995; Finsterle, 1999; and Gallagher and Finsterle, 2004). Additionally, TOUGH2 has been previously applied with success to model capillary barriers problems (Oldenburg and Pruess, 1993; Webb and Stormont, 1995; Webb, 1998; Ho and Webb, 1998).

Capillary barriers have been considered as an alternative method for hydraulic isolation of buried waste. A capillary barrier consists of a fine soil layer overlying a coarse soil layer. The upper layer acts as a capillary layer while the lower layer acts as a capillary block. The matric potential in the finer and coarser layers comes to equilibrium at steady state. If the potential at the layer interface is sufficiently negative, the contrast of unsaturated hydraulic properties between the two soils can delay the vertical drainage.

While numerous mathematical studies investigating water behavior in capillary barriers have been reported, a smaller number of laboratory studies, particularly for two-dimensional conditions, have been reported (Bussière et al., 2003; Tami et al., 2004).

Recently, centrifuge experimental techniques have been applied to investigate problems involving unsaturated flow (e.g., Soga et al., 2003; Rezzoug et al., 2004; Lo et al., 2005). Centrifuge force increases the effective weight of pore fluid, and it leads the increase of fluid velocity. Table 1 shows conventional scaling relationships of the centrifuge model. By reducing a geometry scale and accelerating pore fluid flow, the centrifuge technique may reduce experimental effort and time by mimicking the relationship between capillary pressure, saturation, and permeability in a reduced scale model over a relatively short time. For example, since testing time is much shorter than the equivalent full scale observation, water loss by evaporation can be minimized. It should be noted that the centrifuge model probably does not conserve “exact” scaling similitude for unsaturated flow (Culligan and Barry, 1998). The degree of disparity due to the violation of scaling similitude is not well understood.

In this report, we present preliminary results from three centrifuge experiments of water movement in a finer soil layer overlying a coarser soil layer. The tests represent a simple capillary barrier condition with different precipitation intensities. The test observations were compared with TOUGH2 simulation results to gain basic understanding of the capillary barrier effect and to evaluate feasibility of both the experimental and numerical techniques.

CENTRIFUGE TEST DESCRIPTION

Two-dimensional centrifuge tests simulating water movement in a fine-over-coarse layer system with different precipitation intensities were performed

Table 1. Scaling relationship of centrifuge models with a scale factor N. The same soil and fluids are used in both model and prototype.

Parameter		Prototype/mode ratio
Gravity	g	1/N
Macroscopic length, eg., barrier thickness	L	N
Microscopic length, e.g., pore throat radius	l	1
Pore fluid velocity	v	1/N
Time	t	N^2
Fluid pressure	p	1
Hydraulic conductivity	K	1/N
Intrinsic permeability	k	1
Soil porosity	n	1
Fluid density	ρ	1
Fluid viscosity	μ	1
Fluid interfacial tension	σ	1

using a 2-m radius geotechnical centrifuge at the Idaho National Laboratory (Smith et al., 2002). The scale models were constructed in a rectangular box container with dimensions of 279×191×25 mm (Figures 1 and 2). One of two side walls was made of 25 mm thick Plexiglas plate to allow visual observation of dye tracer movement. Capillary pressure in the fine layer was monitored at several locations using miniature tensiometers. The experimental apparatus was inclined to a slope of 9°.

Ottawa sand (US Silica, F110) with a mean particle diameter (D_{50}) of 0.1 mm and a uniformity coefficient (C_u) of 1.6 was used for the fine layer material, and filtration sand (Oglebay Norton, 10-20), which is very uniform with D_{50} of 1.6 mm and C_u of less than 1.4, was used for the coarse layer material. The model was prepared by packing the bottom of the experiment with 22 mm of dry filtration sand, followed by moist Ottawa sand at 10% water content to a compacted thickness of 132 mm. Porosity of the fine layer was 0.43. Saturated hydraulic conductivity (3.22×10^{-5} m/sec) and the van Genuchten parameters (α=1.07 m^{-1} and n =13; van Genuchten, 1980), for the Ottawa sand were estimated from constant head permeability tests and hanging-column tests, respectively. Parameters for the filtration sand were initially set at α=3.45 m^{-1} and n=4.348 based upon a compositional analysis estimate provided by the RETC code (van Genuchten et al., 1991). With this in mind, numerical simulations were performed to visually determine the magnitude of the van Genuchten alpha parameter for the filtration sand. Future modeling efforts will include the determination of fluid parameters using actual pressure readings through a formal inversion process using iTOUGH2.

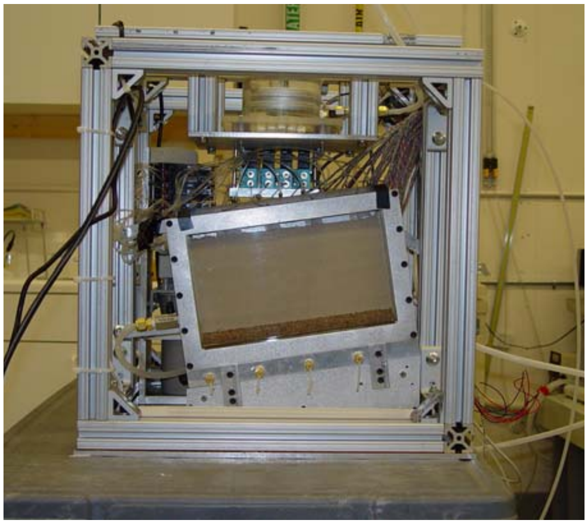

Figure 1. Centrifuge test setup before mounted on the centrifuge platform

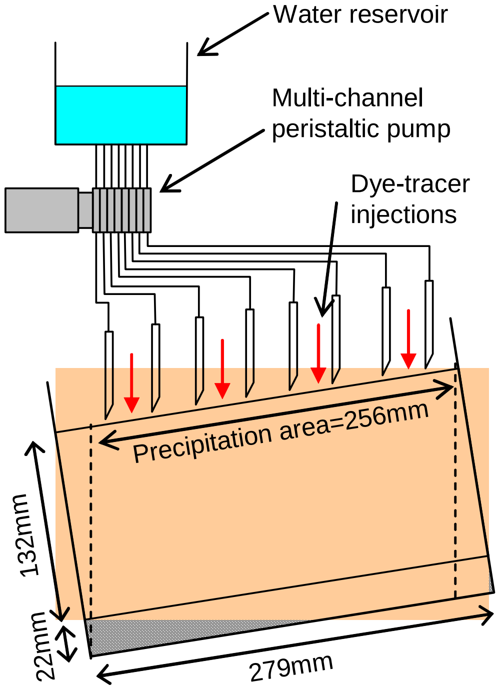

Figure 2. Schematic of scale model

A precipitation simulator was used to supply water on the top of the experiment. Precipitation was accommodated with eight needles to distribute water uniformly to the soil surface, as shown in Figure 2. To avoid erosion, water dripping points were located just above the soil surface. The precipitation intensity (15.4, 24.1, or 45.3 ml/min) was regulated by a multi-channel peristaltic pump. For this study, the lower part of the slope was closed so that the diverted water eventually entered the coarse layer and drained out of the container through drainage ports located on the container base. All three tests presented in this paper were conducted at 10g. In prototype scale, length of the domain is 2.79 m and thicknesses of the coarse layer and the overlying fine layer are approximately 0.22 m and 1.32 m, respectively.

After steady precipitation condition was achieved at 10g, dye tracer was introduced from several locations. Injection rate and volume of the tracer were small compared with the precipitated water, and hence influence by the tracer injection on the flow domain was assumed to be negligible. After the tracer reached the interface between the soil layers, the precipitation was subsequently terminated and transitions of the tracer paths were monitored.

SIMULATION OF EXPERIMENTS

All three centrifuge experiments were simulated using the EOS9 module (saturated-unsaturated flow) of the TOUGH2 code (Pruess et al., 1999). The domain of X × Y × Z = 25.4 × 279 × 254 mm was discretized into a two-dimensional model of uniform gridblocks of size ΔX × ΔY × ΔZ = 25.4 × 5.58 × 4.4 mm (Figure 3). A higher resolution grid with gridblock sizes of ΔX × ΔY × ΔZ = 25.4 × 3.10 × 2.75 mm was also considered. The results from the higher resolution grid and the coarse grid are essentially the same.

Boundary conditions are no flow along the subvertical sidewalls, constant infiltration rate along the top (precipitation length 256 mm) and unit head gradient flow conditions for the bottom (drainage ports at the base). An upstream weighting scheme for mobilities was used in all simulations and the magnitude of the acceleration vector was set to 98.1 (m/s^2).

RESULTS AND DISCUSSION

Shown in Figure 4 are the liquid saturations and liquid flow direction at steady state conditions for the first dye experiment (Test #1). As indicated by the dye trace in Figure 3 and flow vectors in Figure 4, water flows primarily vertically downward until it is diverted near the interface between the fine and coarse sands. Note that the vectors in Figure 4 are only shown for the fine sand. Because of the proximity of the drainage boundary, the velocity in the filtration sand (coarse sand) is considerable higher making unpractical the representation of the vectors using the same scale. At the bottom of the coarse layer water flow is vertical, exiting the model domain.

Simulated flow vectors corresponding to precipitation intensities of 15.4, 24.1, and 45.3 ml/min are superimposed on dye traces from the experiments in Figures 5, 6, and 7, respectively. In order to obtain a better match between observed dye-trace and simulated results, the van Genuchten parameter alpha (α) for the filtration sand was changed for each test (Table 2).

The mass flow vectors for the different infiltration rates are very distinct. As expected, the largest water diversion was seen in the lowest infiltration case, Test#1. It is also seen, due to the closed boundary condition of the downstream side, that diversion length became shorter near the downstream side. While the water diversion occurred sharply near the layer interface when the infiltration is low, it became duller at the larger infiltration rate.

The comparison between observation (dye trace) and simulated vectors is qualitatively reasonable for all the tests. The numerical values for van Genuchten's alpha (α) used for each test are listed in Table 2. Additionally, a series of numerical simulation was performed in order to asses the influence of the magnitude of alpha for higher infiltration rates (Test #3) on the divergence length. As expected, the results show that divergence increases as the value of α increases. It was also noticed that a maximum value of $\alpha = 54.19\ m^{-1}$ could be used for the filtration sand (coarse layer) for the infiltration rate use during Test #3. Using higher values for α will result in an unrealistic flow field with two separate divergence zones. The first one occurs where, as expected, water flows downstream along the interface; while a second one occurs where water is being forced upward along the interface. This unusual behavior may be indicative of an instability for large α, or result from inaccuracies due to discretization errors (grid resolution, differencing scheme, or permeability/mobility weighting).

Table 2. van Genuchten alpha used in numerical simulations for the coarse layer (filtration sand)

Test #	Infiltration rate	Alpha (α)
1	15.4 ml/min	$18.17\ m^{-1}$
2	24.1 ml/min	$7.21\ m^{-1}$
3	45.3 ml/min	$8.59\ m^{-1}$

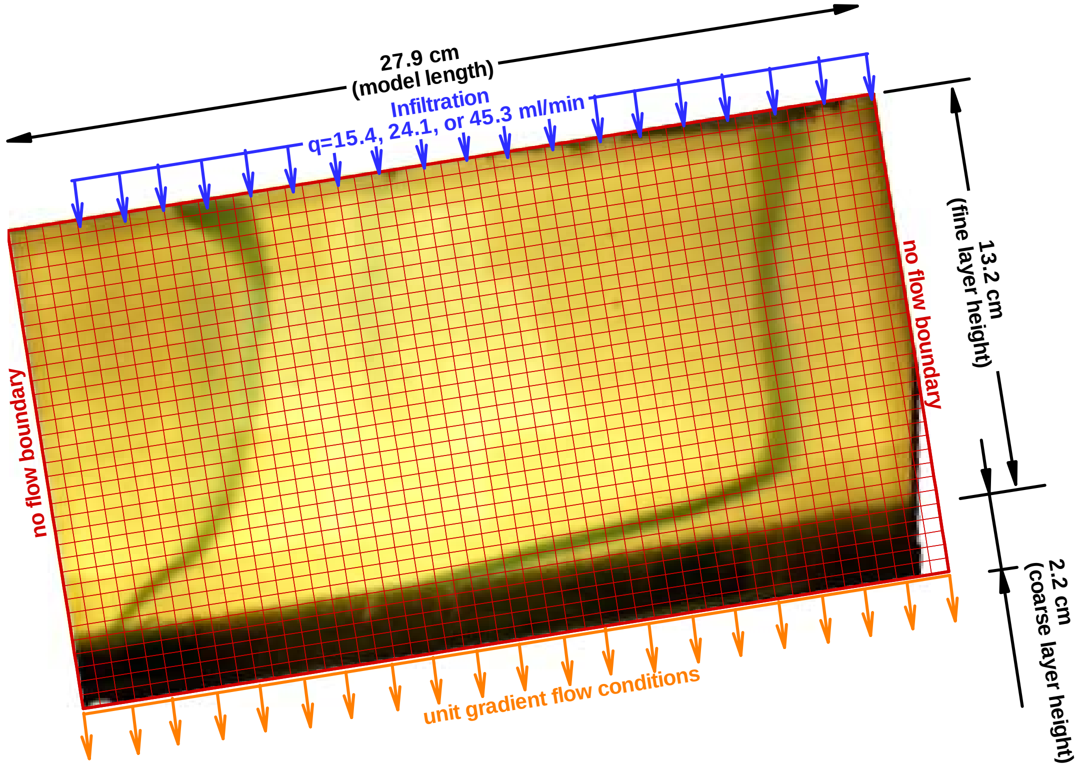

Figure 3. Flow domain and discretization for the centrifuge capillary barrier model.

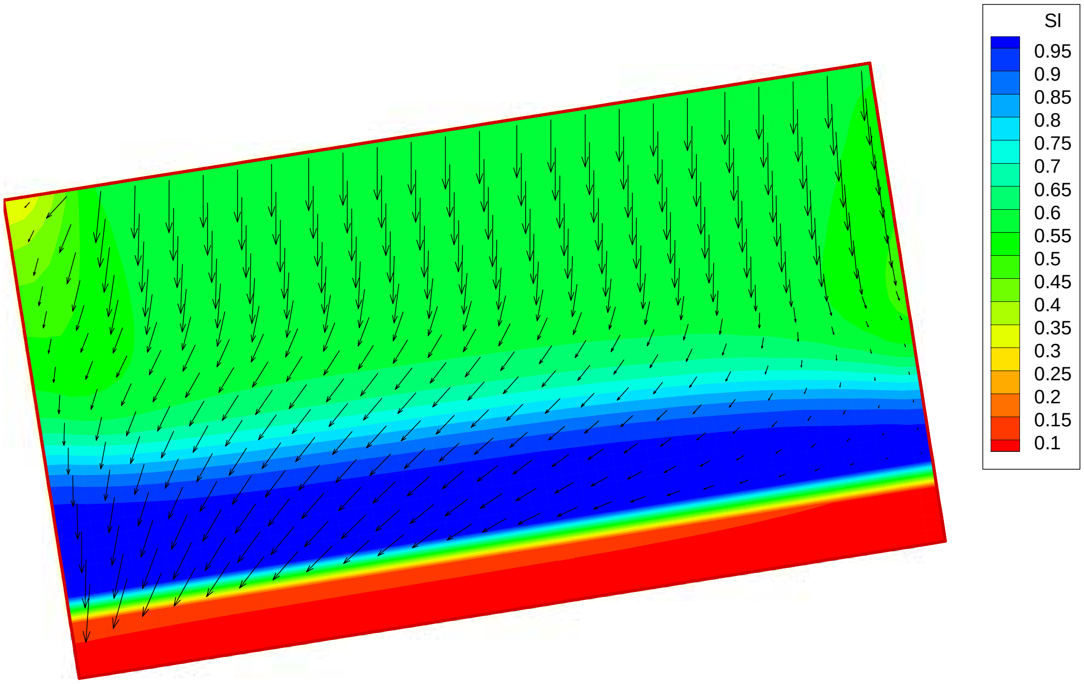

Figure 4. Simulated liquid saturations and liquid flow vectors for Test #1

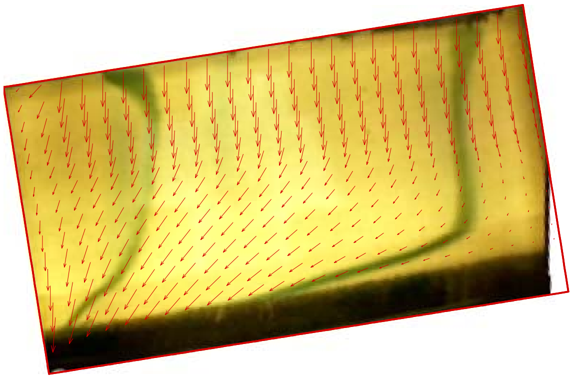

Figure 5. Dye traces and simulated liquid flow vectors for test #1.

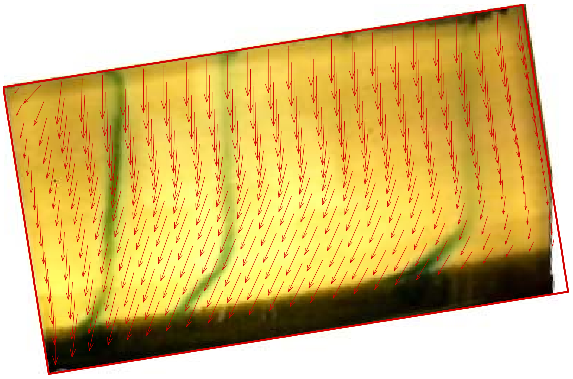

Figure 6. Dye traces and simulated liquid flow vectors for test #2.

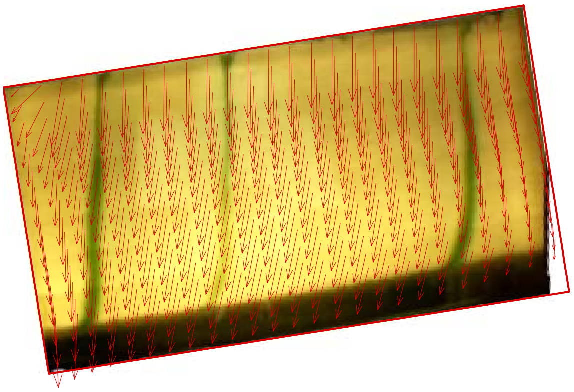

Figure 7. Dye traces and simulated liquid flow vectors for test #3.

CONCLUDING REMARKS

In this paper, we presented the newly developed centrifuge test system and the preliminary test results including comparison with numerical simulations using TOUGH2 and discussed the influence of rainfall intensity and boundary conditions on the capillary barrier performance.

A longer diversion length at lower rainfall intensity was observed in the physical models. It was also found that the diversion length on the downstream side could be shorter when compared to the upstream side due to flow impedance effects of the downstream boundary. The tracer visualization and numerical simulations identified vertical water infiltration in the coarse layer.

Preliminary numerical simulation results show that the TOUGH2 generated flow field (flow vectors) matches the overall general observed flow pattern at low and intermediate infiltration rates. Physical model results at high infiltration rate were not accurately captured. Nevertheless, the overall system behavior is considered reasonably well captured for the purpose of this modeling study, which demonstrates the code's ability to capture the capillary barrier effect for centrifuge experiments. Future work will include the use of pressure readings to obtain a better insight of the flow in the centrifuge experiment and to determine fluid parameters through a formal inversion process using iTOUGH2 (Finsterle, 1999).

ACKNOWLEDGMENT

This work was supported by the BBWI Corporate Funded Research and Development Program. The authors are grateful to Joseph R. Lord, Tim Kaser, and James T. Johnson of the INL for their technical support. The authors would also like to thank Earl D. Mattson of the INL and Angelos N. Findikakis of Bechtel National, Inc. for their support.

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