Presented at the TOUGH '95 Workshop, Lawrence Berkeley Laboratory, Berkeley, CA, March 20-22, 1995.

Modeling of Capillary Barriers and Comparison to Data

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Measurements of capillary barrier performance have been conducted in above-grade wooden structures (boxes) configured to measure the water balance as shown in Figure 1. The capillary-barrier portion of the boxes is 6.0 m long, 2.0 m wide, and 1.2 m high with a slope of 5%. A coarse-grained material was placed in the bottom 25-cm of the box with a 90-cm deep fine-grained material (local soil) on top. A region for laterally diverted water to accumulate and drain was created in the last 1.0 m of the box. The soil at the top is terraced into five, 1.4 m long, level intervals to prevent runoff when adding water. Water is added uniformly to the entire top of the box at a rate of about 66 l/day, or an infiltration rate of 1.7 m/year. The top of the box is covered with fiber-reinforced plastic to minimize evaporation of water, discourage plant growth, and prevent rainfall from contacting the soil. Five drains are spaced along the bottom of the coarse layer. These drains discretize the coarse layer into five collection regions to provide a means of identifying the breakthrough location into the coarse layer. A drain is also located in the downdip collection region of the box. Soil moisture changes were measured in the fine-grained material with a frequency-domain reflectometry (FDR) probe, which was calibrated using soil from the field site at a known moisture content and density. The location of the vertical and horizontal access pipes for the probe is given in Figure 1.

Vertical moisture content data as a function of time and location are shown in Figure 2 for the first (#1) and last (#5) vertical FDR locations. Early-time data for the soil-wetting phase are shown out to 43 days. After this time, the moisture content profiles change very little. In addition to the data shown, measurements were also made within a few centimeters of the top of the soil. However, the FDR access pipes vibrated due to the wind, creating a small open annulus around the access tubes near the surface. This open annulus, and the possibility of preferred infiltration around the access tubes near the surface, interfered with the measurement, so these near-surface data are not included. Horizontal moisture content data were also obtained but are not shown because some measured values were influenced by a pipe coupling around the tubes.

In addition to moisture content data, drainage data for the six drains were obtained. The initial water flow from the drains occurred at drain 6, downstream of the capillary barrier at about 44 days followed quickly by the rest of the drains except drain 1, which never had water flow. As expected, the drainage rate increases from drain 2 to drain 5. These data are not shown in this paper since the present analysis is concerned with the soil-wetting phase and prediction of the saturation profiles with time. Consideration of the drainage data will be addressed after the soil-wetting phase analysis is complete.

Properties of the local soil were measured including unsaturated properties, while properties of the underlying coarse-grained material, which is a poorly-graded round stone, have been estimated from the literature; the appropriate values are listed in Table 1. The van Genuchten (van Genuchten, 1978, 1980) two-phase characteristic curves were used to fit the data.

Table 1
Material properties

	Fine (measured)	Coarse (estimated)
Porosity	0.394	0.42
Permeability (m^2)	1.23×10^{-13}	3.5×10^{-8}
S_{lr}	0.213	0.012
S_{ls}	0.99	0.99
m	0.465	0.543
α (Pa^{-1})	1.86×10^{-4}	5.03×10^{-2}

Data-Model Comparison

It was assumed that a capillary barrier numerical model could be developed with TOUGH2 and, using the above soil properties, that the model predictions would be reasonably similar to the measurements. Such was the case for the lab-scale infiltration data of Vauclin et al. (1979) which was successfully analyzed by Moridis and Pruess (1992) using TOUGH. Based on this belief, a detailed two-dimensional model of the capillary barrier geometry was developed consisting of over 1800 elements. The initial liquid saturation of the fine layer was estimated as 40 percent, or an initial moisture content of just under 16 percent, based on moisture in the original soil and water added to the soil during construction of the boxes. Water was added to the top of the model at a constant rate corresponding to the average value from the tests, and the soil-wetting phase and water drainage were calculated.

As shown in Figure 3 for FDR locations 1 and 5, however, the predicted moisture content profiles are significantly different than the data, especially at later times. Both the predicted moisture content values are greater and the predicted profiles are much steeper than the data. The significant differences between the numerical and experimental results have resulted in plans to conduct a numerical sensitivity study to evaluate the important soil properties that could cause such large differences. This study is currently in process and is not reported here.

One of the most significant differences between the numerical predictions and the data is the range of moisture content values. While the long-term data seem to be clustered around moisture contents varying between 20 and 40 percent, the predictions are limited to values between 30 and 40 percent.

As clearly seen from the model results in Figure 3, transient flow in capillary barriers can be broken into two distinct regimes, a suction regime or soil-wetting phase, and a flow regime. The suction regime occurs early on when the infiltration rate is higher than the local liquid-phase permeability (intrinsic permeability times relative permeability) such that the excess infiltrated water goes to increasing the local moisture content (and the relative permeability) until the local permeability is high enough to readily transmit water at the given infiltration rate. In the flow regime, the local permeability is equal to or higher than the flow rate and the additional water flows through the system. The moisture content may be constant or increase with depth depending on the characteristic curves. The transition between these two flow regimes occurs when the local permeability is just equal to the infiltration rate. If one measures or assumes water relative permeability expressions and appropriate constants, the wetting-phase saturation or moisture content for this transition can be calculated.

For example, the model predictions are based on an infiltration rate of 1.7 m/year (5.6×10^{-15} m^2), while the soil intrinsic permeability is 1.23×10^{-13} m^2, or about 37 m/year. Therefore, the relative permeability is equal to 0.046 for the transition between the suction and the flow regimes. Based on the assumed soil properties and the van Genuchten wetting-phase relative permeability expressions:

$$S_e = \frac{S - S_{lr}}{S_{ls} - S_{lr}} \tag{1}$$

$$k_{r,w} = S_e^{1/2} \left(1 - \left(1 - S_e^{1/m}\right)^m\right)^2 , \tag{2}$$

the relative permeability equals 0.046 at an effective saturation of about 0.68 or a moisture content of 29 percent (saturation of 0.74), consistent with the model predictions shown earlier.

Sensitivity studies are underway varying the intrinsic permeability, relative permeability, and residual saturations in order to evaluate the influence on the profiles. The general influence on the range of saturation or moisture content values can be estimated by the above expressions. In addition, the shape of the saturation profiles is dependent on the capillary pressure and the two-phase characteristic curves. Therefore, the use of ITOUGH2 (Finsterle, 1992) is being considered for further evaluation of the data-model comparison.

Conclusions

Capillary barrier data have been obtained in above-grade wooden structures (boxes) configured to measure the water balance. Simulations of the capillary barrier performance have been conducted with TOUGH2 based on measured and assumed soil properties. The predicted moisture content profiles in the soil-wetting phase for the soil are significantly different than the measured values. A numerical sensitivity study to evaluate the important soil properties that could cause such large differences is currently underway.

Additional future work on capillary barrier performance prediction will evaluate the performance of a new EOS module being developed by Karsten Pruess based on Richards' equation. In some preliminary tests, the numerical performance of TOUGH2 for applications similar to capillary barriers was improved tremendously. Further evaluation of this new module is underway.

Acknowledgment

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

References

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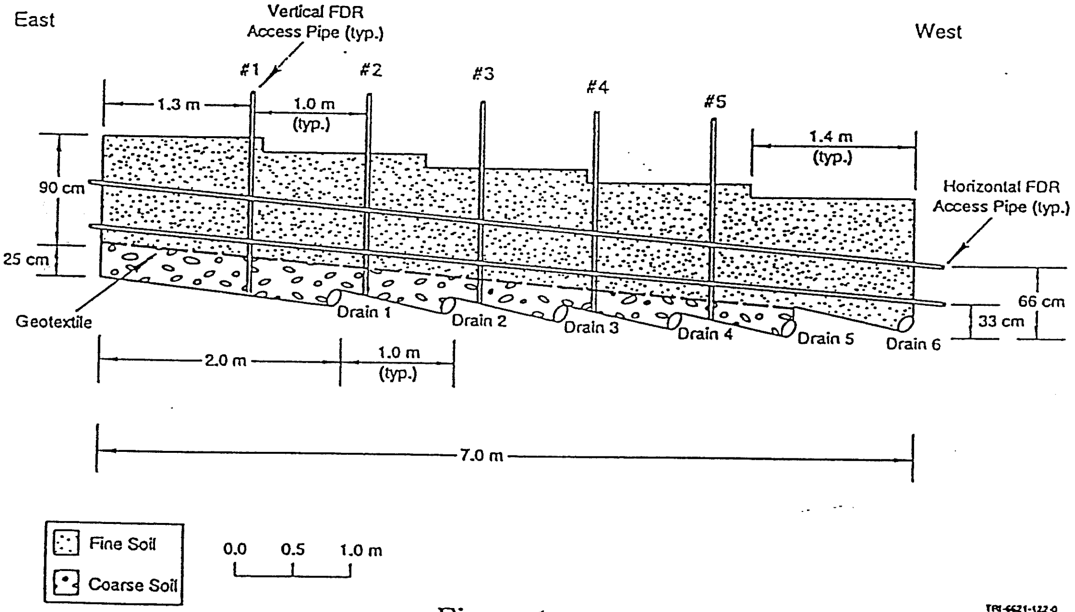
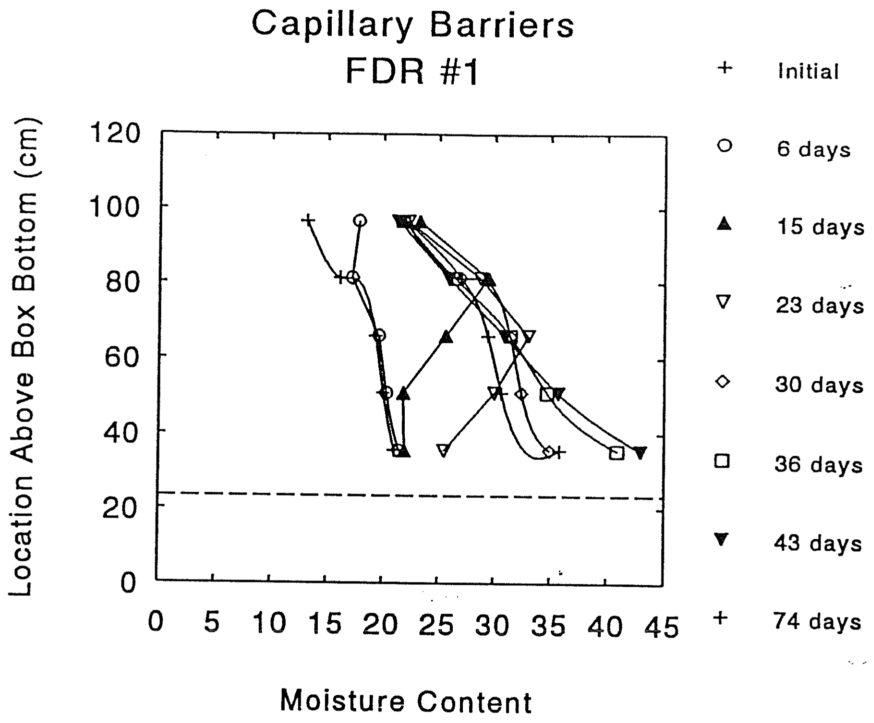


Figure 1
Capillary Barrier Box Experiment



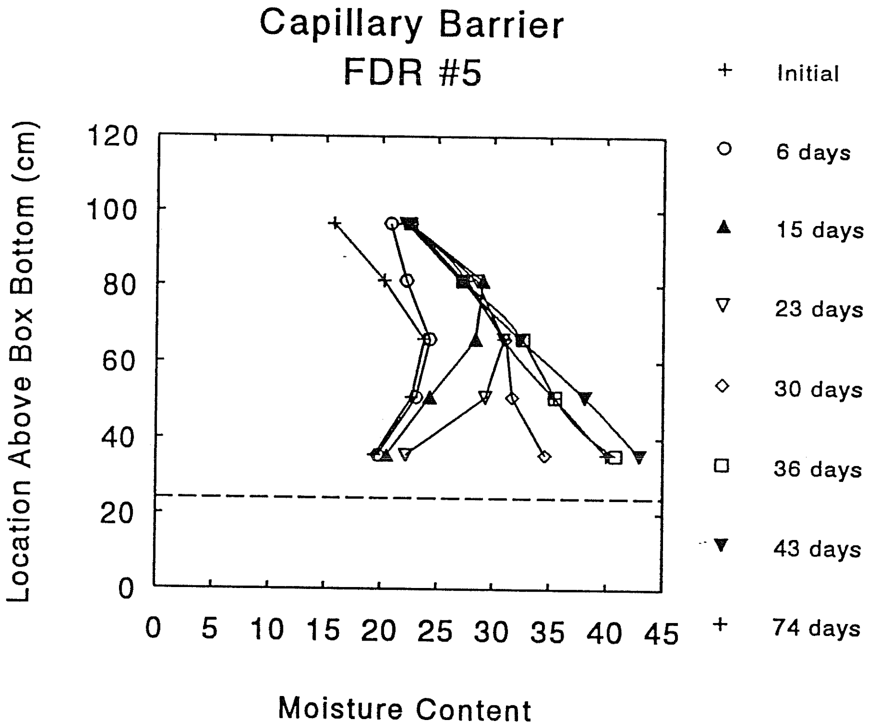


Figure 2
Moisture Content Data

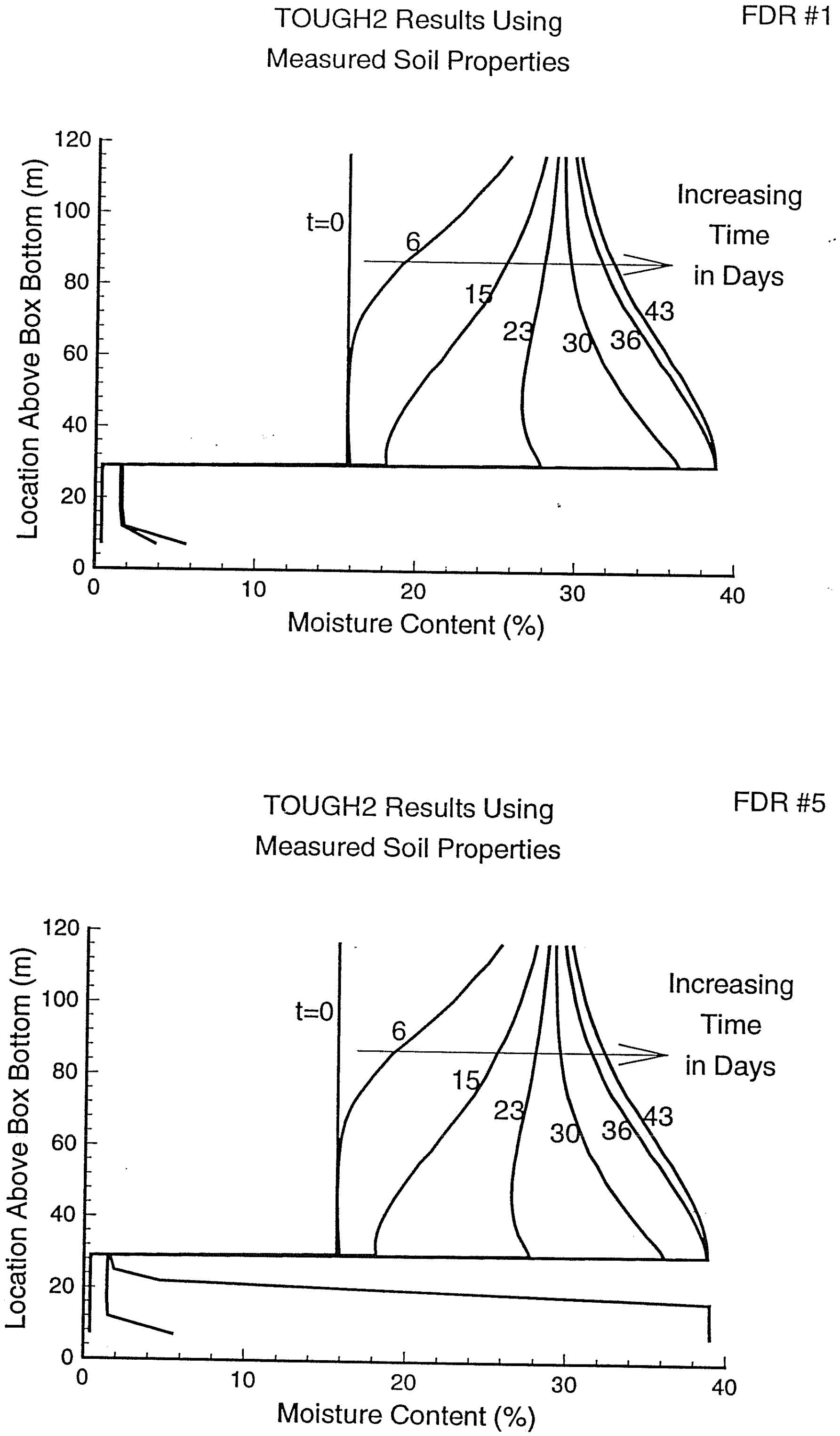


Figure 3
TOUGH2 Predictions Using Measured Soil Properties