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Field Investigation of the Drift Shadow

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Abstract— *The "Drift Shadow" is defined as the relatively drier region that forms below subsurface cavities or drifts in unsaturated rock. Its existence has been predicted through analytical and numerical models of unsaturated flow. However, these theoretical predictions have not been demonstrated empirically to date. In this project we plan to test the drift shadow concept through field investigations and compare our observations to simulations. Based on modeling studies we have an identified a suitable site to perform the study at an inactive mine in a sandstone formation. Pretest modeling studies and preliminary characterization of the site are being used to develop the field scale tests.*

I. INTRODUCTION

A drift shadow is a region below an opening in the unsaturated zone, such as a mine drift that is relatively drier than the surrounding medium, and thus has reduced transport. Drift shadows occur because the drift shelters the region from downward-percolating water. In the unsaturated zone, downward-percolating water will encounter the drift and water will accumulate at the top. If the flow rate is sufficient relative to the flow rate of the water diverted laterally, seepage will occur; however, a portion of the water will be diverted around the drift. Below the drift, capillarity is not strong enough in all cases to fully draw the diverted water into the region immediately under the drift's floor, resulting in a "shadow". Numerical and analytical models of water flow through unsaturated rock support the concept of a drift shadow, and predict that 1) an area relatively wetter than the surrounding rock mass will occur above a mined or natural void, and 2) a relatively drier zone will form beneath it [1, 2]. Nevertheless, to date there are no conclusive laboratory/field observations that confirm the occurrence of drift shadow.

Fig 1. Conceptual model of flow around a drift, showing the capillary barrier at the drift crown, and the drift shadow below the drift.

The objective of this research is (1) to fill this knowledge gap through field experiments and (2) to quantify the essential characteristics of the shadow zone. Confirmation of the occurrence and characteristics of drift shadow is important for several reasons. First, verifying the occurrence of drift shadow will improve confidence in the theory and numerical models of flow through unsaturated media used in investigations of the proposed nuclear waste repository at Yucca Mountain. Second, understanding its occurrence and transport properties will allow better prediction of radionuclide transport from waste-emplacement drifts. Third, the drift shadow could also be used to further improve repository performance by placing drifts above waste-emplacement drifts to shadow the lower drifts from seepage that may transport radionuclides from the repository.

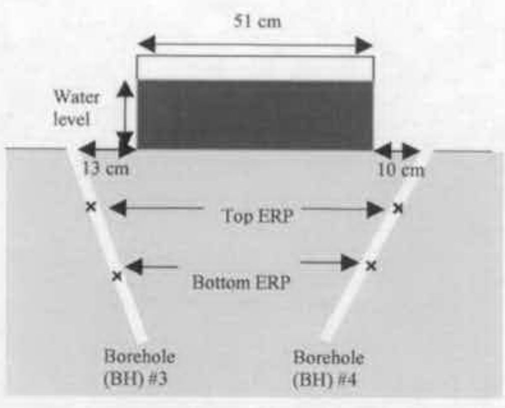
In Section II of this paper, we provide an overview of the proposed field investigations and preliminary site characterizations we have performed to date. Section III describes pre-test predictions for the proposed field investigations, and we conclude with a summary in Section IV.

II. FIELD INVESTIGATIONS

Based on our analysis of the conditions that result in the shadowing effect and the examination of many sites, we have selected the Hazel-Atlas silica-sand mine located at the Black Diamond Mines Regional Preserve in Antioch, California to carry out our field investigation. The location and configuration of this mine make it an excellent site to observe and measure drift shadow characteristics. The mine is located in a porous sandstone unit of the Domengine Formation, an approximately 230 meter (750 feet) thick series of interbedded Eocene-age shales, coals, and massive-bedded sandstones [3]. The mining method used at the mine required the development of two parallel drifts, one above the other, driven along the strike of the mined sandstone stratum. This configuration provides the opportunity to 1) look for hydrologic and geochemical indications of a drift shadow below the upper drift, and 2) introduce water into the rock mass on the floor of the upper drift and to observe and measure its flow around the underlying drift to look for the resulting drift shadow. Preliminary characterization of the sandstone at our test site in the mine is discussed below, followed by descriptions of the passive and active hydrologic tests to be performed.

II.A. Preliminary Characterization

To characterize the properties of the sandstone, two falling head infiltrometer tests were conducted inside the bottom drift of our test site. The second test was conducted two weeks after the first one at the same location. A 51 cm diameter ring with a pressure transducer installed at the bottom of the ring to record the change in the water level over time, was used to supply water. To minimize evaporation during the tests, the top of the ring was covered with plastic. Two 5 cm diameter boreholes (denoted as #3 and #4) with a depth of 38 cm were drilled adjacent to the ring and instrumented with electrical resistance probes (ERPs) to monitor the infiltration front. The orientation of the boreholes and the location of the ERPs are shown in Fig. 2. An inflatable packer was used to seal the boreholes and press the ERPs against the rock. The ERPs provide a qualitative indication of water saturation and have been successfully used in field tests at Yucca Mountain, Nevada [4].



	BH #3	BH #4
Top ERP Depth (cm)	11	10
Bottom ERP Depth (cm)	19	18

Fig. 2. Schematic of infiltrometer and two adjacent boreholes instrumented with ERPs.

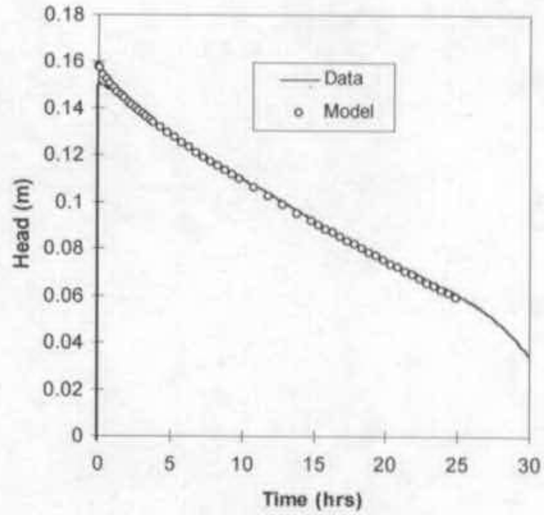


Fig. 3. Measured and simulated pressure head change in the ring from Test #2.

The measured change in water level over time from the second infiltrometer test is shown in Fig. 3. A three-dimensional model that assumed homogeneous rock properties was used to simulate this water level change, and the computed best-fit response for permeability and initial saturation values is also presented in Fig. 3. The parameters used in the simulations are summarized in Table 1. A porosity of 0.20 was measured in the

Table 1. Parameters for infiltrometer simulations

Porosity	0.20
Permeability (best fit to data)	1×10^{-14} m^2
Initial Saturation (best fit to data)	
Test #1	0.20
Test #2	0.40
van Genuchten parameters of Berea sandstone [5]:	
residual saturation	0.01
m	4.50
α	1/12000 Pa^{-1}

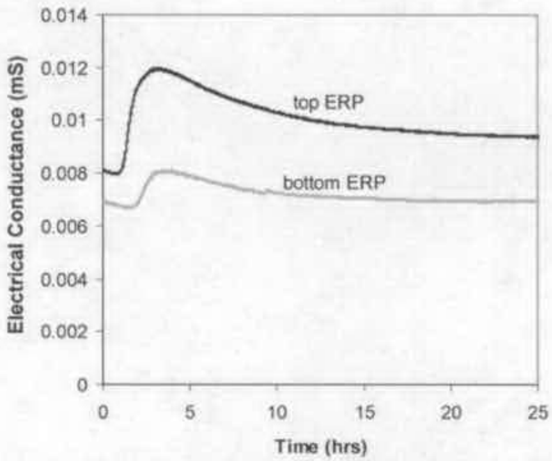


Fig. 4. Measured ERP conductances in Borehole #4 from Test #2.

laboratory from computed tomography images of cores from our test site.

Electrical conductance values measured using the ERPs in Borehole #4 for the second test are shown in Fig. 4. A rapid increase in the conductance is observed earlier in the top ERP compared to the bottom ERP, occurring 1 hour and 2 hours, respectively, after the start of the test. This increase indicates an increase in the water saturation and the arrival of the wetting front at the ERP. After the peak in the conductance, the measured values decrease with time before water in the infiltrometer ring had completely drained.

The decrease in electrical conductance was probably caused by dilution of dissolved ions and not because the water saturation in the rock had decreased. Initially, the advancing wetting front would be preceeded primarily by water nearly in chemical equilibrium with the rock; therefore, the front would have a higher conductivity than the water behind it. Although ERPs work well in rock because they are flexible and can be designed to make good contact with the rock, our preliminary results indicate that instruments less sensitive to changes in ion concentration such as gypsum blocks should be used in future tests.

II.B. Passive Hydrologic Measurements

The passive method relies on the natural hydrologic conditions that exist at the study site. The drift shadow, if it exists, will have formed as a result of natural groundwater percolation. We will obtain cores using dry drilling techniques from around the upper drift in a radial

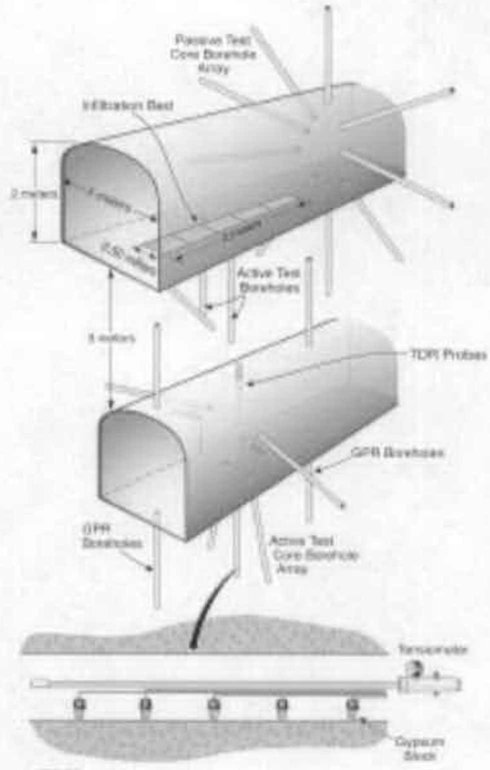


Fig. 5. Schematic of boreholes and instrumentation for the active and passive hydrologic tests

pattern (Fig. 5), with a minimum of four cores collected – one vertically upwards, two horizontally in the side walls, and the fourth vertically downwards. The retrieved cores will be preserved in the field, and then scanned in the laboratory using x-ray computed tomography to look for higher-density regions resulting from evaporite minerals. They will then be sectioned and analyzed for water content using a gravimetric technique, as well as analyzed for chemistry. We will also install various sensors at selected locations to measure the in-situ moisture conditions.

II.B. Active Hydrological Testing

The purpose of the active hydrologic test is to introduce water in the upper drift of an overlying pair of drifts, and make observations in and around the lower drift. Tensiometers, gypsum blocks, time-domain reflectometry (TDR), and ground penetrating radar (GPR) will be used to monitor the change in moisture content and potential over time as water is released (Fig. 5). The proposed borehole configuration around the bottom drift shown in Fig. 5 was chosen such that measurements are made in the most pertinent locations to see whether the zone immediately underneath the lower drift remains relatively drier compared to the sides and top of the drift and zones deeper in the rock. The spacing of the instruments inside the boreholes will be guided by pre-test prediction results. Because the active test provides control over the quantity and composition of the water that is released into the formation, the results are expected to better constrain theoretical predictions.

III. PRE-TEST MODELING

To help field test design, pre-test simulations have been performed considering various test configurations and parameters. These simulations are intended to provide information that will be used in designing various aspects of the proposed test including (1) dimensions of the infiltration plot, (2) magnitude of flux boundary condition, (3) location, spacing, and types of moisture sensors that will be installed in monitoring boreholes, and (4) duration of stable shadow zone formation.

For this purpose, we developed a three-dimensional iTOUGH2 model. Considering the vertical planes of symmetry along the axis of the drift and normal to the axis of the drift, the model accounts only for a quarter of the space of interest (5 m wide, 2.5 m deep, and 10 m high) as shown in Fig. 6. A niche with a roof shaped as a semi-circular arc and a square bottom was removed from the model block. The distance from the top of the model to the drift roof is 4 m. An infiltration plot of 0.25 m width and 1.5 m depth (representing an actual infiltration plot of 0.5 m by 3 m) was added to the top of the model. A constant flux boundary condition (representing steady state percolation of 100 mm/yr) was imposed along the top boundary. Free gravity-drainage was imposed on the bottom of the model, while all the sidewalls are specified as no flow boundaries.

The parameters used in these simulations are consistent with those used for the infiltrometer simulations discussed in Section II with the exception of permeability. Permeability is the most important parameter affecting the duration of the proposed tests. The permeability estimate calculated from the infiltrometer tests (~ 10mD) is low compared to other reported permeability values for this sandstone formation. Considering this uncertainty, we also considered permeability values of 100 mD and 300 mD.

Using the steady-state saturations as the initial condition, several simulations of controlled flux infiltration were performed. The imposed infiltration fluxes were such that the resultant steady-state percolation fluxes were approximately 30 %, 60 %, and 90 % of the respective saturated hydraulic conductivities. A summary of the imposed percolation fluxes is given in Table 2. During each simulation, saturation changes with time

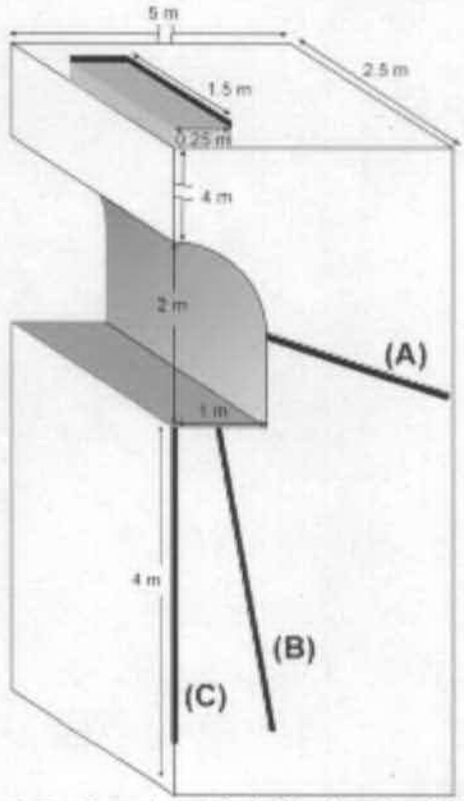


Fig. 6. Configuration of the infiltration plot, drift, and monitoring boreholes for the 3-D pre-test simulations.

along three boreholes were monitored. Figs. 7 and 8 show the saturation distribution along these boreholes during 500 days of continuous constant-infiltration tests for permeabilities of 100 mD and 300 mD, respectively.

The simulated observations indicate that the steady-state water content distribution is not sensitive to scaled percolation flux (infiltration ratio). However, given a scaled percolation flux (e.g., 0.3), the time needed to reach steady state is shorter as the permeability increases. The region that takes the longest to reach steady state is the outer boundary of the shadow zone (note the water content of the farthest observation points in Boreholes B

Table 2. Permeability and imposed infiltration rate combinations used in pretest predictions.

	k (mD)		
Infiltration ratio	10	100	300
	Imposed Infiltration (L/day)		
0.3	1	10	30
0.6	2	20	60
0.9	3	30	90

and C in Figs. 7 and 8). But a relatively stable shadow zone forms close to the drift before full steady state is established. Thus, in order to confirm the existence of a shadow zone, the field tests need not last until a steady-state condition is fully developed.

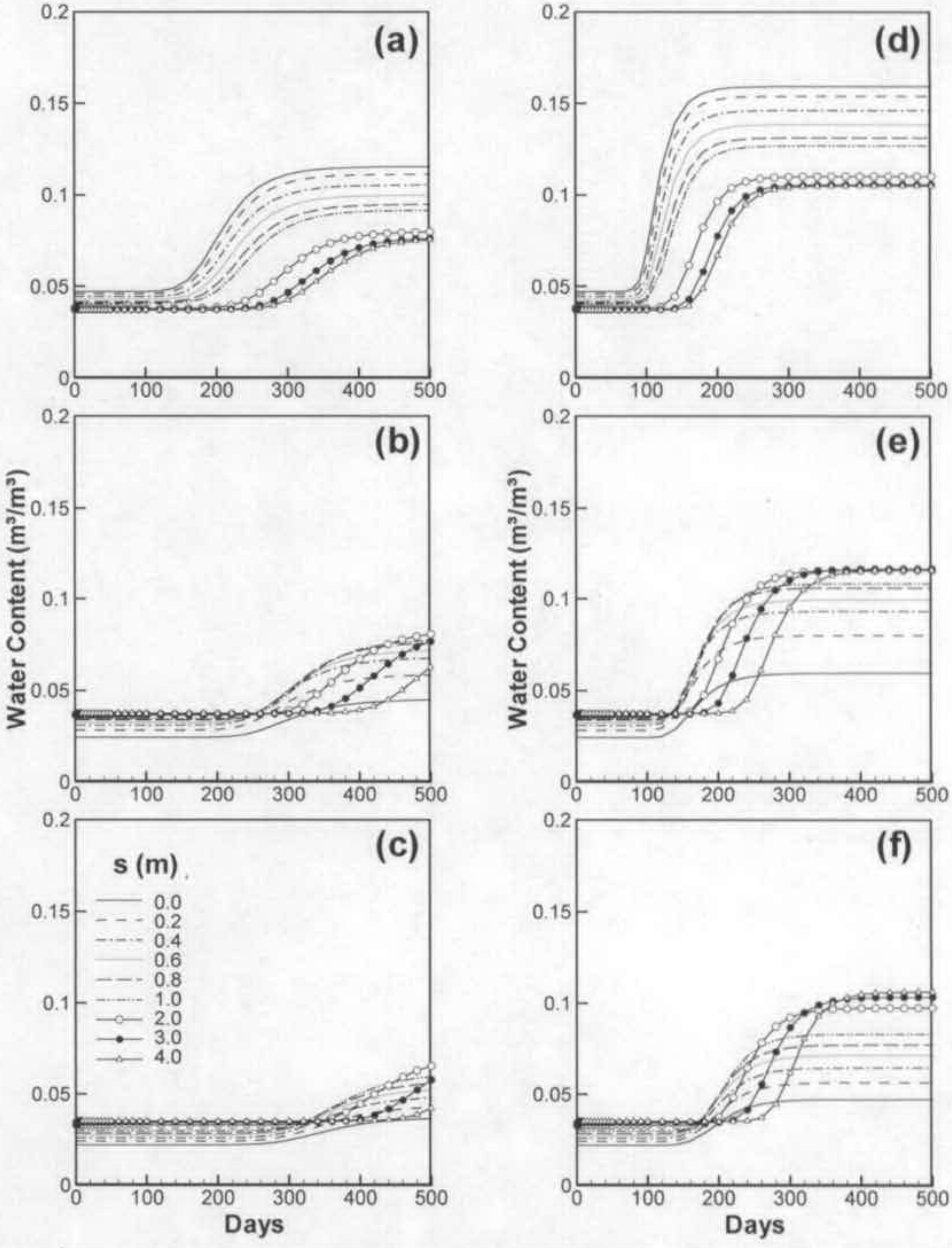


Fig. 7. Simulated volumetric water content [m^3/m^3] changes along the three observation boreholes (marked as A, B, and C in Fig. 6) for 100 mD permeability. The different lines indicate a distance s [m] from the borehole collars. (a) – (c) are for percolation flux of 10 L/day and (d) – (f) are for 30 L/day. (a) and (d) are for Borehole A, (b) and (e) for Borehole B, and (c) and (f) for Borehole C.

During the course of the field experiments, the water content of the formation will undergo considerable change ranging from approximately 0.025 m^3/m^3 to 0.16 m^3/m^3 (~10% to 80% saturation). Selection of monitoring

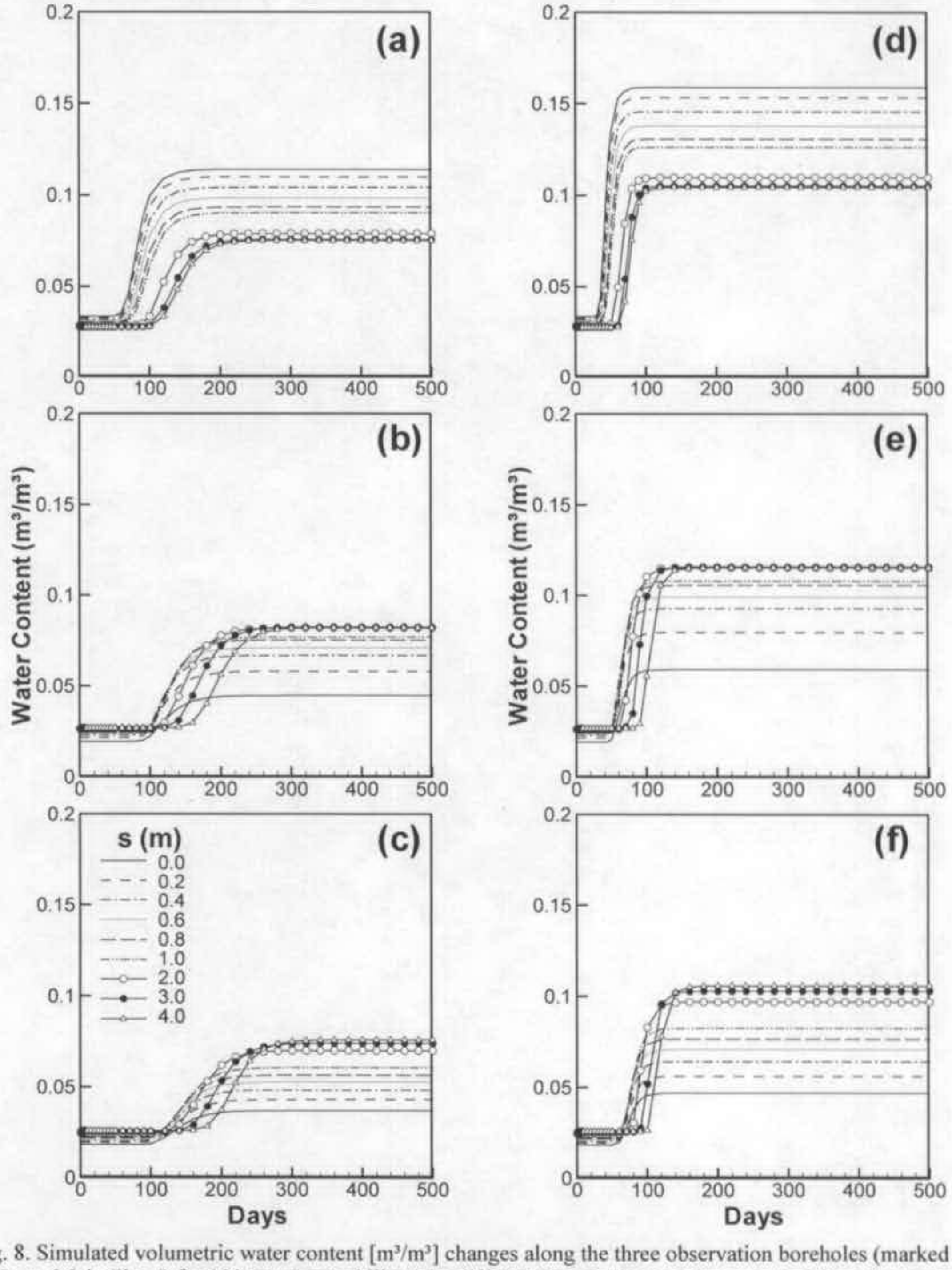


Fig. 8. Simulated volumetric water content [m^3/m^3] changes along the three observation boreholes (marked as A, B, and C in Fig. 6) for 300 mD permeability. The different lines indicate a distance s [m] from the borehole collars. (a) – (c) are for percolation flux of 30 L/day and (d) – (f) are for 90 L/day. (a) and (d) are for Borehole A, (b) and (e) for Borehole B, and (c) and (f) for Borehole C.

sensors will be optimized to satisfy these requirements. The spacing of the simulated observation points along the observation boreholes appears to provide sufficient information to indicate the temporal development of the drift shadow as well as to delineate the boundary of a fully developed drift shadow.

IV. SUMMARY

Our proposed field test design for investigating the drift shadow is guided by pre-test predictions as well as site characterization information. We will conduct an active test where water potential and saturation measurements will be obtained using multiple techniques. A passive test in which ambient cores will be analyzed for water content and chemistry will also be performed to look for the signature of a drift shadow formed over the last 60 years. Preliminary characterization of the sandstone was performed using falling head infiltrometer experiments and inverse modeling of these tests. In addition, we performed numerous pre-test predictions that enabled us to understand the time-scale of the proposed study, infiltration flux requirements, and spacing and type of monitoring equipment that will be needed.

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