Influence of Clastic Dikes on Vertical Migration of Contaminants in the Vadose Zone at Hanford

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Research Objective

This research project addresses the effect of clastic dikes on contaminant transport in the vadose zone. Clastic dikes are vertically oriented subsurface heterogeneities common at the Hanford Site, including within the subsurface sediments below the tank farms in the 200 West Area. Previous studies have suggested that clastic dikes may provide a fast path for transport of leaking fluid from the tanks through the vadose zone.

This research is testing the hypothesis that clastic dikes at the Hanford Site provide preferential pathways that enhance the vertical movement of moisture and contaminants through the vadose zone. Current flow and transport models of the vadose zone at the 200 Areas are based on relatively simple hydrogeologic models that assume horizontally layered sediments with no preferential vertical flow paths. To address those scientific needs, our research includes field and modeling studies of the spatial distribution of clastic dikes, the hydrologic properties within dikes, and the potential effect of clastic injection dikes on fluid flow through the vadose zone. The data and models of the clastic dike networks produced for this project should be directly applicable to fate and transport studies conducted at the 200 West Hanford tank farms.

Research Progress and Implications

This report summarizes progress after the first 32 months of a 3-year project. In 2001, the project extended its study of the small-scale hydrogeologic properties of clastic dikes. The main focus of the project was on study of a site near Army Loop Road that had initially been surveyed using ground-penetrating radar in 2000. The ground-penetrating radar survey and the air photo and field mapping were used to select a site to trench across a clastic dike. In June 2001, a clastic dike at the Army Loop Road site was trenched with a backhoe to a depth of ~3.5 m (Figure 1). The exposed clastic dike is in the sand-dominated facies of the Hanford formation. The dike excavated at the Army Loop Road site was much thicker than the dike excavated in 2000 at the S-16 Pond site (2 m vs. 0.7 m).

The dike was excavated in three different levels, each approximately a meter high. After the excavation of each level, the slopes surrounding the excavation were pushed back and the excavation was taken down another level. In this way, we were able to image and measure the properties of cross sections of the dike and matrix at three different levels that were approximately one on top of the other, without creating a safety hazard in the unstable sediment. The face exposed at each level was mapped, and sediment samples were taken for laboratory analysis. We imaged the face using an infrared (IR) camera and a digital 35-mm camera, then made a large number of air permeability measurements.

Figure 1. Clastic Dike Excavation on the Hanford Site

During the last fiscal year, members of the project team at New Mexico Tech made substantial improvements to the air minipermeameter system. The LSAMP II air minipermeameter developed by New Mexico Tech that was employed in the previous fieldwork had a practical range of ~ 9.7x10-04 to 4.9x10-06 m/sec, corresponding to fine to medium sand. However, there are numerous silt bands in the dikes as well, but it was not practical to make measurements in the finer-grained units because the measurements took too long to make. This year, investigators from New Mexico Tech attempted to modify the system so that it could be used to make measurements in some of the finer-grained sediments. The factor that controls the time that it takes to make a measurement (and therefore the lower end of the practical range of the instrument) is the inner tip seal pressure (P_i). Because $P_i = (mg)/A$, where m and A are the mass and area of the piston, respectively, and g is the acceleration due to gravity, in order to increase the tip seal pressure, it is necessary to add mass to the piston because the area of the piston remains the same. However, the calibration of the permeameter assumes that the piston reaches terminal velocity before it reaches the upper photo sensor, and that puts an upper limit to how much mass can be added to the system. The investigators at New Mexico Tech performed a series of calibrations in the laboratory and determined that the mass of the piston could be increased by loading up to an order of magnitude additional mass on the top of the piston with only a 2% error in the measured air permeability values. The increase in mass of the piston extended the range of the air minipermeameter on the lower end by a full order of magnitude.

We employed two air minipermeameters during the fieldwork at the Army Loop Road site—a standard instrument and one with the extended range. This allowed us to make substantially more measurements in 2001 than during the previous year. We took a total of about 450 measurements on the three tiers, one-third in the dike and two thirds in the matrix. The results indicate the median air permeability of the dike is about one order of magnitude lower than the permeability in the matrix, and that is similar to the results obtained last year. The variability of the data from the dike is much higher than that of the matrix, with a coefficient of variation (i.e., ratio of standard deviation to the mean) of 1.2 in the dike vs. 0.6 in the matrix. The overall variability of air permeability in the dike-matrix system is about four orders of magnitude. This is an important observation, because some methods used for upscaling permeability data assume the variability in the system is low, about an order of magnitude, which means it would be questionable to apply those methods to the clastic dike and its surrounding sediments.

In addition to making a number of measurements of air permeability, we also imaged each face in the excavation using a high-resolution IR camera. Figure 2 shows two composite images of the middle level in the trench. The lower image was made with an ordinary digital camera and the upper image was made using the IR camera. The contrast in the IR imagery is due to variation in the moisture content of the sediment; darker colors indicate more moisture and tend to be associated with finer-grained units with lower air permeability. The dike can be seen as the banded interval that takes up the middle third of the image, and is about 2 m wide.

We found that the IR data and the air permeability moisture data collected from the dike and surrounding matrix are positively correlated with one another, with a linear correlation coefficient of 0.73. Variogram analysis of the two data sets indicated that the spatial continuity of the air permeability and IR data were very similar. Based on the relationship between the two

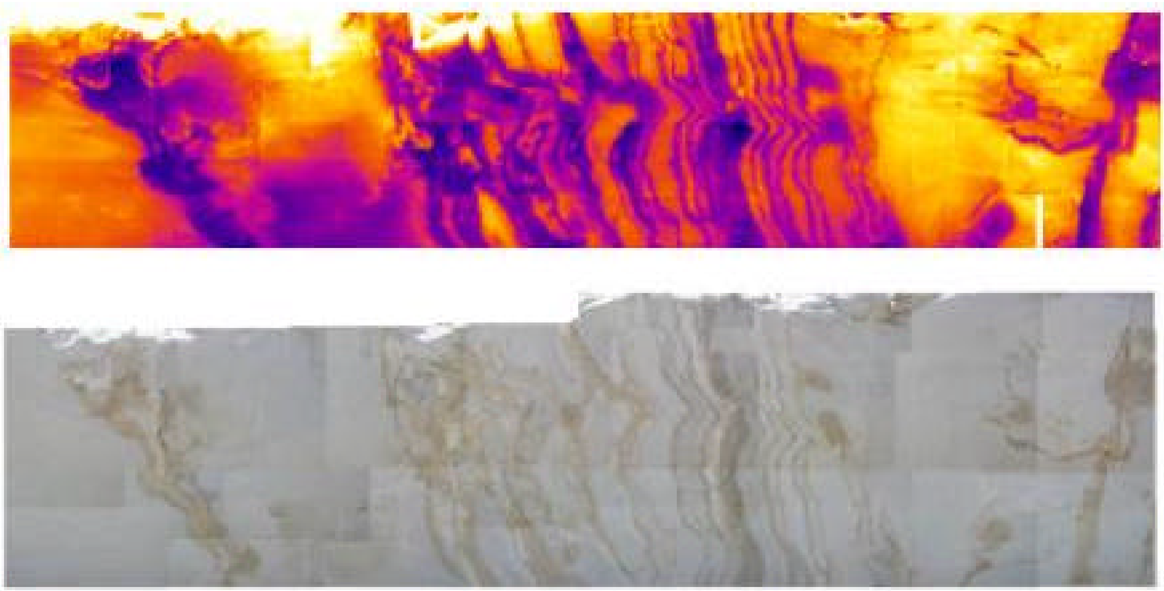

Figure 2. Composite Images of Middle Tier, Clastic Dike Excavation Site. Top shows infrared camera image; bottom displays image made using digital camera.

variables, we used sequential Gaussian simulation to generate simulated estimates of the air permeability in two dimensions over the entire exposure of the dike and matrix with very high resolution (centimeter-scale). The number of simulated air permeability measurements for the entire exposure was approximately 10.5 million, which would be impractical to achieve by taking direct measurements with the air-minipermeameter. The simulations of the air permeability honored the 450 air permeability measurements as well as the IR image through the collocated cokriging algorithm. The high-resolution map of the estimated hydraulic conductivity will be used for input to flow and transport modeling and as the basis for studies of the scaling properties of the system.

One feature noted during our previous excavations of clastic dikes is that there often appears to be a zone of lower permeability in the matrix near the clastic dike. To test that hypothesis, we took several horizontal transects in the matrix on either side of the dike on several different levels. Several of these transects did in fact show a decrease in permeability near the dike. There is no obvious change in grain size near the dike, but we will be performing grain size analysis to verify that. We will also examine the matrix sediment to see if there is an appreciable increase in cementation near the dike.

We made an effort this year to measure the continuity of the vertical bands seen within the clastic dike. A transect was laid out on the floor of the middle layer of the excavation on a horizontal exposure of the dike. Each band encountered in the transect was then traced up and down the excavation to see if it was continuous. The measured continuity is the total trace of one band along each vertical face and across the horizontal exposures (the "floors" of the excavation) linking the vertical faces. So the measured continuity is a combination of both vertical and horizontal continuity within the 2.5-dimensional excavation. The vertical bands that were measured did not include the very thin and very fine-grained clay and silt skins (usually less than 1 cm thick) associated with the major bands. The clastic dike bands that were characterized had a median thickness of 5 cm and ranged from 2.5 to 14 cm. In most cases, the bands could be traced for about 1.6 m before they pinched out or were obstructed by a clay/silt skin cutting across the band. The range of continuity observed was from 0.2 to 7.7 m, with all but one of the bands having an apparent continuity of less than about 2.5 m. This degree of continuity will affect transport through the clastic dike and will be used to guide construction of models of the properties within the dike.

A large-scale infiltration experiment was conducted at the Army Loop Road site in 2001. A drip irrigation system was used to apply the specified fluxes. The application area was centered on the dike and aligned with the longer axis perpendicular to the dike. Three fluxes of water were applied to the clastic dike and surrounding matrix, and the progress of the infiltrating water was monitored for each flux rate. Water content, matric potential, and electrical conductivity were measured throughout the tests using a neutron probe, cross-borehole radar, tensiometers, and time domain reflectometry (TDR) probes. Eight boreholes were emplaced to a depth of about 7 m and used for the neutron probe and cross-borehole radar measurements. This depth will provide significant information because there are no reports of observations of flow within dikes at this large a scale. For example, in all of the tests reported by Fecht et al. (1998), the maximum depth of observation was < 1.0 m. The measurement frequency during the infiltration test varied depending on the experimental conditions. The TDR probes and tensiometers were installed to a depth of 0.5 m on a transect oriented perpendicular to the dike.

The three fluxes applied were 0.1, 0.01, and 0.001K_s, in that order. For typical soils, this translates roughly into flux values of 10^{-3}, 10^{-4}, and 10^{-5} cm/s. Total flux applied was approximately 15,000 l. Similar fluxes have been used in previous field tests of surface soils at the Hanford Site (see Khaleel 1999, Appendix C). Higher fluxes are difficult to maintain because of the water supply; they also are prone to generate ponding and runoff, which degrade the value of the infiltration test. Lower irrigation fluxes more nearly approximate natural fluxes but they pose problems because of the time required to achieve steady-state conditions. Relating each flux to the resulting equilibrium water content will provide a measure of the unsaturated conductivity function (Youngs 1964). The water content and matric potential data provide a direct measure of in situ water retention.

Once steady state was achieved with the third (and lowest) flux rate, the irrigation supply tank was switched to a solution of KBr and the dye known as Brilliant Blue FCF. The presence of the KBr will significantly affect the TDR signals and make it easier to detect the wetting front in the subsurface. The flux was continued until the KBr moved below the TDR sensing zone (about 0.5 m). Further movement of the water was monitored with neutron probe and cross-borehole radar measurements.

The excavation began after the application of the tracer in the infiltration area. The main excavation face was approximately 8 to 10 m from the edge of the infiltration zone, so that the moisture would not affect the air permeability measurements or IR imaging. However, after construction of the main excavation area was complete, an additional face was cut at the edge of the infiltration area so that the distribution of the tracers could be examined. The upper portion of Figure 3 shows a composite color photographic image of what we termed the “dye” face, with the lower portion of the figure being a map of the moisture distribution in the face. The photographic image shows the very heterogeneous distribution of the blue dye. The dike is in the center-right area of the image, from 3 to 5 m, and tends to transmit less dye. However, some of the deepest penetrations of the dye occur in restricted bands within the dike (Figure 3). The map of the moisture distribution in the lower portion of Figure 3 was made using TDR probe measurements on a 15-cm by 15-cm grid across the entire face. Although the moisture map captures the main features seen in the photographic image, it is obvious that important heterogeneity in the distribution of dye and moisture is not captured in the map, even with the

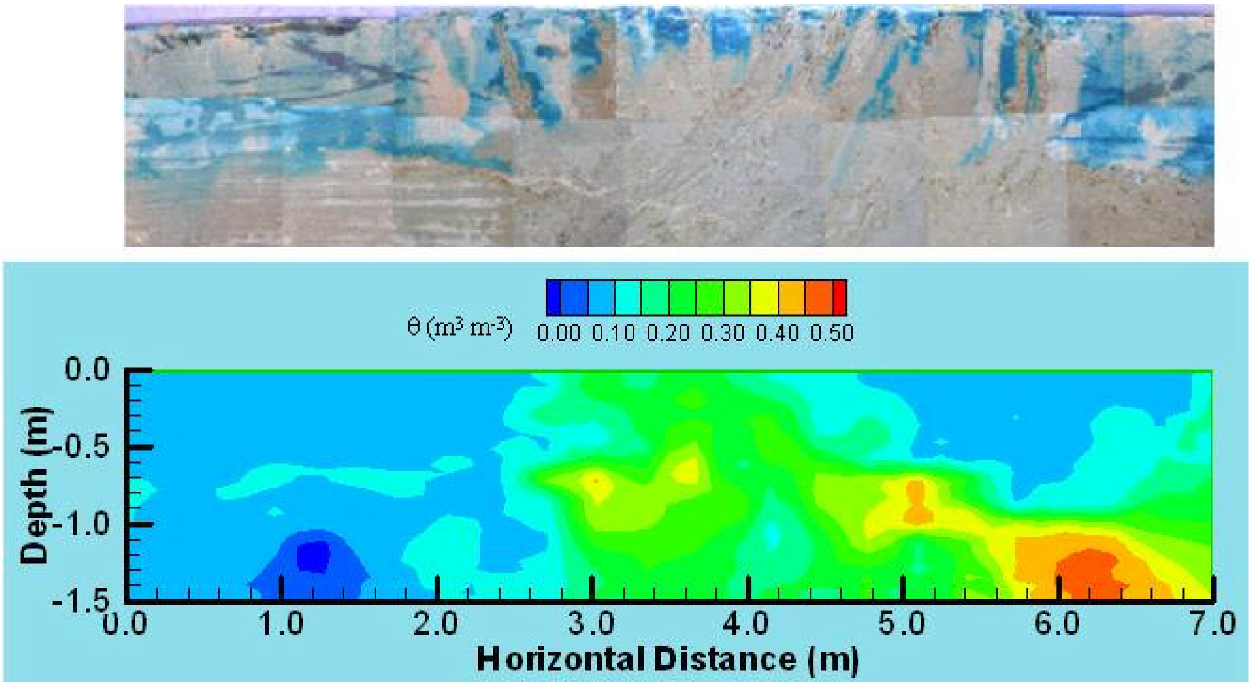

Figure 3. Images of Excavated Portion of Infiltration Experiment. Top: composite image of dye penetration. Bottom: contour map of clastic dike water content. measurements for surface shown in upper image.

relatively dense grid of TDR measurements. Figure 3 shows the vertically integrated moisture distribution every 15 cm and indicates quite clearly that much greater levels of moisture are stored within the clastic dike.

We used tomographic ground-penetrating radar to map the distribution of moisture between pairs of boreholes as the infiltration experiment progressed. Horizontal and vertical resolution of the data is 0.1 m. We took measurements immediately prior to the start of the infiltration experiment near the end of May; immediately after the infiltration had ceased in mid-June; and several months afterward to image the redistribution of the moisture with time. The radar tomography successfully imaged the changing moisture distribution for pairs of boreholes that were on the same side of the clastic dike, but was unable to image the dike itself when the dike was located between the pair of boreholes. This may be due to the near-vertical orientation of the dike and the high rader attenuation potential of the material within the dike.

One important feature noted in the excavation and infiltration experiment was a clastic sill that emanates from one side of the dike. This sill was detected prior to the excavation, when the access boreholes for geophysical monitoring of the infiltration experiment were being emplaced with a cone penetrometer (CPT). Moisture data from the CPT probe, which were recorded prior to any activities at the site, indicated the presence of a high-moisture zone at a depth of about 5 ft that was present only on the west side of the dike and not the east side. Based on previous experience at the S-16 Pond excavation in 2000, we suspected that the high moisture zone on the west side of the dike was a clastic sill. Subsequently, we found that the sill exerted a major influence on the movement of moisture during the infiltration experiment. Where there is no sill, the moisture appears to have migrated uniformly downward through the sediment. On the western side of the dike, however, moisture penetrates below the sill only at later time periods. When the sill was exposed during the excavation, we found that moisture had migrated several meters laterally within the sill, carrying moisture well outside the infiltration zone. This suggests that clastic sills are important controls on vadose zone transport, at least at local scales. The results also indicate that even though the air permeability and saturated hydraulic conductivity within the dike and sill are very low, clastic dikes may still be fast transport paths under unsaturated conditions in the vadose zone.

Planned Activities

During the remainder of FY 2002, we will complete analysis of the data gathered during the infiltration experiment and the excavation. The data collected from this experiment will be used to derive flow and transport parameters for the dike and surrounding matrix, as well as provide field data with which to perform geostatistical and hydraulic flow modeling. We will continue to apply geostatistical methods to produce numerical two- and three-dimensional grids of the infiltration site for flow and transport modeling of the vadose zone. Flow and transport modeling will be performed in late FY 2002, and the resulting transport models will be compared with observations made during the transport experiments.

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