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Application of high resolution crosswell radar and seismic for mapping flow in the vadose zone

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Summary

Geophysical imaging in the vadose zone poses unique issues. Groundwater contamination at DOE's Hanford, Washington site needs optimal imaging because extremely high drilling costs make direct characterization quite expensive. We conducted seismic and radar crosswell experiments to help answer basic questions about high resolution geophysical characterization. We acquired time lapse surveys during controlled injections of river water and saline solution. Radar imaging of dielectric changes delineated geological layers and moisture movement with 0.25 m resolution. Seismic velocity measurements delineated lithology at 0.25 m resolution with sensitivity to porosity and density changes in sediments and penetration of over 20 m using two sources of different bandwidths.

Introduction

To effectively clean up many contaminated sites there is a need for information on heterogeneities at scales ranging from the centimeter to tens of meters, as these features can alter contaminant transport significantly. At the Department of Energy's Hanford, Washington site drilling costs have exceeded $1M per borehole (50 m deep). This cost limits the number of point scale measurements resulting in an inability to track highly mobile species through the vadose zone. Methods are needed to describe the complete vadose zone plume and to determine processes controlling accelerated contamination of groundwater

The main questions addressed with the crosswell methods in this study were :

- What aspects of the vadose zone-groundwater system control flow geometry?
- What physical properties or mechanisms control flow and transport in unconsolidated soils of the vadose zone?
- What is the optimum suite of geophysical field tests to provide information for predicting flow and transport behavior?
- How can the information obtained during site characterization be used for building confidence in predictive numerical models?

Methods

Fully developed, application of geophysics should enable location of contaminant distributions. Questions addressed in this study were the sensitivity, resolution, and accuracy of the radar and seismic crosswell methods in deriving the spatial and temporal distribution of properties controlling transport and contaminant distribution between and away from boreholes and the surface.
Overall there are two broad hypotheses being addressed in the crosswell geophysical work:

(1) Geophysical methods can identify physical and chemical heterogeneity controlling contaminant transport at a meaningful scale.

(2) Geophysical methods have the sensitivity to directly or indirectly detect the location of the fluids and/or contaminants at a practical concentration (i.e. subsurface has been altered enough to create anomalies that can be detected, i.e., mechanical, electrical, thermal, etc.).

The primary purpose of the crosswell radar and seismic imaging was to provide detailed information on the lithology and structure as well as provide the same level of detail on the location of the fluid transport during carefully controlled injection experiments. The focus of the measurements was to determine the state variables controlling water movement. (i.e. water content, physical heterogeneities and if possible water potential, chemical concentrations and temperature). It was also desired to determine if the density of the fluid would change the flow behavior. A second major goal was to evaluate these methods and/or modify the methods for use at tracking leaks from tanks at Hanford during clean up operations.

There were two major injection events at the site which were monitored with the crosswell radar and seismic methods, one in the spring of 2000 which used Columbia river water and one in the spring of 2001 which used a saline solution (sodium thiosulfate, density of 1.3 g/cc) chased by Columbia river water. In 2000 in four 4000-L increments of Columbia river water were injected over a 6-week period. In 2001 five increments of approximately 4000-L of a sodium thiosulfate solution were injected over a five week period, followed by three 4000-L injections of Columbia river water. In 2000 the crosswell data were combined with neutron logging results in steel cased wells. The radar methods were applied in a time lapse sense to determine changes in the moisture content, thus there was repeated measurements at the same sites. The crosswell seismic measurements were designed to examine structural and lithologic heterogeneity, thus used only once. We assumed before we applied the seismic measurements that they would be less sensitive to fluid content in the vadose zone, however, as will be seen below the seismic measurements may have high enough frequency content and resolution to provide valuable independent information from the radar measurements.

Figure 1 shows a plan view of the well configuration at the injection test site with the wells marked as "X" as the wells used for the crosswell radar and seismic studies. This site was developed in the 1980's as part of work to understand flow and transport in the vadose zone at Hanford. Thirty two steel cased wells were put in at that time. Additional PVC wells were emplaced for the work described here. These "X" wells were located, based on past experience from prior injection experiments, at the most likely location of flow during the injection experiments.

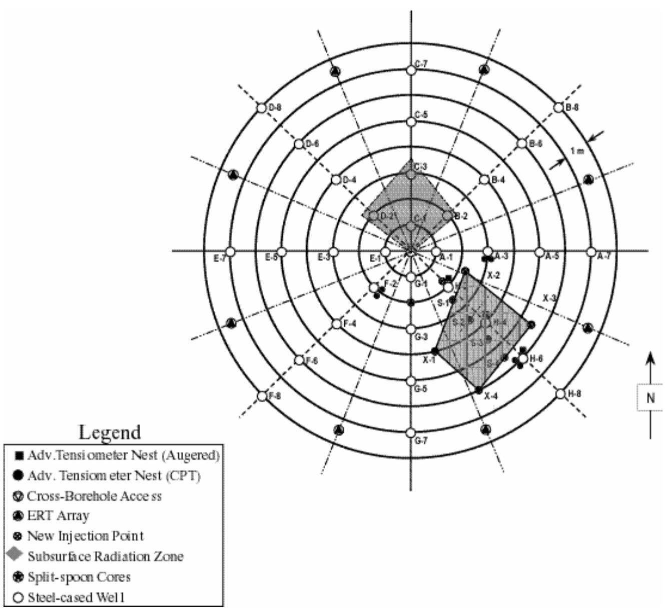

Figure 1 Well array at the Test Site in the 200 East Area at Hanford, Washington. The lower shaded area between X1, X2, X3 and X4 was the target area for the crosswell. The scale is 1 meter between circles.

Crosswell Radar

The ground penetrating radar (GPR) work consisted of repeated cross well tomographic data sets being collected between the six possible X-well pairs. In 2000 a total of four different data sets were collected: one prior to injection as a background data set, two during the injections and one after the injections. In 2001 there were also a total of four data collection visits were made to the site**.** These include a visit which constituted the base line data set, two days prior to the start of the injection, followed by the monitoring during an initial release of 1900 L of sodium thiosulfate. The next data set was acquired 30 days later after 19,000 L of sodium thiosulfate had been injected. The last data set was collected 18 days later after 3785 L of a mixture of tank sludge and river water and 7570 L of Columbia river water had been injected. All of the radar data were collected using the PulseEKKO 100 GPR system with 200 MHz center frequency antennas. The step size for data collection between all well pairs was 0.125 meters in 2000 and 0.25 meters in 2001.

Crosswell Seismic

The crosswell seismic was collected after all of the infiltration tests were completed in both 2000 and 2001. This was due to the fact that the wells used for the crosswell seismic had to be filled with water to enable coupling of the hydrophones and the piezoelectric and mechanical orbital sources. Because we did not know if the wells would leak we did not want to let other water into the formation during the infiltration tests. Until this experiment it has been our experience that it is very difficult to collect high resolution seismic data (in the kilohertz range) in a vadose zone geology. This is due to the fact that partial saturation usually greatly attenuates seismic energy. In 2000 there were four different seismic crosswell sections obtained, three high resolution sections and one long offset section using a distant 6" steel cased hole for a source hole. The three high resolution sections were collected by placing a 24 element hydrophone array in well X4 which was filled with water. A 1.5" diameter by 4" long piezoelectric seismic source was then used in wells X3, X2, and X1. The long offset section was obtained by leaving the hydrophone array in well X4 (1/2 meter sensor spacing) and placing a 4" diameter orbital vibrator source in a well which was also filled with water, approximately 19 meters away from X4. The purpose of this was to see how far seismic energy could be transmitted in the vadose zone. The orbital vibrator, a stronger source than the piezoelectric, puts out lower frequencies, in the 50 to 400 Hz range. In 2001 only the high frequency crosswell seismic data were collected. The piezoelectric data were collected at ¼ meter intervals for both source and receiver. The piezoelectric source put out energy from 1 to 10 kHz. Assuming that the resolution is on the order of ¼ wave length, and with measured velocities of about 700 m/s, we had resolution of 10 cm for the piezoelectric data and 60 cm for the orbital source.

Radar Results

Electromagnetic wave slownesses (the reciprocal of velocity) were estimated for this study using the travel times of the propagation waves and a straight ray algebraic reconstruction inversion technique (Peterson et al, 1985; Peterson, 2001). A velocity pixel dimension of 0.25 x 0.25

meters was used for the image inversion. The pre-injection radar data set (in addition to the seismic data) was used to delineate the stratigraphic layering which had a velocity range of approximately 0.11-0.16 m/ns (typical for unsaturated, unconsolidated sands). The tomograms suggest the presence of seven distinct radar velocity layers, each continuous across the length of the tomogram and ranging in thickness from 0.25 to 3.5 meters. These seven layers extend across the entire set of radar profiles.

The electromagnetic wave velocity (v), obtained from the slowness estimates, can be converted to dielectric constant (κ) using: $\kappa = c^2/v^2$ where c is the velocity of electromagnetic waves through air. Dielectric constants in geologic materials range from approximately 3 to 25. As the dielectric constant of air is 1 and water is 80, water content will have the dominant affect on the dielectric constant. Neutron logs were obtained to calibrate the data There was good spatial correlation between the neutron data and the radar results. Figure 2 shows an example of the differencing the traveling times between the POST1 (acquired one week after the second injection) and the base line measurements (collected in May 2000). After inverting these differences, we obtain an estimate for the change in radar properties. Because the geology remains constant, the observed change in dielectric constant should indicate the change in moisture. Figure 2 shows the changes in moisture content for three of the well pairs associated with POST1. The results indicate that the greatest changes in moisture occur just above the low moisture zone at 6.5 meters depth (Layer 3) and just above the low moisture feature at 10 meters depth (Layer 6). In fact, there appear to be no changes in moisture (or retention in water content) below 10 meters.

The 2001 injections were designed to be very similar to the 2000 injections, but with a denser solution. The hydrogeologists hypothesized that the denser, more viscous solutions may not have the same flow characteristics as the river water used in 2000. In 2001 we wanted to use time lapse measurements to determine if the heavier sodium thiosulfate was flowing in the same manner as the river water in 2000. There was also a hypothesis that the sodium thiosulfate would be affected by the moisture (or residual water content). Figure 3 shows quite different results for 2000 and 2001 after 500 gallons each. In 2000 the river water appears to have gone straight down to the boundary of the fine scale layer, then traveled across the layer in a horizontal manner. In 2001 the more viscous sodium thiosulfate apparently did not go straight down but traveled horizontally towards X1, then sinking to the layer below before going down gradient (perpendicular to the plane of X1 and X2).

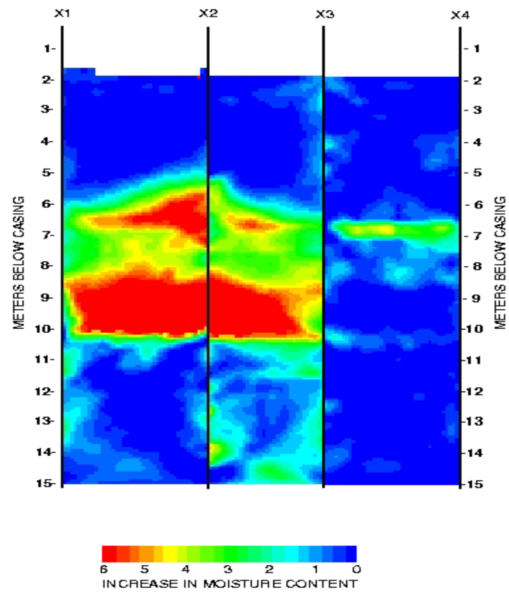

Figure 2 Changes in moisture content (%) after the first water injection in 2000.

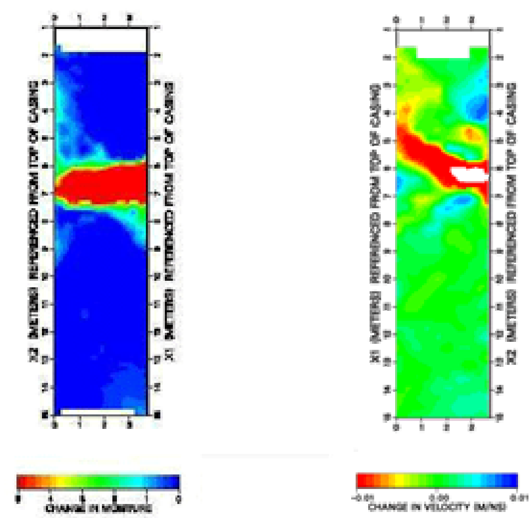

Figure 3 The 2000 and 2001 radar result after 900 gallons of injection of water and sodium thiosulfate, respectively, note the different fluid travel paths.

Seismic Results

Seismic data gives a completely independent measure of the physical properties compared to electrical and radar methods. Both high frequency (2 - 3 kHz) and lower frequency (70 - 300 Hz) data were collected. The results to date are very surprising in their high quality, for both the close spacing X wells and the long offset work. In 2000 data were acquired from the X1-X4 borehole pair and was processed for seismic velocity structure. The same algorithm and parameters were used for this inversion of seismic data as were used for the radar data. Figure 4 shows a result of the tomography achieved with the seismic data. Note that the seismic velocities are quite low, just above the velocity of air. The seismic velocities resolve the same stratigraphy as the radar velocity estimates, however, the high radar velocity layers coincide with the low seismic velocity layers and visa versa. This is most likely due to the fact that electromagnetic wave velocities are high in air, while the acoustic wave velocities are low in air. Therefore, in unsaturated material, the seismic waves should travel slowest in high porosity material, and electromagnetic waves should travel fastest in high porosity material.

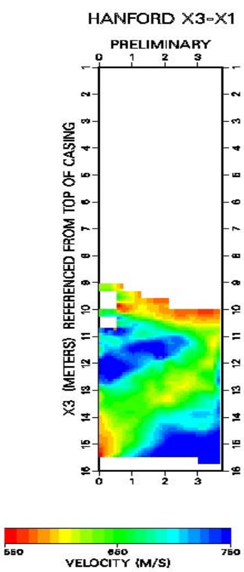

Figure 4. Seismic cross section X3 to X2, , the radar data, the higher velocities correspond to the tighter sediments

Summary and Conclusions

Overall the radar and seismic results were good. At the time of design of the experiments we did not know how well these two methods could penetrate or resolve the moisture content and structure. It appears that the radar could easily go up to 5, even 10 meters between boreholes at 200 Mhz and even father (up to 20 to 40 m) at 50 Mhz. The seismic results indicate that at several hundred hertz propagation of 20 to 30 meters is possible. One of the most important results is that together the seismic and radar are complementary in their properties estimation. The radar being primarily sensitive to changes in moisture content, and the seismic being primarily sensitive to porosity. Time lapse radar can show moisture content changes with high resolution, with the seismic showing high resolution lithology. The significant results for each method are:

Radar:
Delineated geological layers 0.25 to 3.5 meters thick with 0.25 m resolution. Delineated moisture movement and content with 0.25 m resolution. Compared favorably with neutron probe measurements. Penetration up to 30 m.
Radar results indicate that the transport of the riverwater is different from that of the heavier and more viscous sodium thiosulfate. It appears that the heavier fluids are not mixing readily with the in-situ fluids and the transport may be influenced by them.

Seismic:
Delineated lithology at .25 m resolution. Penetration over 20 meters, with a possibility of up to 30 or more meters. Maps porosity and density differences of the sediments.

Overall the radar and seismic data imply that the fluid property differences (density , viscosity, surface tension) between the river water and the sodium thiosulfate do make a difference in flow characteristics.

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