Project Number: 70052
Title: Material Property Estimation for Direct Detection of DNAPL using Integrated Ground-Penetrating Radar Velocity, Imaging and Attribute Analysis
Date: 6-15-2002
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Research Objective

The focus of our work is direct detection of DNAPLs, specifically chlorinated solvents, via material property estimation from surface ground-penetrating radar (GPR) data. We combine sophisticated GPR processing methodology with quantitative attribute analysis and material property estimation to determine the location and extent of residual and/or pooled DNAPL in both the vadose and saturated zones. An important byproduct of our research is state-of-the-art imaging which allows us to pinpoint attribute anomalies, characterize stratigraphy, identify fracture zones, and locate buried objects. Implementation and verification of these methodologies will be a significant advance in GPR research and in meeting DOE's need for reliable in-situ characterization of DNAPL contamination.

Chlorinated solvents have much lower electric permittivity and conductivity than water. An electrical property contrast is induced when solvents displace water in the sediment column resulting in an anomalous GPR signature. To directly identify zones of DNAPL contamination, we focus on three aspects of reflected wave behavior - propagation velocity, frequency dependent attenuation, and amplitude variation with offset (AVO). Velocity analysis provides a direct estimate of electric permittivity, attenuation analysis provides a measure of conductivity, and AVO behavior is used to estimate the permittivity ratio at a reflecting boundary. Areas of anomalously low electric permittivity and conductivity are identified as potential DNAPL rich zones. Preliminary work illustrated significant potential for quantitative direct detection methodologies in identifying shallow DNAPL source zones. It is now necessary to verify these methodologies in a field setting. To this end, the project is field oriented and has three primary objectives:

1) Develop a suite of methodologies for direct detection of DNAPLs from surface GPR data
2) Controlled field verification at well characterized, contaminated sites
3) Exploratory contaminant detection in a field setting to be verified through direct sampling

Field experiments are being conducted at the Savannah River and Hanford sites, at five DOD sites (Dover AFB, DE; McClellan AFB, CA; Port Hueneme, CA; Wurtsmith AFB, MI; Hill AFB, UT) and at a former refinery site near Cincinnati, Ohio.

Research Progress and Implications

This section summarizes work after 33 months of a three-year project. To date, we have conducted GPR feasibility tests at 7 locations and collected nearly 67,500 sq. ft. of multi-offset 3D GPR data, primarily in TE polarizition mode, but with a significant amount in TM mode. Field sites include the DOE Savannah River and Hanford sites, Dover Air Force Base, DE, Hill Air Force Base, UT, and a former Chevron refinery near Cincinnati, Ohio. Additionally, we have completed implementation of a non-linear

inversion algorithm for computing the permittivity ratio at a reflecting boundary from GPR AVO data (Bradford et al., in review). We are continuing development of GPR specific AVO analysis software suitable for application to production scale data volumes. Training of four undergraduate research assistants and one graduate student have been supported by this project, exceeding the goals outlined in the original proposal. We have made significant strides towards achieving the primary research objective: field demonstration of NAPL detection using GPR velocity and attribute analysis (Deeds and Bradford, 2002). Preliminary results of site specific studies are presented below.

In January, 2000, we conducted a 2366 sq. ft., 3-D, multi-offset, GPR survey at the A-014 outfall of A/M Area (U). The survey was designed to encompass a shallow (<25ft) DNAPL zone, with little or no contamination near the edges and a heavily contaminated zone near the center. Using pre-stack depth migration velocity analysis and imaging, we identified a high velocity anomaly associated with a channel-like feature that had not been previously identified. This is consistent with accumulation of low permittivity DNAPL. In August, 2001 four cores were acquired to test for the presence of DNAPL. Two cores were acquired within the high velocity zone, and two were acquired just east of the high velocity zone. No NAPL was found directly within the high velocity zone, but relatively high concentrations were found adjacent to, and below the trough feature. We are left to conclude that the high velocities we measured are related to a change in lithology. However, the presence of high levels of contaminate directly adjacent to, and below the trough, supports the interpretation of this feature as a primary DNAPL migration route. The dataset does illustrate the non-unique nature of the geophysical response, but we feel the experiment was a qualified success since we achieved important but secondary objectives such as electrical property anomaly identification, mapping a contaminant migration route and estimating near surface water content.

In October of 2000, we acquired a 32,000 sq. ft., 3-D multi-offset GPR survey at OU-1, Hill AFB, UT. Survey objectives included imaging a clay aquitard at a depth of 25 - 40 ft and direct detection of an LNAPL plume. The free product plume that covers approximately 7 acres with measured thickness of as much as 1 ft. Using pre-stack depth migration velocity analysis and imaging we were able to extract a detailed map of upper aquitard surface. Velocity and AVO analysis revealed a high velocity anomaly lying within a topographic low on the clay surface. In September, 2001, four continuous cores were pulled from within the anomalous zone, and a fifth core was pulled just outside of anomalous zone for background control. All five cores indicate a relatively homogeneous stratigraphy from the surface to the clay layer, and no lithologic boundary is evident that explains the anomalous reflection. Elevated levels of hydrocarbon (varying from 1% - 4% total volume) were discovered within the high velocity anomaly, and the control core had only a thin trace of hydrocarbon which was well below the resolution of the GPR signal. This result is significant for several reasons. First, we believe this to be the first reported case of GPR AVO and migration velocity analysis being used for direct detection of NAPL in an uncontrolled field setting over an existing plume. And second, the NAPL was found in a location previously thought to lie outside the plume boundary. The key to this success was quantitative analysis of multi-offset radar data to identify electric property anomalies that may otherwise have gone unnoticed in qualitative interpretation of conventional radar profiles.

Currently, we are completing the data acquisition component of an exploratory project at Hill AFB. This field project is designed to first identify GPR anomalies consistent with LNAPL accumulation, then investigate the anomalies using detailed multi-offset GPR acquisition and analyses. This will be followed by verification with direct sampling. In May, 2002, we acquired approximately 50,000 linear ft. of common-offset GPR data covering much of the OU-1 site. These data were used to identify zones for targeted multi-offset data acquisition. Acquisition of multi-offset data is ongoing and is scheduled for completion on 6-15-2002.

Our original work plan called for acquiring data at two National Environmental Technology Test Sites (NETTS) in California (Port Hueneme and McClellan AFB). Feasibility tests during September of 2001 demonstrated that soil conditions at these sites were not suitable for GPR investigation, and we began to search for an additional contaminated test site. This led to the identification of a former Chevron refinery outside of Cincinnati, OH as a potential test site. In January, 2002 we acquired approximately 5600 linear ft. of 2D multi-fold GPR data (50 MHz) consisting of both TE and TM configurations along three transects ranging in length from 500 ft to 900 ft. The survey objective was a 10-15 ft thick smear zone, lying 30 - 50 ft bgs, contaminated primarily with gasoline and diesel fuel. We chose a large scale 2D acquisition geometry to evaluate "regional" variations in plume geometry due to the sparse distribution of borehole characterization points. We acquired data at high water table conditions with essentially no floating product. In this case, the electrical properties of the contaminated interval may be similar to DNAPL accumulation in the saturated zone. Data quality at the site is excellent with good penetration to depths of 40 ft - 80 ft. In initial processing we have identified reflections from the top and bottom of an interval consistent with the contaminated zone identified in boreholes. Whether the radar response in this interval is stratigraphy controlled or controlled purely by the fluid distribution remains to be determined but in this preliminary analysis, potential for successful detection of the NAPL zone appears high. The results of ongoing quantitative analysis will solidify our interpretation at this site.

We have completed data acquisition for a controlled DNAPL (tetrachloroethylene) injection and GPR monitoring project at the Dover National Test Site, Dover AFB, DE. Data from this site contain significantly higher noise levels than initially expected, but reflections are evident from within the target interval and potential for successful DNAPL detection is reasonable. Processing of these data are ongoing. In conjunction with planning the controlled injection experiment, we have implemented a methodology for integrating multi-phase flow and GPR modeling. This allows us to investigate temporal changes in GPR response to a dynamic contaminant distribution.

During April, 2002, we collected 27,500 sq. ft. of 3D, multi-offset GPR data in the vicinity of the Z-9 trench in the 200 West area at the Hanford site. Data were collected in two surveys, one conducted with 50 MHz antennas, and the second, higher resolution dataset, acquired with 100 MHz antennas. It is not clear that the target depth of 30 m was reached due to a low signal to noise ratio in the data caused by surface scatter from a nearby soil vapor extraction system. There is some evidence for deep reflections at the site, but potential for DNAPL detection is relatively low. Data quality to a depth of about 10 m is excellent and we are investigating water content variations derived from GPR velocity analysis in the shallow section.

Planned Activities

- July, 2002: Field investigation at the former Wurtsmith AFB, MI.
- July, 2002: Revisit the Chevron refinery for investigation at low water table conditions
- August, 2002: 200 West and 100 Area investigations at the Hanford Site in areas with minimal surface obstructions to minimize surface scatter contamination of the data.

References

Bradford, J.H., Talwani, M., and Loughridge, J., in review, NAPL detection using GPR AVO analysis: Geophysics.

Deeds, J.C., and Bradford, J.H., 2002, Characterization of an aquitard and direct detection of LNAPL at Hill Air Force Base using GPR AVO and migration velocity analyses, GPR 2002: Santa Barbara, CA.