Project Number: 70052
Title: Material Property Estimation for Direct Detection of DNAPL using Integrated Ground-Penetrating Radar Velocity, Imaging and Attribute Analysis
Date: 6-15-2004
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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), at a former refinery site near Cincinnati, Ohio, and at a creosote wood preserving site in Fayetville, NC.

Research Progress and Implications

This section summarizes work after 57 months (3yr project + 24 month extension). We have exceeded all objectives outlined in our original workplan, including an extensive field effort involving over 12 sites located throughout the continental U.S. Additionally we have conducted a number of ancillary experiments at little or no additional cost to the project. We have completed our field data acquisition effort with acquisition of full scale 2D and 3D multi-offset, multi polarization datasets at 10 research sites in 8 field areas. These include:

- DOE Savannah River Site (A-14 Outfall)
- DOE Hanford Site (Z-9 Trench, 618-10 Burial Ground/316-4 Crib, 100N Interception Trench)
- Hill Air Force Base (Operable Unit 1)
- Dover Air Force Base - Dover National Test Site
- Former Wurtsmith Air Force Base (FT-02)
- EPA Cape Fear Wood Preserving Site, Fayetville, NC.
- Former Chevron Refinery, Cincinnati, OH.
- Boise State University, Boise, ID (Laboratory Scale Experiment).

The data are comprised of 37,250 linear ft. of 25-30 fold, multi-offset GPR data which includes 91,800 sq. ft. of 3D acquisition. Additionally, we have completed implementation of a non-linear inversion algorithm for computing the permittivity ratio at a reflecting boundary from GPR AVO data. We are continuing development of GPR specific AVO and attenuation analysis software suitable for application to production scale data volumes. We have developed tools for thin-bed GPR AVO analysis. Training of six undergraduate research assistants and one graduate student have been supported by this project, exceeding the goals outlined in the original proposal. We have successful field demonstration of NAPL detection using GPR velocity and attribute analysis at Hill Air Force Base, Wurtsmith Air Force Base, EPA Cape Fear Site, and in a laboratory scale experiment at Boise State University. Here, we define a successful demonstration as having derived electrical properties from the GPR data that are consistent with the location and concentration of contaminants determined through direct sampling. Further, we have detected significant anomalies associated with known NAPL contaminate zones at the DOE Hanford and Savannah River sites, and the Chevron Refinery near Cincinnati. We are currently completing quantitative analyses of these data.

It should be noted that our original work plan called for acquiring datasets at two National Environmental Technology Test Sites (NETTS) in California (Port Hueneme and McClellan AFB). Feasibility tests during September, 2001, demonstrated that soil conditions at these sites were not suitable for GPR investigation, and we began to search for additional contaminated test sites. This led to the identification of the former Chevron refinery outside Cincinnati, OH (LNAPL), and the Cape Fear Wood Preserving Site (DNAPL) as substitute test sites.

To date, we have presented 7 papers resulting from this project at 6 national meetings. Further, we have 3 papers near completion for submission to peer reviewed journals, and plan submission of an additional 6 peer reviewed papers within the next 6 months. A list of presented papers and planned submissions is included in Appendix A.

Appendix A: List of papers resulting from Project #70052

Oral and Poster presentations

Bradford, J.H., 2003a, GPR offset-dependent reflectivity analysis for characterization of a high-conductivity LNAPL plume, SAGEEP 2003 Symposium on the Application of Geophysics to Environmental and Engineering Problems: San Antonio, TX, Env. Eng. Geophys. Soc., p. 238-252.

—, 2003b, Using GPR to estimate water content at the Hanford Site: Acquisition and Processing Methodologies, 2003 GSA Ann. Mtg., Volume 35: GSA Abstracts with Programs: Seattle, Geol. Soc. Amer.

—, 2004a, 3D Multi-Offset, Multi-Polarization Acquisition and Processing of GPR Data: A Controlled DNAPL Spill Experiment, SAGEEP 2004 Symposium on the Application of Geophysics to Environmental and Engineering Problems: Colorado Springs, CO, Env. Eng. Geophys. Soc., p. 514-527.

—, 2004b, Acquisition and Processing of Multi-Fold GPR Data for Characterization of Shallow Groundwater Systems, Eos Trans. AGU, Volume 85: Jt. Assem. Suppl.: Montreal, Quebec, Canada, p. Abstract NS41A-06.

—, 2004c, Multi-offset acquisition and processing of GPR data, Geological Society of America Abstracts with Programs, Volume 36, p. 76.

Bradford, J.H., and Loughridge, J., 2003, Application of two-pass migration to 3D GPR data, SAGEEP 2003: San Antonio, Env. Eng. Geophys. Soc., p. 598-612.

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 analysis, *in* Koppenjan, S., and Lee, H., eds., GPR 2002, Ninth International Conference on Ground Penetrating Radar, Volume 4758: Proceedings: Santa Barbara, CA, Intl. Soc. for Optl. Eng., p. 323-329.

Papers planned for submission within the next month

Bradford, J.H., Thin bed GPR AVO analysis, theory and field examples, *Geophysics*

Bradford, J.H., Applying reflection tomography to multi-fold GPR data, *Geophysics*

Bradford, J.H., Talwani, M.,and Loughridge, J., GPR AVO response to a 3D sub-wavelength permittivity anomaly, *Geophysics*

Papers planned for submission within the next 6 months

Bradford, J.H., Quantitative analysis of the GPR response to a weathered LNAPL plume at the former Wurtsmith AFB, *Groundwater*

Bradford, J.H., Direct detection of LNAPL contamination at Hill Air Force Base using quantitative GPR analysis, *Environmental and Engineering Geoscience*

Bradford, J.H., Using the GPR attenuation response to detect DNAPL: An example from the EPA Cape Fear Creosote Site, *Geophysics*

Bradford,J.H., Detecting DNAPL using surface and transmission GPR tomography: A laboratory scale experiment, *Geophysics*

Bradford, J.H., Using GPR reflection tomography to measure the water content distribution at contaminated sites within the DOE Hanford complex, *Environmental and Engineering Geoscience*

Loughridge, J. and Bradford, J.H., Using two-pass migration to image 3D GPR data, *Journal of*

Environmental and Engineering Geophysics