Non-Invasive Determination of the Location and Distribution of Free-Phase Dense Nonaqueous Phase Liquids (DNAPL) by Seismic Reflection Techniques

Semi-Annual Technical Progress Report

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by

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Abstract

This semi-annual technical progress report is for Task 4 site evaluation, Task 5 seismic reflection design and acquisition, and Task 6 seismic reflection processing and interpretation on DOE contact number DE-AR26-98FT40369. The project had planned one additional deployment to another site other than Savannah River Site (SRS) or DOE Hanford. During this reporting period the project had an ASME peer review. The findings and recommendation of the review panel, as well as the project team response to comments, are in Appendix A. After the SUBCON midyear review in Albuquerque, NM and the peer review it was decided that two additional deployments would be performed. The first deployment is to test the feasibility of using non-invasive seismic reflection and AVO analysis as monitoring to assist in determining the effectiveness of Dynamic Underground Stripping (DUS) in removal of DNAPL.

Under the rescope of the project, Task 4 would be performed at the Charleston Navy Weapons Station, Charleston, SC and not at the Dynamic Underground Stripping (DUS) project at SRS. The project team had already completed Task 4 at the M-area seepage basin, only a few hundred yards away from the DUS site. Because the geology is the same, Task 4 was not necessary. However, a Vertical Seismic Profile (VSP) was conducted in one well to calibrate the geology to the seismic data. The first deployment to the DUS Site (Tasks 5 and 6) has been completed. Once the steam has been turned off these tasks will be performed again to compare the results to the pre-steam data. The results from the first deployment to the DUS site indicated a seismic amplitude anomaly at the location and depths of the known high concentrations of DNAPL.

The deployment to another site with different geologic conditions was supposed to occur during this reporting period. The first site selected was DOE Paducah, Kentucky. After almost eight months of negotiation, site access was denied requiring the selection of another site. An alternate, site the Department of Defense (DOD) Charleston Navy Weapons Station, Charleston, SC was selected in consultation with National Energy Technology Laboratory (NETL) and DOD Navy Facilities Engineering Command Southern Division (NAVFAC) personnel. Tasks 4, 5, and 6 will be performed at the Charleston Navy Weapons Station. Task 4 will be executed twice. The project team had almost completed Task 4 at Paducah before access was denied.
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1.0 Introduction

This semi-annual technical progress report outlines the status of Task 4 (site evaluation), Task 5 (seismic reflection design and acquisition), and Task 6 (seismic reflection processing and interpretation) under DOE contact DE-AR26-98FT40369. The project had planned one additional deployment to another site other than Savannah River Site (SRS) or DOE Hanford. The project had an ASME peer review. The findings and recommendation of the review panel, as well as the project team response to comments, are in Appendix A. After the SUBCON midyear review in Albuquerque, NM and the positive peer review, it was decided to add two additional deployments.

Under the rescope of the project, Task 4 would be performed at the new site and not at the Dynamic Underground Stripping (DUS) project at SRS (Figure 1). Because the project team had already completed Task 4 at the M-area seepage basin, only a few hundred yards away from the DUS site and has similar geology, it was not necessary. However, a Vertical Seismic Profile (VSP) was conducted in one well to calibrate the geology to the seismic data. Task 5 and Task 6 have been performed once at the DUS site and will be performed at DUS once the steam has been turned off. Tasks 4, 5, and 6 will be performed at the Charleston Navy Weapons Station.

2.0 Executive Summary

This semi-annual technical progress report is for Task 4 (site evaluation), Task 5 (seismic reflection design and acquisition), and Task 6 (seismic reflection processing and interpretation) on DOE contact number DE-AR26-98FT40369. The project had planned one additional deployment to another site other than Savannah River Site (SRS) or DOE Hanford. During this reporting period the project had an ASME peer review. The findings and recommendation of the review panel, as well as the project team response to comments, are in Appendix A. After the SUBCON midyear review in Albuquerque, NM and the peer review it was decided that two additional deployments would be performed. The first deployment is to test the feasibility of using non-invasive seismic reflection and AVO analysis as monitoring to assist in determining the effectiveness of Dynamic Underground Stripping (DUS) in removal of DNAPL. The site selected for this feasibility study is the solvent storage area at M-area Savannah River Site. The second site is to test the concept under a differing set of conditions.

Under the rescope of the project, Task 4 would be performed at the new site and not at the Dynamic Underground Stripping (DUS) project at SRS. The project team had already completed Task 4 at the M-area seepage basin, a only few hundred yards away from the DUS site. Because the geology is the same, Task 4 was not necessary. However, a Vertical Seismic Profile (VSP) was conducted in one well to calibrate the geology to the seismic data. The first deployment to the DUS Site (Tasks 5 and 6) has been completed. Once the steam has been turned off these tasks will be performed again to compare the results to the pre-steam data. The results from the first deployment to the DUS site
indicated a seismic amplitude anomaly at the location and depths of the known high concentrations of DNAPL.

The deployment to another site with different geologic conditions was supposed to occur during this reporting period. The first site selected was DOE Paducah, KY. After almost eight months of negotiation, site access was denied requiring the selection of another site. An alternate site, the DOD Charleston Navy Weapons Station, Charleston, SC was selected in consultation with NETL and DOD NAVFAC personnel. Tasks 4, 5, and 6 will be performed at the Charleston Navy Weapons Station. Task 5 will be executed twice. The project team had almost completed Task 5 at Paducah before access was denied.

3.0 Project Objectives

The research, as initially proposed, was a 14 month proof of concept study to determine the location and distribution of subsurface DNAPL contamination at the 200 West area, DOE Hanford Site by the use of two and three-dimensional high resolution seismic reflection data and borehole geophysical surveys. The major change in the objectives is now the proof of concept is now being applied to the M-area solvent tanks at Savannah River Site and at the Charleston Navy Weapons Station, Charleston, SC. The specific objectives of the research at both sites are:

- Subsurface imaging of geologic sinks where DNAPL can pool.
- Direct detection of DNAPL by use of the seismic reflection amplitude versus offset (AVO) method.
- Testing the feasibility of using high-resolution seismic techniques and AVO analysis as a monitoring tool in evaluating the effectiveness of DUS technique at the M-area solvent tanks.

4.0 Project Accomplishments

The first deployment was to test the feasibility of using AVO analysis to determine the effectiveness of Dynamic Underground Stripping (DUS) at the M-area solvent tanks located at Savannah River Site. The feasibility study involves two deployments: 1) the acquisition, processing, and interpretation of a 2D seismic line for AVO analysis prior to the injection of steam, and 2) after the steam injection ceases, reoccupying the same shot and receiver locations, acquiring, processing and interpreting the data to detect if any change is present from the destruction of DNAPL. The first deployment was successful in imaging AVO anomalies at the depth and location where DNAPL existed (note, the AVO anomalies on seismic line DUS-1 have the same characteristics as the AVO anomalies that were encountered at the M-area seepage basin where this technique was first tested (Waddell et al., 1997). When steam injection is terminated, the project team will deploy back to the DUS site and reoccupy the same receiver and shot locations to reshoot the seismic line. The primary purpose is see if the
AVO anomaly has changed or is absent. This will confirm that the AVO effect was caused by the presence of DNAPL.

Task 5 for the SMU-12 site at the Charleston Navy Weapons Station (CNWS) commenced in late December. Initial review of existing data has been completed at the end of December and three Vertical Seismic Profiles (VSP) are planned in three wells on site. Both P and S-wave VSPs will be collected from each well. Data from the VSP will provide P-wave and S-wave velocities that will be used in the AVO modeling to determine if free phase trichloroethylene (TCE) or tetrachloroethylene (PCE) has an AVO effect on the surface seismic amplitude.

During this reporting period the project had an ASME peer review. The findings and recommendation of the review panel, as well as the project team response to comments, are in Appendix A.

The project team has developed a methodology for evaluating sites to determine if this technology is feasible for locating DNAPL. The approach taken consists of three steps: 1) evaluation of existing geological and geophysical data concerning the amount and distribution of DNAPL, 2) seismic modeling to determine whether or not an AVO anomaly would be expected from DNAPL saturated sediments, and 3) acquisition and processing of a seismic line designed specifically to image the DNAPL.

5.0 Problems Encountered

The second deployment for year 2000 is to another site with differing geologic conditions. The first site selected was DOE Paducah, KY. After almost eight months of negotiation, site access was denied requiring the selection of another site. The alternate site is the DOD Charleston Navy Weapons Station, Charleston, SC. Task 5 (site evaluation) will be performed twice due to the project team’s near completion of Task 5 at Paducah before access was denied.

One potential problem is lack of knowledge of how the increased subsurface temperature will affect the seismic response. To the project team’s knowledge there has been no research on the effects of heating and steam injection on the seismic response in shallow unconsolidated coastal plain sediments.
FIGURE 1. Location map of the 2-D seismic line DUS-1 acquired for AVO analysis. Well labeled “Nasty” has the highest concentration of solvent. Well DUS-010 is the extraction well for recovery of the injected steam and a Vertical Seismic Profile (VSP) was conducted in DUS-010 for velocity control in calibrating the seismic data back to the geology in the well.

6.0 Experimental: Seismic Amplitude Theory and Modeling

6.1 Theory

In the 1960's petroleum companies recognized that in young sediments (Tertiary age) large seismic amplitudes were associated with gas saturated sands. However, it was soon realized that not all large seismic amplitudes represented hydrocarbon saturated sands. The normal incidence (NI) reflectivity (bright spot) techniques involved three different scenarios based upon a water saturated state and a hydrocarbon saturated state.
The three scenarios are:

1) Dim-spot - a large positive amplitude that is reduced to a smaller positive amplitude
2) Phase reversal - a small positive amplitude that changes to small negative amplitude
3) Bright spot - a negative amplitude increasing to a large negative amplitude.

The dim-spot is generally associated with a large acoustic impedance contrast and is a technique for inferring lithology. Bright spot anomalies are generally used for interpreting lithology and estimating sand thickness. Phase reversal reflections are not generally reliable because geologic features (e.g. faults) can cause the reflections to appear to reverse phase. Thus, a reflection phase reversal does not necessarily indicate a change in lithology (Verm and Hilterman, 1995). The bright spot technique was the first direct hydrocarbon indicator.

In 1984, Ostrander published an article entitled "Plane-wave reflection coefficients for gas sands at non-normal angles of incidence." Ostrander observed that the P wave reflection coefficient at the interface between two media varies with the angle of incidence of the impinging energy. Ostrander also investigated the phenomenon of compressional wave reflection amplitude variation with angle of incidence and changes in Poisson’s ratio. Poisson’s ratio is defined as the ratio of transverse strain to longitudinal strain and can be expressed in terms of P wave and S wave velocity (Sheriff, 1991).

\[
\sigma = \frac{1}{2} \left( \frac{V_p}{V_s} \right)^2 - 1
\]

\[
\sigma = \text{Poisson’s ratio}
\]
\[
V_p = \text{compressional wave velocity}
\]
\[
V_s = \text{shear wave velocity}
\]

Much of Ostrander’s work was based upon Koefoed’s 1955 work on determining the reflection coefficients of plane longitudinal waves reflected at a boundary between two elastic media. Koefoed observed that if there were two elastic media with the top medium having a smaller Poisson’s ratio than the underlying medium there would be an increase in the reflection coefficient with increasing angle of incidence. He also observed that if
Poisson’s ratio of the lower medium was lower than the overlying medium, the opposite would occur with a decrease in the reflection coefficient with an increase in the angle of incidence. Another observation showed that the relative change in reflection coefficient increases as the velocity contrast between two media decreases. Koefoed also observed that if Poisson’s ratio for two media was increased, but kept equal, the reflection coefficient at the larger angles of incidence would also increase. Ostrander (1984) observed that changes in Poisson’s ratio caused by the presence of hydrocarbons in the pore space has dramatic effect on the P wave reflection coefficients and that these effects can be related to seismic amplitude anomalies.

In order to understand amplitude versus offset (AVO) analysis, one has to understand offset dependent reflectivity. Offset dependent reflectivity is defined as the variation of the reflection and transmission coefficients with changing of the incident angle (Castagna and Backus, 1993). The offset refers to source to receiver separation. Increasing source to receiver separation results in increasing angle of incidence for raypaths as measured from the normal to a horizontal interface. Coincident source and receiver locations results in what is termed normal incidence, i.e. vertical transmission and reflection from a horizontal interface. The amplitude of the reflected and transmitted waves are described by the reflection and transmission coefficients. The following discussion describes the equations and theory used to determine amplitude for both the reflected and transmitted waves at an acoustic boundary for normal incident energy and non-normal incident energy, i.e. offset dependent reflectivity. Note that this discussion is for a simplistic model of a single interface. The majority of reflections observed on a seismic profile are the superposition of events from multiple layers and has a more complex AVO response.

As implemented in the petroleum industry, AVO analysis involves comparing modeled AVO responses with field data to find a deviation from an expected background response. The expected background response is usually taken to be a water saturated reservoir; hence, the deviation from the expected response is an indication of hydrocarbon presence but does not indicate quantity. DNAPLs have the similar acoustic characteristics as liquid hydrocarbons in that their density is heavier than air or water; therefore, if DNAPL is present in free-phase and in large enough quantities, similar types of analyzes as those performed for the petroleum industry can be applied to directly detect the presence of DNAPL.

An understanding of reflection AVO techniques can be obtained by a review of elastic wave propagation. A P wave incident on a boundary between two linear elastic homogeneous isotropic (LEHI) media generates four types of waves: 1) transmitted P wave, 2) reflected P wave, 3) reflected S wave, and 4) transmitted S wave (Figure 2). The amplitudes of the reflected and transmitted waves at the boundary depend upon the P wave and S wave velocities. The density of the two media and the angles of incidence and refraction, are determined from Snell’s law.
FIGURE 2. Elastic waves generated at a boundary. A P-wave incident at an angle on a boundary between two linear elastic homogenous isotropic (LEHI) materials generates four wave types: reflected P, reflected S, transmitted P, and transmitted S. The angles of reflection and refraction are governed by Snell’s law from optics. The material properties of the media are described by the P-wave velocity, density, and Poisson’s ratio. The S-wave velocity can be found from the P-wave velocity and Poisson’s ratio.

Snell’s law is

\[
\frac{\sin \Theta_1}{V_{p1}} = \frac{\sin \Theta_1}{V_{p1}} = \frac{\sin \Theta_1}{V_{s1}} = \frac{\sin \Theta_2}{V_{s2}} \tag{2}
\]

\(V_{p1}\) = P wave velocity in medium 1,
\(V_{p2}\) = P wave velocity in medium 2,
\(V_{s1}\) = S wave velocity in medium 1,
\(V_{s2}\) = S wave velocity in medium 2,
\(\theta_1\) = incident P wave angle,
\(\theta_2\) = transmitted P wave angle,
\(\theta_1\) = reflected S wave angle,
\(\theta_2\) = transmitted S wave angle, and
\(p\) is the ray parameter.
The reflection coefficient of the P wave as a function of the incident angle, $R_p (\theta_1)$, is defined as the ratio of the amplitude of the reflected P wave to that of the incident P wave (Castagna and Backus, 1993). The P wave transmission coefficient, $T_p (\theta_1)$, is the ratio of the amplitude of the transmitted P wave to that of the incident P wave (Castagna and Backus, 1993). The P wave reflection coefficient, $R_p$, at normal incidence is given by the following equation:

$$R_p = \frac{I_{p2} - I_{p1}}{I_{p2} + I_{p1}} = \frac{1}{2} \Delta I_p \approx \frac{1}{2} \ln \frac{I_{p2}}{I_{p1}}$$

(3)

$I_{p2} = \text{acoustic impedance of medium 2} = \rho_2 V_{p2}$

$\rho_2 = \text{density of medium 2}$

$I_{p1} = \text{acoustic impedance of medium 1} = \rho_1 V_{p1}$

$\rho_1 = \text{density of medium 1}$

$I_{pa} = \text{average acoustic impedance across the interface} = \frac{(I_{p2} + I_{p1})}{2}$, and

$\Delta I_p = I_{p2} - I_{p1}$.

The P-wave transmission coefficient at normal incidence $T_p$ is given by:

$$T_p = 1 - R_p$$

(4)

The variation of the reflection and transmission coefficients with incident angle and source to receiver offset is referred to as offset dependent reflectivity (Castagna and Backus, 1993). The values of the reflection and transmission coefficients for non-normal angles of incidence are given by the Zoeppritz (1919) equations. Zoeppritz equations (Graul, 1996) are given below:

$$\begin{bmatrix}
\sin \Theta_t & \cos \Theta_t & -\sin \Theta_t & \cos \Theta_t \\
-\cos \Theta_t & \sin \Theta_t & -\cos \Theta_t & -\sin \Theta_t \\
\sin 2 \Theta_t & \frac{V_j}{W_j} \cos 2 \Theta_t & \rho_j W_j V_j \sin 2 \Theta_t & -\frac{\rho_j W_j}{\rho_j V_j} \cos 2 \Theta_t  \\
\cos 2 \Theta_t & -\frac{W_j}{V_j} \sin 2 \Theta_t & -\frac{\rho_j W_j}{\rho_j V_j} \cos 2 \Theta_t & \frac{\rho_j W_j}{\rho_j V_j} \sin 2 \Theta_t
\end{bmatrix}
\begin{bmatrix}
A_{1p} \\
A_{2p} \\
A_{3p} \\
A_{4p}
\end{bmatrix}
= 
\begin{bmatrix}
-\sin \Theta_t \\
-\cos \Theta_t \\
\sin 2 \Theta_t \\
-\cos 2 \Theta_t
\end{bmatrix}
(5)

NI and PR are defined as
\[ NI = \frac{(\alpha_2 \rho_2) - (\alpha_1 \rho_1)}{(\alpha_2 \rho_2) + (\alpha_1 \rho_1)} = \frac{(z_2 - z_1)}{(z_2 + z_1)} \]  \hspace{1cm} (6)

\[ PR = \frac{\Delta \sigma}{(1 - \sigma_{avg})^2} \]  \hspace{1cm} (7)

\( z \) is the acoustic impedance:

(Verm and Hilterman, 1995). Reflection AVO can be thought of as a combination of normal incidence reflectivity and a far offset reflectivity, or “Poisson reflectivity,” that arises primarily as a result of changes in the Poisson’s ratio between media.

To implement AVO analysis, the NI and PR coefficients are extracted from a common depth point (CDP) gather. Initially the CDP gather is transformed from a function of offset to incident angle. This transformation requires knowledge of the root mean square (RMS) velocity, which is ideally obtained from borehole sonic logs. In the absence of sonic logs a rough estimate of the RMS velocity can be obtained from the normal moveout (NMO) stacking velocities. Next, the NI and PR coefficients are found by fitting either Equation (6) or (7) to the amplitudes.

6.2 Modeling

The most important aspect to this study is the AVO modeling, to determine whether or not an AVO anomaly would be expected from DNAPL saturated sediments. If a AVO anomaly occurs when natural pore fluid (water) is replaced with DNAPL which was used to design the field acquisition parameters for seismic profile DUS-1. The type of model was generated using the Zoeppritz equations. The model is a sand wedge saturated with either water or TCE overlying either a clay layer or a water saturated sand overlying a TCE saturated sand (Table 1).

Using the parameters in Table 1, the results of the modeling suggested that there would be an AVO effect caused by the presence of DNAPL (Figure 3). Furthermore, these results indicated that changes in the reflection coefficient would begin to occur at approximately 35° angle of incidence. Using this information the seismic lines were designed such that half the receivers would be under this incident angle and half would be over.
TABLE 1 Parameters used to generate AVO models.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>$V_p$</th>
<th>$V_s$</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft/s</td>
<td>ft/s</td>
<td>g/cc</td>
</tr>
<tr>
<td>Wedge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Sand</td>
<td>5800</td>
<td>1450</td>
<td>1.9</td>
</tr>
<tr>
<td>TCE Sand</td>
<td>4968</td>
<td>1634</td>
<td>2.07</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>5600</td>
<td>1300</td>
<td>1.85</td>
</tr>
<tr>
<td>Water Sand</td>
<td>5600</td>
<td>1460</td>
<td>1.89</td>
</tr>
</tbody>
</table>

FIGURE 3. Graph of reflection coefficient versus angle of incidence using the Zoeppritz equations for water saturated sand overlying the “green clay”, TCE saturated sand overlying the “green clay”, and water saturated sand overlying TCE saturated sand. At the sand/clay interface the reflection coefficient is slightly negative and becomes more negative with increasing angle of incidence. At large angles of incidence (greater than $50^\circ$) this effect is pronounced. TCE saturated sand overlying the “green clay”, the amplitude is slightly negative, but at $30^\circ$ the reflection coefficient goes from slightly negative to positive and increases with angle of incidence. If water saturated sand is overlying TCE saturated sand, the reflection coefficient at $0^\circ$ angle of incidence is near 0, or is slightly negative, and at $40^\circ$ becomes increasingly negative.

7.0 Results and Discussion: Dynamic Underground Stripping (DUS) Savannah River Site

The Savannah River Site (SRS) is located in South Carolina on the South Carolina-Georgia border. During the Cold War, SRS was a major production facility of nuclear materials for defense purposes. Since the late 1980’s an emphasis on environmental restoration has led to the development of programs and strategies to
remediate DNAPL spill at the site. One area of SRS targeted for remediation is the M-area solvent storage tanks.

The M-area solvent storage tanks were where chlorinated solvents were unloaded from railroad tank cars and trucks and stored prior to being used in the degreasing operations. The chlorinated solvents, including free-phase constituents, have been detected in the groundwater near the solvent tanks since 1981. The majority of the DNAPL found in the subsurface is composed of TCE, PCE, and Trichloroethane (TCA) (Looney, 1992). Environmental remediation strategies have included groundwater pump and treat, soil vapor extraction, in situ air stripping, in situ biomediation, in situ hydrous pyrolysis/oxidation and dynamic underground stripping (DUS).

The near-surface geology at the M-area solvent storage tanks is comprised of Eocene age Upper Coastal Plain sedimentary units. On the surface is the “Upland unit” which consists of cobbles and coarse sand ranging in thickness from zero to fifty feet. Underlying the “Upland unit” are the Tobacco Road and Dry Branch formations that are composed of fine to medium grain sand, clayey sand, and discontinuous layers of clay. The amount of clay in the formations decreases with depth. Directly below the Dry Branch Formation is the Warley Hill Formation that ranges in thickness from 0 to 10 feet and occurs at a depth of approximately 165 feet below the surface in the M-area solvent tank area. This clay, when present, is considered the confining unit which separates the overlying surficial aquifer from the semi- to confined aquifer below. The DNAPL in the M-area pools on top of the “green clay”.

7.1 Seismic Reflection Profiles

7.1.1 Seismic Data Acquisition

The project consisted of recoding one seismic profile, line DUS-1, across the area where high concentrations of solvent have been reported and where a free-phase component is suspected (Figure 1).

All of the data were collected with a 24 bit Geometrics Strataview seismograph recording 120 channels. The M-area is a notorious low signal-to-noise seismic data area. Test lines were shot prior to the acquisition of the M-series lines at the M-seepage basin using mini-vibrator, downhole Seisgun™, and EWG-1 weight drop sources. None of these sources were able to combine the requirements of adequate signal penetration, high frequency content, and minimal source generated noise. Lastly, a 10 lb. sledgehammer was tested. The sledgehammer was found to be a repeatable high frequency source that generated a relatively small surface wave. Therefore at the DUS site we employed the sledgehammer as the seismic source.

The acquisition parameters for seismic line DUS-1 appear in Table 2. The parameters such as group spacing, near offset, and far offset, were based on the modeling results. The target interval was the “green clay” aquitard at approximately 155 feet below land surface. The recording offsets were chosen in such a way as to have at least 15 to 20 geophone groups under 30° angle of incidence to maximize the AVO effect described above and also image the very shallow sediments. The data were acquired using a
asymmetrical split spread. With this spread design the data had far offsets of 40 ft and 200 ft.

TABLE 2 Acquisition parameters for seismic line DUS-1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels</td>
<td>120</td>
</tr>
<tr>
<td>Group interval</td>
<td>2 ft.</td>
</tr>
<tr>
<td>Shot interval</td>
<td>2 ft.</td>
</tr>
<tr>
<td>Near offset</td>
<td>1 ft.</td>
</tr>
<tr>
<td>Far offset</td>
<td>40 ft 200 ft.</td>
</tr>
<tr>
<td>Nominal CDP fold</td>
<td>60</td>
</tr>
<tr>
<td>Geophone frequency</td>
<td>40 Hz</td>
</tr>
<tr>
<td>Energy source</td>
<td>Hammer /8 hits</td>
</tr>
<tr>
<td>Sample rate</td>
<td>0.25 ms</td>
</tr>
<tr>
<td>Record length</td>
<td>500 ms</td>
</tr>
</tbody>
</table>

7.1.2 Seismic Data Processing

The seismic data were processed with standard CDP data processing sequence (Yilmaz, 1987) that included frequency-wave number filtering (F-K or pie slice filtering) to eliminate linear noise trains, spiking deconvolution, and iterative velocity analysis and residual statics application. For display, the data were filtered to a 90-275 Hz bandpass and five point running mean was applied to enhance the lateral continuity of reflections.

8.0 Direct Detection of DNAPL

At the M-area solvent tanks two primary types of DNAPL are present below the water table, TCE and PCE. The latter being the predominate type of solvent.

In this project one method, ranged limited stacking, was used to investigate any AVO effects caused by the presence of DNAPL. As previously mentioned, the recording geometry was such that 15 to 20 geophone groups were under 30° angle of incidence. If the models were correct, there would not be any significant change in amplitude under 30°. In this method, data were gathered and stacked using subsets of the range of offsets to produce a near offset section (Figure 4 top) and far offset section (Figure 4 lower). AVO anomalies produced by the presence of DNAPL should manifest as high amplitudes present on the far offset section, but not on the near offset section.

Profile M-1 Offset Range Limited Stack

In Figure 4 the upper profile is a near offset stack and the lower profile is a far offset stack. If there are any AVO anomalies, they should be present on the far offset stack and absent on the near offset stack. At shot point (SP) 210 at about 120 ms is an anomaly at the location where the highest concentration of TCE was found. On the near offset stack the anomaly is absent. The anomaly appears to extend from shot point 200 at
about 120 ms to shot point 248. This anomaly is adjacent to the well labeled Nasty which had the highest measured concentration of solvent.

![Offset range limited stacks for profile DUS-1. Near offset section (top), and far offset (bottom), the bottom section was generated by stacking offsets greater than 58 feet. High amplitudes that occur only at far offsets should denote presence of DNAPL. Every second trace is plotted. CDP spacing is one foot. The amplitude envelope (magnitude of Hilbert transform) is displayed.](image)

**FIGURE 4.** Offset range limited stacks for profile DUS-1. Near offset section (top), and far offset (bottom), the bottom section was generated by stacking offsets greater than 58 feet. High amplitudes that occur only at far offsets should denote presence of DNAPL. Every second trace is plotted. CDP spacing is one foot. The amplitude envelope (magnitude of Hilbert transform) is displayed.

### 9.0 Conclusion

At the M-area solvent tank facility, DUS site at Savannah River Site it appears that DNAPLs have been imaged in the subsurface using high-resolution seismic data. A second deployment to DUS will determine if changes in seismic amplitude are due to DNAPL removal. However, very little data on the effects of shallow steam injection on the soil properties are available.

If the modeling suggests that there is a change in seismic amplitude due to the presence of DNAPL at the Charleston Navy Weapons Station then the project team will proceed with Tasks 5 and 6.
Caution must be exercised in applying this technique to other areas. Before any seismic data are acquired some basic modeling has to be done. The modeling will determine what is the minimum amount of DNAPL that can be imaged given the geologic conditions for a particular site and provide the necessary data for designing seismic acquisition parameters.

10.0 References


Appendix A

In May of 2000 the ASME peer review panel reviewed this project. Listed are their recommendations and comments.

A. The Project Team demonstrated that the project is addressing identifiable needs of DOE’s EM program. DNAPLs are documented problems at many DOE sites and the characterization of DNAPL-residence areas is a prerequisite for the selection and design of effective remediation technologies.

B. The Project Team adequately reviewed the pertinent AVO technical literature but failed to provide a pertinent shallow reflection literature review.

C. It is difficult to evaluate the conclusions cited in the topical report because of the limited amount of available information. The unavailability of the results of the intermediate processing steps makes it problematic to assess the validity of these conclusions. In addition, as correctly pointed out by the Project Team, the Gassmann equations used in the prediction model were not designed for the unconsolidated materials encountered on the DOE sites. Moreover, no theoretical or laboratory work has been performed to develop alternative equations for unconsolidated materials. The Interim Report (1) clearly states that AVO can be used to detect relatively high concentrations of CCl₄. The RP finds that the report (1) presents a less convincing case than the Technical Report (2) that AVO can be used to detect DNAPLs. The Technical Report (2) clearly involved AVO analysis and showed seismic anomalies that corresponded to high concentrations of DNAPL found in wells. The Interim Report (1) does not present data showing explicit use of AVO analysis. The report (1) does not show plots of far offsets versus near offsets. Instead, the conclusions are based on a questionable qualitative assessment of amplitude. The Interim Report (1) indicates that where there is high concentration of CCl₄ the seismic amplitudes decrease, i.e., a dim-out occurs. This dim-out could also be caused by changing lithologic conditions or even by near-surface conditions unrelated to the reflective interface. The RP does not believe that the project conclusions are supported by the data collected at Hanford. To support these conclusions, additional confirmation drilling, borehole logging, and chemical sampling are required at Hanford. Figure 9 of the Technical Report (2) shows a significant anomaly between Common Depth Points (CDPs) 590 and 610. Figure 10 of the report (2) shows an anomaly between CDPs 630 and 670. Both these anomalies should be tested by drilling and sampling.

D. The use of Seismic Reflection for this application may be viewed as a logical extension of existing technologies for lithology and fluid-saturation assessment, but convincing evidence is not available that DNAPLs can be reliably detected.

E. If we assume that DNAPLs can be detected with seismic reflection, then the practical limits of detection in terms of minimum depth and plume size can be determined through the well-known half-wavelength criterion. The maximum depth is determined by the penetration depth of the seismic signal. However, the determination of the chemical composition of DNAPLs is unlikely to be feasible with this method.

F. The technical uncertainties associated with the development and application of this technology have been partially identified but insufficiently addressed. For example,
the Project Team did not fully consider possible sources of amplitude variation observed at Hanford other than changes in CCl4 concentrations. Due to budgetary constraints, the Project Team was unable to address some of the uncertainties that might have been evaluated through additional drilling.

G. If it works, this technology may be superior to commercially available DNAPL detection options. However, it is likely that DNAPL characterization will require the integration of multiple techniques.

H. This technology has the potential to adequately determine the spatial extent of free-phase DNAPLs in the subsurface. However, at many DOE sites, DNAPL characterization requires both free-phase and residual DNAPL detection, and it is unlikely that this technique could detect residual DNAPLs.

I. This technology is not ready for site deployment because there are too many unanswered questions. For example, the technology has not been evaluated under sufficiently diverse hydrogeological and contaminant conditions.

J. This technology does not appear to be patentable because it was presented by the Project Team at an American Association of Petroleum Geologists convention and published as an abstract more than two years ago.

K. The Project Team did not present a clear path towards the commercialization of this technology. However, all of the hardware, software, and scientific literature necessary for commercialization are readily available in the public domain.

L. The successful implementation of this technology would have a clear benefit in terms of environmental safety and health risk reduction for workers and the environment. The technique minimizes worker exposure and waste generation during DNAPL characterization.

M. Based on the fact that the seismic exploration technology is applied worldwide, it appears that sufficient data have been collected to respond to regulatory, stakeholder, and risk evaluations.

N. The Project Team has not published peer-reviewed articles resulting from this project, but it has submitted two manuscripts that are being reviewed by peer-reviewed journals.

O. Based on the overall assessment, this project should be continued.

In addition, the RP has the following findings:

P. The Project Team has inferred the detection by seismic methods of DNAPLs in concentrations of the order of tens to hundreds of parts per million. There is no solid independent scientific evidence that this may be possible. Three possible explanations exist for the Project Team’s observations:

P.1. The results confirmed by drilling may be a fortuitous coincidence.

P.2. The Project Team’s results may represent a case of detecting much higher levels of DNAPL than estimated by chemical methods (i.e., the chemical sampling may not have accurately represented the DNAPL content of the volume surveyed by the seismic reflection technique). The volume and geometry of the subsurface material interrogated using seismic reflection and chemical (groundwater or core) sampling may be quite
different. The seismic reflection method averages concentrations over volumes proportional to the seismic wavelengths (i.e., meters to tens of meters) whereas the chemical methods average over extracted volumes.

P.3. Low concentrations of DNAPL may chemically or physically alter the seismic properties of selected geologic materials (e.g., clays) in a manner not yet understood.

Q. Some of the contour maps from the Interim Report (1) show features that are not supported by the data. These features may be artifacts from the contouring algorithm, but the report (1) does not mention this possibility.

RECOMMENDATIONS

Based on a careful assessment of the information presented to the RP and the findings developed in response to the review criteria, the RP provides the following recommendations:

Additional confirmation drilling, testing, and chemical sampling should be done to further evaluate the seismic work already done at Savannah River and Hanford Sites. If the technology continues to show promise after Recommendation 1 has been implemented, then it should be further evaluated at DNAPL sites representing different hydrogeologic and contaminant conditions. In order to check the validity of the Gassmann equations for unconsolidated materials, controlled experiments should be conducted in a large (meters) containment vessel to examine the seismic response to the introduction of DNAPL into water-saturated sand overlying clay. Alternatively, field evaluations could be conducted using controlled DNAPL releases into well-characterized formations. The resulting DNAPL-contaminated volume should have minimum dimensions of several seismic wavelengths and be monitored with seismic reflection and other DNAPL characterization techniques. The Project Team should provide as much information as possible to the scientific community. The Project Team should publish scientific papers in peer-reviewed journals and post intermediate processing results on a web site in an easily-accessible format (e.g., PDF).

This project should be peer reviewed once the above-listed recommendations have been implemented.

Response to the Peer Review Recommendations

The project team believes that at Savannah River Site there is adequate well data to evaluate the AVO analysis. Two wells were drilled on AVO anomalies. The concentrations found in the wells were in the parts per million. There are also wells located on the three initial seismic lines M-1, M-2, and M-3 where there were no AVO anomalies observed that had solvent concentrations indicative of dissolved phase only, which support the regions of non-detect. We were not specific in identifying these non-detect wells during the peer review. Due to the extreme cost of drilling and installing a well (≈ $200,000 plus) at Hanford, the project team feels that it is not feasible to drill. However two possible solutions to verifying the results of the AVO analysis of CCl₄
plume at the 200 west area are possible. First, acquire shear-wave seismic data along seismic lines Z-9-1 and Z-9-2. Shear waves are not affected by changes in fluid content within the pore space since liquids (air, water, and CCl₄) do not have shear strength. Any variation in amplitude along the Plio-Pleistocene contact or along the Plio-Pleistocene caliche contact would be attributed to a change in lithology along the contact. If amplitude changes observed on the shear wave data would be compared with the anomalies associated with CCl₄ the P-wave data. If the shear wave data amplitudes remain unchanged at the location of an AVO anomaly, a very good argument exists that the amplitude is caused by a change in the pore fluid. The second technique requires the use of the CPT truck in an attempt to direct push in areas where the AVO anomalies are located and sample the intervals. Also, the areas where the seismic data indicates no free phase CCl₄ would also be tested.

We are presently deploying to the Charleston Navy Weapons station to test the technique where the geohydrologic and contaminate conditions are different from either Savannah River Site or Hanford. As explained above we have conducted AVO modeling studies in some areas in Nebraska where this technique appears not to work. We have discussed conducting some control tank test and have attempting to contact people where this experiment could be conducted, but have not gotten a response. A proposal is in preparation for submittal to the Basic Sciences Program to address some of the fundamental properties of the technique. The project team currently has one peer review paper on the Hanford project accepted in GROUNDWATER. The team has another paper in review in GEOPHYSICAL PROSPECTING. We will soon have the Hanford Report out on our web site.