TechData Sheet

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Environmental Security Technology Certification Program

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Three-Dimensional Site Characterization Technologies for DNAPL Contaminated Sites

Part 1. High-Resolution Seismic Reflection Imaging Surveys

Introduction

Geophysical exploration is a form of subsurface characterization in which physical measurements made at the ground surface provide information on specific features and conditions present in the subsurface. Seismic imaging involves transmitting acoustic impulses (i.e., sound or pressure waves) at a site from ground surface downward into the subsurface, causing the impulses to reflect off of interfaces between physical layers within the subsurface and ultimately return to ground surface. The arrival times and intensities of the reflections first are recorded by an array of sensors (i.e., geophones) that are placed carefully across the area of interest, and then are processed by sophisticated computer programs that ultimately generate a series of images of subsurface conditions. Finally, a qualified geophysicist interprets these images in an effort to construct a conceptual model of the subsurface, a modeling process which frequently draws on other data available for the site (e.g., knowledge of regional and site geology, borehole logs, site history, and contaminant data). The conceptual model is a qualitative understanding of subsurface conditions used to best explain key issues such as the exact location of contaminant sources and the nature and extent of contamination at the site.

Benefits/Advantages

In the petroleum industry, three-dimensional (3-D) seismic imaging is a proven technology to explore for and detect natural gas reservoirs. It is also very useful in identifying geologic settings where petroleum may be present. In environmental site characterization, seismic imaging technology generally has been effective at detecting, delineating, and imaging major geologic features such as depth to bedrock; the orientation and thickness of geologic or hydrogeologic layers or "units;" and structural features, such as the presence, orientation, and extent of joints or faults.

Seismic imaging technology is typically far less invasive than many other more conventional methods of subsurface site characterization (e.g., drilling and sampling). Therefore, 3-D seismic technology presents less risk of generating investigation-derived wastes or spreading contaminants, the latter being a frequent serious concern when characterizing dense non-aquous phase liquid (DNAPL) source areas.

Also, seismic imaging technology can be used to create a fully 3-D image that may depict subsurface features and conditions. Besides other geophysical methods, no other widely available characterization technology or method can produce a 3-D image of this nature. For example, drilling and sampling or direct push methods only produce "point" data. Conceptual models built only on point data require interpolation between data points. Such interpolation may result in the omission of important site features that point data may fail to detect.

Limitations

No geophysical methods, including seismic imaging, are stand-alone technologies. Rather, to be most effective, seismic surveys need to be designed carefully and need to include the use of pre-existing regional and site-specific geologic, hydrogeologic, and contaminant information as well as knowledge of the history of site use and contaminant release. Seismic imaging (and interpretation) also almost always requires confirmatory drilling and sampling. During a seismic survey, on-site boreholes or wells must be entered to collect vertical seismic profiles (VSP), which are measurements of the velocity at which soil and rock intervals beneath the sites are transmitting acoustic energy. Also, seismic images are not unique solutions; rather, seismic images contribute value to a more integrated conceptual site model, provided that confirmatory drilling and sampling "prove" the seismic interpretations.

Seismic imaging technology was developed by the petroleum industry, where it often is used to explore for subsurface gas reserves. Although this technology is very effective at locating larger-sized gas and, indirectly, petroleum deposits at great depths, the technology has not proven to be effective at detecting the presence of much smaller and shallower free-phase DNAPL sources.

Considerations Prior to Implementation

Useful implementation of 3-D seismic imaging depends on a variety of factors. Remedial Project Managers (RPM) need to answer the following questions:

- What is the site's history and how did contamination occur at the site?
- How much subsurface investigation has already been conducted at the site?
- What is the regional and local geologic setting of the site?
- How complex is the site's geology?
- Is the site's geology predominantly bedrock or soil?

Survey demonstrations generally indicated that 3-D seismic imaging might yield better results at bedrock sites. It is important that the site or area of interest be accessible to conduct a surface survey. It is not necessary that the area be completely free of obstacles, such as buildings and roads, but the clearer the area is, the faster the survey can be conducted.

Field Demonstrations

Under the sponsorship of the Department of Defense (DOD) Environmental Security Technology Certification Program (ESTCP), this 3-D seismic technology was demonstrated by contractors for the Naval Facilities Engineering Service Center (NFESC) at four DOD sites: ***Letterkenny Army Depot***, former ***NAS Alameda***, ***Tinker AFB***, and ***Allegany Ballistics Laboratory***. During these demonstrations, 3-D seismic imaging generally provided useful information relating to subsurface geology and hydrostratigraphy. At one site, 3-D seismic imaging technology led to the discovery of free phase DNAPL. However, the overall results of these demonstrations indicated that the technology cannot reliably and consistently detect free-phase DNAPL contaminant sources or dissolved plumes.

Planning/Preparation/Implementation/Results

High-resolution 3-D surveys consisted of the following six steps:

(1) Perform site research and generate a geologic model. Before conducting a 3-D seismic survey, it is necessary to research the site and generate a geologic model for the site. Site research consists of reviewing pertinent background information on the site (its history, regional geology and techtonics, hydrology and hydrogeology, and contaminant distribution). Reviewing regional topographic data and geophysical data (e.g., aeromagnetics, and seismicity), airphoto and satellite data can also be useful. Aerial photography and satellite imagery are used to construct fracture trace analyses. Fracture trace analyses are used to evaluate the role that fractures within bedrock and overburden might have on the migration of contaminants. All of this information and these diverse data sets can contribute to the site conceptual model.

(2) Survey the site's VSPs and develop a velocity model for the site's subsurface stratigraphy. A VSP is a geophysical field test that measures one-way seismic velocity values for exact depth intervals beneath a site. Seismic velocity varies in soil and rock because soil and rock units are inherently anisotropic and heterogeneous due to variations in such physical characteristics as mineral content, bulk density, degree and type of cementation, and pore fluid content. VSP provide the means to calibrate or "tie" the 3-D subsurface seismic data to correct physical depths. VSP data must be collected either in pre-existing monitoring wells or in borings that are drilled as part of the seismic survey. Figure 1 is a schematic illustrating the collection of a VSP.

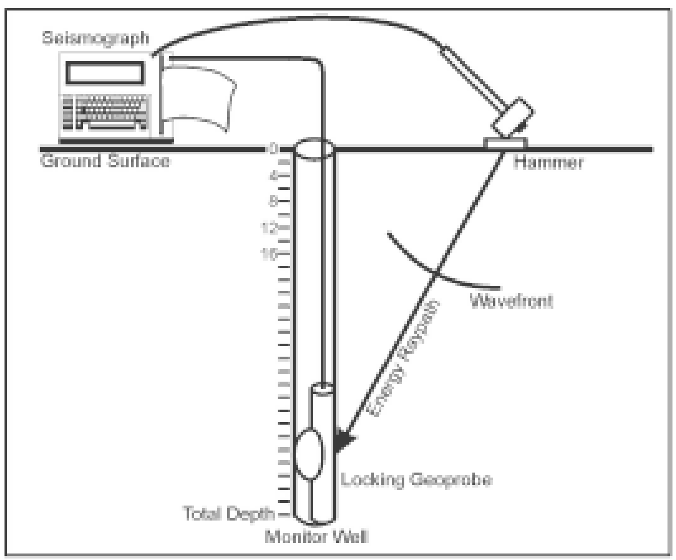

Figure 1. Vertical seismic profile schematic.

(3) Conduct a land survey to position the seismic survey grid. A land survey is performed prior to each 3-D seismic survey to accurately and precisely locate important site features and to enable proper positioning of the pre-designed seismic survey grid relative to key surface and subsurface features and anticipated target locations. Figure 2 illustrates the layout of a 3-D seismic survey.

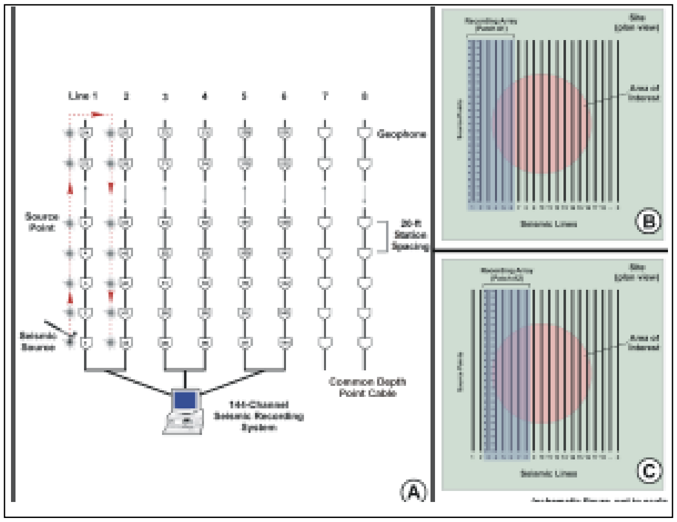

Figure 2. 3-D data acquisition schematic.

(4) Perform the 3-D seismic reflection survey and collect time versus reflection data. The size and geometry of the 3-D survey is determined partially by technical factors such as the required depth of investigation, the shallowest zone of interest below ground surface, and the required resolution of the seismic imagery to be generated from the data. Data are acquired during a 3-D survey by moving the sonic source and the geophones systematically across the area of interest.

(5) Process and interpret the 3-D seismic data, in part by performing attribute analyses to delineate anomalies that may represent fractures and/or may possibly represent the presence of free-phase immiscible contaminants (i.e., NAPLs). Once the data are collected, they are sent to a qualified data processing organization that performs a variety of sortings, corrections, analyses and compensations. After processing, the data are visualized using other computer software. The data sets then are visually evaluated and compared to the conceptual geologic model. Corrections are made to the model as indicated by the seismic results. Attribute analyses, another type of numerical processing, also can be run on the data. Attribute analyses are used to identify unique locations in the 3-D seismic record that may potentially imply the presence of free-phase contamination. Figure 3 presents a depiction of the elements contained in the processed results of a 3-D survey.

(6) Prioritize anomaly-based targets and drill and sample these targets to confirm or refute presence of fractures, confining units, or free-phase contamination. Once the seismic data has been collected, processed, visualized, and interpreted, the results can be used to make corrections or improvements to the pre-existing conceptual geologic model of the site. Under ideal circumstances, the results reveal information about subsurface conditions and features that were unknown or not well-delineated with prior characterization data. Additional drilling may be needed to prove seismic interpretations and predictions. Figure 4 is a profile of an attribute-processed seismic profile at the former NAS Alameda demonstration site. This figure highlights anomalous zones or "hot spots" in the seismic record.

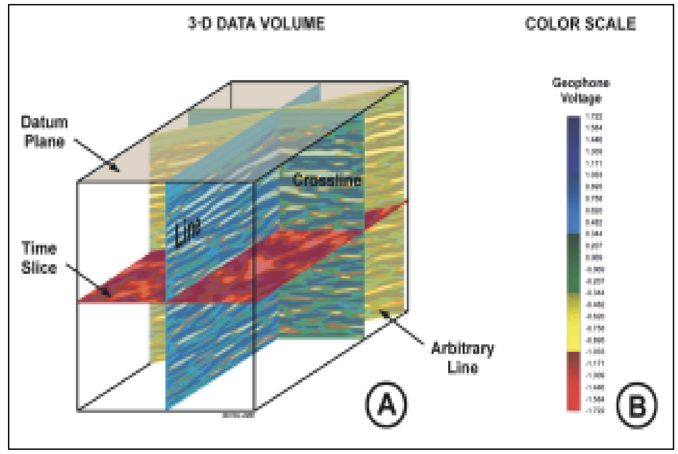

Figure 3. 3-D data volume schematic and seismic plot.

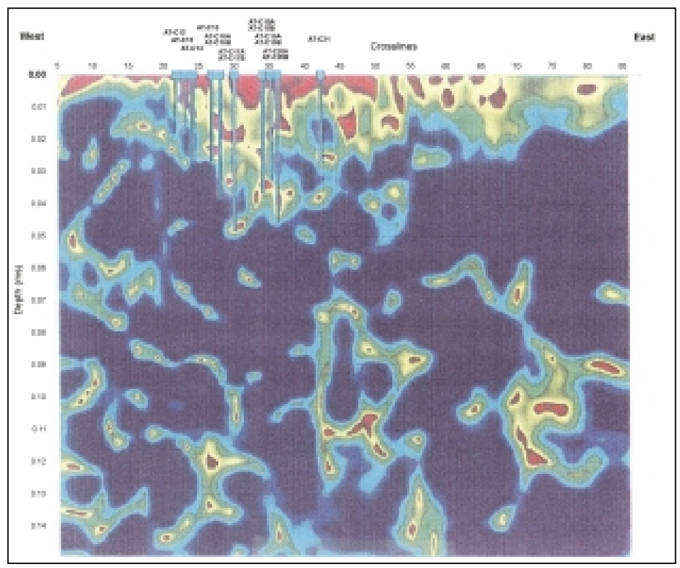

Figure 4. Envelope attribute of validation targets at NAS Alameda.

Validation probings are also shown on the profile. Despite the results from the attribute analysis, no DNAPLs were found in these borings. Table 1 shows the chemical results from validation drilling at three ESTCP demonstration sites. These results indicate that DNAPL was detected at only one of 27 locations where seismic surveying predicted that DNAPL was present.

The lack of consistent DNAPL detection during the ESTCP demonstrations implies that seismic imaging may not be effective at directly finding DNAPL at typical contaminated sites. However, every site is different, and the process may be more effective at highly-contaminated sites with known DNAPL sources. Furthermore, seismic imaging can be very effective at helping to "narrow down" the choices of drilling locations to perform, site characterization, and/or remedial action.

Table 1. Summary of Chemical Results from the 27 Targets Tested During 3-D Seismic Demonstration

Target Borehore ID	Minimum CVOC Concentration Detected at Target Depth (ppb)	Target Confidence[(a)]	Target Reached	Presence of DNAPL in Target Validated
Letterkenny Army Depot				
LB-1	4,270	Medium	No (several hundred feet high)[(b)]	NA
LB-2	735	Medium	Yes	No
LB-5	389	Medium	Yes	No
LB-6	2,933,000	Medium	Yes	Yes
LB-7	49,900	Medium	No (very hard to test due to great depth)	NA
***NAS Alameda**[(c)]*				
AB-1	ND	Medium	No (ll feet high)[(b)]	No
AB-2	ND	High	No (4 feet high)[(b)]	Strong no
AB-3	ND	Medium	Yes	No
AB-4	29,942	Medium	Yes	No
AB-5	320	Low	Yes	No
AB-6A	12	High	Yes	Strong no
AB-6B	ND	High	No (10 feet high)[(b)]	No
AB-7	ND	High	No (13 feet high)[(b)]	No
AB-8	300	High	No (2 feet high)[(b)]	Strong no
AB-9	ND	High	No (1 foot high)[(b)]	Strong no
AB-10	ND	Medium	Yes	No
AB-11	2,755	High	No (9 feet high)[(b)]	No
AB-12A	1,147	Medium	Yes	No
AB-12B	ND	Medium	Yes	No
AB-13	14	Medium	No (6 feet high)[(b)]	No
AB-14	29,485	Medium	Yes	No
AB-15	12,111	High	Yes	No
AB-16	27	High	Yes	Strong no
AB-17	ND	Medium	Yes	No
AB-18	ND	High	Yes	Strong no
Tinker AFB				
TB-1	230	Medium	Yes	No
TB-4	1,620	Medium	Yes	No
TB-6	56	Medium	Yes	No

(a) Interpreted/predicted likelihood that target contained DNAPL.
(b) Difference in feet between predicted target depth and depth above target to which a CPT or Geoprobe screen was set to collect groundwater samples.
(c) At NAS Alameda it was not possible to run VSP because the diameters or CPT and Geoprobe holes are very narrow; therefore, it was not possible to confirm target depths or if targets actually were reached.
ND = Not detected.

Cost-Effectiveness

The cost-effectiveness of a 3-D seismic survey can vary depending on results that are generated. Based on ESTCP-funded demonstrations at four DOD sites, the average cost of a 3-D seismic survey is estimated to be about $125,000. If the results of the survey reveal new site features that make significant changes to the conceptual model and lead to the discovery of more efficient ways of delineating and removing site contamination, then survey costs are an excellent investment. However, survey results may reveal little new information about the site that is useful in implementing site remediation. In those cases, the cost of a survey ends up being a poor investment. Table 2 presents average costs for four seismic surveys performed during the demonstration.

Table 2. Average Cost Performance Chart[(a)]

Cost Element	Cost ($)
Site research/plan	14,804
Seismic survey and VSP	56,591
Data processing/interpretation	19,478
Attribute analysis	15,941
Plans and reports	19,983
Total average costs	$126,797

[(a)]Excludes costs incurred at Allegany Ballistics Laboratory.

Part 2. Electromagnetic Resistivity Surveys

Introduction

Geophysical exploration is a form of subsurface characterization in which physical measurements made both in boreholes and at the ground surface provide information on specific features and conditions in the subsurface. Demonstrations have been performed to show that electromagnetic (EM) surveys are capable of detecting the presence of subsurface DNAPL contamination. An EM survey is a surface-to-borehole geophysical process that generates a 3-D image of subsurface features based on their high resistive properties. Theoretically, because DNAPL is more electrically resistive than groundwater, a resistivity survey may be able to detect the presence of DNAPL. The survey is used to generate a set of images representing the 3-D distribution of bulk resistivity values across the site.

A qualified geophysicist interprets these images to construct a more advanced conceptual model of the subsurface that identifies areas or zones of DNAPL contamination. Frequently, construction of this model draws on other data available for the site (e.g., knowledge of regional and site geology, borehole logs, site history, and contaminant data). The conceptual model is a qualitative understanding of subsurface conditions used to best explain key issues such as the location of contaminant sources and the nature and extent of contamination. This knowledge of subsurface conditions may significantly assist efforts to perform contaminant source zone remediation.

Benefits/Advantages

Ideally, an EM survey provides detailed 3-D characterization information related to subsurface hydrocarbon contamination and geologic features. This information leads to a more efficient and effective site remediation because it enables direct treatment of the contaminant source area.

Also, a more thorough understanding of subsurface conditions permits monitoring and recovery wells to be located and screened for optimum DNAPL delineation and removal. Improved performance in these wells thereby reduces the need for additional monitoring and sampling.

Finally, the data collection process for EM resistivity surveys is only slightly invasive. Hence, site characterizations can be accomplished with little or no impact to the activities at sites with high traffic and difficult to access areas.

Limitations

EM surveying is not a “stand-alone” process that can be used as the sole means of detecting and delineating DNAPL and defining and delineating subsurface conditions. This technique images highly resistive fluids and materials, and thereby requires chemical analysis of physical samples to verify subsurface contamination. The verification process is accomplished after acquiring, processing, and analyzing the EM data and generating 3-D models of suspected areas of hydrocarbon contamination. Drilling and sampling or direct push evaluations are needed to verify the EM model. Although the objective of a geophysical survey is to provide information similar to that produced from invasive methods of characterization, there will be differences in the results.

An EM survey area is limited to a radius of approximately 300 feet (an approximately 6.5-acre circular area) around each instrumentation well. Hence, the general location of a suspected contaminant source is needed to focus an EM survey. The depth of the instrumentation well limits the maximum depth of investigation. The technique is only effective within 300 feet of ground surface. Figure 5 is a schematic showing the general layout and components utilized during a 3-D EM resistivity survey.

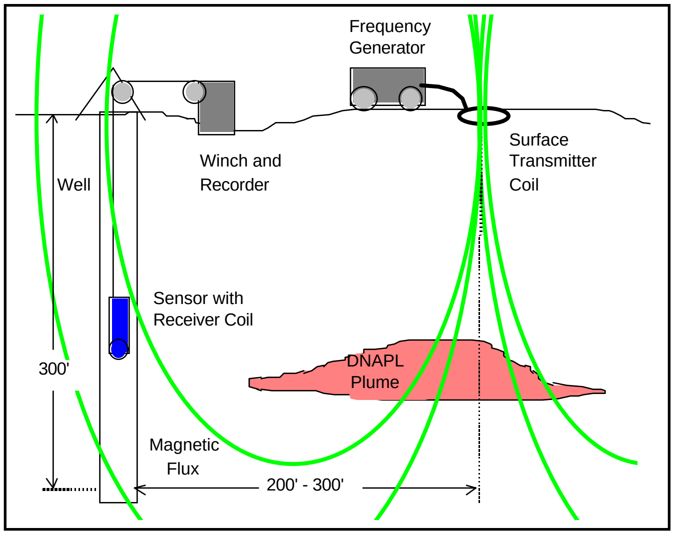

Figure 5. 3-D resistivity transmitter and receiver system.

Field Demonstrations

This technology was demonstrated by NFESC at two DOD sites: former NAS Alameda and Tinker AFB. During these demonstrations, EM 3-D resistivity surveys generally provided useful information relating to subsurface geology and hydrostratigraphy. However, the ability of EM surveying to directly detect DNAPL was hindered by an apparent lack of high levels of contamination. A significant finding from those demonstrations was that DNAPL site characterizations using EM surveying methods should be conducted at sites where high concentrations of dissolved DNAPL (>100 ppm) are thought to exist

Considerations Prior to Implementation

Useful implementation of EM resistivity imaging is dependent on a variety of factors. RPM need to answer the following questions:

- What is the site's history and how did contamination occur at the site?
- How much subsurface investigation has already been conducted at the site.
- What is the regional and local geologic setting of the site?
- How complex is the site's geology?
- Is the site's geology predominantly bedrock or soil?

Also, survey demonstrations performed for ESTCP indicated generally that 3-D seismic imaging might yield the best results at bedrock sites.

Planning/Preparation/Implementation/Results

The process of conducting a 3-D EM resistivity survey consists of the following eight steps:

(1) Install two or more instrumentation wells to allow for redundant signal paths and to ensure good data quality. The wells consist of 2-inch polyvinyl chloride (PVC) casing. Maximum well depth, which is limited by system performance, is about 300 feet.

(2) Place an EM receiver in the instrumentation well.

(3) Induce a magnetic field into the earth at points located around the well.

(4) Record the EM signal(s) at the sensor. These data can produce a cross-sectional view of the subsurface between the sensor and the point of induction. For each point, the sensor is positioned at 0.1-foot increments from the bottom of the well up to ground level. As the point and sensor are moved, a 3-D matrix of data is generated of the EM intensity.

(5) Process the data and generate a 3-D representation of relative resistivity.

(6) Locate the subsurface DNAPL contamination by identifying localized regions of increased relative resistivity (a resistivity anomaly).

(7) Identify stratigraphic features by differentiating zones of smaller systematic differences in resistivity.

(8) Collect three physical samples of media (low, medium, and high contamination predictions) for ground truth. The technology implementors collect verification samples after each prediction. Figure 6 illustrates the layout of a demonstration survey conducted at Tinker AFB.

The primary EM field consists of a large, long wavelength signal (1,400 amp-meter^2 EM moment at the subsurface, at a bandwidth of 263 Hz). The primary signal response is strongly influenced by regions of very high resistivity. Superimposed on this primary source signal response are the much smaller amplitude signal responses from secondary subsurface currents, which are generated at the boundaries and within the bodies of resistivity change.The primary and secondary fields are converted to apparent resistivity (from voltage to ohm-meters) to identify the presence of highly resistive anomalies (i.e., areas of contamination) and of physical properties in the earth, respectively.

Electrical noise is filtered out by tuning the system to a narrow bandwidth (263 Hz), and by optimizing receiver well locations based on low noise levels. Unknown, artificial noise generators are identified by shape and signal amplitude. Naturally occurring subsurface ferro-magnetic materials are insignificant to measurable resistivity changes.

The resolution of the survey data can vary depending on the transmitter location grid spacing. For surface grid spacings of 20 feet, the survey results are typically accurate within 2 feet vertically and 10 feet laterally. Each survey and analysis is based

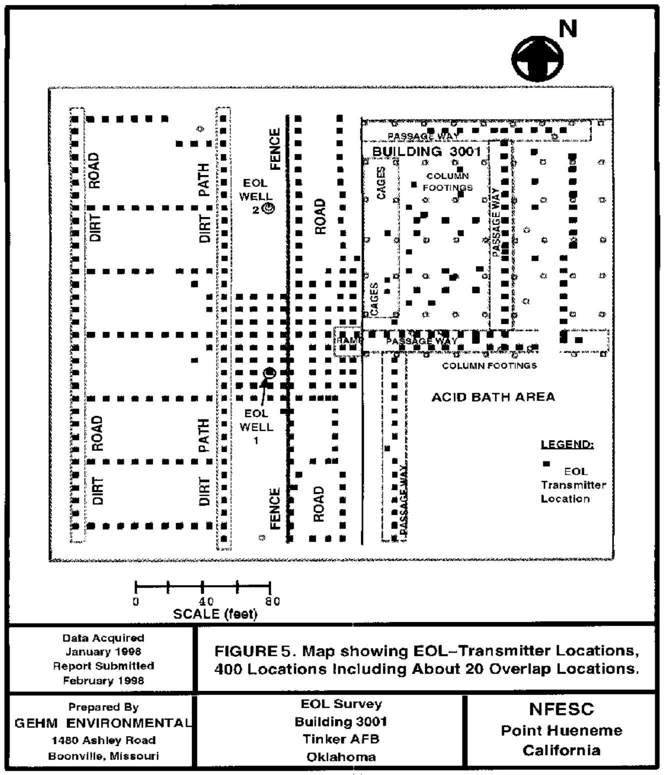

Figure 6. Transmitter locations - Tinker AFB.

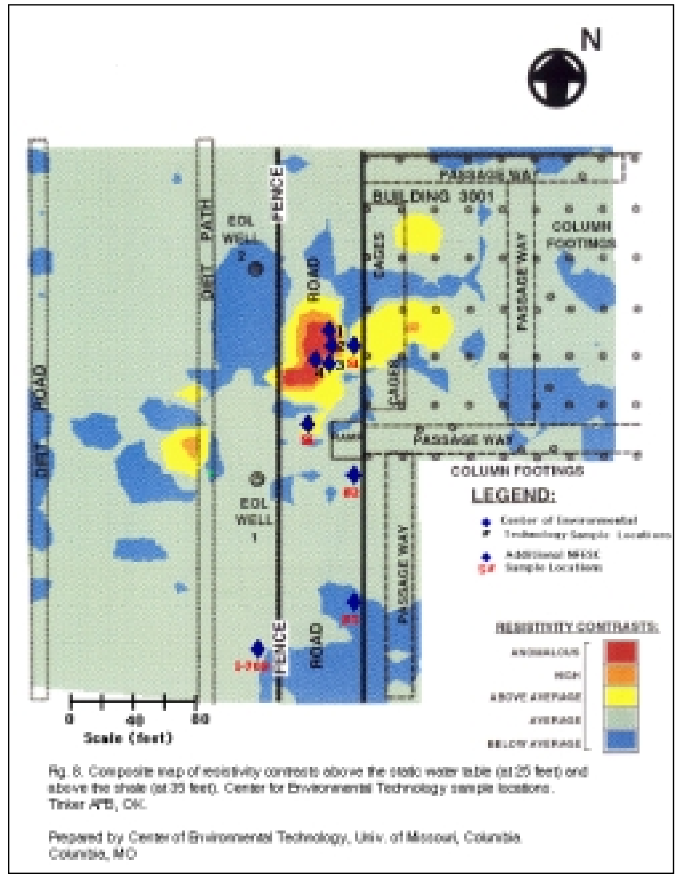

Figure 7. Composite map of resistivity contrasts.

on tens of thousands of sampled data points. The processed data can be presented either in 3-D form or as depth-specific slice and cross-section images. Contours of relative resistivity in either of these formats can be developed and used to track the resistivity patterns of the soils or other near-surface materials. Higher contaminant concentrations will be represented by higher resistivity values. This relationship is not always linear, however, because of changes in geology within contaminated areas. Figure 7 presents a "plan-view" slice from survey results above the static water table at 25 feet and above the shale at 35 feet generated from the Tinker AFB EM survey.

Cost Factors and Cost-Effectiveness

The cost to perform a 3-D EM survey depends on factors such as the amount of pre-existing site information; the size of the source area; the size and depth of the area of concern; the resolution needed to image the target accurately; the type of EM source needed to image the target; surface features and conditions at the site; and site accessibility. Processing costs are higher for higher resolution surveys.

The cost effectiveness of a 3-D EM resistivity survey can vary depending on results that are generated. Based on ESTCP-funded demonstrations at four DOD sites, the average cost of a 3-D EM resistivity survey might be about $45,000. If the results of the survey reveal new site features that make significant changes to the conceptual model and lead to the discovery of more efficient ways of delineating and removing site contamination, then survey costs would be an excellent investment. However, survey results may reveal little new information about the site that is useful in implementing site remediation, and in those cases the cost of a survey then would be a poor investment.

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