INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0517

Tomographic Site Characterization Using CPT, ERT, and GPR

Industry Programs and Subsurface Contaminants Focus Area

Prepared for
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Innovative Technology Summary Report

Tomographic Site Characterization Using CPT, ERT, and GPR

OST/TMS ID 284

Industry Programs and Subsurface Contaminants Focus Area

Demonstrated at
ARA Vermont Test Site
South Royalton, Vermont
Savannah River Site - Upper Three Runs Aquifer and TNX Area
Aiken, South Carolina

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

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SECTION 1

SUMMARY

Technology Summary

Problem

The U.S. Department of Energy (DOE) is responsible for the cleanup of inactive sites and for bringing DOE sites and facilities into compliance with federal, state, and local laws and regulations. Advanced characterization and monitoring technologies are needed which can make environmental restoration and waste management more efficient and less costly. DOE has identified a need for sensors, sensor deployment means, and sensor data processing, including sensor data-fusion for:

- Detection and monitoring of contaminants in soils, groundwater, and process effluents
- Expediting site characterization
- Geological and hydrogeological characterization and monitoring of the subsurface environment.

These techniques are required to better characterize the physical, hydrogeological, and chemical properties of the subsurface while minimizing and optimizing the use of boreholes and monitoring wells.

Solution

Applied Research Associates, Inc. (ARA) has developed a geophysical tomographic system (Figure 1) for site characterization and monitoring which incorporates results from Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR). Both ERT and GPR have proven to be useful techniques for imaging subsurface structures and processes, however, each has advantages and disadvantages. For example, GPR is more effective in sandy material and ERT is more effective in clayey material. In combination, the two methods should provide a more robust model of the subsurface than many other geophysical methods.

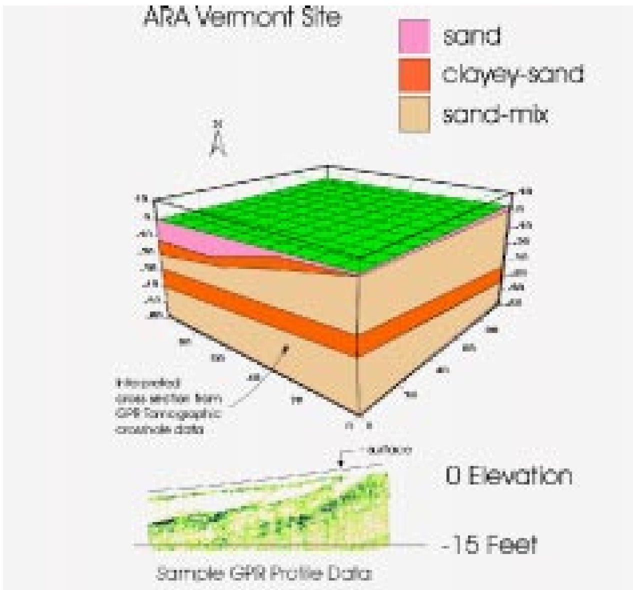

Figure 1. Tomographic site characterization using CPT, ERT, and GPR.

GPR surveys are generally performed on the ground surface. Downhole deployment has been limited by high cost and lack of hardware configured specifically for downhole use. This technology allows collection of better data (because it is downhole) at a lower cost than other downhole methods. Use of the cone penetrometer technology (CPT) as a delivery system to install ERT electrodes and GPR antennas, offers ease of operation, reduced costs and minimal invasiveness. Such an integrated system would provide real-time, in situ subsurface characterization of contaminants, subsurface conditions (geology, hydrology), and treatment processes.

How It Works

CPT has proven to be an efficient and cost effective method for accessing the subsurface without drilling. ERT and GPR are geophysical characterization methods capable of high resolution imaging. Use of the cone penetrometer as a delivery system to install ERT electrodes and GPR antennas offers ease of operation, reduced costs and minimal invasiveness.

ERT images are generated from measurements of electrical resistance. Because the electrical resistance of soil and rock is dependent on soil type, fluid saturation, and chemistry, ERT can be used to monitor or detect subsurface processes such as water infiltration, underground tank leaks, and steam or electrical heating during soil cleanup operations. Two- or three-dimensional subsurface images are produced by transmitting energy along many paths through the region being studied and using the measurements of the resistivity of the medium to produce a tomographic image. ERT provides dramatically increased resolution and sensitivity while also saving on drilling costs and site damage because fewer boreholes are required than in standard borehole logging. These advantages are increased further when ERT is deployed using CPT instead of drilling.

GPR, on the other hand, produces a real-time, underground cross-sectional image by transmitting pulses of ultra high frequency radio waves (microwave electromagnetic energy) down into the ground through a transducer or antenna. The transmitted energy is reflected from various buried objects or distinct contacts between different earth materials. The antenna then receives the reflected waves and stores them in the digital control unit. This data is used to produce a cross-sectional profile or record of subsurface features.

Advantages Over the Baseline

Baseline methods commonly used for site characterization include installation of soil borings, monitoring wells, and piezometers. ERT and GPR have also proven to be useful techniques for imaging of subsurface structures and processes. ERT and GPR are often deployed downhole using drilling techniques. While this method can place the sensor closer to the region of interest and overcome high attenuation in the near-surface soils, there may not be good contact between the sensor and the surrounding soil. Drilling is slow, produces secondary waste, and can be expensive. GPR surveys may also be conducted at the surface. However, there are many critical environmental monitoring situations where surface GPR does not provide the depth of penetration or necessary resolution. In order to extend the range around the CPT hole, ARA has developed a borehole GPR system which is installed by CPT.

Drilling only provides information at selected points along the length of each drillhole and then assumptions are made about what lies between each point. The CPT-deployed ERT and GPR characterization system provides a complete, real time profile from ground surface to depth of penetration thereby identifying important layers that may be missed in an interval sampling approach. Significant advantages include:

- Deployment is faster and more cost effective than conventional drilling and sampling
- CPT is minimally invasive, minimizing potential cross contamination and secondary waste
- System provides continuous data on the subsurface stratigraphy in real time
- System reduces worker contact with contaminated soils

Potential Markets

The potential market for the CPT-deployed integrated ERT and GPR characterization system is significant because it addresses a range of DOE applications which fall into two categories: site characterization and monitoring. Technologies used for site characterization and monitoring have numerous and diverse applications within site cleanup and waste management operations.

Demonstration Summary

Three test sites were chosen for technology demonstration of the integrated CPT, ERT, and GPR characterization system. Each of these field demonstrations presented a unique opportunity to test these integrated technologies in a variety of soil conditions and types, in both saturated and unsaturated zones. The first test was held at ARA’s site in Vermont while the second and third tests were conducted at DOE’s Savannah River Site (SRS).

The system was tested first at ARA’s Vermont Test Site which contained a range of electromagnetic subsurface conditions for testing the ERT and GPR capabilities. These conditions included soils containing interbedded sands and clays with variable moisture content. The objective was to field test the prototype electrodes and designs, CPT installation of the vertical electrode arrays, and ERT and GPR data acquisition and imaging, before going to a DOE site. Results from this test indicated that the ERT equipment was insufficient to transmit the necessary electric current through high resistivity soils. Because of this, new, more powerful ERT equipment was purchased for use with the system.

The second demonstration was held at SRS in an uncontaminated area of the unconfined portion of the Upper Three Runs (UTR) aquifer. The test site was located in a field of monitoring wells installed and used for field demonstration purposes by Clemson University. This demonstration included field deployment of GeoWells (PVC well casing with pre-installed electrodes at pre-determined locations along the length of the casing) with CPT, integrating CPT data to improve inversion model imaging, ERT and GPR data acquisition, and using CPT, ERT and GPR to image the changes exerted on the aquifer during a pumping test.

In the third demonstration, ARA's system was implemented at the Geosiphon well located in the floodplain of the Savannah River at TNX. The Geosiphon cell is a passive flow treatment well utilizing zero valent iron reduction to treat contaminated groundwater. It treats contaminated water abiotically by drawing the water through iron filings using the natural groundwater head differences to replace pumping in a well. The treated water is siphoned and discharged to the river. This passive treatment system is used to remediate VOCs, primarily TCE and carbon tetrachloride in groundwater. Questions had been raised with respect to the effectiveness of the Geosiphon well. Therefore, additional information on the zone of influence of the system was needed. The ARA system was used to delineate the zone of influence of the Geosiphon treatment well. A transect across the flow line was imaged prior to initiation of flow in the well. Sodium bromide was then added to the monitoring well. Flow in the Geosiphon was initiated and several measurements made at designated time intervals (days) to determine the effect of the well on the flow pathline. This type of technology provides unique information for monitoring of a variety of remedial systems including air stripping, in-situ heating, and in-well treatment systems.

Contacts

Technical

James Shinn, Principal Investigator, Applied Research Associates, e-mail: jshinn@ned.ara.com, Telephone:(802) 763-8348

Management

Karen L. Cohen, Project Manger, Federal Energy Technology Center, e-mail: cohen@fetc.doe.gov, Telephone:(412) 386-6667
Robert C. Bedick, Product Manager, Federal Energy Technology Center, e-mail: rbedic@fetc.doe.gov, Telephone: (304) 285-4505
Jefrey S. Walker, EM-53, Program Manager, Office of Science and Technology, e-mail: jeffrey.walker@em.doe.gov, Telephone: (301) 903-8621

Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST Reference # for Tomographic Site Characterization Using CPT, ERT, & GPR is 0284.

SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

Purpose/Goal of Technology

The goal of this project was to successfully integrate three existing technologies into a successful, cost efficient sensor unit and deployment method. The following describes these three technologies.

Cone Penetrometer Technology

CPT was originally developed in the Netherlands in 1934 for geotechnical site investigations. The original CPT involved mechanical measurements of the penetration resistance on a conical tip. Major components of the modern CPT include the instrumented probe, the instrumentation conditioning and recording system, the hydraulic push system, and the vehicle on which the system is mounted. A schematic of ARA's CPT probe is shown in Figure 2. The common configuration provides the mass for a hydraulic push force of about 20 tons (18,000 kgs). Standardization for the geotechnical applications of the CPT was established by the American Society of Testing and Materials (ASTM) in 1986. This standard allows for a probe diameter of 1.44 or 1.75 inches (3.658 cm or 4.445 cm). The most common for standard work is the 1.44 inch probe. In addition to being an excellent platform for making continuous measurements of contaminant information with depth, the CPT is also useful for pushing monitoring sensors into the subsurface and for taking gas, water, or soil samples for environmental testing.

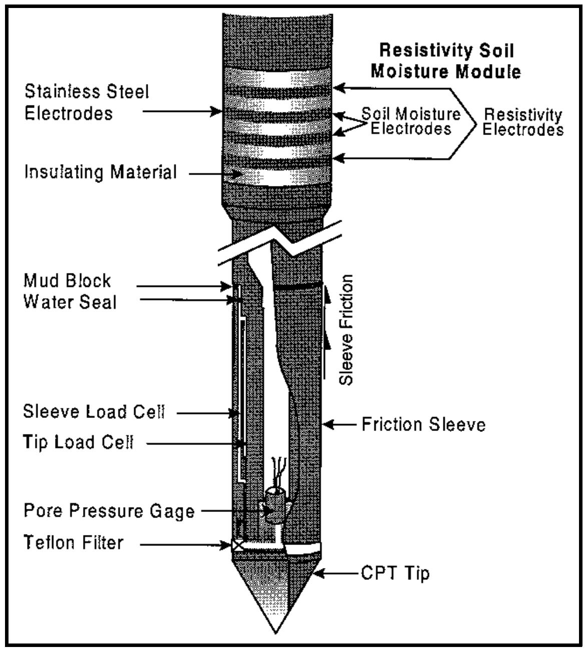

Figure 2. ARA's cone penetrometer probe.

Electrical Resistivity Tomography

In environmental restoration applications the role of electrical resistivity is to assist in subsurface characterization. The task includes not only specifying the location of contamination, but also mapping the physical and chemical properties of the ground that control their distribution and movement. In the most general sense, mapping electrical resistivity is important for conditioning or constraining the hydrological models of contaminant transport and retention. These models are usually based on drill-hole tests and suffer from extrapolation of point measurements, made also between holes, to the volume between the holes. The electrical resistivity of most soils and rocks depends on the conduction paths afforded by fluids in the pore spaces. Resistivity is determined by the porosity, saturation, pore fluid salinity, and clay content. Because resistivity is also influenced by the dissolved solids in groundwater, mapping it may be the only direct detection method for high concentrations that form ionic species. ERT has a variety of applications which include:

- Site characterization in soil remediation projects
- Detection and location of subsurface leaks
- Cleanup process control and evaluation of cleanup technique effectiveness
- Nondestructive evaluation of large structures such as pavements, buildings, and dams

ARA includes a Resistivity Module in its cone penetrometer instrumentation for measuring resistivity in the adjacent soil. As part of the CPT push rod, the module consists of four circular electrodes in contact with the soil. The electrodes are separated by insulators. The outer electrodes are used to induce an electrical current into the soil matrix. The inner two electrodes are used to measure the strength of the induced electrical field. The amount of voltage potential drop in the electric field is a function of the resistivity of the soil.

A schematic of the ERT technique is provided in Figure 3. To produce a tomographic section the resistivity of the medium must be measured along many paths. This requirement is typically met by using two (or more) drill-holes on either side of the region of interest. The signal source is located in one hole, and the receiver in the other. By making measurements with both the source and receiver at a number of different positions in their respective holes, one can obtain data for a multitude of current paths that cross the region to be imaged. The ERT technique uses quasi-dc methods where conduction currents are greater than displacement currents. For most soils, electrical resistivity ranges from 10 to 10^5 ohm meters and the dielectric constant, which is dictated by the water content, from 4 (dry) to 40 (saturated). In low resistivity conditions, the displacement current, or dielectric effect, is insignificant for frequencies less than 100 kHz. Therefore, ERT is more effective in low resistivity environments.

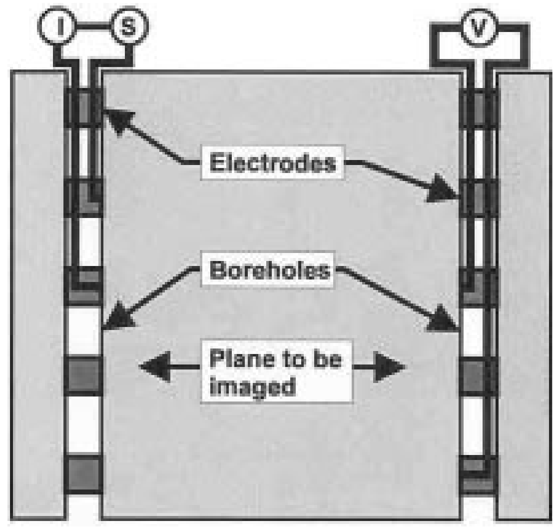

Figure 3. Electrical Resistance Tomography

ERT relies on computer processing to form an image from thousands of data points gathered at a site. A technique called mathematical inversion is used to construct an image (tomogram) of subsurface features which have distinct differences in resistance from their surroundings. The analyst creating the tomogram generates a theoretical mathematical model. The object imaged represents what must be present to produce the actual resistance measurement data.

Ground Penetrating Radar

GPR has been used for more than twenty years at chemical and nuclear waste disposal sites as a non-invasive technique for site characterization. It produces a continuous cross-sectional profile or record of subsurface features. GPR operates by transmitting pulses of ultra high frequency radio waves (microwave electromagnetic energy) down into the ground through a transducer or antenna. The transmitted energy is reflected from various buried objects or distinct contacts between different earth materials. The antenna then receives the reflected waves and stores them in the digital control unit. When the transmitted signal enters the ground, it contacts objects or subsurface strata with different electrical conductivities and dielectric constants. Part of the GPR waves reflect off of the object or interface, while the rest of the waves pass through to the next interface. The reflected signals return to the antenna, pass through the antenna, and are received by the digital control unit.

The GPR system produces a real-time, underground cross-sectional image. GPR surveys have many applications for detecting and locating subsurface features, both natural and man-made. These include:

- Buried objects
- Utility lines
- Tank (UST) & drum location
- Unexploded ordnance (UXO)
- Landfill trenches and cells
- Cemetery and grave location
- Caves, karst, sinkholes, mines, building and roadway subsidence
- Archaeological sites

Standard GPR surveys are conducted from the surface of the ground providing geotechnical information from the surface to depths up to 100 feet (30 meters) in low conductivity materials such as dry sand or granite. Clays, shale, and other high conductivity materials may attenuate or absorb GPR signals, greatly decreasing the depth of penetration to 3 feet (1 meter) or less. Commercially available GPR systems operate over the frequency range of 10 MHz to 1000MHz. The lower frequencies provide better penetration but poor resolution, while the higher frequencies give poor penetration, but good resolution.

There are many critical environmental monitoring situations where surface GPR does not provide the depth of penetration or necessary resolution. Borehole radar can place the sensor closer to the region of interest, overcoming high attenuation in the near-surface soils. However, this approach is invasive, slow and expensive because extensive drilling is required. CPT probes can acquire geotechnical data in soils in less time and at a lower cost. In order to extend the range around the CPT hole, ARA has developed a borehole GPR system for use in CPT-installed wells.

Integration of GPR & ERT

GPR methods use frequencies from 10 to 1000 MHz where the response is controlled by water content as well as conductivity and where the depth of penetration is limited by attenuation due to low resistivity (high conductivity). While ERT proves to be more effective in low resistivity environments, GPR is more effective in high resistivity conditions. Combining the two methods, through an intelligent data fusion process, in a single site characterization survey will greatly enhance the available information about the subsurface conditions at the site.

Figure 4 demonstrates possible data collection approaches for GPR measurements. These transmission measurements include hole-to-hole and hole-to-surface measurements. At each downhole position the surface antenna is scanned radially from the hole. For cross-hole tomography (GPRT), one CPT antenna is held stationary while the other unit is moved. The process is repeated until the volume between the holes is covered.

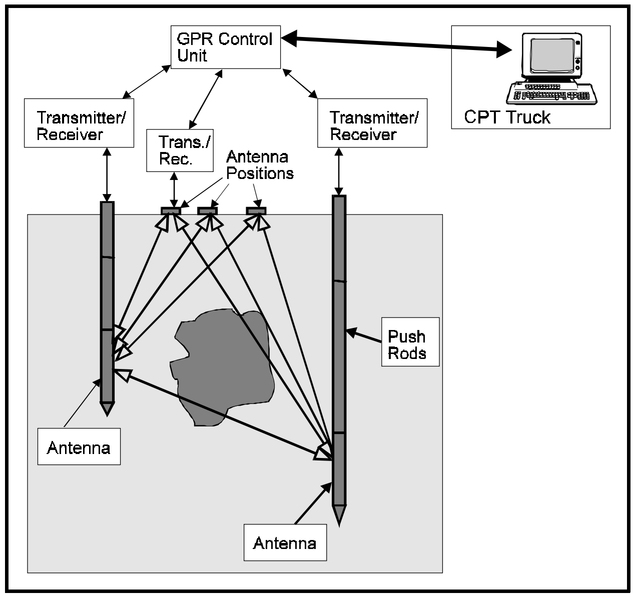

Figure 4. Data collection approach for cross-hole GPR tomographic measurements. Several ray paths are shown for typical transmitter-receiver positions on the surface and in the holes.

Soil Moisture Sensor

A Soil Moisture Sensor (SMS) was used during the field evaluation tests of the ERT and GPR systems. The SMS logs the moisture content of the soil surrounding a borehole as the probe is advanced down the hole. Since radar propagation in soils is strongly influenced by moisture content, SMS measurements help with GPR interpretation. The ARA CPT SMS uses a Resonant Frequency Modulation (RFM) approach to determine the dielectric constant and, ultimately, soil moisture. This approach consists of installing a custom designed circuit board in a CPT probe which is then interfaced with standard CPT equipment, eliminating the need for specialized measurement equipment. A second advantage of this approach is that cable distances are unlimited as all conditioning and processing of the signal occurs downhole, eliminating the effect of cable length-induced attenuation.

System Operation

The ARA system integrates CPT, ERT, and GPR technologies in order to gain increased resolution at depth at lower cost than conventional downhole applications. Once fully developed, ARA may offer this technology as a service or it may offer to sell systems to other contractors who would provide this service.

The ARA system features the use of GeoWells for subsurface data collection. GeoWells consist of PVC well casing with pre-installed electrodes at pre-determined locations along the length of the casing. A GeoWell is essentially a well in which multiple sensors can be deployed. Some initial data may be needed to help determine GeoWell spacing (for cross-hole data acquisition) and finalize other design parameters. GeoWell installation begins with standard CPT pushes to appropriate depth at each planned GeoWell location. CPT logs of tip, sleeve, pore pressure, and resistivity data are recorded at each well location. These CPT data are eventually compared to GPR and ERT data to ensure consistency. Each CPT hole is eventually reoccupied using a CPT rod with an oversized sacrificial CPT tip to pull PVC well casing containing electrodes into the hole. The same hole can be used for both ERT and GPR data acquisition.

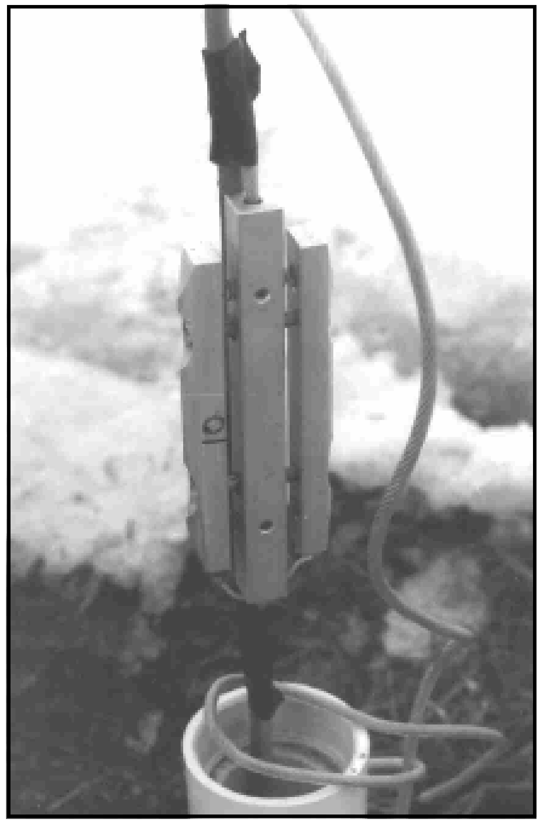

Figure 5. Photo and schematic of ERT contactors deployed in GeoWell.

For ERT data acquisition, a contactor assembly with associated wiring is lowered into the GeoWell as is demonstrated in Figure 5. The software used for processing ERT data was supplied by Lawrence Livermore National Laboratory (Miletto and LaBrecque 1996, and Ramirez 1996).

For GPR data acquisition, antenna assemblies are deployed into GeoWells. A picture of GPR test equipment and antennas is provided in Figure 6. The antennas are partially shown in the foreground and the 100-foot downhole cables are coiled in the background. The software used for processing the GPR borehole data to generate tomographic images is 3DTOM (Marsily 1986), a DOS-compatible computer program developed by the U.S. Bureau of Mines for three dimensional tomographic imaging of the subsurface at mine sites.

Data handling is improved through the use of computer algorithms and data fusion techniques. Final analysis and development of detailed conclusions is similar to currently used ERT and GPR baseline technology. ERT contactor assemblies and GPR antennas may be easily removed from the GeoWells, stored, then re-deployed in the GeoWells, if necessary.

The operational parameters for tomographic site characterization using CPT, ERT and GPR are provided below:

- CPT: Operational Parameters and Conditions
  - — CPT has proven to be an efficient and cost effective method for accessing the subsurface without drilling
  - — The maximum depth of penetration possible varies with soil type
  - — Highly effective in sandy and clayey soils
  - — Has difficulty in soils with large cobbles and/or boulders and cemented layers

— Has been applied at sites as deep as 300 ft, but is generally applied to depths up to 150 ft (U.S. DOE 1996)
— Has the capability of grouting the hole as the rods are retracted

- ERT: Operational Parameters and Conditions

  — The role of electrical resistivity is to assist in characterizing a site (i.e. conditioning or constraining the hydrological models of contaminant transport and retention)
  — ERT is more effective in low resistivity environments

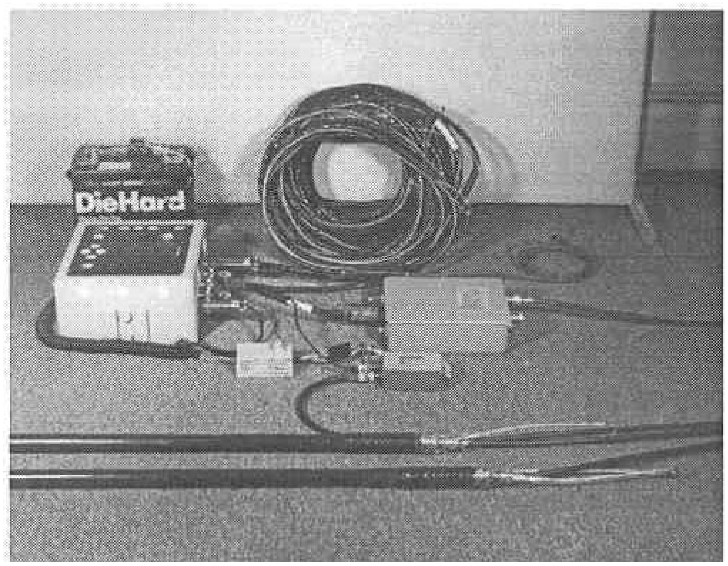

Figure 6. Picture of GPR borehole test equipment.

- GPR: Operational Parameters and Conditions

  — GPR is more effective in high resistivity environments
  — GPR systems with low frequency ranges provide better penetration but poor resolution while the higher frequencies give poor penetration but good resolution

SECTION 3

PERFORMANCE

Demonstration Plan

Various site conditions and soil characteristics may prohibit the usefulness of either GPR or ERT when used alone. However, CPT data and deployment methods can overcome the problems soil types and conditions may present and improve these types of imaging methods by providing additional information on the subsurface. To demonstrate this, three test sites were chosen. Each site presented a unique opportunity to test the benefits of these integrated technologies in a variety of soil conditions and soil types, in both unsaturated and saturated zones.

Vermont Test Site

The ARA Vermont Test Site is an open grassy field on a hill approximately 160 ft above the White River in South Royalton, VT. The soils are interbedded sands with clay lenses and thin clay layers with the water table located approximately 160 ft below ground surface (bgs). The test plan included installing four GeoWells on a square grid with an infusion well at the center of the square. ERT and GPR tomographic data would be taken before and after the infusion of approximately 100 gallons of salt water. The major objectives were to field test the prototype electrodes and designs, installation of the vertical electrode arrays, and ERT and GPR data acquisition and imaging, before proceeding to a DOE test site.

SRS MWD Test Site

The second demonstration was conducted in an uncontaminated area located at SRS in Aiken, SC in the unconfined portion of the Upper Three Runs Aquifer. The test site was located in a field of monitoring wells installed and used for field demonstrations by Clemson University. The subsurface consisted of layers made up of alternating quartzitic sand and clay with the sand containing varying amounts of silt with depth. The water table in this area was approximately 72 ft bgs. The objective for this demonstration was to integrate CPT, ERT and GPR to successfully image changes in the subsurface due to an event that would produce changes in the soil's properties. Specifically, electrodes were placed in the subsurface (using CPT) surrounding a pumping well and images were constructed from test data taken before and during a pumping test event using CPT, ERT and GPR techniques.

TNX Area Test Site

The final demonstration was conducted at the TNX area of SRS where a Geosiphon is being used as part of a groundwater remediation system. The Geosiphon cell is a passive flow treatment well utilizing zero valent iron reduction to treat contaminated water. The treated water is siphoned and discharged to the receiving body of water. The geology of the upper water table in this area consisted mostly of unconsolidated sands with a few clay layers and discontinuous cemented sand layers. The water table aquifer began at approximately 4 ft bgs and there was a clay layer located at 20 ft bgs separating the upper water table aquifer from the water table aquifer below the clay layer. The contaminants in the aquifer are located

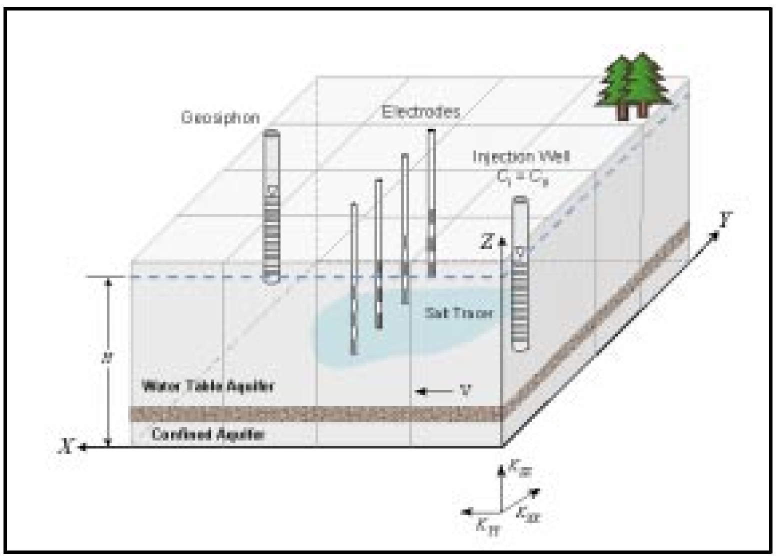

Figure 7. Orthographic view of tracer test at TNX area. The Geosiphon, monitoring wells, and electrodes were installed to 20 ft. bgs. Confining layer shown is at 20 ft. bgs.

above this clay layer, and the Geosiphon cell was installed to the clay layer at a depth of 20 feet.

Through the use of a tracer (salt water), which alters the pore fluid salinity of the aquifer, and the combination of CPT with ERT and GPR, the preferential flow patterns surrounding the Geosiphon in its zone of influence were monitored over time. ERT and GPR surveys were taken before, during, and after tracer injection. During this process, samples were extracted from the electrodes to determine the salinity content of the groundwater at discrete depth intervals. As the tracer plume moved nearer the Geosiphon, changes in resistivity were detected and used to develop images of the groundwater flow field. The expected results of the field test design were estimated using numerical flow modeling and mass transport modeling for determining the mass of solute that can be expected during the monitoring phase. The images resulting from the modeling process helped design the field layout of the tracer test for optimum results. A pictorial view of the test is shown in Figure 7.

Results

The success of remediation activities is highly dependent on accurate information of the soil properties and hydrogeologic conditions of the site. The integrated sensor package that ARA developed and tested under this contract provide increased information using minimally invasive methods to more accurately and optimally determine hydrogeologic parameters and soil and site conditions. The results of this program now make it possible to install ERT and GPR units by the CPT method and thereby reduce installation costs and total costs for ERT and GPR surveys. In addition, CPT provides valuable geologic data which will improve the ERT results by providing information on soil resistivity and improve GPR results by providing information on soil moisture

A breadboard ERT borehole system and a breadboard GPR borehole system were built and successfully tested. CPT GeoWells were installed at ARA's Vermont Test Site and at a DOE site for field testing of the two cross-hole systems. A salt water infusion test at the VT and TNX sites demonstrated the ability of the ERT and GPR techniques to image time-variant processes. The pre-infusion and post-infusion tomographic images for both systems clearly showed sand and clay layers and salt water plumes. The field test conducted at the TNX area confirmed the ERT monitoring results in the saturated zone through the use of dual electrode samplers. The sampling corroborated the ERT images of where tracer movement occurred confirming the ERT results. The field test results also demonstrated that the ERT system did not disturb ongoing Geosiphon remediation activities while it was being used in the same area as the Geosiphon. The results of the MWD site demonstrated that CPT-installed GeoWells can be used for both ERT and GPR borehole tomographic subsurface imaging.

Vermont Test Site

GPR tomographic cross-hole data collected at the Vermont test site was used to develop an interpreted cross-sectional 3D map of major subsurface layers as seen in Figure 9. Combining the surface topography plot and the GPR profiles with CPT data, the depth to soil interfaces from a horizontal datum plane is calculated. The top of the first clayey layer is at approximately 15 feet below ground surface at the center of the grid. Using real-depth measurements from CPT records and contiguous records from GPR data, this clayey layer was easily located and mapped. This layer dips to the northwest, therefore, saline water introduced at the infiltration well to model plume behavior flowed in the northwesterly direction (verified by

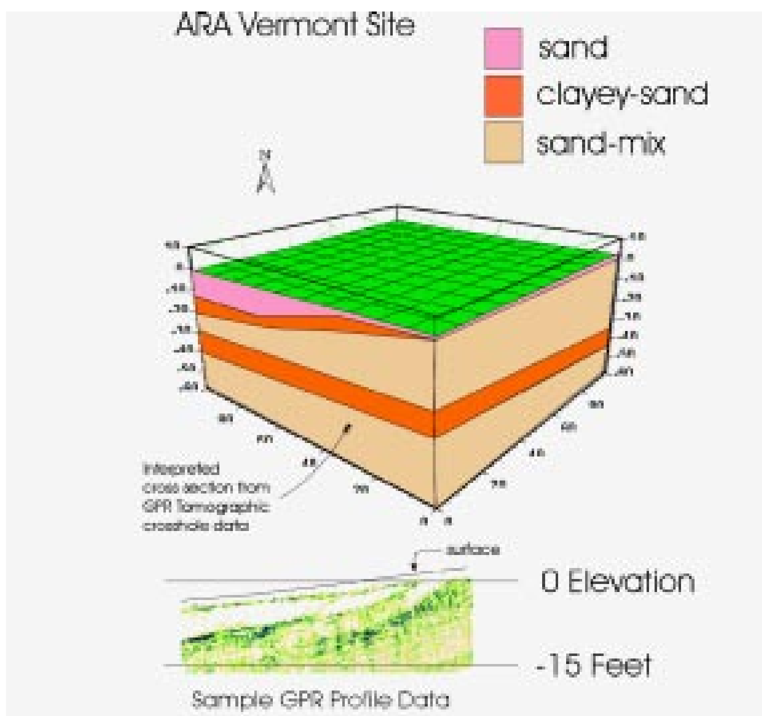

Figure 8. 3D map of major subsurface layers.

both ERT and GPR data), as opposed to the surface contour, which dips to the south. Optimum configuration and installation methods for GeoWells were determined at this site in preparation for DOE site demonstrations. The ability to use the same hole for both ERT and GPR was tested and confirmed at this site.

SRS MWD Test Site

GPR and ERT surveys before and during pumping were used to image the changes in the saturated zone due to pumping. ERT data analysis indicated the upper clay layer dips seven feet in elevation across the test area, which is centered on a pumping well. This data is in agreement with CPT data and indicates that the ERT method can verify subtle dips in geology. ERT data prior to pumping was used to generate a tomograph that showed a sharp decrease in resistivity at the water table (72 feet below ground surface), which agrees with existing data. During pumping, a general increase in resistivity shown in the tomograph generated for the same location is attributable to water being removed from this zone. The results of the borehole GPR testing compared favorably with the ERT and CPT results at the MWD site. Installation and operation of GeoWells at this site added to the experience needed to apply this technology successfully at additional sites. Further experience was gained with data analysis software and data fusion to improve efficiency with additional applications of the technology.

SRS TNX Area Test Site

Injection of a tracer salt into the subsurface, with monitoring over time using integrated ERT and limited CPT and GPR data provided new information about the groundwater flow patterns toward the Geosiphon, including capture zone, dispersion, and preferential flow through subsurface layers. ERT and GPR findings were validated by extracting water samples at discreet depths, using dual-purpose CPT-installed electrodes. Little, if any, interference occurred with the performance of the Geosiphon or the overall remediation activity. ERT tomographic images indicated significant decrease in resistivity above the 11 foot depth, indicating a preferential pathway toward the Geosiphon. GPR results yielded limited information as a crosshole tomographic image was unobtainable due to extremely low resistivity in the subsurface.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

CPT has proven to be an efficient and cost effective method for accessing the subsurface without drilling. ERT and GPR have proven to be useful techniques for imaging of subsurface structures and anomalies. Combining the two methods, through an intelligent data fusion process, in a single site characterization survey will greatly enhance the available information about the subsurface conditions at the site. ERT and GPR images can easily be enhanced with other CPT sensor data, i.e. tip stress lithology, in situ gas chromatography, and laser fluorescence chemical analysis. ERT and GPR will be a means to extend this information beyond the probe hole to regions between CPT holes.

The combination of these technologies - CPT, ERT, GPR and chemical sensors - will find broad applications. Shallow investigations (less than 100 feet) are especially important for environmental remediation, such as imaging and mapping confining layers, defining permeable zones, delineating contamination plumes, and detecting leaks from tanks and landfills. These methods can also be used for imaging time dependent in situ remedial actions, such as steam floods, electrical heating, RF heating, surfactant floods, and air sparging.

This project addresses a range of problems which fall into two categories: site characterization and monitoring. Technologies used for these purposes have numerous and diverse applications within site cleanup and waste management operations. Specific applications where cost effective underground imaging is very important include:

- Expediting site characterization
- Detection and monitoring of contaminants in soils, groundwater, and process effluents
- Developing very high resolution imaging techniques for monitoring remediation and cleanup activities
- Delineating the continuity of soil layers between penetrometer holes
- Locating and mapping sand and clay lenses between penetrometer holes
- Mapping dense, non-aqueous phase liquids plumes
- Defining spatial and temporal behavior of a steam flood for dynamic stripping
- Monitoring a thermal front
- Characterization of burial trenches and pits, including boundaries and contents
- In situ measurement of physical properties, i. e., porosity, density and moisture content

Competing Technologies

Baseline Technologies

The most commonly used method for site characterization is soil borings. A significant disadvantage of this approach is the amount of waste generated by drilling. Drilling removes all of the soil material from the drillhole up to the ground surface. This material may be contaminated, representing a hazard to both the workers and the environment. In addition to being invasive, drilling is slow and can be expensive.

Characterization can also be accomplished by the installation of monitoring wells, piezometers, as well as CPT measurements. Ground surface deployment of GPR is another common method used for site characterization. Borehole installation of GPR and ERT has been utilized to extend the range of these technologies. This method can place the sensor closer to the region of interest, overcoming high attenuation in the near-surface soils. However, there are several disadvantages to this approach. The major disadvantage of this approach is that there may not be good contact between the sensor and the surrounding soil. The disadvantages associated with drilling are also a problem with this method

Conventional drilling is the baseline method to deploy downhole GPR and ERT. Both ERT and GPR have proven to be useful techniques for imaging subsurface structures and processes, however, their effectiveness is dependent on soil conditions. GPR is more effective in sandy material and ERT is more effective in clayey material. There are also many critical environmental monitoring situations where surface GPR does not provide the depth of penetration or necessary resolution.

Advantages Over Baseline

- CPT is generally faster and more cost effective than conventional drilling and sampling.
- Allows in situ detection.
- Probe is in continual contact with the surrounding soil, providing continuous data on subsurface stratigraphy with minimal amount of soil disturbance that may compromise measurements being made.
- Provides a complete, real time profile is created from ground surface to depth of penetration thereby identifying important layers that may be missed in an interval sampling approach.
- Minimally invasive approach to site characterization that minimizes potential cross contamination and secondary waste.
- Increased worker safety due to reduction of exposure to potentially hazardous materials.

Strengths of Baseline Technology

- Conventional drilling techniques are rugged and applicable to all types of subsurface geological conditions.
- Laboratory sample analysis provides quantitative results including chemical constituency.
- Quantitative laboratory analysis of soil and groundwater is reliable, legally defensible, and often required by regulatory agencies.

Patents/Commercialization/Sponsor

Research and development of the Tomographic Site Characterization Using CPT, ERT, and GPR technology was sponsored by the DOE's Federal Energy Technology Center (FETC). The technology was demonstrated in conjunction with the DOE's Savannah River Site.

SECTION 5

COST

Methodology

The cost information for the CPT, ERT and GPR system presented in this section was provided by ARA, the technology developer, and is based on demonstration of the technology at SRS. The cost analysis includes a brief description of each of the cost elements of the technology. The costs for the demonstration at the MWD area at SRS are presented next. Finally, a cost comparison is performed to assess the cost advantage of utilizing CPT to deploy the ERT and GPR compared to deployment by conventional drilling.

The following summary provides a description of the cost elements associated with deployment of the CPT, ERT and GPR system. The total cost may be thought of as a sum of following components:

- Investigation/Design/Permitting
- CPT Mobilization/Data Acquisition/Electrode Installation
- Electrode Manufacturing/Assembly
- ERT/GPR Data Acquisition
- Analysis/Reporting

Investigation/Design/Permitting

To deploy this technology at a DOE site, numerous permits must be submitted, reviewed and approved before work may begin and are dependent on the level of effort and contamination at the site.

- Permitting Cost: $2,000 to $10,000

Sufficient planning of the field investigation includes modeling the expected outcome to help in experimental design. Numerical modeling of the outcome using estimates of field parameters will help design the frequency and total number of electrode strings needed to gather quantitatively significant data. In this way, an estimate can be made of the minimum number of electrodes to manufacture.

- Planning Cost: $800 to $5,000

CPT Mobilization/Data Acquisition/Electrode Installation

The costs associated with mobilizing the CPT to a site are dependent on mileage. The cost to install electrodes, GeoWells, and gather CPT profiling data is dependent on the size of the field effort. CPT rates are based on the ability to push 500 linear ft per day.

- Mobilization/Demobilization: $2 to $4/mile
- CPT data acquisition/GeoWell Installation: $2,200 to $3,000 per day

Manufacturing/Assembly

ERT requires the use of electrodes either inserted into the ground, or on the ground surface, and wired to a geophysical data acquisition system. They are usually manufactured and assembled according to the results of numerical modeling based on the estimated site characterization parameters at the site. Once the experiment design has been determined the appropriate radar equipment can be selected and either purchased or rented on a daily or monthly basis.

- Manufacturing/Assembly: $45 to $57 per electrode

ERT/GPR Data Acquisition

Both ERT and GPR require geophysical data acquisition equipment. A simple test may be to gather ERT and GPR data between two boreholes, each with a small number of electrodes. Numerical inversion of the data may reveal a few simple cross sections. More complicated testing, such as imaging changes that are occurring in the subsurface over time, would require more time in the field gathering data, and inverting for possible time lapse imaging. The ERT and GPR costs (below) do not reflect the cost of a laptop computer, nor a separate power source required for the laptop while taking ERT data, to avoid electrical noise interference that may be caused by a power grid.

- Engineering Staff (no equipment use fee): $800 per day
- ERT Geophysical Data Acquisition System: $604 per day
- Borehole GPR Data Acquisition System: $295 per day

Analysis/Reporting

Results of the experiment may simply be a few cross sectional images, or may require full detailed explanation of field techniques, data acquisition, and extensive data inversion and analysis.

- Engineering Staff: 40 to 200 hrs.
- Total Reporting Cost: $1000 to $10,000

The total cost involved in site characterization is highly dependent on the level of effort and the state of the site. Unforeseen costs due to difficult geology, equipment failure, weather, or extensive delays in permitting due to complex field experiments, are not uncommon and can contribute significantly to the total cost of site characterization.

Demonstration Costs for MWD Area of SRS

Demonstration of the CPT, ERT and GPR system at the MWD Area of SRS was conducted to observe the performance of a pumping well. Six GeoWells were installed to a depth of 80 feet for ERT and GPR data acquisition. The GeoWells were installed in three days and subsurface data was collected by CPT instruments during well installation. Each well contained 20 electrodes for ERT analysis. ERT and GPR data acquisition was performed over 10 working days: 5 days before initiation of pumping and 5 days after initiation of pumping.

The MWD area is not contaminated, therefore, permitting requirements were minimal and the permitting costs were relatively low. The level of analysis and reporting was extensive, therefore the cost for these tasks in on the higher end of the scale. The costs for the demonstration at the MWD are summarized in Table 1.

Table 1. Summary of MWD-Area Demonstration Costs

Task Description	Unit Cost	Qty	Cost
Permitting	-	-	$3,500
Design/Planning	-	-	$3,500
Mobilization	$4/mile	[1]0	$0
CPT Data Acquisition and GeoWell Installation	$2,600/day	3	$7,800
Electrode Manufacture/Assembly	$51/each	120	$6,120
Data Acquisition-Engineering	$800/day	10	$8,000
ERT Data Acquisition System	$600/day	10	$600
GPR Data Acquisition System	$295/day	10	$2,950
Analysis Reporting	-	-	$10,000
		Sub-total	$42,470
General and Administrative Overhead (10%), Fee (5%), Total :15%			$6,371
		Total	$48,841

[1] CPT Rig already on site

Cost for ERT and GPR deployed by conventional drilling

A primary goal of this project was to make possible the installation of down-hole ERT and GPR equipment by CPT, thus reducing installation costs. To demonstrate the cost saving provided by CPT, the costs for the demonstration at the MWD area were also calculated under the assumption that conventional drilling was utilized to install the down-hole equipment. For the purposes of this cost analysis, it is assumed that the site is contaminated. This assumption is made to show the cost savings that CPT provides through the elimination of drill cuttings. Conventional drilling produces drill cuttings and disposal of drill cuttings is a significant cost at a contaminated site. Drilling costs at SRS were based on MSE Technology Applications, Inc. ,1999. The following assumptions also apply:

- Hollow stem auger drilling is utilized to install ERT and GPR equipment
- Split spoon sampling would be utilized to gather geologic information (soil resistivity) for modeling assumptions
- Drill cuttings will be generated at a rate of 1 - 55 gallon drum per 16 ft of 8-inch diameter borehole
- Drill cuttings will be disposed at a landfill as a hazardous solid waste

Table 2. Costs for ERT and GPR by conventional drilling

Task Description	Unit Cost	Qty	Cost
Permitting	-	-	$3,500
Design/Planning	-	-	$3,500
Mobilization	$4/mile	[1]0	$0
[2]Installation by hollow-stem auger drilling			
Hollow stem auger drilling	$10/ft	480	$4,800
Split-spoon sampling	$20/ft	480	$9,600
Disposal of drill cuttings	$266/drum	30	$7,980
			$22,380
Electrode Manufacture/Assembly	$51/electrode	120	$6,120
Data Acquisition-Engineering	$800/day	10	$8,000
ERT Data Acquisition System	$600/day	10	$600
GPR Data Acquisition System	$295/day	10	$2,950
Analysis Reporting	-	-	$10,000
Sub-total			$57,050
General and Administrative Overhead (10%), Fee (5%), Total :15%			$8,558
Total			$65,608

[1]Drill rig already on site, [2] MSE Technology Applications, Inc.(1999)

COST CONCLUSIONS

Based on the stated assumptions of each technology, the following conclusions are presented:

- The analysis indicates a cost savings of approximately 25% ($16,767) when comparing characterization conducted with CPT deployed ERT and GPR compared with that deployed using conventional drilling methods based on the scenario presented.
- The CPT deployed ERT and GPR characterization system represents the most cost effective method for obtaining a complete, real time profile of the subsurface .
- The total cost involved in site characterization is highly dependent on the level of effort required based on site-specific conditions and data needed.

A primary benefit of CPT deployment that is not necessarily quantifiable in the cost analysis is the information gained during a CPT push prior to GeoWell installation. This information is used to improve the GPR and ERT images. CPT high resolution profiles are obtained from pushing cones with resistivity, soil moisture, pore pressure, tip and sleeve sensors. This information is utilized to determine soil classification information and estimated soil stratigraphy.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

In order to deploy this technology at a DOE site, numerous permits must be submitted, reviewed and approved before work may begin. These permitting requirements may vary, depending on the level of effort and contamination at the site. Some site specific requirements may include a work clearance permit, an excavation/trenching checklist, monitoring well approval, program plan approval, an injection control permit, a site specific health and safety plan and site clearance requests. Additional regulatory considerations include:

- At federal facilities, a National Environmental Policy Act (NEPA) review is required

- Normal drilling/sampling activities generate investigation derived wastes (IDWs) such as drilling fluids, cuttings, and equipment decontamination fluids which must be handled according to the Resource Conservation and Recovery Act (RCRA). CPT generates only minimal IDW (decontamination fluid only).

- No special permits are required for the operation of CPT. Regulatory approval is typically handled as in standard drilling where a drilling plan is submitted to the appropriate regulatory agency for their approval prior to initiation of field activities.

- Occupational Safety and Health Administration (OSHA) requirements for CPT operation should be less stringent than standard drilling techniques (CPT produces less noise, no waste, no rotary parts, no hammer drive mechanisms, etc.)

- Results gained through this technology are meant to enhance general understanding and visualization of site characterization results. They do not take the place of analysis by a certified analytical laboratory with regard to meeting local, state, or federal regulatory requirements.

- This technology is meant to be a field screening tool to aid in the efficiency and accuracy of site characterization and evaluation of remediation effectiveness. Confirmation samples are typically required by regulators to document site characterization and remediation effectiveness.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Measurements are collected in situ, thus minimizing site personnel exposure to high concentrations of contaminants during sample collection, transport and analysis.

Community Safety

- CPT will have a minimal impact on the labor force and the economy of the region.

Environmental Impact

- Environmental impacts of CPT are generally less than with conventional drilling.
  - No drill cutting or drilling liquids are produced during operation.
  - CPT is minimally intrusive and does not mobilize contamination: holes are smaller in diameter than most drill rods, and can be grouted during retraction of the CPT rods.
  - The entire system can be decontaminated at the surface with a minimal amount of fluid.

Socioeconomic Impacts and Community Perception

- Utilization of CPT-deployed characterization sensors will have a minimal impact on the labor force and the economy of the region .

- The general public has limited familiarity with CPT, but would be expected to support it as an improvement over baseline technology, as it is less intrusive than drilling.

SECTION 7

LESSONS LEARNED

Implementation Considerations

Prior to implementation, the end user should consider the capabilities and limitations of the CPT deployed ERT and GPR. Both ERT and GPR have proven to be useful techniques for imaging subsurface structures and processes. In combination, the two methods should provide a more robust model of the subsurface than other geophysical methods. Using the CPT as a delivery system to install ERT electrodes and GPR antennas offers ease of operation, reduced costs and minimal invasiveness. Such a system would provide real-time, in situ subsurface characterization of contaminants, subsurface conditions (geology, hydrology), and treatment processes. Limitations of the technology are discussed below.

Technology Limitations

- Maximum depth of penetration of CPT probes varies greatly with soil type and appropriate geologic conditions may be needed to assure penetration to required depths.
- Results of various GPR and ERT data acquisition systems indicated that sufficiently rugged and powerful systems are required to make good quantitative measurements in different lithologies and field experimental designs.
- Commercially available GPR equipment is more mature than ERT, but optimized for surface surveys, not borehole applications

Needs for Future Development

- Development of an ERT system which uses a combination of fixed and roaming vertical electrode arrays (VEAs) with CPT and near real-time data inversion would greatly improve the performance and reduce cost of ERT surveys

Technology Selection Considerations

- Specific job requirements and site specific geologic conditions will dictate the application of the best technology for site characterization. Innovative technologies such as Tomographic Site Characterization Using CPT, ERT, & GPR, should be considered within the toolbox of available technologies.
- This technology is applicable to a range of problems which fall into the categories of site characterization and/or monitoring and would have numerous applications within site cleanup and waste management operations.

APPENDIX A

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