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**MINIMALLY INVASIVE THREE-DIMENSIONAL
SITE CHARACTERIZATION SYSTEM**

Final Report, Contract No. 02112410

By

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PREFACE

Currently available technology is not adequate to assess environmental contamination at Department of Energy (DOE) sites, take permanent remedial action, and eliminate or minimize the environmental impact of future operations. Technical resources to address these shortcomings exist within the DOE community and the private sector, but the involvement of the private sector in attaining permanent and cost-effective solutions has been limited.

During 1990, on behalf of DOE's Office of Technology Development, Argonne National Laboratory (ANL) conducted a competitive procurement of research and development projects addressing soil remediation, groundwater remediation, site characterization, and contaminant containment. Fifteen contracts were negotiated in these areas.

This report documents work performed as part of the Private Sector Research and Development Program sponsored by the DOE's Office of Technology Development within the Environmental Restoration and Waste Management Program. The research and development work described herein was conducted under contract to ANL.

On behalf of DOE and ANL, I wish to thank the performing contractor and especially the report authors for their cooperation and their contribution to development of new processes for characterization and remediation of DOE's environmental problems. We anticipate that the R&D investment described here will be repaid many-fold in the application of better, faster, safer, and cheaper technologies.

Details of the procurement process and status reports for all 15 of the contractors performing under this program can be found in "Applied Research and Development Private Sector Accomplishments - Interim Report" (Report No. DOE/CH-9216) by Nicholas J. Beskid, Jas S. Devgun, Mitchell D. Erickson and Margaret M. Zielke.

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ABSTRACT

This paper presents an improved strategy for hazardous site characterization. The major components of the system are: (1) an enhanced cone penetrometer test, (2) surface geophysical surveys and (3) a field database and visualization code. The objective of the effort was to develop a method of combining geophysical data with cone penetrometer data in the field to produce a synergistic effect.

Various aspects of the method were tested at three sites. The results from each site are discussed and the data compared. This method allows the data to be interpreted more fully with greater certainty, is faster, cheaper and leads to a more accurate site characterization. Utilizing the cone penetrometer test rather than the standard drilling, sampling and laboratory testing reduces the workers exposure to hazardous materials and minimizes the hazardous material disposal problems.

The technologies employed in this effort are, for the most part, state-of-the-art procedures. The approach of using data from various measurement systems to develop a synergistic effect was a unique contribution to environmental site characterization. The use of the cone penetrometer for providing "ground truth" data and as a platform for subsurface sensors in environmental site characterization represents a significant advancement in environmental site characterization.

MINIMALLY INVASIVE THREE-DIMENSIONAL
SITE CHARACTERIZATION SYSTEM
EXECUTIVE SUMMARY

INTRODUCTION.

Environmental cleanup is clearly the engineering challenge of the 90's. The number of contaminated sites, under both government and private control, and the cost associated with their cleanup is well documented. The Office of Technology Assessment estimates that cleanup of the 1,246 sites now on the National Priority List will cost \$500 billion. The Government Accounting Office has estimated that this list could grow to 368,000 sites if a more comprehensive inventory were taken. If the State Superfund cleanups, Department of Defense, Department of Energy (DOE), private party cleanups, leaking underground storage tanks, and RCRA corrective action cleanups are added, then the engineering challenge is substantial.

The magnitude of the environmental cleanup problem has led the DOE to implement a Research, Development, Demonstration, Test, and Evaluation (RDDT&E) program with the goal of finding faster, better, safer, and cheaper methods of accomplishing this massive program. The research reported here is a result from one project in that RDDT&E program.

The characterization of the subsurface stratigraphy and the nature and extent of the contamination is fundamental to the design of a cleanup strategy for any site. Characterization is currently done using a rather standard procedure involving surface geophysical techniques, drilling, sampling and laboratory testing, and the placement of monitoring wells. The U.S. Army Corps of Engineers estimates that to have 95% confidence that they have detected every contaminated site within the Rocky Mountain Arsenal, they would need to drill 297,000 borings which would cost more than one billion dollars. The conventional process is plagued by the lack of interactive analysis of the data from the various sources, inherent slowness and high cost of drilling and sampling, time and cost required for laboratory testing, and lack of real-time decision making capability.

The objective of this program was to develop a method of combining the geophysical data normally generated in a site characterization program with data which can be obtained with an Electric Cone Penetrometer Technique (ECPT) and to develop a procedure which would allow the analysis of this data to be accomplished in the field in near-real time.

Synergism is defined as "the total effect is greater than the sum of the individual effects." It was anticipated in this program that using the results of geophysical measurements to guide the cone

penetrometer work and, in turn, using the results of CPT measurements to aid in interpreting the geophysical models would result in synergistic effects producing faster, more accurate site characterization than would be possible using either method alone. It was taken as established that the ECPT method is more rapid and cost effective than drilling for evaluating subsurface geotechnical conditions.

TECHNOLOGY PERFORMANCE.

Various parts of the site characterization techniques considered in this study were tested at three different sites: near a landfill for the towns of Bethel and Royalton, Vermont; near the Los Lunas Volcano in New Mexico; and at the Homestake Partners Mill site near Grants, New Mexico.

The purpose of the work at the Bethel-Royalton Landfill was to evaluate the synergism between ECPT downhole resistivity and the surface geophysical resistivity measurements. One surface resistivity line and four ECPT probes were accomplished. The inversion of the surface resistivity data produced a number of possible solutions (layer depths and the resistivities of the layers) which were consistent with the data. All solutions produced two layers with an interface depth ranging from 25 to 44 ft below the surface. The resistivity of the second layer ranged from 60 to 150 ohm-m.

The resistivity data from the ECPT indicated a major reduction of resistivity at about the 12 ft depth. The stratigraphy developed from the standard ECPT data indicated this was the water table location. Based on this information, the surface data were reanalyzed forcing the resistivity drop to occur at 11.6 ft below the surface (the water table depth). The resulting resistivity profile from the surface data is shown overlain with the ECPT data in Figure A. This analysis resulted in a resistivity estimate in the saturated zone (i.e., layer below 11.6 ft) on the order of 150 ohm-m. The resistivity of the ground water in the vicinity of the landfill, but well up gradient from the plume, is reported to be 280 ohm-m. The lower resistivity measured by both the ECPT and the surface survey indicate that the water at the location of the measurements may be contaminated with conductive leachates from the landfill. This was detected by both techniques, but independent analysis of the two data sets produced significant differences in the estimate of the depth to the contaminated layer. However, by fixing one free variable in the surface data analysis based on the ECPT ground truth data, the two data sets produced a consistent model of the site. Although this study did not have the resources to completely characterize the site, the results of this evaluation suggest that the extent of the conductive plume could be quickly and relatively inexpensively mapped with a surface resistivity survey and a few ECPT measurements.

A second site, near Los Lunas, New Mexico, was selected to demonstrate the synergism of surface and ECPT seismic measurements. One key use of the surface reflection survey technique is to

Figure A. Forced surface resistivity inversion vs. ECPT resistivity data.

locate buried geologic features such as faults and buried channels. A buried channel had been identified in an exposed section at this site. This provided a rare opportunity to check the interpretation of a reflection survey. The intention was to use seismic velocities from the ECPT downhole seismic survey to convert the surface reflection time sections to depth sections. Unfortunately, the ECPT was unable to push below about 38 ft due to a hard, thick caliche layer. Therefore, only the velocity of the top layer and depth to the first major reflector were obtained. These data were used in the analysis of the reflection results, and were supplemented with velocities of the deeper layers estimated from a refraction survey. It was determined that the buried channel visible in the exposed sections of the site was accurately identified in the reflection survey data.

The objective of the work at the third site (Homestake Partners Mill) was to test all of the survey techniques and to generate enough data to exercise a database and a visualization code at a site where independent data were available to confirm our results. Figure B is a contour plot of the resistivity of the weathered shale basement layer determined from the surface resistivity survey. This plot was prepared by the data visualization code after entering the survey data into the database. The measurements represent the composite resistivity of the soil-rock sequence. Since the weathered shale is rather uniform in composition, the differences in resistivity reflect the variation in resistivity of the water in the shale fractures and voids. The zone of low resistivity down the center of the site suggests a concentration of the contaminant due to a geologic feature. The reflection survey indicated a buried channel in this location and explains this configuration.

TECHNOLOGY STATUS.

This study provided a limited evaluation of the synergistic benefit of combining surface geophysical methods with ECPT measurements in establishing subsurface site conditions. The study also evaluated the use of a database program, with geostatistical processing routines, and a graphics visualization package for facilitating data analysis.

The geophysical methods evaluated here were surface seismic reflection surveying and surface resistivity surveying. The experimental aspects of these methods are relatively mature. The analysis methods are less developed. Although simple, horizontally-layered geologies can be interpreted, the analysis of complex, multi-layered, three-dimensional (3D) geologies requires augmentation of the surface survey results with underground measurements. The ECPT was used to provide these results.

The ECPT technology, for the standard geotechnical measurements of tip and sleeve resistance, is well established. The use of the ECPT for downhole seismic surveying and resistivity measurements is a more recent development. Downhole seismic surveying has been used by Applied Research

Figure B. Contour map of the surface electrical resistivity basement of the Homestake Partners Mill Site.

Associates, Inc. (ARA) and others over the past few years and is becoming well established. Although several groups have claimed the use of ECPT resistivity cones over the last several years, there is not much evidence on their use and success in the literature. In this study, we expended a lot of effort designing, building, and fielding a resistivity cone that would survive the severe friction, gouging, and distortion encountered in probing hard sands, caliches, and gravels to large depths.

The speed with which large quantities of subsurface data can be generated using the ECPT suggests that replacement of much of the standard drilling and sampling currently used in site characterization programs with ECPT penetrations could reduce the cost of the site investigation process. The ECPT is limited only by the limited sensors currently available. The development of additional sensors for the ECPT will have a high payoff in insitu characterization.

The usefulness of the combination of downhole ECPT measurements with surface reflection and resistivity measurements was well established by this program. It was demonstrated that downhole ECPT measurements provide fine, accurate detail of the subsurface and provide quantitative support to the surface geophysical methods. As a result, the value of the surface measurements is greatly increased. The surface methods can then be used for rapid and relatively inexpensive surveying of large areas.

Modern database programs with graphic visualization software provide significant enhancement to the analysis of ECPT and surface geophysical results. However, the software available was not, for this program, sufficiently user friendly or integrated to permit rapid turnaround in the field to support real-time decision making. However, processing all the data obtained at a site through the same database and visualization package at the same time proved to be a major advantage for the analyst.

In conclusion, all of the technologies considered and their synergy were demonstrated in this program. The approach used here can and should be incorporated into all site investigation programs. The use of the approach at its current technology status will greatly improve the speed and accuracy of site investigation programs and reduce their cost. Parallel programs should be pursued to develop and demonstrate ECPT compatible contaminant and groundwater flow sensors, and to improve our ability to process and display measured data in the field on a schedule which will support real-time decision making.

TECHNOLOGY DESCRIPTION.

The major components of the minimally-invasive, three-dimensional site characterization method evaluated in this study are: (1) an enhanced Electric Cone Penetrometer Test, (2) surface resistivity and surface reflection geophysical methods, and (3) a field database and visualization code.

The Electric Cone Penetrometer hydraulically pushes a 1.450-in diameter instrumented probe into the ground. The data from the ECPT probe are recorded and stored. Standard data from the ECPT are the load (force) on the 60° conical tip, the frictional load on the sleeve of the cone, and pressure in the fluid within the soil pores. This data may be analyzed to develop a characterization of the soils, the layering, and the water table location. Additional sensors allow measurement of the soil-water matrix resistivity and the seismic profile of the site.

The surface geophysical tools used in this project were seismic reflection and electrical resistivity. Seismic reflection detects seismic impedance contrasts in the underground which can identify hydrogeologic features. Reflection analysis yields "time sections" (i.e., site cross-sections of data traces vs. testbed location). "Variable area/wiggle trace" representation of the data in this time-range space allows location of reflection horizons. Reflection surveys do not provide explicit measures of seismic wave velocities. These velocities are normally obtained from refraction and/or (more accurately) downhole or uphole surveys. The ARA ECPT provides an efficient and accurate system for performing P- and S-wave downhole seismic tests. The seismic velocities measured by these tests are used to convert the reflection time sections to depth sections. The ECPT can also be used to interpret anomalous results in the reflection survey data.

Resistivity is sensitive to, among other things, concentration of conductive (e.g., some leachates) contaminants in groundwater. The surface resistivity survey allows investigation of a large area in a rapid, continuous manner. Trends in surface resistivity data in many instances infer trends in contaminant concentration. Surface resistivity measurements are used to establish a layered site resistivity model from theoretical layered half-space models. Surface measurements alone, however, cannot resolve inherent ambiguity between the layer depths and the resistance of the materials within the layers. The downhole resistivity measurements made with the ECPT provide ground truth data for layer interfaces and layer resistances. This direct measurement of resistivity vs. depth may then be used to establish constraints on the inversion of the surface data. This synergistic analysis of the surface and downhole resistivity data leads to higher confidence in the results.

To evaluate and present large volumes of data rapidly, a database and visualization code is required. A commercially available code developed for geotechnical and mining applications was selected for this project. This code contained the statistical and modeling routines required to process and present the results of the site characterization program.

SECTION 1.0 INTRODUCTION

1.1 TECHNOLOGY SCOPE.

Site characterization and contaminant plume identification and location are the first steps in every environmental site restoration program. The current approach is a phased process involving surface geophysics, drilling and sampling, laboratory testing, and placement of monitoring wells. This process suffers from a number of drawbacks. It is slow and expensive, it produces contaminated waste which must be disposed of, and it often results in an incomplete or inaccurate interpretation of the subsurface conditions.

The objective of the Minimally Invasive Three-Dimensional Site Characterization method is to assist in resolving these deficiencies. The current research and development project applies fully-coordinated surface and subsurface exploration activities with a relational database management system to efficiently combine the results from those activities. The subsurface exploration is performed using the Electric Cone Penetrometer Test (ECPT) which is a less invasive, faster, and cheaper method for performance of that phase of characterization than is drilling. The ECPT is termed minimally invasive because no drilling waste is created and no drilling fluid which could become contaminated is used. In addition, it provides the opportunity to make downhole geophysical measurements during the penetration, which may be used in the analysis of the standard surface geophysical measurements, rendering higher confidence in those measurements. This interactive analysis of the data leads to a synergistic effect in that more information (or higher confidence information) can be obtained than if the data are analyzed and presented independently. The ECPT obtains subsurface characterization data as well as downhole geophysical data. This downhole geophysical data limits the degrees of freedom available in the geophysical data interpretation by providing ground truth data at the penetration location. These data are coincidental with the site stratigraphy obtained from the standard ECPT measurements.

The ECPT is accomplished by hydraulically pushing an instrumented probe into the ground. This method of advance causes little disturbance and does not transport contaminated material (i.e., drill cuttings) to the surface. Tip and sleeve resistance to penetration, and pore pressure are measured during cone advance allowing for precise identification of subsurface conditions such as water table location and changes in soil type. Other measurements, such as electrical resistivity and seismic velocity, are made to provide the ground truth measurements for use with the surface geophysical measurements.

While the ECPT provides direct, subsurface measurements at selected points, general reconnaissance is achieved through surface geophysical surveys. Seismic reflection profiling and electrical resistivity were chosen for the current effort to illustrate the methodology, but other tools may be

appropriate for specific site/contaminant conditions. Surface geophysical techniques provide rapid coverage of large areas, and allow identification of anomalies as well as interpretation of the conditions in the regions between the ECPT measurements.

The approach is facilitated by combining the results from each of the survey tools within a relational database that possesses state-of-the-art graphics and analysis tools (e.g., statistics, estimation, and modeling algorithms), and that can be operated on an on-site workstation. Data can be supplied to the database in near real time; subsequent data review can reveal information suggesting proactive changes in the survey plan to enhance the information. Interesting or questionable locations may be identified for obtaining additional data.

The product of this effort is a system which produces a synergism among the various data sets. The ECPT results enhance the information gained from surface geophysics and reduce the uncertainties in interpretation of those data. The surface geophysics fill the gaps between the ECPT locations. The relational database enhances the analysis capability while the survey is in progress, allowing adjustments to the survey plan which consider the expanding information base. Ultimately, more information regarding site character will be gathered in less time and at less expense than when using the current approach.

1.2 TECHNOLOGY PROGRAM REQUIREMENTS.

The Applied Research Associates, Inc. (ARA) Minimally-Invasive, Three-Dimensional Site Characterization System supports the Department of Energy (DOE)/OTD mission by providing faster, safer, less costly, and better site characterization. This leads to optimum placement of monitoring wells and a more accurate picture of the subsurface conditions. This approach also reduces the potential for site personnel exposure to hazardous materials, and minimizes the hazardous material disposal problems associated with the exploration process.

SECTION 2.0

METHODOLOGY AND APPROACH

2.1 FACILITIES AND EQUIPMENT.

The following paragraphs describe the equipment components used for the development of the Minimally Invasive Three-Dimensional Site Characterization System.

2.1.1 Electric Cone Penetrometer.

The electronic cone penetrometer test was originally developed for use in consolidated clay soils (Reference 1). Over the years, cone and push system designs have evolved to the point where they can now also be used in rather strong cemented soils. ARA's penetrometer consists of an instrumented probe which is forced into the ground using a hydraulic load frame mounted on a heavy truck, with the weight of the truck providing the necessary reaction mass. The probe has a conical tip and a friction sleeve which independently measure vertical resistance beneath the tip, as well as frictional resistance on the side of the probe as functions of depth. A schematic view of ARA's penetrometer probe is shown in Figure 1. A pressure transducer in the cone is used to measure the pore water pressure as the probe is pushed into the ground. The probe includes three seismic transducers, which are used to perform downhole seismic surveys. In addition, a resistivity module is attached to the cone assembly to measure variances in soil conductance.

The penetrometer probe is of standard dimensions having a 1.405-in outside diameter, 60° conical tip, and a 1.405-in diameter by 5.27-in-long friction sleeve. The shoulder between the base of the tip and the porous filter is 0.08 in long. A 1.5-in expander, located 5.25 in behind the top of the friction sleeve, pushes the penetration hole open and reduces the frictional drag on the push tubes behind the probe. The penetrometer is normally advanced vertically into the soil at a constant rate of 48 in/min, although this rate must sometimes be reduced as hard layers are encountered. The ECPT is conducted in accordance with ASTM D3441 (Reference 2).

Inside the probe, two load cells independently measure the vertical resistance against the conical tip and the side friction along the sleeve. Each load cell is a cylinder of uniform cross section inside the probe which is instrumented with four strain gages in a full-bridge circuit. Forces are sensed by the load cells and the data are transmitted from the probe assembly via a cable running through the push rods. The analog data are digitized, recorded, and plotted by computer in the penetrometer truck. A set of data is normally recorded each second, for a minimum resolution of about one data point every 0.8 in of cone advance. The depth of penetration is measured using a string potentiometer mounted on the push frame.

Figure 1. Schematic of ARA penetrometer probe.

The piezo-cone probe senses the pore pressure immediately behind the tip. The filter is located behind the tip and is protected from the direct thrust of the penetrometer. The measured pore pressure can be used to correct the tip resistance data (discussed below) as recommended in Reference 3. The magnitude of the penetration pore pressure is a function of the soil compressibility and, most importantly, its permeability. In freely draining soil layers, the measured pore pressures will be very close to the hydrostatic pressure computed from the elevation of the water table. When low permeability soil layers are encountered, excess pore pressures generated by the penetration process cannot dissipate rapidly and this results in measured pore pressures which are significantly higher than the hydrostatic pressures. Whenever the penetrometer is stopped to add another section of push tube, or when a pore pressure dissipation test is run, the excess pore pressure will begin to dissipate. When the penetration is resumed, the pore pressure quickly rises. This process causes the spikes that may appear in the pore pressure data.

The seismic cone penetrometer test was developed in the early 1980's, and is gaining rapid acceptance in the geotechnical community (Reference 4). As with the conventional ECPT, initial development work has concentrated in weak materials. The ARA seismic cone penetrometer test utilizes three geophones (Geospace Model GS-14-28 velocity gages) mounted inside the penetrometer probe to detect the arrival at depth of seismic waves generated on the surface. Two horizontal transducers monitor shear wave (S-wave) traces from which the shear wave velocity can be determined. A third geophone, mounted vertically, is used to measure the compression wave (P-wave) traces and to subsequently derive the compressional wave velocity. For the seismic tests, the cone penetrometer is stopped at prescribed depth intervals, and S- and P- waves are generated on the ground surface near the push rods. Both average downhole velocities and velocities between the depth intervals can be computed from the arrival time data. High energy shear waves are generated by either an automated shear wave source mounted inside of the CPT rig's front pad or by hitting the pad with a sledge hammer. The impact on the front lifting pad of the penetrometer truck induces a horizontal polarized shear wave. By striking the opposite end of the pad, a shear wave of opposite polarity can be generated. The point of impact of the shear hammers is 52 in horizontally from the penetrometer push rod. Compressive waves are generated by hitting a plate with a sledge hammer. The point of impact is 115 in horizontally away from the push rod.

The resistivity module is a four-electrode device. Electrodes are .25-in-wide, 1.75-in-diameter steel rings isolated from the steel push rod and from each other by an insulating material. The outer electrodes are at 3.25-in spacing and the inner electrodes are at 1.75-in spacing center to center. The outer electrodes are the field current source and inner electrodes sense field voltage as is commonly done in surface resistivity surveys. An alternating field current at a frequency of approximately 170 Hz is used to avoid electrode polarization effects.

Electronic data acquisition equipment for the cone penetrometer consists of an IBM-compatible 486 computer with a graphics monitor and a rack of eight ECTRON signal conditioners. Analog signals are transmitted from the probe to the signal conditioners where the ECPT data are amplified and filtered at one Hz. Seismic signals are amplified as required and filtered with a 1000-Hz, low-pass filter. Once amplified, the analog signals are transmitted to a MetraByte Hi-Res, 16-bit, high-speed, analog-to-digital converter board. There, the signals are digitized; usually at the rate of one sample per second for the penetration data and 5,000 samples per second for the seismic data. The digital data are then read into memory, plotted on a graphics monitor, and written to the internal hard disk for future processing. Data displayed on the screen can be used to determine site layering as it is encountered. This allows important decisions to be made in real time directly in the field. Upon completion of the test, the penetration, dissipation, seismic, and resistivity data are plotted. Plots can typically be available within 30 minutes of completing the test.

As a quality control measure, as well as a check for instrument damage, the load cells, the pressure transducer, and the resistivity sensor are routinely calibrated in the field. Calibrations are completed with the probe ready to insert into the ground so that any factor affecting any component of the instrumentation system will be included and detected during the calibration.

The tip and sleeve load cells are calibrated with the conical tip and friction sleeve in place on the probe. For each calibration, the probe is placed in the push frame and loaded onto a precision reference load cell. The reference load cell is periodically calibrated in ARA's laboratory against NIST traceable standards. To calibrate the pore pressure transducer, the saturated probe is inserted into a pressure chamber with air pressure supplied by the compressor on the truck. The reference transducer in the pressure chamber is also periodically calibrated against an NIST traceable instrument in ARA's laboratory. Additionally, the string potentiometer, used to measure the depth of penetration, is calibrated against a Lufkin ruler.

The seismic transducers are not calibrated since only the time of the signal arrival is used in the calculation of wave speeds.

Field calibration of the resistivity probe is made with the probe in free air. A zero field current calibration is made with the outer electrode open and a maximum field current calibration is made with the outer electrodes shorted. Zero voltage is calibrated by shorting the inner electrodes. Maximum voltage is calibrated by connecting a three-resistor network across the four electrode terminals.

2.1.2 Electrogeophysical Equipment.

The electrogeophysical equipment used on this project was manufactured by Zonge Engineering & Research Organization of Tucson, Arizona (References 5 and 6). A transmitting loop antenna was jointly designed by ARA and Sandia Research Associates, Inc. A current clamp was fabricated by ARA to allow the Zonge equipment to be used for dipole-dipole arrays.

The Zonge equipment included:

- 1) GDP-16/4 Receiver;
- 2) ZT-20 Transmitter;
- 3) TEM/3 Antennas;
- 4) Two-way fiber optic link;
- 5) Accessories including antenna stands, cables, and battery chargers.

The transmitting loop antenna was one meter in diameter and consisted of 96 turns of AWG #14 wire with insulation rated at 600 V. A five-turn current sense winding was included to provide a reference voltage proportional to the current in the coil and the magnetic field. Tuning capacitors were used to reduce the loop impedance at high frequencies and utilize the transmitter power.

The equipment was initially tested in a loop-loop configuration as shown in Figure 2. A systematic phase shift was discovered in the fiber optic equipment as a function of the sense winding voltage from the loop antennae. This problem probably could have been overcome with a redesigned limiting amplifier on the sense winding. However, jitter in the clock signal through the fiber optic system was discovered as well. At this point it was decided to run subsequent tests using a two-pair shielded cable for transmission of clock and reference signals between the receiver and transmitter locations. Subsequent tests with this configuration produced some results which appeared reasonable. However, data were not as repeatable as the data obtained with a dipole-dipole array on the same site. The survey data for the tests sites was collected with the equipment reconfigured as shown in Figure 3 in a dipole-dipole configuration.

2.1.3 Seismic Reflection Equipment.

The seismic energy source used for the surface surveys for this project is a "soft" dropped weight (U.S. Patent No. 4124090). This weight consists of lead birdshot contained in a heavy leather bag with a steel clamp and a support loop at the top. It weighs 550 lb and is dropped to the ground from a height of 6.5 ft. The weight is lifted by electric winch and is supported from an A-frame mounted in the rear of a one-ton, four-wheel-drive truck. The "soft" weight eliminates source bounce, producing a clean, repeatable

Note: Two-pair shielded cable was substituted for fiber optic link.

Figure 2. Loop-loop survey configuration.

Figure 3. Dipole-dipole configuration.

seismic impulse with useable frequency content in about the 5-Hz to 240-Hz range. The data from two to four weight drops are usually summed at each recording position.

The receivers used are twelve Mark Products G-21 10-Hz, digital-grade, gimbal-mounted, self-orienting, vertical drag geophones. They are attached to cables towed behind the seismic truck. Two geophone spacings are used in different circumstances — either 16.5 ft for shallow emphasis, or 33 ft for deeper emphasis. In the case of the shallow emphasis technique, the total length of the receiver array, from weight-drop impact point to farthest geophone, is 198 ft. With the deeper emphasis array, this length is 396 ft. Where the 16.5-ft receiver spacing is used, the source point/recording positions are chained 8.25 ft apart along the seismic line, for 640 recordings per line mile. Where the 33-ft geophone spacing is used, the recording positions are 16.5 ft apart along the line, producing 320 recordings per mile.

The recording instrument is an EG&G Geometrics ES2401 multi-channel seismograph system. The output of each of the 12 geophones is recorded separately. Both analog (paper) and digital (3-1/2 in HD diskette) recordings are made at each recording position. The normal record length is 0.5 s with 0.5 ms sample interval for the shallow emphasis technique and 1.0 s and 1 ms for the deeper emphasis technique. Recording filters are normally 50 Hz to 500 Hz, with a 60-Hz notch filter.

2.2 EXPERIMENTAL.

2.2.1 Electric Cone Penetrometer Experiments.

The only part of the ECPT equipment used on this program which required additional development was the resistivity module. Laboratory and field experiments were conducted to evaluate the resistivity module cone and electronics, both of which were designed and fabricated by ARA.

The resistivity cone was calibrated in a 55-gallon plastic barrel using deionized water. The resistivity of the solution was varied by the addition of sodium chloride. The plastic barrel was nonconducting and was sufficiently large to eliminate significant boundary effects. Current electrodes were driven with alternating current to avoid effects of electrode polarization. Resistivities of water solutions were initially measured in simple column experiments and later using a commercial water conductivity meter (Hanna Instruments, Model HI8033, serial no. 983598). The objective of these experiments was to establish a geometric factor, which when multiplied by the voltage observed across the inner electrodes, and divided by the current through the outer electrodes, yields the resistivity of the solution. The use of a water solution was preferred over soils for calibration because variations of soil contact resistance affect the voltage/current ratio. Experiments were conducted with the push rod isolated and in contact with the solution because it was thought that the conducting rod in the field might effect the calibration factor.

However, no effect was observed. The results correlated very well with a simple analytical model that ignored the effects of the conducting push rod in the electrical field.

The original design for the resistivity probe used ceramic insulators to isolate the electrodes. This material worked well in clay soils, but the ceramic is quite brittle and tended to crack when pushed through gravelly materials. Several other insulating materials were tried with very limited success. After completion of the field work for this program, a Kevlar material (Hydlan Z Nylon/Kevlar thermo-plastic composite) was obtained. It has performed very well on subsequent programs.

2.2.2 Seismic Reflection Experiments.

The surface seismic reflection equipment and procedures used on this project were all well developed and evaluated. No additional development was required.

2.2.3 Electrogeophysics Experiments.

At the start of the project, several alternative resistivity surveying methods were considered, including controlled-source, audio-frequency magnetotellurics (CSAMT) (Reference 6), electromagnetic (EM) conductivity, and dipole-dipole methods. Based on analysis of the expected system performance and fielding requirements, the electromagnetic conductivity method, also referred to as the loop-loop method, was selected (References 7, 8, and 9). Zonge Engineering equipment was selected because it appeared to provide greater survey flexibility than other known electrogeophysical equipment. Both field and laboratory experiments were conducted to evaluate the system and components.

Early field trials produced poor results, and component tests were conducted to attempt to isolate the problems. Tests were conducted to evaluate the fiber optic cable used to synchronize the transmitter with the receiver, the receiving antennas, and the receiver itself. The fiber optic cable interface electronics were found to have a phase shift that correlated with the level of the transmitted signal due to the level-detecting circuits. Because the transmitter antenna was tuned, and the current level varied with frequency, it was required that the fiber link be calibrated with respect to frequency. Following calibration of the fiber optic cable, long-term monitoring on an oscilloscope revealed that a random jitter was also present. As a result of these experiments, it was concluded that an electrical cable would be used for the field trials.

Calibration tests of the receiving antennas indicated that they were nominally performing according to data supplied by Zonge Engineering. Tests of the receiver indicated uncertainty of phase measurements at low signal levels, which could be partially overcome by extensive signal stacking.

Stacking significantly extended the time required to take field data. The other alternative was to increase the transmitted power, which tended to reduce the field portability of the system.

A final field trial of the EM conductivity system was conducted at a site west of Albuquerque, NM, believed to be deep sand with little or no clay. Soundings were made with the EM conductivity system and with a Wenner array. The conductivity data showed some promising trends. However, direct interpretation of the data gave results that were unrealistic and that were not consistent with the results obtained with the Wenner array. Regression analysis of the data indicated that the system might contain a delay on the order of 3 ms that was not accounted for. Data at a range of 250 ft between antennas were too noisy to be useful.

The conclusions reached from these experimental activities were:

- The complexity of an EM conductivity survey using this equipment was excessive when compared to the potential advantages.
- Resolving the remaining problems did not promise benefits great enough to justify the effort and expense required.
- The cost of an EM conductivity survey with the Zonge equipment would exceed the cost of a dipole-dipole survey because of equipment cost and high-skill-level personnel required to field the system and interpret the data.
- Geonics equipment should have been selected for an EM conductivity survey although there is doubt if that equipment would have worked well at depths of interest and low resistivity levels encountered at the Homestake site.

2.3 DATA REDUCTION AND INTERPRETATION.

2.3.1 Electric Cone Penetrometer Data.

2.3.1.1 Data Reduction. Figure 4 illustrates a typical electric cone penetration profile. The measured sleeve friction, corrected tip resistance, pore pressure, calculated friction ratio, and calculated hydrostatic pore pressure are plotted as functions of elevation. The surveyed coordinates of the test location are provided at the top of the plot.

Tip resistance, q_c (psi) is obtained by dividing the vertical force, in pounds, on the conical tip by the effective tip area, $A(t)$ (1.55 in^2). The tip resistance is then corrected for pore pressures acting behind the conical tip as discussed below. The corrected tip resistance, q_T (psi), is plotted in the penetration profile. The sleeve friction, f_s (psi), is obtained by dividing the total frictional force on the sleeve (as measured by the sleeve load cell) by the sleeve's surface area (23.25 in^2). The offset between the depth

North 32372.0 ft. East 45726.0 ft. Elevation 41.26 ft.

Figure 4. Typical ECPT penetration data.

at the tip and the depth at the friction sleeve is corrected by shifting the sleeve friction profile downward so that it corresponds to the depth at the centroid of the tip. In addition to the tip resistance and sleeve friction, a friction ratio profile is plotted for each location. This ratio is the sleeve friction expressed as a percentage of the tip resistance at a given depth. In uncemented soils, the friction ratio can be correlated to soil behavior.

The penetration pore pressure that is measured as the probe is advanced is also plotted in Figure 4. The piezo-cone probe senses the pore pressure immediately behind the tip. The magnitude of the penetration pore pressure is a function of the soil compressibility and, most importantly, permeability. In freely draining soil layers, the measured pore pressures will be very close to the hydrostatic pressure computed from the elevation of the water table. When low permeability soil layers are encountered, excess pore pressures generated by the penetration process cannot dissipate rapidly, and this results in measured pore pressures which are higher than the hydrostatic pressures.

Cone penetrometers, by necessity, must have a joint between the tip and sleeve. Pore pressure acting behind the tip decreases the total tip resistance that would be measured if the penetrometer was without joints. The influence of pore pressure in this joint is compensated for by using the net area concept (Reference 3). The corrected tip resistance is given by:

$$q_T = q_c + u \left(1 - \frac{A_n}{A_T} \right)$$

where: q_T = corrected tip resistance (psi)

q_c = measured tip resistance (psi)

u = penetration pore pressure measured behind the tip (psi)

A_n = net area behind the tip not subjected to the pore pressure (1.257 in²)

A_T = projected area of the tip (1.550 in²)

Laboratory calibrations have verified this equation for ARA's piezo-cone design.

A joint also exists behind the top of the sleeve (see Figure 1). However, since the sleeve is designed to have the same cross sectional area on both ends, the pore pressures acting on the ends of the sleeve cancel out. Laboratory tests have verified that the sleeve is not subjected to unequal end area effects. Thus, no correction for pore pressure is needed for the sleeve friction data.

Typical seismic shear wave traces are shown in Figure 5. The distance, D_s , is the straight line distance from the seismic source to the seismic transducers in the cone probe. Arrival times of the shear

Figure 5. Typical shear wave traces from seismic cone penetrometer tests.

waves are indicated on the figure. At some depths, compression wave contamination of the shear wave signal is observed, such that the first apparent arrival is not necessarily the shear wave arrival. The procedure used to select the shear arrival time is to choose the arrival of the first major shear wave. The use of polarized shear waves clarifies this time-of-arrival.

Typical compressional wave traces from the same site are shown in Figure 6. Determining the arrival time of the compressional wave is relatively more difficult. As shown in Figure 6, the inflection point where the particle velocity begins to change rapidly is selected as the arrival time. This point can usually be determined with consistency.

The resistivity electronic module provides two channels of data, with one channel being the current delivered to the outer rings, and the other consisting of the measured voltage drop measured across the inner two steel rings of the probe. The resistivity electronic board is designed such that the signal varies between ± 5 volt signal and no additional amplification is required. As with the other channels of data, the current and potential signals are filtered at 1 Hz and stored as digital data. The current and voltage potential data are then converted to apparent resistivity of the earth using equation:

$$\rho = K \frac{V}{I}$$

where: ρ = resistivity
 K = probe constant
 V = voltage potential
 I = current

The resistivity data is then plotted as a function of elevation (or depth)

2.3.1.2 Data Interpretation. Tip stress, friction ratio and penetration pore pressure profiles are the most important parameters for estimating soil behavior type from ECPT data. The magnitude of the tip resistance is a function of the strength of the soil, with stronger materials having higher tip resistances. In general, tip resistance increases as the coarse grained soil content increases and decreases as the fine grained content increases. This trend can be affected by the degree of consolidation of the soils, with the degree of consolidation increasing both the tip and sleeve resistance. Over consolidation can be caused by previous loading of the soil or by desiccation. For a given soil, the tip resistance increases with depth due to the increase in overburden stresses.

Figure 6. Typical compression wave traces from seismic cone penetrometer tests.

The friction ratio is a good indicator of the cohesiveness of the soil, which in turn reflects the fine grained soil content. Soils which are predominantly fine grained have friction ratios generally greater than 2, and sandy soils have ratios of 2 or less. The penetration pore pressure response is a function of the soil's shear stiffness, hydraulic conductivity, and density. For normally consolidated soils, the penetration pore pressure will be greater than the static pore pressure for clays and silts and equal to the static pore pressure for clean sands. In over consolidated, dense soils, the pore pressure response can be less than the static pore pressure, especially in those soils which tend to dilate, such as silty sands. The combination of the friction ratio and pore pressure response provide a good identification of the soil stratigraphy. With this basic understanding of the ECPT data, an analyst can interpret the soil behavior type and stratigraphy.

Plots of normalized tip resistance versus friction ratio and normalized tip resistance versus penetration pore pressure can be used to determine soil behavior type as a function of depth. Both methods of soil classification are based on empirical charts developed by Robertson (Reference 3). The soil classification is determined from the charts shown in Figure 7 by using the normalized corrected tip stress and pore pressure ratio, B_q , or normalized friction ratio of f_{sn} . The pore pressure ratio is defined as:

$$B_q = \frac{U_{meas} - U_o}{q_T - \sigma_{vo}}$$

where: U_{meas} = measured penetration pore pressure

U_o = static pore pressure, determined from the water table elevation

q_T = corrected tip resistance

σ_{vo} = total overburden stress

and the normalized friction ratio is defined as:

$$f_{SN} = \frac{f_s}{q_T - \sigma_{vo}} \times 100$$

and the normalized tip resistance is defined as:

$$q_{NT} = \frac{q_T - \sigma_{vo}}{\sigma_{vo}}$$

Soil Classification

1. Sensitive, Fine Grained
2. Organic Soils-Peat
3. Clays - Clay to Silty Clay
4. Silty Mixtures - Clayey Silt to Sandy Silt

5. Sand Mixtures - Silty Sand to Sandy Silt

6. Sands - Clean Sand to Silty Sand

7. Gravelly Sand to Sand

8. Very Stiff Sand to Clayey* Sand

9. Very Stiff, Fine Grained*

(*) Heavily Overconsolidated or Cemented

Figure 7. Soil classification using the cone penetration tests (Reference 3).

The intersection point of the q_T and B_q or f_{SN} values normally falls in a description zone. The description zone number corresponds to a soil description as shown in the figure. At some depths, the ECPT data will fall outside of the range of the description chart. When this occurs, no data are plotted and a break is seen in the profile.

ARA has modified this procedure to describe intermediate soil types. These two charts are combined into a single profile based on engineering judgment and any available data from the site. The soil profiles are very detailed, frequently indicating significant variability in soil types over small changes in elevation. To provide a simplified soil stratigraphy for comparison to standard boring logs, a layering and generalized description system has been implemented. A minimum layer thickness of 1.5 ft was selected. Layer thicknesses are determined based on the variability of the soil description profile. The layer sequence is begun at the ground surface, and layer thicknesses are determined based on deviation from the running mean of the soil description number. Whenever an additional 4.5 in increment deviates from the running mean by more than 0.50, a new layer is started, otherwise, this material is added to the layer above and the next 4.5 in section is evaluated.

The soil type for the layer is determined by the mean value for the complete layer. The eleven types are classified as:

<u>Classification Range</u>	<u>Soil Type</u>
1.00 - 2.25	Sensitive Clay
2.25 - 2.75	Soft Clay
2.75 - 3.25	Clay
3.25 - 3.75	Silty Clay
3.75 - 4.25	Clayey Silt
4.25 - 4.75	Sandy Fine Grained
4.75 - 5.75	Sand Mixture
5.75 - 6.75	Sand
6.75 - 7.50	Gravelly Sand
7.50 - 9.00	Over Consolidated (OC)

Soil descriptions for a typical ECPT push are shown in Figure 8. File material descriptions logged by a geologist in an adjacent hole are also shown for comparison. The agreement is quite good.

*Classification Key

- 1 - Sensitive
- 2 - Peat
- 3 - Clay
- 4 - Silt Mix
- 5 - Sand Mix
- 6 - Sand
- 7 - Gravelly Sand
- 8, 9 - Over Consolidated

Figure 8. Soil descriptions from interpretation of the ECPT data.

2.3.2 Seismic Reflection Data.

The digital reflection records are processed on a 80386/87-based microcomputer to produce seismic record sections which may be interpreted for geologic features such as buried channels, faults, and folds which will affect the site hydrology. For the optimization of shallow data (e.g., from less than about 150 ft deep), record sections using only the nearest one or two seismic traces are constructed. In this case, a high-frequency band pass, such as 180 Hz to 500 Hz, is often used. One-eighth second to one-quarter second is commonly plotted for these sections.

For deeper data, all traces are utilized. The data are reduced through a series of computer processes in which slant stacking is applied. After the data are transcribed to the computer and edited, coherent noise subtraction (CNS) is applied. This is a process by which the reflection records are scanned (slant-stacked or sonogrammed) through the apparent range of coherent noise, typically 7 ms to 47 ms per trace, which usually includes refractions, groundroll, and airwaves. The resulting slant-stacked records are then subtracted from the field records, which commonly reduces the coherent noise by 18 dB to 24 dB. Next, the records (those made after CNS) are slant-stacked in the predictable dip range of reflections (usually -6 ms to +6 ms per trace). The data are then common-depth-point (CDP) stacked 1200% and filtered (commonly 50 Hz to 240 Hz). The total reduction of coherent noise by the combination of CNS, slant signal stacking, CDP stacking, and frequency filtering is on the order of 48 dB. If the data prove to show many troublesome diffractions, which often happens in alluvial sedimentary sections, migration may be employed to reduce the diffractions. Finally, a variable area or variable area/wiggle trace record section is plotted.

The shallow data are the principal information of interest in most environmental site investigations, so most of the interpretive effort concerns these results. The shallow record section is carefully examined, and lineups or events thought likely to be layer interface reflections are marked. These times are converted to depths using the seismic velocities and layer depths determined from the ECPT downhole surveys. A refraction analysis of the first arrivals from the traces provides backup information.

In addition to filling in between the ECPT locations, these deeper data provide information on any major geologic features which are beyond the depth of the cone penetrometer data.

2.3.3 Electrogeophysical Data Reduction and Interpretation.

The Zonge receiver that was used for both EM conductivity trials and for subsequent Wenner surveys provides a direct screen readout and automatically logs measurement data. Data were manually logged during the survey as well. During a Wenner survey, apparent resistivity was calculated with each

sounding. EM conductivity data were downloaded from the receiver, formatted compatible with spreadsheet software, reduced to phase angle changes (Δ) by applying antenna and cable corrections, and then converted to conductivity. Apparent resistivity from Wenner arrays was reviewed with each sounding for consistency, and the sounding was repeated if it appeared to be questionable. A limited number of soundings had to be repeated; primarily due to a poor electrode stake connection. Raw data were printed out each day and compared with the log book to ensure there were no logging errors.

Commercial software, RESIX-PLUS, by INTERPEX, Ltd., (Reference 10) of Golden, CO, was used for inversion of apparent resistivity from Wenner arrays. The inversion software was tested by entering theoretical apparent resistivity for two-layered problems and was found to replicate the original model. The software provides a plot of apparent resistivity versus array spacing in log-log space. This allows identification of questionable measurements. Inversions can be run with and without questionable data points to allow the data analyst to determine whether or not the measurements are in error. The apparent resistivity versus array spacing generally are characterized by smooth curves, and bad data are not difficult to recognize. The analyst has options concerning whether layer resistivities and/or depths are fixed to known values from the ECPT survey, or of allowing the inversion routine to determine a fit with all parameters free. Output of the inversion software is in the form of plots and tables. Layer depth and resistivity output were then formatted for subsequent entry into the integrated site database.

2.3.4 Relational Database/Visualization Code.

The ultimate purpose of site characterization is to provide the necessary data to support the design of the remediation for the site. An integral part of that design is the understanding and prediction of the fluid and contaminant flow at the site. These processes involve not only the data obtained during the minimally invasive site characterization discussed here, but also other data obtained from historical records, previous investigations, and monitoring wells. The handling of such a large volume of data, and their analysis and presentation in formats which provide the maximum insight into the site, are major undertakings. To illustrate an approach for this task we have developed the architecture for an Adaptive Site Evaluation Strategy. The flow diagram for this strategy is shown in Figure 9.

The strategy ties the site characterization, transport calculations, and sampling approach into a database along with the prior information and provides a probabilistic framework for decisions concerning the value of additional data in improving the transport calculations.

The development and implementation of this entire strategy was beyond the scope of this project. However, it is important in structuring the codes which were used to do so in a way that they fit

Figure 9. Adaptive Site Evaluation Strategy.

into an overall strategy for data handling. The database we selected for this synergistic site characterization effort was intended as an integral part of the eventual Adaptive Site Evaluation Strategy framework.

The ARA site characterization methodology relies on advanced graphics and analysis to promote the synergism between the various survey methods. The software package TECHBASE, (Reference 11) developed by MineSOFT, Ltd. of Lakewood, CO, was used. TECHBASE capabilities include statistical analysis, estimation modeling, and data display within a relational database structure. This software performs univariate and multivariate statistical analysis of stored data. System graphics include plots of statistics and data display. Data plotting, contouring, cross-sections, perspective views, and vector drawings are possible. Point estimator methods include trend surface, triangulation, polygonal, and minimum curvature in two dimensions, and inverse distance and kriging in both two and three dimensions.

Table 1 provides a list of factors considered in choosing a database software package. TECHBASE was chosen because it uniquely accomplishes each of the ascribed tasks; i.e., the databasing, the data analysis and modeling, and the graphics. Other codes exist with more sophisticated graphics, but these would require separate codes for the databasing and modeling. Most database packages support primitive graphics and are limited to simple data calculations, versus the sophisticated statistics and estimation routines available in TECHBASE. TECHBASE is available on a multitude of platforms, allowing the technology developed under this research to be more universally applied. This project was accomplished via a Silicon Graphics, Inc. Personal Iris workstation, but TECHBASE is also PC-compatible and is available for use on several main frame computers. Finally, the size of the database is limited only by computer memory, and not by the code, thereby being capable of handling the large number of data points measured during an ECPT survey.

The software structure allows comparative analysis and plotting of data from different sources. For example, a cross-section through a site may include ECPT and surface resistivity profiles with surfaces determined from the seismic reflection survey. The ECPT profiles would represent direct interpretation of the data; the surface resistivity profiles would result from inversion of the apparent resistivity data; the surfaces (layers interfaces) would result from entering point interpretations of each seismic line and applying one of the estimation routines to interpolate the data. Differences or similarities in the results may be easily identified. Additionally, the surfaces estimated from the different data sets may be plotted in contour plots and three-dimensional (3D) surface plots for further comparison. Full color graphics and numerous pattern fill types enhance the data display. Plot overlay capability allows for separately developed information to be compared on a single display.

Table 1. Factors Considered in Choosing a Database Software Package.

1. Database must archive data, their location in time and space, and all its descriptors for retrieval and use in multiple operations.
2. Database must provide basic data review graphics and statistics
 - a.) Maps
 - b.) 3-D Graphics
 - c.) Kriging
 - d.) Visuals for combining and overlaying
3. Database must provide for combining different data families with common elements; such as layer boundaries from ECPT seismic, Finite Element Analysis, etc., and evaluate the relative agreement and confidence.
4. Some fundamental analytical work must be possible in the database.
5. Database must answer questions about its own sufficiency.
 - a.) Parameter sensitivities
 - b.) Areal data sufficiency
 - c.) Statistics
6. Database must provide graphical displays to develop site.
 - a.) Stratigraphic model
 - b.) Property description maps
 - c.) Hydrologic flowpaths
 - d.) Conceptual hydrogeologic model
7. Database must support the graphics for presentation of results.
8. Database must serve as archive and analytical sample tracking and documentary record of whole site characterization.

No attempt was made under this program to automate the synergistic analysis of the data. This was done manually by analyzing the available data and identifying the areas of different interpretation of the site. The data which represented the most direct and accurate measurement of a site feature were then used to place constraints on the interpretation of the other data sets. This was generally layer depths, especially water table rock depths, measured with the ECPT. This process is repeated with different constraints until the results of the different surveys present a consistent interpretation of the site.

This synergistic data analysis should not be confused with what is often called "data fusion," where the data are averaged using weighing factors based on the confidence in each data set.

2.4 QUALITY ASSURANCE.

The quality assurance (QA) strategy for the ARA Minimally Invasive Site Characterization Methodology development was based on the documentation of calculations, modeling, and development activities in a preliminary project report format, and record keeping to document the QA status of existing and acquired hardware and software (Reference 12). Any changes made to acquired elements of the data acquisition system were documented according to the guidelines contained in the Sandia National Laboratory (SNL) document entitled, "Quality Assurance Implementation Procedure - Software Quality Assurance Requirement", (References 12 and 13).

The conceptual framework for the integration of existing, acquired, and developed elements into a site characterization system was provided by Reference 14 and was based on a conceptual site model. The conceptual site model permitted the application of the site data quality objectives to define the site characterization capabilities needed by the integrated site characterization system. These requirements allowed for assessment of the adequacy of existing elements of hardware and software. Instrumental detection requirements, database requirements, data handling standards, and the adequacy of analyzed results from each element of the system were assessed. Reports on the expected performance of each element were prepared for the QA file.

An example of the application of this technical and QA approach was the assessment of the suitability of several electrogeophysical methods. Resolution requirements and site parameters were developed from the conceptual site model. Appropriate forward and inversion models were chosen and applied to parametric sensitivity testing of each method. Instrumentation systems which could be used to acquire field data were identified (those available from Zonge Engineering and Research Organization, Inc. and Geonics, Ltd). These systems had manufacturer QA certification to DOE standards, and provided extensive instrumental sensitivity and statistical data variability backup information. Although the comparison of the site geophysical models and the manufacturers' data identified that the Zonge data

acquisition system could meet the project data needs, bench testing and field testing of that equipment failed to conform to required sensitivities. Reports documenting this assessment were assembled. Each report was dated and signed by the staff and by the project technical area leader. Separate copies were included in both the project QA files and the technical area files. This is documented in detail in References 15 and 16.

Evaluation of the existing seismic and cone penetrometer systems was based on past performance, and comparison to data quality needs was derived from the conceptual site model. Computational requirements were assessed based upon the processing needs and data quantities developed from each of the methodologies, and the analytical needs of the overall database with reference to the conceptual site model.

As the development tasks were nearing completion, three field testing sites were selected. A field testing plan (Reference 17) was prepared, reviewed, and placed in the project QA file. A data analysis plan (Reference 18) was also prepared, reviewed, and placed in the project QA file. Field tests were conducted at the sites in general conformance with the test plan and results were analyzed in general conformance with the analysis plan.

SECTION 3.0

RESULTS AND DISCUSSION

3.1 INTRODUCTION.

Various components of the Minimally Invasive Three-Dimensional Site Characterization System were evaluated at three test sites. These sites included the Bethel-Royalton Landfill, VT, the Los Lunas Volcano, NM, and the Homestake Partners uranium mill site near Milan, NM.

3.2 BETHEL-ROYALTON LANDFILL SURVEY.

3.2.1 Objective.

The objective of the Bethel-Royalton, VT, Landfill investigation was to perform an assessment of the synergism between the ECPT and a surface electrical resistivity survey.

3.2.2 Background.

Previous investigations of this area were prompted by the apparent degradation of the water supply in the vicinity of the landfill. One possible source of the ground water contamination is a leachate plume from the landfill. Prior investigations included geological, seismic reflection, magnetics, electrical resistivity, EM terrain conductivity, and self potential surveys (Reference 19). Monitoring wells were also installed down-gradient from the landfill. The site consists of 8 to 20 ft of unsaturated sediments underlain by 30 to 60 ft of saturated sediments and/or glacial till, one to three layers of sand, and/or sand and gravel with intermixed clays, and the quartz-mica schist of the Gila Mountain formation. The bedrock topography is a result of glaciation. The rock has very little porosity, but fracturing of the rock has resulted in the development of reservoir quality porosity and permeability. There is no impermeable layer between the aquifer in the glacial overburden and the bedrock aquifer.

3.2.3 Results.

Wenner array soundings were conducted at four locations along the line illustrated in Figure 10. Array spacings for each sounding were 20 ft, 30 ft, 40 ft, 60 ft, and 80 ft. The array spreads extended along the survey line. One ECPT was performed at each Wenner sounding point. Figure 11 shows a representative suite of data for one of these penetrations, BR01C. The ECPT probe included tip resistance, sleeve resistance, pore pressure, and electrical resistivity. The subsurface stratigraphy developed from the ECPT data is shown in Figure 12. The X at the bottom of each penetration indicates ECPT refusal which is interpreted as the top of the weathered schist of the Gila Mountain formation.

Figure 10. Bethel-Royalton Landfill site map.

Figure 11. ECPT data from location BRO1C, Bethel-Royallon Landfill (WT indicates water table).

Figure 12. Bethel-Royalton Landfill test site interpretation.

Figure 13 shows a typical set of data from one of the Wenner sounding locations. Both the measured apparent resistivity data versus the electrode spacing and the inversion of these data are shown. The inversion program RESIX-PLUS produced a number of possible solutions to the layer depths and the resistivities of the layers. They were all two layer solutions with an interface depth ranging from 25 to 44 ft below the surface. The resistivity of the second layer ranged from 60 to 150 ohm-m. The data point at the 30-ft spacing appears inconsistent and contributes to the large variation in inversion results.

The surface resistivity reflects the full three-dimensional conditions. The slope of the top of the bedrock indicated by penetration refusal between soundings BR01E and BR02E is quite steep, as evidenced by the penetration depths of BR01C and BR03C. (Later penetrations performed between BR01C and BR03C confirmed that the edge of the buried ravine is very near to BR01C.) The result would be that the intermediate surface spacings for BR01E may have been influenced by much shallower bedrock depths than exist at and near the actual sounding location. The resulting inversion would be influenced by the higher resistivity (bedrock) material.

The ground truth data provided by the ECPT resistivity measurements, however, allow the reduction of the degrees of freedom in the surface interpretation and illustrates the advantage of the synergistic interpretation of the two data sets. Since the water table location is measured with high confidence with the ECPT, this depth was fixed and the surface data inversions were repeated. Figure 14 shows the resulting comparison. While the surface data clearly does not show the detail indicated by the downhole measurement, the two are now in excellent agreement and both present a clear picture of the subsurface conditions.

The resistivity of the water in the vicinity of the landfill, but well away from the contamination plume, averages about 280 ohm-m.

The survey indicated that the water in the location of the measurements is contaminated (decreased resistivity). While this was detected by both techniques, the ECPT data fixed the depth to the saturated zone and therefore significantly reduced the uncertainty in the interpretation of the surface data. The extent of the contamination plume could now be quickly and inexpensively mapped with a surface resistivity survey and a few ECPT resistivity measurements.

3.3 LOS LUNAS VOLCANO SURVEY.

3.3.1 Objective.

The objective of the Los Lunas Volcano, NM, site testing was to evaluate the ability to locate a buried channel with a seismic reflection survey. The survey was performed on a mesa surface, parallel to a

Figure 13. Surface resistivity data and inversions, Bethel-Royalton Landfill.

Figure 14. Forced surface resistivity inversion vs. ECPT resistivity data.

deep cut which exposes the local structure to visual inspection. Downhole seismic data from the ECPT were to be used in the analysis of the reflection data.

3.3.2 Background.

The silty soil and gravel beds of the Santa Fe formation dip 5° to 15° concentrically away from a central volcanic plug. Pleistocene sandy and clayey beds in angular depositional contact above the Santa Fe formation dip more gently to the west, generally parallel to the mesa surface. A channel set into the Pleistocene sediments, with its bottom at about the Santa Fe/Pleistocene contact, is visible at the exposure. A review of aerial photography of the area suggests that the channel is straight, trending almost due west. Thin (18-in), locally discontinuous, caliche layers parallel the upper mesa surface, capping the Pleistocene sediments.

Figure 15 presents a topographic map of the Los Lunas Volcano test area. The locations of the seismic profile line and four ECPT penetrations performed at this site are shown on the map.

3.3.3 Results.

The seismic profile was conducted employing the 33-ft-spaced geophone spread. Data were reduced and interpreted as specified in Section 2.3.2.

Figure 16 presents a portion of the wiggle trace time-based section developed from the reflection data. Three major reflections are delineated in the figure. The uppermost reflection appeared to correspond to the near-surface caliche evident in the cut face. This reflection corresponds to an average two-way travel time of 30 ms, or a one-way travel time of 15 ms. Analysis of seismic ECPT data (see Figure 17) identified the compression wavespeed of the material above the caliche to be 2,390 ft/s. Combined with the one-way travel time, the depth to the caliche reflection is 35.9 ft. Penetration tests met refusal at this interface at depths ranging from 30.0 ft to 38.3 ft. Since the ECPT was not able to penetrate the caliche layer, it was impossible to obtain the downhole wave speeds below about 35 ft to use in analysis of the seismic reflection data. As a result, the reflection time sections were not converted to depth sections.

The other two reflection horizons illustrate the information which the reflection survey produces. The uppermost of these is likely intermittent caliche. The deepest reflection represents the contact between the Santa Fe formation and the Pleistocene deposited beds. The channel visually identified in the cut face is visible in the reflection horizon centered at about station 25. Detection of this channel with the seismic reflection data is significant since buried channels are important hydrogeologic features which can act as conduits for transport of contaminated ground water.

Figure 15. A topographic view of the Los Lunas Volcano test area.

Figure 16. LLOIS seismic line; portion including channel centered under Station 25.

Figure 17. Los Lunas Volcano test site ECPT p-wave seismic records.

3.4 HOMESTAKE PARTNERS MILL SITE.

3.4.1 Objective.

The objectives of the investigation at the Homestake Partners mill site were to evaluate all of the surface and downhole survey techniques in a more comprehensive manner at a single site and to obtain enough data to evaluate the database and visualization software.

3.4.2 Background.

The Homestake Partners uranium mill site near Milan, NM, has known contamination of salts and heavy metals which have leaked from the mill tailings pile into a perched water aquifer. Ongoing remediation of the site uses pump and treat procedures. Injection wells, downstream from the tailings pile near the site boundary, pump water from the regional aquifer into the perched aquifer. The intent is to force the contaminated ground water back toward the source where a series of wells extracts the contaminated water for treatment by evaporation.

3.4.3 Results.

The layout of the Homestake site and locations of the measurements made for this investigation are shown in Figure 18. The surface resistivity data were taken over the entire site to provide the primary data for the visualization programs. Two ECPT locations were made to coincide with the reflection lines and five were collocated with Wenner array points.

The natural flow of the perched aquifer (based on previous studies) was from the northwest to the southeast. The purpose of the injection and extraction wells was to reverse this flow on the site and thus prevent the contamination from leaving the site.

Problems were encountered with both the ECPT seismic and resistivity surveys. The trigger electronics and poor coupling of energy prevented obtaining any p-wave data although shear wave data were obtained at the two planned locations. The insulators separating the conductors on the resistivity probe were sheared off or torn by the weathered shale on the first push so only one ECPT resistivity profile was obtained. While these problems prevented obtaining the entire data set desired, they were not considered critical since this type of data had been obtained at the other sites. Fixes to both of these problems were made after the Homestake study and they are discussed in Section 4.

Figure 18. Homestake Partners test site map.

Figure 19 shows a full ECPT data set for one push at the Homestake Partners site. These include electrical resistivity, tip resistance, sleeve resistance, pore pressure, and a shear wave profile. Of particular interest is the zone between the approximately 6540-ft and 6520-ft elevations. This zone is evidenced by low penetration resistance (both tip and sleeve), low electrical resistivity, high pore pressure, and low shear wavespeed; probably a clay zone holding water in capillary suspension. A cross-section through the site (Section A-A' on Figure 18) is shown in Figure 20. This illustrates the relation between the shear wave velocity inversion layer and low tip resistance by including the shear wave velocity profile from HP08C. A second rendering of this section (Figure 21) shows the consistent correlation between high pore pressure and low tip stress. Figure 22 uses ECPT pore pressure and resistivity data to illustrate that the high pore pressure saturated zone is a zone of low resistivity, indicating that resistivity could be a parameter for tracking ground water at this site.

Figure 23 shows excellent comparison between the ECPT resistivity profile and the profile resulting from inversion of the surface EM data at the location. This observation suggests that surface resistivity could be correlated with the high pore pressure zones in the soil. Figure 24 illustrates that low resistivity layers in the inversion profiles agree quite well with the high pore pressure zones, particularly considering the variability in location of these zones and the 3-D nature of the surface measurements.

The surface resistivity measurements did not identify the aquiclude at this site due to the highly conductive nature of the ground water/clay matrix. However, two seismic reflection lines were performed as shown in Figure 18. Analysis of the time sections provided an estimate of the character of the aquiclude as indicated in Figure 25. The sections indicate a possible buried channel as evidenced by the dips in the estimated horizons. These data were not converted to depth sections due to the hardware malfunctions which prevented ECPT compression wave seismic tests. The relatively flat nature of the site, though, allows a valid refraction analysis of the reflection data set. The resulting composite profile is shown in Figure 26.

The refraction analysis identifies a strong refractor interface which represents the top of the aquiclude ("weathered shale"). This depth, 61 ft, is consistent with the depths of penetration refusal for this site; HPO3C, shown in Figure 19, met refusal at 63.2 ft. Hence, the reflection survey identified a hydrogeologic feature which at this site could not be interpreted from the surface resistivity data.

Data at this site suggest that to gain insight into a complex hydrogeology setting, a number of survey techniques are necessary. The ECPT electric resistivity data provide corroboration of the surface resistivity data. The seismic reflection data located a buried channel and allowed extrapolation of the aquiclude depth determined by ECPT refusal. Both of these provide important stratigraphic information for interpreting site hydrogeology.

Figure 19. HPO3C data plotted by TECHBASE.

Figure 20. Homestake Partners test site ECPT tip stress and shear wave profiles along section A-A'.

Figure 21. Homestake Partners test site ECPT tip stress and pore pressure profiles along section A-A'.

Figure 22. Homestake Partners test site ECPT pore pressure and resistivity profiles along section A-A'.

Figure 23. Homestake Partners test site ECPT resistivity and surface resistivity, and surface resistivity inversion profiles.

Figure 24. Homestake Partners test site ECPT pore pressure and surface resistivity inversion profiles along section A-A'.

a) HP01S

b) HP02S

Note: East-West range is in "stations"; station separation is 8.25 ft.

Figure 25. Homestake Partners test site reflection seismic time-sections.

Figure 26. Velocity model from refraction data, lines HPO1S and HPO2S, Homestake Mill area.

Figure 27 shows a contour map, prepared with TECHBASE, of the surface electrical resistivity basement for this site. The contours are consistent with the hydrogeology of the site. That is:

- Areas of resistivity (red zones), indicating high contaminant levels, exist down gradient from both the large tailing pile on the north end of the site and small tailings impoundments on the east side of the site.
- Areas of high resistivity, indicating lower contaminant levels, exist along the south and west property boundaries reflecting the dilution effect of injection wells at these locations.
- The general trend of the moderate resistivity, moderate contaminant levels (yellow zone), is consistent with the existence of a northwest-southeast trending transport channel in the aquiclude.

Figure 27. Contour map of the surface electrical resistivity basement of the Homestake Partners Mill Site.

SECTION 4.0 TECHNOLOGY STATUS

The technologies employed in this effort were, for the most part, state-of-the-art applications. The approach of using the data from various measurement systems to develop a synergistic effect was a unique contribution to environmental site characterization. The usefulness of the ECPT in environmental site investigations, in providing subsurface "ground truth data," as a platform for subsurface sensors, and in evaluating subsurface stratigraphy, represents a significant advancement in site characterization.

The geophysical methods evaluated here were surface seismic reflection surveying and surface resistivity surveying. The experimental aspects of these methods are relatively mature. The analysis methods are less developed. Although simple, horizontally-layered geologies can be interpreted, the analysis of complex, multi-layered, three-dimensional geologies requires augmentation of the surface survey results with underground measurements. The ECPT was used to provide these results.

The ECPT technology, for the standard geotechnical measurements of tip and sleeve resistance, is well established. The use of the ECPT for downhole seismic surveying and resistivity measurements is a more recent development. Downhole seismic surveying has been used by ARA and others over the past few years and is becoming well established. Although several groups have used ECPT resistivity cones over the last several years, there is not much information on their use and success in the literature. In this study, we expended a lot of effort designing, building, and fielding a resistivity cone that would survive the severe friction, gouging, and distortion encountered in probing hard sands, caliches, and gravels to large depths. Designs that worked at shallow depths in soft sands and clays were unsuccessful at the sites evaluated here. The two areas of hardware malfunctions at the Homestake site, the seismic p-wave system and the resistivity conductor material, have subsequently been corrected. An improved p-wave coupling system, consisting of a short steel pile topped with a steel plate, has been used extensively at the Savannah River Site (SRS) (Reference 20) with very good results. The insulation material for the resistivity probe was changed to a Hydralar Z Nylon/Kevlar, thermo-plastic composite manufactured by A.L. Hyde Company. This material has proven very survivable at work also at the SRS (Reference 21).

Modern database programs with graphic visualization software provide significant enhancement to the analysis of ECPT and surface geophysical results. However, the software available was not, for this program, sufficiently user friendly or integrated to permit rapid turnaround in the field to support real-time decision making. However, processing all the data obtained at a site through the same database and visualization package at the same time proved to be a major advantage for the analyst. The automated comparison of different data sets, the ability to use one data set to provide constraints on the reduction

and interpretation of other data sets, as well as the ability to easily make plots and develop models of the site leads to higher confidence and better understanding of the subsurface conditions, and higher confidence in the results.

Additional work has also been done on the visualization of the data by linking TECHBASE with AVS, a three-dimensional solid modeling program, through a code named GEOVIS, which was written by ARA. This was demonstrated as a part of the SRS project (Reference 21) and at Tinker AFB as part of a cone penetrometer laser induced fluorescence project for the Air Force (Reference 22).

Portions of the site characterization procedures evaluated in this project have subsequently been demonstrated at both the Hanford (Reference 23 and 24), SRS, and Tinker AFB sites. The outcome of those demonstrations, in addition to evaluating the improved systems, is that the ECPT is an extremely useful technique for environmental site characterization. In addition to providing stratigraphic information and ground truth data for surface geophysical surveys, it has proven to be very useful in obtaining soil, water, and gas samples, placing monitoring and soil vapor extraction wells, and acting as a platform for additional sensors such as radiation detector, Raman spectroscopy, and laser induced fluorescence. Its advantages over standard drilling procedures are that no drilling waste is created, the workers are subject to less exposure to harmful materials, and it is faster and cheaper. As a result of these demonstrations as part of the DOE's integrated demonstration program, the minimally invasive three-dimensional site characterization system is ready for implementation.

Cost comparisons with current technology are difficult because of the influence of the subsurface conditions on the possible production rates of both the ECPT and drilling and sampling, as well as the impact of the protocol for handling and disposing of the spoils generated by a drilling program. The surface geophysical surveys used here are standard techniques, and no cost differences are expected when they are used in this application. A study by Los Alamos National Laboratory (Reference 25) concludes that when a site characterization is conducted using an ECPT, savings can be on the order of 25 to 50 percent.

SECTION 5.0
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