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Sonic CPT Probing in Support of DNAPL Characterization

Final Report

Martin L. Gildea, John W. Haas, Stephen P. Farrington, Daniel E. Chitty, Wesley L. Bratton and James D. Smith II

Applied Research Associates, Inc.
New England Division
415 Waterman Road
South Royalton VT 05068

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AIR FORCE RESEARCH LABORATORY
MATERIALS & MANUFACTURING DIRECTORATE
AIR EXPEDITIONARY FORCES TECHNOLOGIES DIVISION
139 BARNES DRIVE, STE 2
TYNDALL AFB FL 32403-5323

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Gina M. Graziano

GINA GRAZIANO, Capt, USAF
Program Manager

Thomas B. Stauffer

THOMAS B. STAUFFER, PhD, DR-IV, DAF
Chief, Weapons Systems Logistics Branch

RANDY L. GROSS, Col, USAF, BSC
Chief, Air Expeditionary Forces Technologies Division

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Martin L. Gildea, John W. Haas III, Stephen P. Farrington, Daniel E. Chitty, Wesley L. Bratton, James D. Shinn II

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Applied Research Associates, Inc.
New England Division
415 Waterman Road
South Royalton, VT 05068

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Responsible Person: Lt. Gina Graziano, AFRL/MLQL, 139 Barnes Dr., Ste. 2, Tyndall AFB, FL 32403-5323, (850) 283-6259

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13. ABSTRACT *(Maximum 200 words)*
The U.S. Department of Defense (DOD) and Department of Energy (DOE) are currently pursuing efforts to identify and remediate thousands of contaminated sites. Current efforts are focused on economizing, and improving the quality of site characterization and remediation processes. Cone Penetrometer Technology (CPT) offers numerous advantages in that it is generally faster, less expensive, safer, and generates far less secondary waste than conventional drilling methods. As a result, DOD and DOE efforts are directed at developing advanced sensors for delivery by the cone penetrometer. To accommodate these new sensors, probe sizes have increased (from 1.44-in OD to 1.75-in OD and currently to 2.25-in OD) and the ability of CPT to reach desired depths has been increased. To enhance the penetration capability of the CPT, a sonic vibratory system was integrated with conventional CPT to advance cone penetrometer sensor packages past currently attainable depths. This CPT enhancement provides an efficient tool for hazardous waste site characterization, remediation, and monitoring.

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Sonic, Cone Penetrometer, Site Characterization, Fluorescense, Sensor, Shock Hardened Sensors, Geoprobe®

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PREFACE

This report was prepared by Applied Research Associates, Inc. New England Division, 415 Waterman Road, South Royalton, Vermont for the United States Air Force Research Laboratory, Air Expeditionary Forces Technologies Division, AFRL/MLQL, 139 Barnes Drive, Suite 2, Tyndall Air Force Base, FL 32403-5323 for contract numbers FO8635-93-C0020, SSG Subtask 8.05.1 and F08637-98-C6002 SSG Subtask 32.02S.

This final report documents the design, development and testing of a sonic cone penetrometer and associated shock-hardened sensors.

The authors wish to acknowledge a number of people for their unfailing support and encouragement throughout this project. Specifically, Mr. Bruce Nielsen, AFRL/MLQL; Mr. Eric Lightner, DoE Office of Industrial Technology; Mr. George Robitaille and Ms. Malissa Ruddle, both from the US Army AEC, Aberdeen Proving Grounds; and finally, Ms. Carol Eddy-Dilek, Mr. Joseph Rossabi, and Mr. Brian Riha, all from the Savannah River Technology Center at SRS.

The work was performed between April 1997 and July 2000. The AFRL/MLQL project officers were Mr. Bruce Nielsen, 1Lt Debbie Davis, and 1Lt Gina Graziano.

EXECUTIVE SUMMARY

1. OBJECTIVE

The overall goal of the sonic CPT program was to expand the applicability of CPT systems for DNAPL characterization and monitoring to DoD and DoE sites with difficult geologies. Conventional CPT systems meet refusal due to insufficient capacity to penetrate hard layers at depth, or due to the gradual buildup of friction along the sides of the push rods. The addition of vibratory energy to the CPT system is designed to help in both of these situations by reducing the frictional resistance of the soil along the side of the rod string. The reduction of the frictional resistance allows a greater proportion of available push force to reach the tip, thereby increasing the penetration depth.

To achieve this goal, a development program consisting of the design, fabrication, and field testing of a sonic CPT system that would enhance the penetration capabilities of standard CPT was undertaken. The following specific objectives were set forth under this development program:

- Design and build an integrated sonic CPT system,
- Test the sonic CPT at DoE and DoD site geologies that historically have been difficult to penetrate with standard CPT,
- Demonstrate improved CPT capabilities for site characterization and monitoring, including penetration of "hard" layers and hardened CPT equipment able to withstand the rigors of sonic or other vigorous dynamic deployment methods (e.g. impact hammering).

2. BACKGROUND

CPT in general has received widespread interest and is becoming a more commonplace tool for environmental site characterization activities at numerous DoD and DoE facilities. There are three major reasons for this growth in popularity: (1) CPT is typically faster and less expensive than drilling techniques, (2) it provides significantly more detailed information about subsurface conditions, and (3) it generates very little drilling waste. Although CPT already offers many benefits for site characterization, the technology can be improved to offer greater utility and increased cost savings by increasing the penetration capability in some recalcitrant lithologies through the use of a sonic vibratory system.

3. SCOPE OF WORK

3.1 PHASE I

During the first phase of development, the sonic CPT drive unit was designed, fabricated, and installed in one of Applied Research Associates, Inc's (ARA) conventional CPT trucks and the system was evaluated under field conditions. A series of field tests were conducted at both DoD and DoE sites including: (1) the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) located in Hanover, New Hampshire, (2) Massachusetts Military Reserve (MMR), Cape Cod, Massachusetts, and (3) Savannah River Site (SRS), Aiken, South Carolina. The goal of the testing was to evaluate the field performance of the sonic CPT system and perform direct comparisons of the depth achieved using the sonic system to that of conventional CPT.

In addition, a one-day technology demonstration of the sonic CPT's capabilities was held on 8 October, 1997 at the SRS M-Basin area. Approximately 40 people from DoE, DoD, and the commercial sector attended the demonstration. Attendees were allowed access to the CPT system to observe the technology in action.

3.2 PHASE II

Phase II of this program began in April, 1998, and consisted of three major tasks: (1) modifying the design of the down-hole electronics to improve the survivability of the sensors for deployment with the sonic CPT, (2) developing shock-isolation designs to allow for the deployment of shock sensitive sensors with sonic CPT, and (3) field evaluation of sonic CPT technology at Kelly AFB in San Antonio, Texas and the Hanford Site in Richland, WA. An additional test of a shock-isolated sensor probe was conducted at CRREL using an impact deployment system.

4. METHODOLOGY

The sonic drive unit utilizes two counter-rotating eccentric weights to induce a sinusoidal driving force equivalent to the vertical acceleration of the eccentric weights times their mass. The counter-rotating weights are adjustable such that the eccentricity of the masses can be changed, yielding five different eccentricity settings. This allows the operator to optimize the system performance by varying the operating frequency range and amplitude. Experience has shown that different geologies respond optimally to different frequencies and amplitudes. For instance, higher frequencies/lower amplitudes perform better in sands and gravels, whereas lower frequencies/higher amplitudes yield better results in clayey soils. In addition, a new rod clamping system was incorporated into the design, as well as a vibration isolation system to reduce the dynamic energy transmitted to the truck chassis.

To fully utilize the potential of a sonic CPT system, the rods and associated sensors required modifications to handle the additional stresses induced by the sonic drive unit. A new rope-thread design was developed, providing a 50% increase in bending strength of the joints. Bending failure is typically the direction of failure observed in the original V-thread style rods. Hardening of down-hole electronics was accomplished by modifying the design and fabrication techniques used on cables and down-hole connectors and ultimately in the down-hole electronics. Using previously developed down-hole digital technology, more channels were made available for down-hole sensors using fewer individual wires. This ultimately reduced the size/weight requirements of the cable and associated connectors, which experience has shown to be the root cause of failure due to higher inertial mass and acceleration induced fatigue of the cable assemblies.

Hardening the down-hole electronics in the CPT cone was achieved by potting the boards in epoxy. This technique has been used in explosives testing instrumentation for many years. Since these digital electronic boards can be used with a variety of sensors, the successful hardening system developed and demonstrated under this program has laid the foundation for future down-hole electronic systems being developed by DoD and DoE for use with sonic CPT.

Improvements to shock sensitive gamma radiation and fluorescence sensor packaging were made by isolating the sensors from the vibrating rod string. The isolation technique developed for the gamma and fluorescence sensors will be applicable to many other shock-sensitive sensors with only minor modifications.

5. RESULTS

Extensive testing throughout the course of the sonic CPT development program indicates that the sonic CPT drive is a robust and dependable unit. The bearing assembly, which supports the eccentric masses, demonstrated adequate heat dissipation during prolonged operation. The shock-isolation system proved sufficient for protecting the truck chassis from severe vibration during sonic testing, although further development in this area is needed to improve shock-isolation during retraction of the rods.

Efforts to shock-isolate several CPT sensors, allowing them to be used in conjunction with the sonic CPT system were also successful. The down-hole, digital CPT cone, soil moisture resistivity, gamma radiation, and fluorescence sensors were shock-hardened and tested under the rigorous conditions at the Hanford and CRREL sites.

The results of the field evaluations clearly demonstrated the ability of the sonic CPT to penetrate beyond the depths attainable with conventional CPT. At MMR Otis AFB, depths of 100 feet were obtained in glacial moraine deposits consisting of coarse-grained sands, gravels and cobbles. Previous attempts by the US Army Corps of Engineers using conventional CPT were thwarted at a depth of only 20 feet below grade. At SRS, the use of the sonic CPT improved the depth attained at each of the penetrations conducted during the evaluation. Success was also measured at the Hanford Site where, at the 100D area, depths of 51 feet were achieved in areas that typically resulted in refusal at depths of just five to seven feet.

6. CONCLUSION

The results show that the sonic CPT development technology enhances conventional CPT by extending its depth capability. The most notable enhancements were realized in coarse-grained soils where sufficient porosity allowed for reorientation of the soil fabric, providing ample room for the soil volume displaced by the probe.

The robust and versatile design of the sonic CPT drive unit can easily be modified to retrofit smaller CPT rigs, effectively increasing the achievable depth capacity with minimal expense. This will be especially useful for the lighter weight Site Characterization and Analysis Penetrometer System (SCAPS) Rigs. The shock-hardening techniques developed during this project indicate that a variety of sensors, even optical sensors such as the fuel fluorescence detector (FFD) or Raman sensors can be successfully deployed using sonic CPT. This will allow for the detection of DNAPLs at greater depths, which was the motivation for the sonic CPT development program.

7. RECOMMENDATIONS

Overall the sonic CPT drive head performed well and has proven to be robust and effective in certain soil stratigraphies. However, there are some characteristics that could be improved.

- A servo valve with feedback control should be implemented to control hydraulic flow. This would allow speed to be controlled in all conditions providing a safer, more controlled operation.
- The strain gauging on the pillow block bolts should be improved to provide better signals to the overload shutdown circuit.
- Better vibration isolation of the vibratory head is also recommended to provide better isolation for a more linear response and for removal of rods.
- A wireline soil sampler would greatly enhance the sonic system by combining the advantages of using a cutting barrel to cut through hard layers with the speed of the wireline system to remove the cuttings.
- For extremely resistant lithologies, as was experienced at SRS, the utility of a wireline rotary auger system would be useful.

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LIST OF ACRONYMS

ARA	Applied Research Associates
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Measurement
CPT	Cone Penetrometer Technology
CRREL	Cold Regions Research and Engineering Laboratory
DAS	Data Acquisition System
DNAPL	Dense Non-Aqueous Phase Liquid
DOD	Department of Defense
DOE	Department of Energy
HPVEE	Hewlett-Packard Visual Engineering Environment
IRP	Installation Restoration Program
MMR	Massachusetts Military Reserve
NED	New England Division
PCB	Polychlorinated Biphenyl
SBIR	Small Business Innovative Research
SRS	Savannah River Site
SSG	Supplemental Support Group
WES	Waterways Experiment Station

1. INTRODUCTION

1.1 BACKGROUND

The sonic CPT is an enhanced cone penetration testing (CPT) system that has been developed by ARA under a contract with the USAF, Air Force Research Lab, Air Expeditionary Forces Technologies Division, #F08637-98-C-6002, SSG 32.02S, with funding provided by DoE and DoD. Cone Penetrometer Technology (CPT) offers numerous advantages in that it is generally faster, less expensive, safer, and generates far less secondary waste than conventional drilling methods. As a result, DoD and DoE efforts have been focused on developing advanced sensors to be delivered by the cone penetrometer. As probe sizes have increased (from 1.44-in to 1.75-in diameter and larger), the ability of CPT to reach a desired depth for a given rig weight (reaction force) has been reduced. Attempts are being made to speed up, economize, and improve the quality of site characterization and remediation processes. Integration of sonic drilling techniques with CPT has advanced cone penetrometer sensor packages past the current depths of refusal and has provided an efficient tool and technique for hazardous waste site characterization, remediation, and monitoring.

Development of the sonic CPT began under a DoE sponsored SBIR study where ARA evaluated the feasibility of integrating a vibratory system with conventional CPT. The results of the SBIR showed that:

- Vibratory technology could be adapted to the conventional CPT push frame allowing greater penetration using standard CPT rod geometries (1.44- and 1.75-inch diameter) on existing DoE/DoD trucks, and other rigs, regardless of weight.
- The ability of medium and light duty cone penetrometer trucks could be enhanced with sonic CPT to penetrate difficult soils and achieve depths currently attainable using only heavy weight trucks.
- CPT to be used for remediation and/or long-term monitoring could be enhanced by the use of sonic CPT for the placement of 2-inch diameter wells.

Based on the findings of the SBIR study, follow-on development was proposed and funded under joint sponsorship by DoE and DoD. This document chronicles the follow-on development of a prototype sonic CPT system capable of increasing production rates and enabling deeper deployment of CPT sensors in troublesome geological formations.

1.2 SCOPE OF WORK

The scope of work completed during the course of this project was divided into two major phases, each funded through a separate contract.

1.2.1 PHASE I

Phase I was funded under contract # FO8635-93-C-0020 SSG Subtask 8.05.1 and consisted of three primary tasks:

Task 1: Project planning and development including field testing site selection.

Task 2: Design and fabrication of the sonic CPT system including a new clamping system and a new CPT rod thread design.

Task 3: Field Evaluation at three DoE/DoD sites including:

- CRREL (DoD)
- MMR (DoD)
- SRS (DoE)

Under Task 1, a preliminary outline was developed to design, manufacture and integrate a field deployable, vibratory head in a conventional CPT rig. In this task, detailed design goals and processes were defined and developed. Also, candidate field test sites were evaluated and selected.

Under Task 2, an advanced sonic CPT head was designed, manufactured, and installed in one of ARA's conventional CPT trucks. A new rod clamping system was incorporated into the head design, as well as a vibration isolation system to minimize the vibration transmitted to the truck chassis. In addition, to increase the effectiveness and versatility of the system, a variable eccentric mass system was incorporated into the sonic CPT head. The variable eccentric mass enables the operator to select the optimum frequency and amplitude of dynamic force generated by the sonic CPT head based on in situ conditions. Since the optimum frequency has been shown to vary as a function of the geological conditions, this modification increased the flexibility and effectiveness of the sonic CPT to penetrate many types of soil.

Task 3 evaluated the effectiveness of sonic CPT in penetrating soil strata that have proven difficult to penetrate with conventional CPT rigs. The first test series was conducted at CRREL. The goal of this testing was to conduct shakedown exercises of the sonic CPT system at a site at which ARA had experience. It also provided an opportunity to compare the results of static testing to the newly developed sonic CPT system.

The second test series was conducted at the MMR, where previous efforts by the US Army Corps of Engineers-Waterways Experimental Station (WES) were thwarted at very shallow depths. The final test series conducted under this phase of the project was performed at SRS. Conventional and sonic CPT penetrations were performed at selected locations so that direct comparison of the depth of penetration could be made between the two technologies. Other important parameters evaluated include the effectiveness of penetration, instrumentation survivability, and equipment reliability.

A one-day technology demonstration of the sonic CPT was held on 8 October, 1997 at the M-Basin area. Approximately 40 people from DoE, DoD, and the commercial sector participated in the demonstration. Attendees were allowed access to the CPT system to observe the technology in action.

1.2.2 PHASE II

Phase II was funded under contract # FO8637-98-C6002 SSG 32.02S. It began in April, 1998 and consisted of three major tasks:

Task 1: Modify the probe design of the down-hole electronics to improve the survivability of the sensors for deployment with the sonic CPT,

Task 2: Develop a shock-isolation design to allow for deployment of shock-sensitive sensors with sonic CPT,

Task 3: Field Evaluation of sonic CPT technology at the DoD's Kelly AFB and the DoE's Hanford, and Paducah sites, including the evaluation of open-barrel cutting shoes.

To fully utilize the potential of a sonic CPT system, hardening of down-hole electronics had to be addressed. Under Task 1, ARA modified the design and fabrication techniques used on cables and down-hole connectors. Experience during previous field testing indicated that it would be desirable to harden the cable connection and reduce the weight of the cable. Under sonic excitation, the mass of the cable used previously was out of phase with the motion of the CPT rods, resulting in significant stresses in the cable connection. To minimize these stresses, a down-hole digital CPT board, developed by ARA for the DoE, was employed. The down-hole digital board provides the advantage of reducing the number of signal conductors from 24 (as was used previously with the sonic CPT) to four allowing a lighter, smaller cable to be used. Hardening the down-hole electronics in the CPT cone was achieved by potting the boards in epoxy. This technique has been used in explosives testing instrumentation for many years. Since these digital electronic boards can be used with a variety of sensors, the successful hardening system developed and demonstrated under this task has laid the foundation for future down-hole electronic systems being developed by DoD and DoE for use with sonic CPT.

Under Task 2, gamma radiation and fluorescence sensors were shock-isolated to enable their use with the sonic CPT system. The gamma radiation detector consists of a sodium iodide crystal attached to a photomultiplier tube. The manufacturer rates the sensor to withstand accelerations up to 25 g. Acceleration as great as 300 g have been measured in the CPT cone during sonic CPT testing. A shock-isolation system was designed to reduce the accelerations experienced by the sensor to below the rated value. In addition, a fuel fluorescence detector (FFD), developed by ARA for conventional static CPT, was hardened and shock-isolated to withstand the rigors of sonic deployment.

The primary goal of the field testing, conducted under Task 3, was to evaluate the effectiveness of sonic CPT in penetrating soil strata that historically have proven difficult to penetrate with conventional CPT rigs. Two field evaluations were completed during this phase of the project. The first test was conducted at Kelly AFB. The goal was to determine if sonic CPT could be used to penetrate a dense caliche material to allow for site characterization of a large chlorinated solvent plume. Various parameters were evaluated including the effectiveness of penetration, instrumentation survivability, and equipment reliability.

The second evaluation took place at the Hanford Site. During this evaluation, the digital CPT cone was tested in the difficult lithology present at the site. In addition, the shock-isolated gamma radiation probe was evaluated for survivability; open drive cutting barrels were also evaluated.

A third evaluation was conducted at CRREL, where an impact deployment system (e.g. Geoprobe®) was used to test the shock hardened FFD sensor.

1.3 OBJECTIVES

The overall goal of the sonic CPT program was to expand the applicability of CPT systems for DNAPL characterization and monitoring to DoD and DoE sites with difficult to penetrate geologies. To achieve this goal, a development program was implemented that would enhance the penetration capabilities of standard CPT. The following specific objectives were set forth under this development program:

- Design and build an integrated sonic CPT system,
- Test the sonic CPT at DoE and DoD site geologies that historically have been difficult to penetrate with standard CPT,
- Demonstrate improved CPT capabilities for site characterization and monitoring.

Conventional CPT systems meet refusal due to insufficient capacity to penetrate a hard layer at depth, or due to the gradual buildup of friction along the sides of the push rods. The addition of sonic vibratory energy to the CPT system is designed to improve performance in both of these situations by reducing the frictional resistance of the soil along the side of the rod string.

The reduction of the frictional resistance allows a greater proportion of available push force to reach the cone penetrometer and thereby increases the achievable penetration depth.

1.4 REPORT OUTLINE

This report documents the results of the project and compiles all of the data collected during the course of the project. Presented in Section 2 is an overview of vibratory theory and preliminary design issues. The prototype design is presented along with a discussion of safety considerations, and instrumentation issues. The objectives, scope and results of each of the field evaluations are presented in Section 3. Section 4 contains a summary of the conclusions drawn from the various testing efforts, and Section 5 presents recommendations for future work.

2. METHODOLOGY

2.1 THEORETICAL CONSIDERATIONS

2.1.1 THEORY

The theory upon which the sonic CPT system is based was researched and refined during the sonic CPT SBIR project conducted by ARA in 1995. Much of the physical theory applicable to sonic CPT originated in conjunction with research into vibratory pile driving processes. As a pile is driven into the ground by a dynamic force (or an impact), a compression wave travels through the pile. The magnitude and speed of the compression wave depend on the force applied, the shaft material, and the shaft geometry. The soil reactions along the shaft and beneath the pile tip cause damping of the compression wave and affect the amount of wave reflection from the tip. The vertical motion of the shaft due to propagation of the compression wave induces a reaction force resulting from shear strain of the adjacent soil, in friction with the shaft. This force acts against the direction of motion of the shaft. The reaction force is related to the shear modulus and shear wave speed of the soil. Likewise, the motion of the tip induces a reaction force that resists penetration of the soil and is related to the compressive and shear characteristics of the soil beneath the tip. When these reaction forces reach the yield strength of the soils in which they are induced, failure of the soil occurs and the shaft undergoes an increment of permanent displacement called “set.” Over many rapid cycles of shaft compression due to cyclic dynamic loading, the summation of these small increments of "set" result in the enhanced speed of penetration of the soil by vibratory driven shafts.

Sonic vibratory advancement of a shaft operates at higher frequency than traditional vibratory driving approaches. The nomenclature "sonic" was derived from the application of excitation frequencies in the audible range to the vibratory advancement of piles and drills. These frequencies sometimes exceed 200 Hertz (Hz). At such frequencies, the mechanics of the soil/shaft interaction are not well understood. This lack of understanding is largely attributable to a paucity of fundamental data regarding soil stress-strain relationships under high-frequency cyclic loading. Most material strength properties are known to be strain-rate dependent and most strain data have been derived from low strain rate experiments.

It is widely theorized that the increased ability of vibratory driven shafts to penetrate hard material at sonic frequencies is due to excitation of the shaft at its natural resonant frequency, which then causes either de-coupling of the soil/shaft system or liquefaction of adjacent soils. This greatly diminishes shaft friction, which allows more applied force to be transmitted to the bearing surface at the tip. While the mechanism of shaft friction reduction is not clear, it is evident from experimentation that higher frequency vibration does increase the ability to penetrate hard materials, which is most likely due to reduced shaft resistance resulting in an increase in the driving forces at the tip.

2.1.2 MODEL DESCRIPTION

Under the earlier SBIR effort, ARA developed an analytical model that uses a wave equation formulation of the internal rod forces. Figure 1 depicts a schematic of the analytical model used showing the rods consisting of discrete masses connected by springs and spring-dashpots to model the soil reactions. Inputs required to define the elastic behavior of the rod include the rod inner and outer diameters, density, and modulus of elasticity. The tip area and tip angle is also required to calculate bearing stresses. The independent soil properties that constitute input to the model include unit weight, internal friction angle, cohesion, elastic shear wave speed, and Poisson's ratio. All other properties used in the model are calculated from these basic properties using well-known and accepted geotechnical engineering formulations.

Calculated soil properties include shear modulus, compression wave speed, and ultimate bearing capacity; all of which depend on the overburden stress. Additional soil related input includes a ratio of ultimate shear stress at the shaft/soil interface to the soil's ultimate shear stress, a ratio of unloading bearing modulus to loading bearing modulus, and a ratio of CPT sleeve stress to CPT tip stress (taken from measured CPT data).

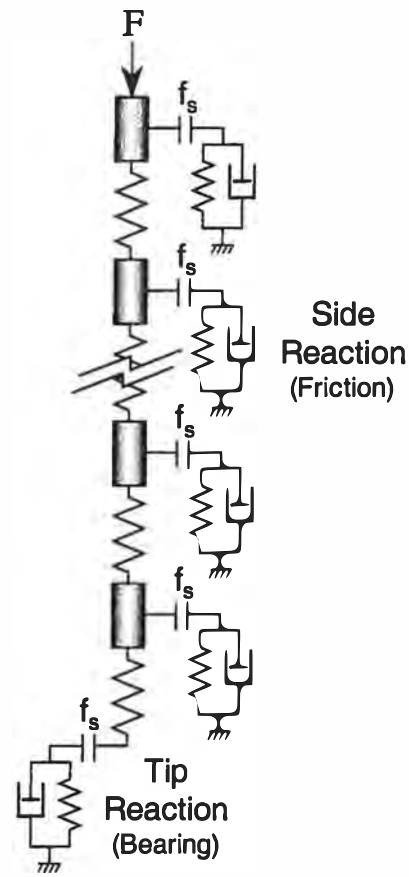


Figure 1. Schematic of analytical model showing the rods consisting of discrete masses connected by springs, and spring-dashpots to model the soil reactions (surface shear).

2.1.3 MODEL VALIDATION

ARA validated the analytical model by comparing modeled quantities to experimental results obtained by Kim, Roesset and Stokoe (1987). Kim, Roesset, and Stokoe conducted a number of vertical vibration tests on small scale piles. The concrete piles were embedded to a given depth in sand of known mechanical properties; a vibratory load of constant dynamic force was applied over a range of frequencies from 100 to 1500 Hz. The energy acceptance of the pile is inferred from the velocity of the drive point normalized to the applied force. This quantity is the inverse of the drive point impedance. Figure 2 and Figure 3 are plots of normalized velocity (inverse drive point impedance) versus drive frequency for two cases, a 5-foot concrete pile and a 10-foot concrete pile. The open circles in each plot represent the experimental results obtained by Kim, Roesset and Stokoe. The X's connected by line segments represent the analytical results obtained from the ARA numerical model. The first peak in each trace (approximately 300 Hz in Figure 2 and approximately 700 Hz in Figure 3) corresponds to a resonance associated with the soil response of the analytical results to variations in soil property inputs. The second peak (around 1400 Hz in Figure 2 and around 1250 Hz in Figure 3) is due to a resonance associated with the pile, as determined by the peak's sensitivity to variations in pile property inputs. Although the resonant frequencies shown appear high relative to the frequencies indicated in prior discussion of sonic CPT theory, the differences are due to the shorter length and higher stiffness of the experimental piles relative to CPT rods.

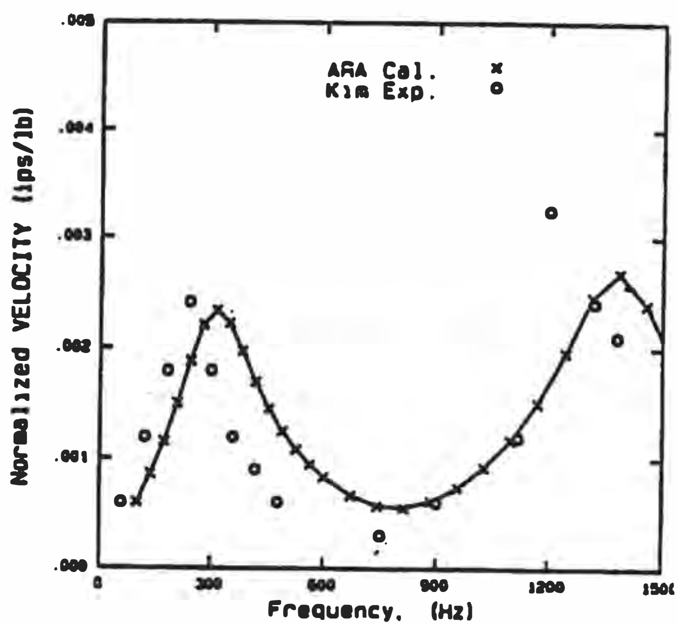


Figure 2. Normalized vertical velocity (inverse drive point impedance) versus drive frequency; a comparison of ARA analytical results to Kim, Roesset, and Stokoe experimental results for a 5-foot pile in sand. Evident is a soil resonance at 300 Hz and a pile resonance at 1400 Hz.

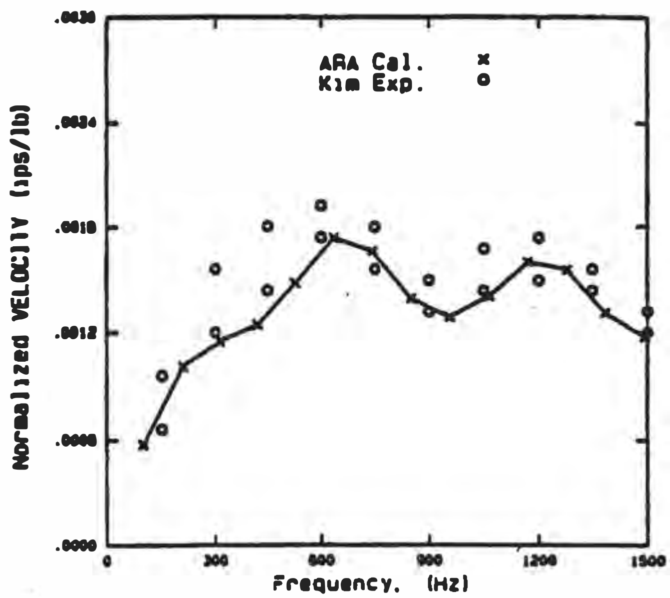


Figure 3. Normalized vertical velocity (inverse drive point impedance) versus drive frequency; a comparison of ARA analytical results to Kim, Roesset, and Stokoe experiment for a 10-foot pile in sand. Two resonances are again evident.

As Figure 2 and Figure 3 show, the ARA analytical model successfully captures the character of the experimental results of Kim, Roesset, and Stokoe in both phase and amplitude. The plots shown represent blind predictions based on the experimental design and soil pile properties published by Kim, Roesset, and Stokoe; no adjustments were made to force a fit to the experimental data. The results show that there are two distinct frequencies at which the pile/soil system accepts energy more readily than at other frequencies. These correspond to a soil-related resonance and a pile-related resonance. As discussed earlier, the pile-related resonance results in the increase in driveability that is exploited by the sonic CPT.

2.1.4 PARAMETRIC MODEL CALCULATIONS

Predictions of cone penetrometer driveability were made using the numerical model. Two theoretical modeling studies were conducted and are discussed below. The first assumed a standard 1.75-inch diameter CPT rod embedded 50 feet into soil whose properties were chosen to represent previous ARA CPT experiences at the Savannah River Site. The tip of the CPT probe was assumed to be embedded in non-cohesive sand of unit weight 115 pounds per cubic foot (pcf). The second condition modeled was identical to the first with the exception that the tip was embedded one inch into a cemented sand layer. The properties of the cemented layer were identical to the overlying layer with the exception that cohesion was set to 15 psi instead of zero. In each case, a combination of 30,000 pounds dynamic load and 30,000 pounds static load were applied to the embedded CPT rod, over a frequency range of 10 to 200 Hz. Penetration rates are plotted versus driving frequency in Figure 4 for each soil condition. Although the frequency range of the analysis extended to 200 Hz, driving frequencies above 150 Hz are not practically achievable due to mechanical limitations. These calculations were conducted to demonstrate sensitivity of the driving rate to frequency, static force, and soil conditions.

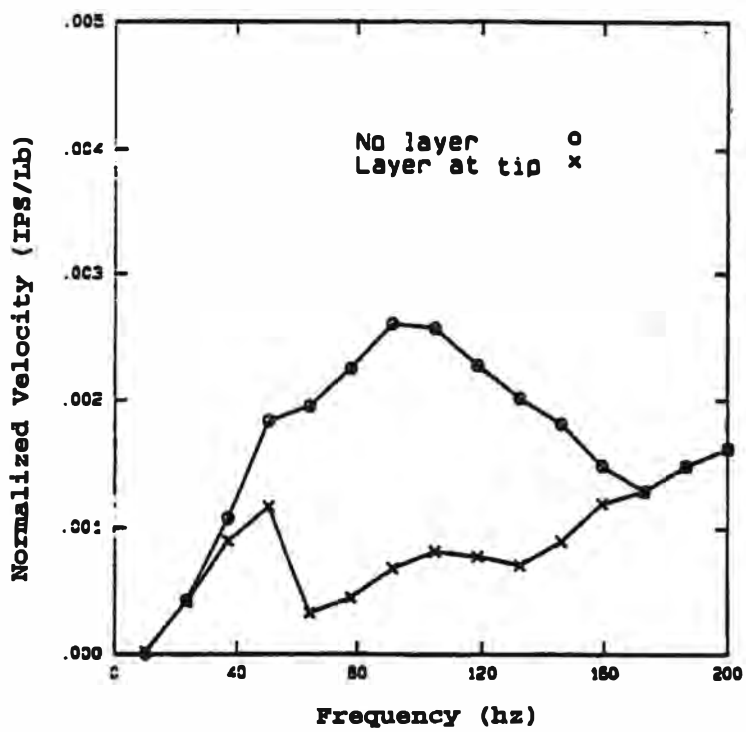


Figure 4. Penetration rate versus drive frequency for a standard CPT geometry under 30,000 lb. dynamic load and 30,000 lb. static load, in two soil conditions that are based on CPT experience at Savannah River Site. The results indicate differences in optimal load and drive frequency for the different soil conditions

As shown in Figure 4, the numerical model results clearly predict maximum penetration speed at a driving frequency of about 100 Hz for the first soil condition. The modeled penetration rate at this sonic frequency is greater than at the lower conventional vibratory frequencies. The lower trace in Figure 4 represents the model predictions made assuming the second soil condition (i.e., tip embedded in a cemented layer). As this trace shows, the presence of the cemented layer affects the placement of the optimal driving frequency, dropping it down into the conventional range at about 45 Hz. This result implied that best penetration in these soil conditions would be achieved by maximizing the driving load at a lower frequency, which indicated a definite utility to being able to change the eccentric masses within the vibratory drive head. The prototype sonic head discussed below was designed to allow such changes.

The parametric model calculations have indicated a clear advantage to using sonic range driving frequencies to advance a CPT probe under some soil conditions, and conventional vibratory driving frequencies with large load under other soil conditions. These indications support the development of a sonic drive head that can deliver equally high dynamic loads over a broad range of frequencies. In the prototype devise design described below, interchangeable eccentric masses allow for this type of flexibility. Parametric calculations such as presented above can be conducted to determine optimum sonic driving frequencies and dynamic and static forces for a given set of soils conditions.

2.1.5 VIBRATORY SYSTEM DESIGN EQUATION

Forces and displacements generated by an eccentric mass vibration can be estimated using a few simple relationships. As shown in Figure 5, the prototype vibratory system consists of two counter-rotating eccentric masses. This system generates force only in the vertical direction. The dynamic force is calculated as follows:

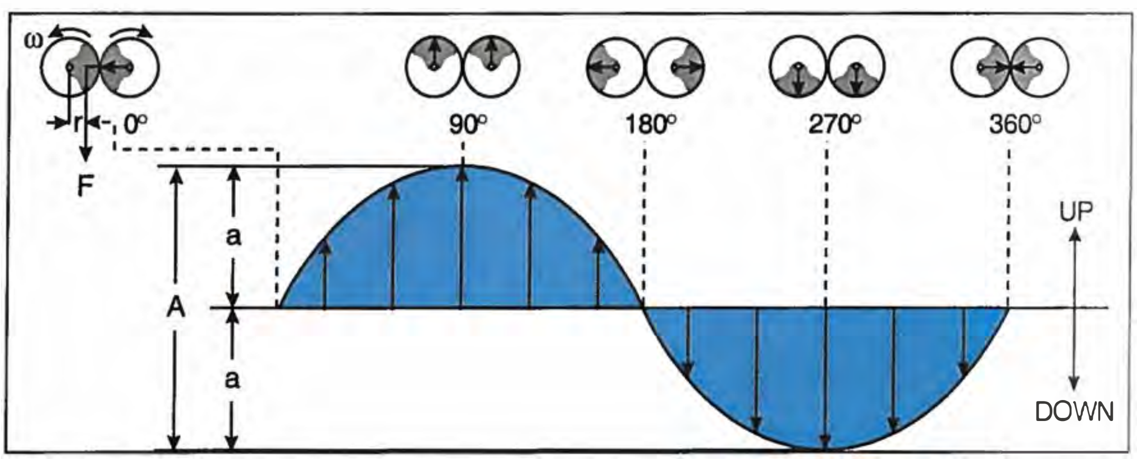


Figure 5. Conceptual illustration of the sonic theory. Note the net force induced by the counter rotating eccentric masses is in the vertical direction. The horizontal forces created by the individual masses cancel each other out.

Vertical position of center of the rotating mass is:

$$s = e\sin(\omega t) \tag{1}$$

Vertical acceleration is the second derivative with respect to time of the vertical position:

$$a = \frac{d^2 s}{dt^2} = -e\omega^2 \sin(\omega t) \tag{2}$$

Force equals mass times acceleration.

$$F(t) = ma = -me\omega^2 \sin(\omega t) \tag{3}$$

Since -1< sin(ωt) < 1, the peak dynamic force is:

$$F = me\omega^2 \tag{4}$$

where: s = vertical displacement

a = vertical acceleration

e = eccentricity

m = rotating mass

em = eccentric moment

ω = the circular frequency of rotation ($2\pi f$)

$F(t)$ = time dependent dynamic force

F = peak dynamic force.

The amplitude induced by the rotating masses is:

$$\mathrm{A} = 2*\left(\frac{em}{M}\right) \tag{5}$$

where: em = eccentric moment

M = dynamic weight in vibrating system (including sonic head, clamp, rods, etc.)

Based on the above calculations, parametric calculations were conducted to design the eccentric masses. A schematic of the eccentric mass system that was fabricated is shown in

Figure 6. Each of the eccentric masses is split, which allows the individual weights to be rotated with respect to each other, thereby changing the eccentric mass of the system. By rotating the weights the operator can easily change the eccentric mass of the system in the field

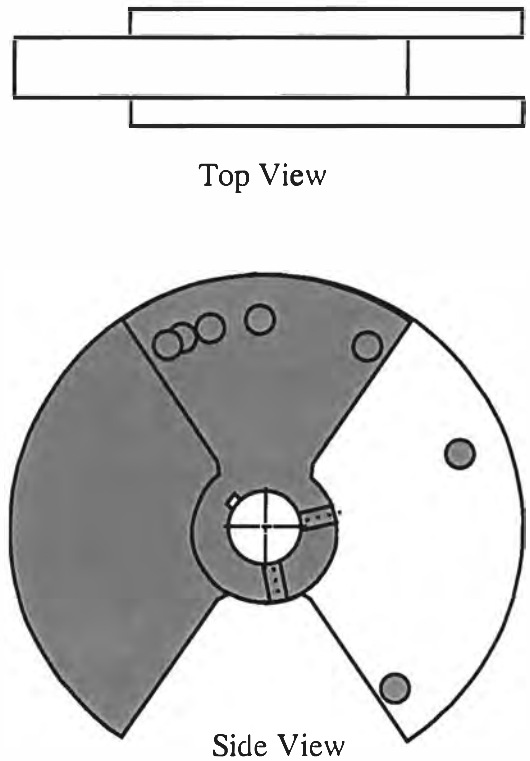


Figure 6. Top and side views of the eccentric masses. By rotating the two half-weights the eccentricity of the system can be varied.

without having to remove the weights from the sonic head, which would entail removing bearings and the bearing pillow block system.

The eccentric mass system was designed to provide a 30,000-lb. peak dynamic force at the frequencies shown in Table 1. Using the above equations, the required eccentric moment and offset angle between the two masses was calculated. Equations 4 and 5 were used to calculate the force and displacement by the system eccentric moment. Plots of estimated force and displacement are shown in Figure 7 and Figure 8.

Initially, these curves were used during the design process to determine the most appropriate weights and offset angles to maximize the versatility of the sonic unit. Once built, these curves were used extensively throughout the testing and evaluation in an effort to relate optimal operating parameters to the various soil types. They also provided a reference to prevent damage to the bearings caused by exceeding the maximum design speed at the individual weight settings.

Table 1. Eccentric offset angles and corresponding eccentric moments and maximum frequency. At maximum frequency, 30,000 lbs. of dynamic force is produced by the rotating masses.

Eccentric Offset Angle (degrees)	Eccentric Moment (in.-lbs.)	Max Frequency (Hz)
0	83.8	41.8
72	67.8	46.5
112	46.9	56.0
143	26.7	74.3
157	16.7	93.7
165	10.9	115.9
170	7.3	141.8

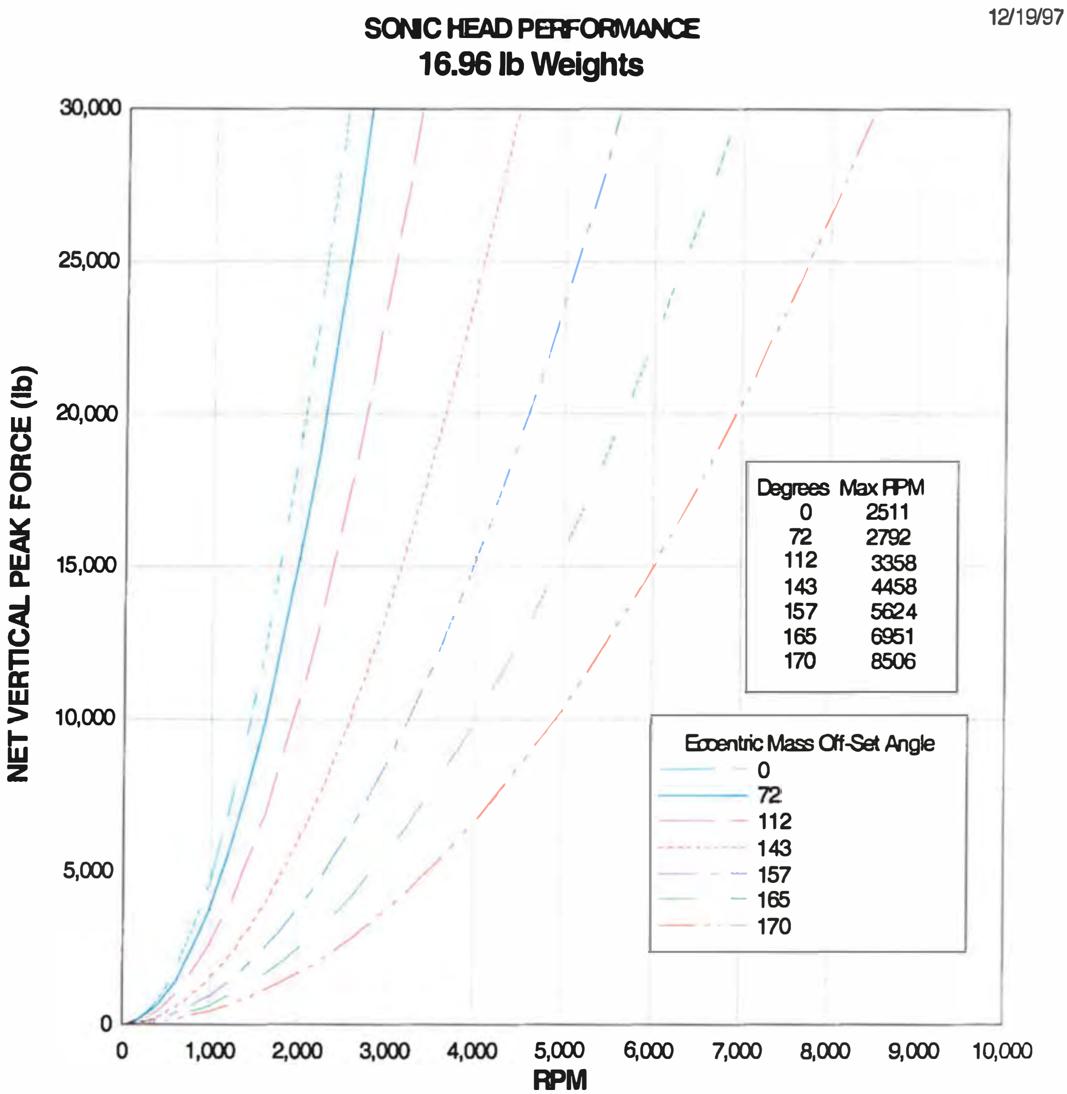


Figure 7. Relationship between rotational speed (rpm) and net vertical peak force for the different eccentric mass offset angles.

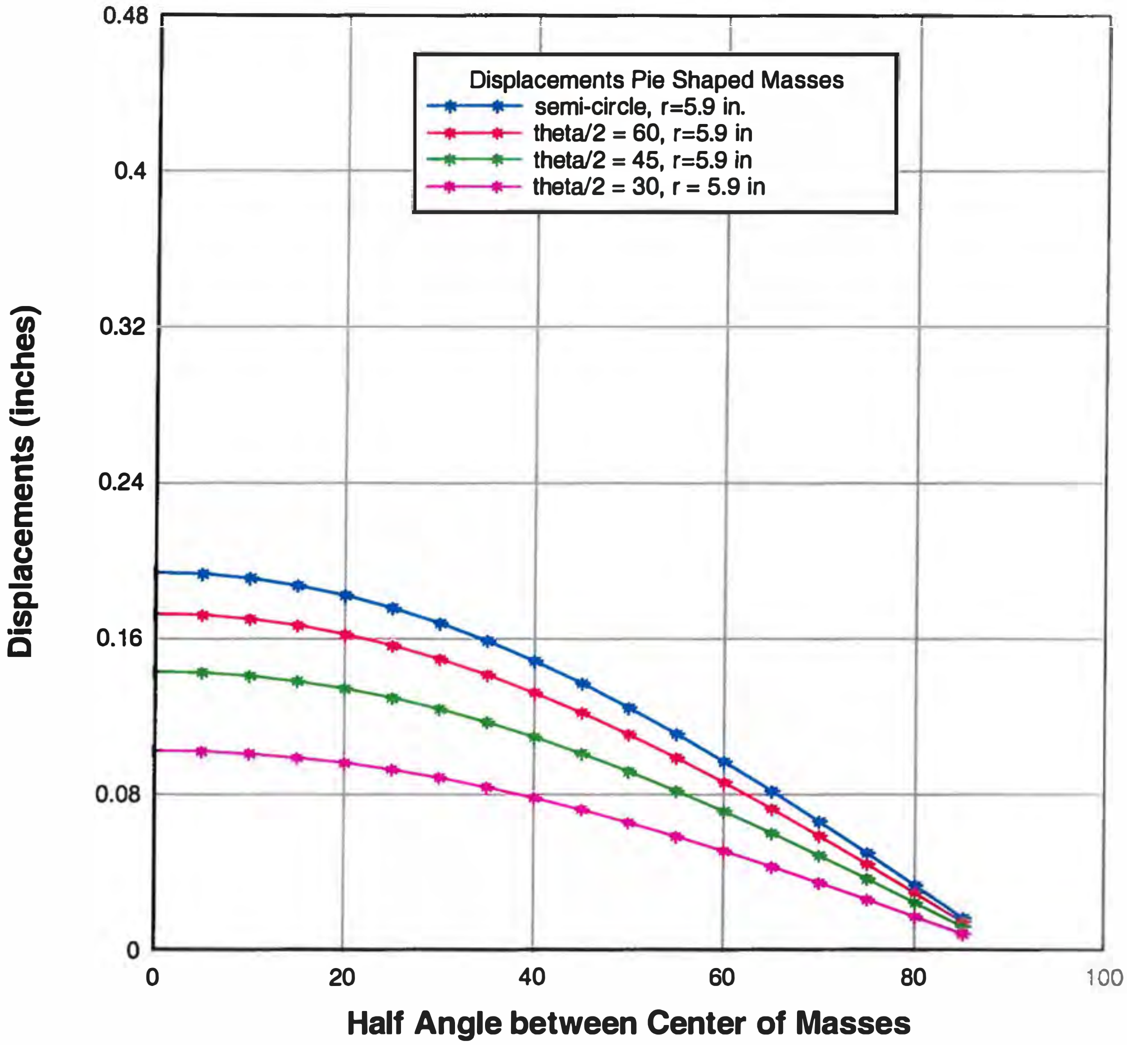


Figure 8. Total displacement developed from 30,000 lb. force for 5.9-inch radius eccentric weights and various weight configurations.

2.2 PROTOTYPE DEVELOPMENT

As a result of the above modeling effort, ARA designed a prototype sonic head for conducting field tests of the sonic CPT. A schematic of the sonic CPT vibratory system is shown in Figure 9. The required operating range of the device in terms of both frequency and dynamic force was derived from parametric prototype design model calculations conducted during the Phase I SBIR project. The drive head utilizes two counter-rotating eccentric weights to induce a sinusoidal driving force equivalent to the vertical acceleration of the eccentric weights times their mass. The counter-rotating weights are adjustable such that the eccentricity of the parts can be changed, yielding seven different eccentricity settings.

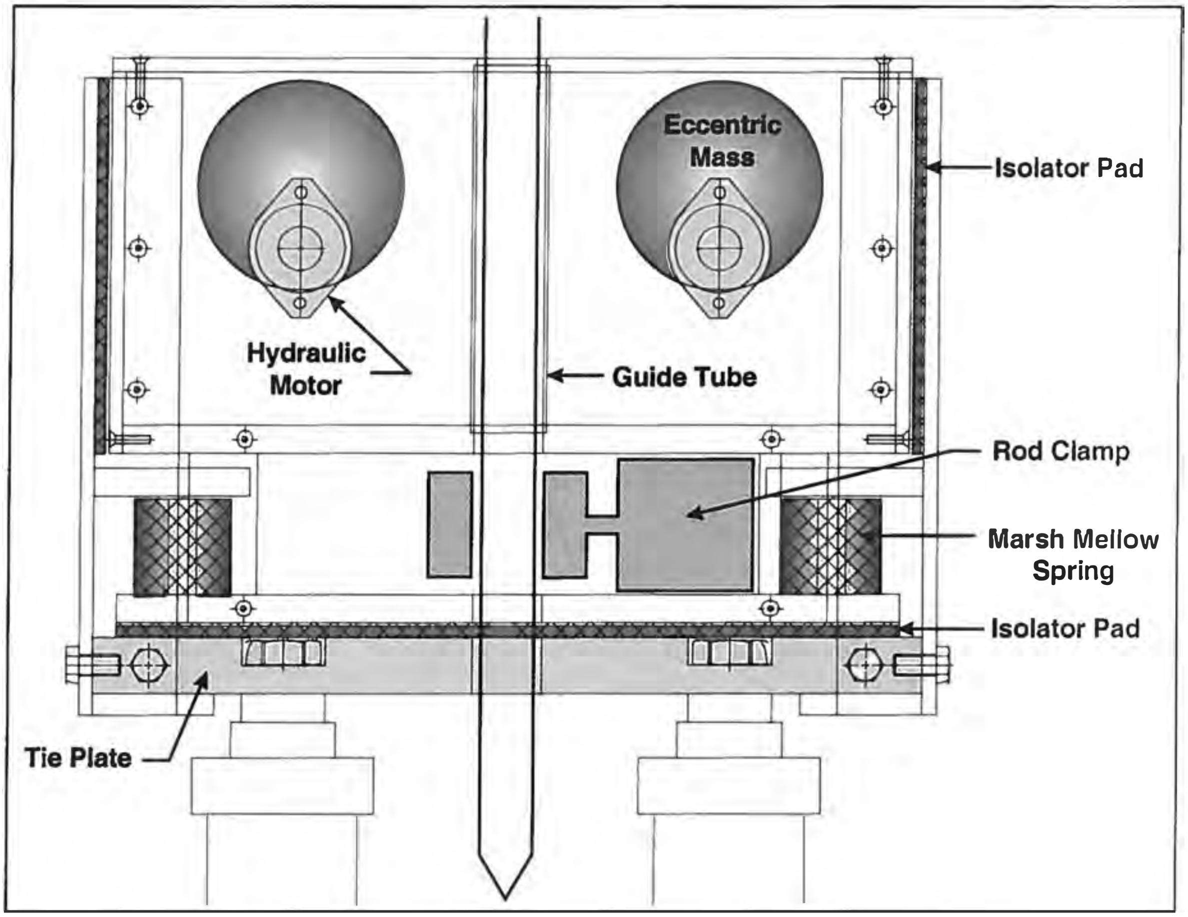


Figure 9. Schematic view of the sonic head incorporating the design elements learned during the phase I modeling efforts.

The prototype drive head contains a vertical tube through its center to allow the passage of CPT rods without interfering with the normal clamp operation. The vibratory head is mounted above the CPT clamp head by vibration isolators that limit propagation of vibrations into the remainder of the clamp system and truck. In this configuration, the vibratory head clamps the push rod directly and the existing hydraulic push cylinders provide bias load required for vibratory advancement of the CPT rod. The prototype vibratory head uses off the shelf parts wherever possible (bearings, hydraulic motor, and gears) to minimize fabrication costs. A separate demand feed style hydraulic pump mounted directly to the truck engine powered the hydraulic motors. An additional heat exchanger was added to manage the additional heat generated by the hydraulic motors.

The corresponding weights and eccentricities were chosen such that the eccentric moment (mass times eccentricity) results in 30,000 pounds of peak dynamic force at the highest frequency in each of the seven frequency ranges. The eccentric moments for each offset angle are listed in Table 1.

2.2.1 BEARING DESIGN

Several options were explored with respect to the bearing design. The overriding design constraint in this design problem was the shaft speed or vibrator frequency. As frequencies of 50 Hz or greater would normally be used, preliminary calculations indicated an unacceptably low bearing life. ARA evaluated several bearing types including unlubricated journals, lubricated journals, and roller elements. The results of this analysis are summarized in Table 2 below.

Table 2. Comparison of various bearing designs evaluated for use with the sonic CPT drivehead.

Bearing Type	*Advantages*	*Disadvantages*
Unlubricated Journal Bearings	Easy to manufacture.	▪ The maximum PV (pressure*velocity) rating of the best unlubricated journal materials is around 6 ksi-fpm. Whereas the sonic CPT application is roughly 15 ksi-fpm.
Lubricated Journal Bearings	None.	▪ Designing these bearings into a system requires significant engineering and development costs, ▪ Incorrect choices in film viscosity, surface material or fluid port geometry can lead to very rapid bearing failure. ▪ Bearing must be designed around a finite range of speeds to maintain proper film thickness.
Rolling Elements	Development costs are minimal.	▪ Not designed to carry high thrust loads, ▪ Major limitations of rolling element bearings are maximum operating speed and heat.

Given these constraints, the bearing selected for the sonic CPT drive head was a double-row spherical roller bearing (Torrington part #'s 2MM-208WIDUL and 205W). These bearings are specifically assembled for use with vibratory systems such as shaker screens. Pillow blocks were not available for this bearing size, so the enclosure/housing was designed and fabricated as part of the vibratory head system. The bearing bore size is 50 mm to accept a shaft designed for fatigue life at peak design loads. The outer bearing diameter is 100 mm, with a width of 40 mm.

For lubrication, three options were evaluated: (1) pumping hydraulic fluid from the primary CPT reservoir through the bearings at 3-5 gallons per minute (gpm), (2) low-pressure bearing grease, and (3) special high-temperature bearing grease. For the prototype vibratory system, special high-temperature bearing grease was selected, as the design and maintenance costs were lower. As part of the evaluation effort, the bearings were instrumented with temperature sensors to measure temperature rise as a function of rotation speed. This allowed for careful monitoring of the bearings allowing the operator to shut down the system if excessive temperatures were detected.

During the initial break-in period for the sonic CPT vibrator, the system was carefully monitored for high-pitched or unusual noises emanating from the vibrator. Under no conditions was the system operated above the maximum frequency specified for the particular eccentric mass setting. To insure that this did not occur, a rotational speed control limit switch was installed inside the speed controller enclosure, out of reach of the operator, only to be changed when the eccentric mass setting was changed.

For safety reasons, the sonic CPT system must always be started at low speed and the speed increased gradually to the desired operating point. This is to allow the grease to be evenly distributed within the bearing races to provide maximum lubrication.

2.2.2 SAFETY CONSIDERATIONS

To determine the acceptability of the thickness of the steel box surrounding the eccentric rotating masses, a fragment penetration analysis was performed. The highest frequency driving mode and the outer radius of the half circle mass was assumed. This assumption yields the maximum radial acceleration of the system. The following parameter magnitudes result from these assumptions:

- Maximum frequency of rotation is 150 Hz (9,000 rpm);
- Maximum radius from center of drive shaft to outside edge of the rotating mass is 5 inches;

These parameters yield a maximum radial acceleration of 4.44×10^6 in/sec^2.

If failure were to occur during a maximum harmonic dynamic drive, the failure would be precipitated at the half circular yoke that holds the rotating weights to the drive shaft. Such a failure would send the rotating mass off at an initial radial acceleration equal to the maximum given above. The resulting fragment is a blunt projectile weighting approximately 53.4 lbs. with a curvature of 5 inches and a thickness of 1.375 inches. To use the THOR penetration equations, it is necessary to determine the impact velocity of the fragment. To calculate the impact velocity of this fragment, a constant acceleration field with the magnitude of the maximum radial acceleration was assumed. The distance traveled was set equal to the clearance of the rotating weights, which is approximately 0.1 in. from the top plate. Using equations:

$$S = \frac{1}{2}at^2 \quad (6)$$

$$V = at \quad (7)$$

where:

S = distance traveled

a = magnitude of constant acceleration field

t = time of flight

V = velocity at S.

This yields an impact velocity of 78.54 ft/sec. For the parameters stated above, the THOR equations predict that the 0.5-inch plate will stop our projectile at 81.4 ft/sec.

An independent check using the BRL penetration equations from ASTM 1980, vol. V, "Report of the ASCE committee on impactive and impulsive loads," yields a limit velocity of 108.9 ft/sec for a 0.5-inch plate. Since the anticipated velocity of impact is only 81.4 ft/sec this calculation also yields no penetration.

2.3 INSTRUMENTATION

2.3.1 DATA ACQUISITION SYSTEM (DAS)

There were two separate data acquisition systems on board the CPT truck during testing. One system was used to monitor and record the standard CPT sensor data in the "static" mode (e.g., tip force, sleeve stress, hydraulic force, and tip and mandrel temperature). The other system monitored and recorded the tip force and acceleration, sleeve stress, and pillow block bolt strain in the sonic mode. During static pushing only the static measurements are made. When pushing in the sonic mode, both static and sonic systems are recording data.

ARA modified our existing CPT data acquisition system to acquire dynamic data during the operation of the sonic head. The software-based system was developed by ARA and was programmed using Hewlett-Packard's HPVEE® data acquisition programming language. Four channels were incorporated into the acquisition system to record sleeve stress, pillow block bolt strain, tip acceleration, and tip stress. Dynamic sleeve and tip data were collected by tapping the respective sensor signals at the main data junction box mounted in the CPT truck. Each signal was processed with a gain of 200 and a 1000-Hz low-pass filter by the dynamic acquisition system. Table 3 lists the types of data recorded during the test.

2.3.2 ROTATIONAL SPEED CONTROL

The operator, by means of a control circuit mounted inside a separate enclosure, controls the sonic head. The control circuit incorporates three means of control: (1) rotational speed control, (2) maximum speed (limit), and (3) emergency shutdown. The speed control is a 10-turn potentiometer and allows the operator near infinite control from zero to maximum speed. The potentiometer can be left at a desired speed setting and the operator can simply turn the sonic head on and off with a switch that activates and deactivates the potentiometer. The maximum speed limit is accomplished with a switch setting inside the box. A switch setting, which corresponds to an eccentric weight setting, is adjusted to prevent operation beyond the maximum design speed for the particular eccentric weight settings. An emergency shutdown switch allows the system to be shut down quickly if needed. Pressing the reset button will reactivate the system. These features provide the operator with a safe, reliable control of the sonic head.

Table 3. Parameters monitored during testing.

Measurement	Static (S) / Dynamic (D)	Range
Tip Stress	S/D	Standard
Sleeve Friction	S/D	Standard
Tip Temperature	S/D	0 - 250° C
Acceleration at Tip	D	0 - 500 g
Rod Displacement (Depth)	S/D	Standard
Dynamic Load	D	0 - 30,000 Lb.
Head-Bolt Load	D	0 - 21,000 Lb.
Bias Load	S/D	0 - 20 tons

2.3.3 PILLOW BLOCK BOLTS

Two bolt strain gauge transducers were custom fabricated by A.L. Designs, Inc. (Buffalo, NY) and were installed in the sonic head securing the upper and lower bearing pillow blocks. The intent was to measure the maximum vertical load developed by the rotating masses within the sonic head. When the load on the bolts reached a threshold level the overload shutdown circuit would trip, shutting down the hydraulic motors that drive the rotating eccentric masses. This functionality was never realized due to material properties of the instrumented bolts. This topic will be discussed in detail in the results and conclusions sections.

2.3.4 ACCELEROMETERS

A PCB® model #353B16 shear accelerometer was mounted on the cone tip to measure the vertical acceleration at the tip resulting from the force generated by the rotating eccentric masses. A second accelerometer was mounted on the sonic head to allow for comparison of the acceleration of the sonic head (source) and the cone tip. This provided an estimate of the efficiency of the energy transfer from the sonic head to the CPT cone. These accelerometers required a current source for their power which was provided by a Dytran Instruments, Inc. current source. The output signal from the CPT cone accelerometer was connected to the portable data acquisition system. The signal from the accelerometer mounted on the sonic head was monitored independently by an analog oscilloscope. Each signal was processed with a gain of 10 and a 1000-Hz low-pass filter.

2.3.5 DIGITAL CONE – SMR – GAMMA PROBE

One of the major goals of the sonic project was to develop methods for integrating shock sensitive sensors with the sonic equipment. Such integration will enhance the versatility of the CPT system for performing site characterizations. To this end, a heavily instrumented probe consisting of tip and sleeve stress, soil moisture, soil resistivity, temperature, and gamma radiation sensors was assembled and evaluated under both static and dynamic conditions at the Hanford site. During static penetration, tip and sleeve stress, tip and soil moisture-resistivity (SMR) mandrel temperature, SMR, total gamma, and depth were monitored. Parameters measured during sonic testing included all of the above plus tip and sonic drive head acceleration, bearing temperature, and rotational frequency (rpm).

The implementation of down-hole digital electronics afforded several advantages for shock resistance. First, previous sonic CPT experience showed that ARA's standard CPT cable was too heavy, resulting in failed connections due to inertial strain. The digital CPT enables the use of a small, lightweight 4-conductor cable for transmitting power and data between the sensors and data acquisition system. Also, the down-hole digital boards could be securely potted in their protective plastic housing using an epoxy resin. Both the digital cone and Resistivity Soil Moisture Probe (RSMP) boards were potted and mounted rigidly in their housings.

As shown in Figure 10, an analog gamma radiation sensor was configured behind the digital sensors. The gamma detector was a sodium iodide (NaI) crystal/photo-multiplier tube unit rated to withstand up to a 25 g acceleration. Since previous testing demonstrated that the cone may experience accelerations up to 300 g during sonic deployment, it was necessary to design and fabricate the shock-isolation system to reduce the acceleration transmitted to the sensor to below 25 g.

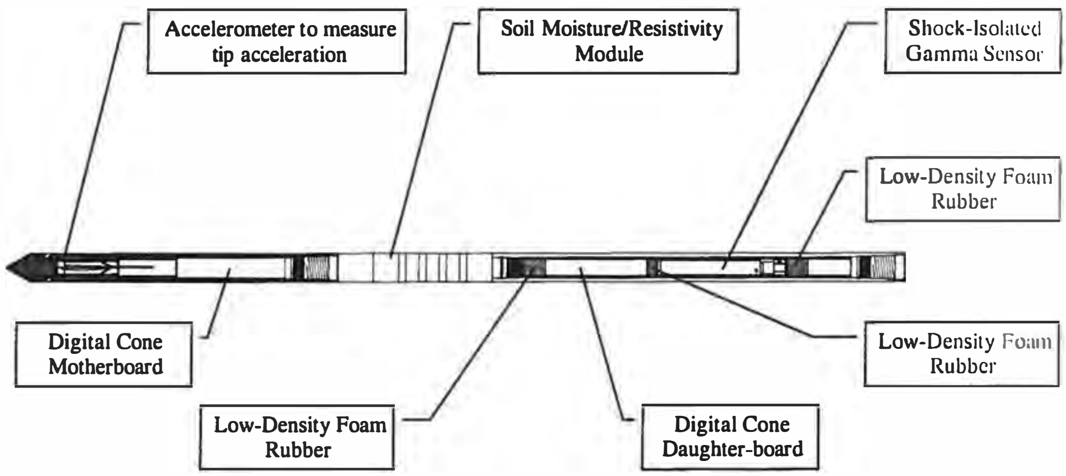


Figure 10. Assembly drawing of the various components of the digital cone -SMR-gamma probe. Note shock-isolators consisting of low-density foam rubber.

To facilitate this, the gamma sensor was housed in a specially designed mandrel that allowed for shock-isolation of the NaI crystal/photomultiplier ahead and behind the unit (see Figure 10) using low-density foam rubber. This technique is similar to that used to isolate sensitive electronics on guided missiles. A separate cable was required to connect the analog gamma sensor to its up-hole support electronics.

2.3.6 DATA ACQUISITION SYSTEM (DAS)

In order to monitor and record all the parameters described above, two separate data acquisition systems were used. ARA's newly developed Digi-Cone© data acquisition system was used to monitor and record digital CPT sensor data in the static mode (e.g., tip stress, sleeve stress, depth, hydraulic force, tip and mandrel temperature). This system interfaced to a portable PC to provide software control and data storage. The other data acquisition system consisted of the standard CPT data acquisition system and was used to monitor and record all of the sonic parameters as well as depth. Data from the two systems were correlated using reference to depth. The depth signal was "split" and monitored on both systems.

2.3.7 HARDENED FUEL FLUORESCENCE DETECTOR

The Fuel Fluorescence Detector (FFD) is a CPT sensor developed several years ago by ARA for the delineation of fuel contaminant plumes. The FFD has proven to be a cost-effective alternative to Laser-Induced Fluorescence and is now in use worldwide.

ARA's conventional FFD uses a low-pressure mercury arc lamp, band-pass filtered at 254 nm, to excite fluorescence of aromatic hydrocarbon fuel components in the ground. Excitation and collection of the fluorescence takes place through a non-scratching sapphire window in the CPT probe, as shown in Figure 11. Fluorescence emitted by the fuels is collected with fiber optics and delivered to a photomultiplier tube for detection. In early versions of the sensor, the detector was configured up-hole, but over the past year the photomultiplier has been moved down-hole into the sensor module.

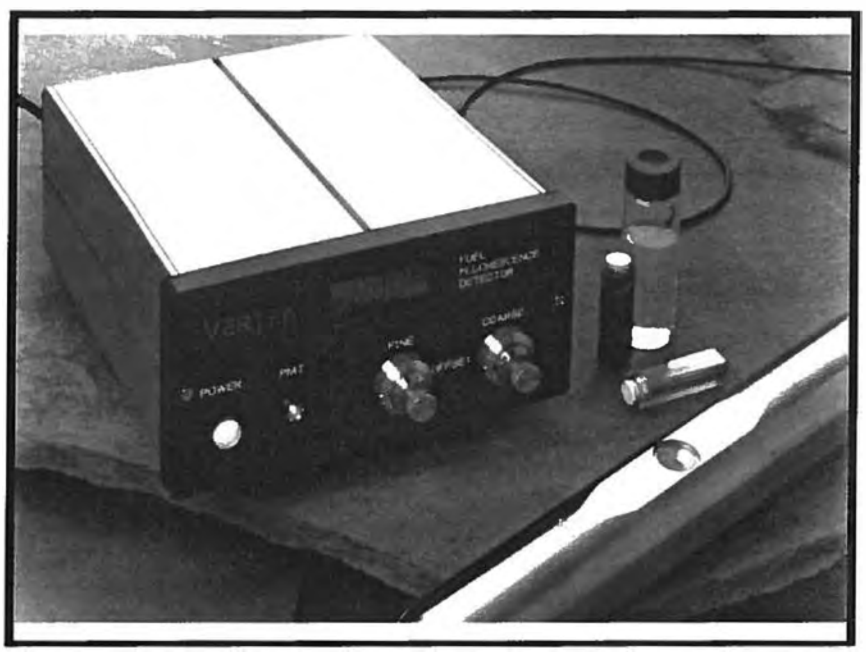


Figure 11. The ARA FFD sensor for the cone penetrometer. The sapphire window through which fluorescence is excited and collected is visible in the side of the probe.

A filter placed in front of the photomultiplier tube provides detection wavelength selectivity. This is important for matching the detection wavelength to the type of fuel at the site. Figure 12 illustrates this point. "Light" fuels such as gasoline or jet fuel, which are rich in benzene derivatives and naphthalenes, fluoresce at UV wavelengths. "Heavier" fuels contain large, polycyclic aromatic compounds that fluoresce at longer wavelengths. As shown in Figure 12, the heaviest materials, such as creosote and coal tar, emit well into the visible region of the spectrum. Clearly, an optical filter optimized for the detection of gasoline would completely miss creosote, and vice versa. In the present FFD, this issue is addressed by incorporating two photomultipliers, each with different filters, into the probe. A three-filter/detector FFD would be ideal; however, the size and cost of currently available photomultiplier tubes precludes this option.

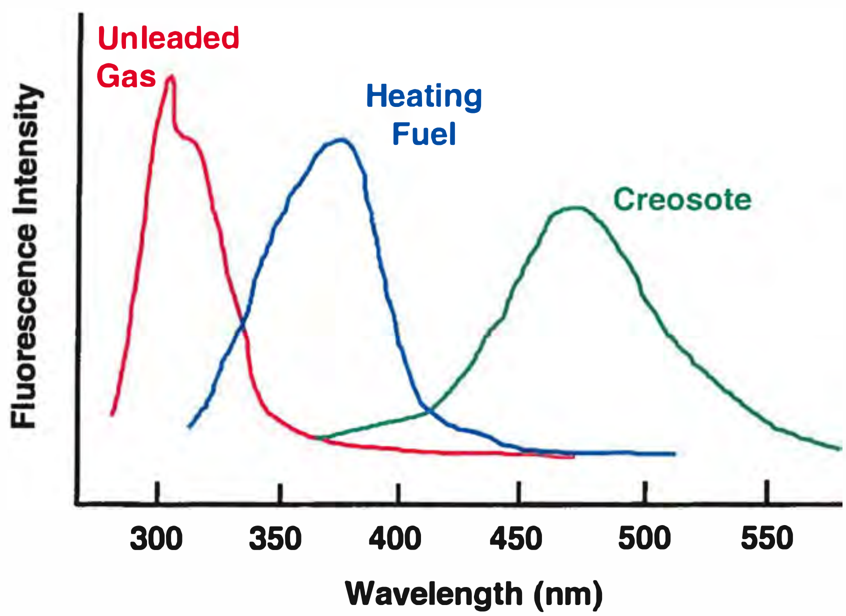


Figure 12. Fluorescence emission spectra for three fuel-related contaminants: "Light" unleaded gasoline, "Medium" home heating fuel, and "Heavy" creosote from a former manufactured gas plant.

Although the FFD has become one of the most valuable CPT tools and has performed reliably in the field, it is not well suited for sonic CPT deployment. Most notably, the photomultiplier tubes are not durable enough to withstand strong vibrations. Furthermore, with all components rigidly mounted in the probe, there is also the potential for lamp or electrical component failure. Therefore, under this project task we proceeded to design and fabricate an FFD that could withstand sonic deployment. The major elements of our approach were to replace the photomultiplier tubes with more durable photodiode detectors, and to shock isolate the entire sensor insert assembly. As an aid to shock-isolation and safety, we designed the system so that nearly all of the components, including the high voltage lamp power supply, were mounted on a single circuit board. The following paragraphs describe specific elements of the ruggedized FFD system:

Photodiode Detectors. Photodiodes are durable, all solid-state detectors that do not require the high voltages needed to operate photomultiplier tubes. They are also many times smaller and less expensive than photomultipliers. Photodiodes with integrated amplifiers are available in cylindrical packages less than 0.5-in diameter and 0.25-in thick. The major limitation of photodiodes is their insensitivity, typically less than 10^{-4} that of the photomultiplier tube. However, the inherent noise of the photodiode is very low, allowing for large signal amplification. Furthermore, much of the advantage of the photomultiplier tube is lost in the ground, where soil background fluorescence is many times greater than the lower detection limit.

To determine if we could achieve acceptable FFD sensitivity with photodiodes, a test module consisting of a UV-enhanced photodiode mounted on a circuit board inside a light-tight box was assembled. An optical filter assembly was configured at the input to the box, in front of the photodiode. An optical fiber delivered fluorescence from a standard sample to the photodetector module. This setup allowed for a direct comparison of the photodiode response to the response of a photomultiplier tube housed in a similar box. For the comparison, the optical fiber was simply switched between the two boxes.

Results obtained using an internally amplified, hybrid photodiode vs. a photomultiplier tube (adjusted to normal operating sensitivity) were highly encouraging. Without additional external gain, the photodiode response to a standard calibration sample was about 1 mV. With an external gain of 100, the photodiode response was 97 mV with 1-2 mV noise. This was very close to the response of the photomultiplier tube, which produced a signal of 83 mV and about 0.5-1 mV noise.

Integrated Circuit Board. Having established feasibility for a FFD using photodiode detectors with modest additional external gains, we proceeded to design a printed circuit board (PCB) that integrated most of the major sensor elements. A photograph of the board is presented as Figure 13. Major PCB components, identified in the photograph, included the following:

- Three filtered photodiodes. The small size and low cost (< $100 each) of the photodiodes allowed us to include the ideal three detectors on the board. External gains of 100 were provided on the board for each photodiode. On-board amplification improves signal-to-noise ratios.

- Mercury lamp power supply. The lamp operates at 900 Vac. A small 12Vdc to 900Vac converter was implemented on the printed circuit board as a safety measure. As a result, high voltages do not have to be transmitted over the CPT cable. On-board voltage conversion is safer.

- Microcontroller. Data acquisition, digitization, and bidirectional serial communications were handled by a microcontroller on the PCB. This approach also enhanced detector signal-to-noise ratios and reduced the number of cable conductors and external connections (a potential weak point) required to the board.

The board shown in Figure 13 was 12.0-in long x 0.80-in wide x 0.63-in high, allowing it to fit easily into the CPT sensor module housing.

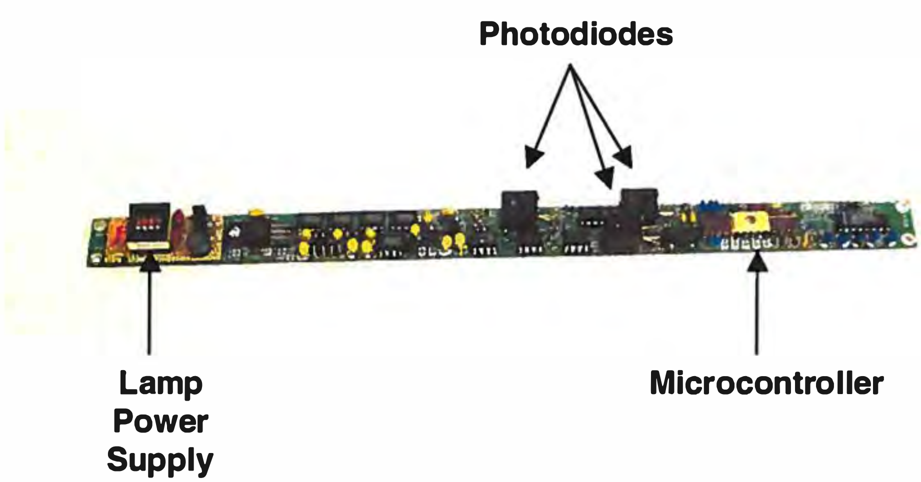


Figure 13. Photograph of the integrated FFD circuit board.

Complete, Shock-Isolated Insert Module. To produce a fully operational down-hole FFD system, the FFD circuit board was mounted behind a stainless steel lamp subassembly as shown in Figure 14. The lamp subassembly included the filtered mercury lamp for exciting fluorescence and three optical fibers for collecting and delivering fluorescence to the photodiode detectors on the FFD circuit board. The optical fibers were all-silica, UV-transmitting fibers with a 365μm diameter core.

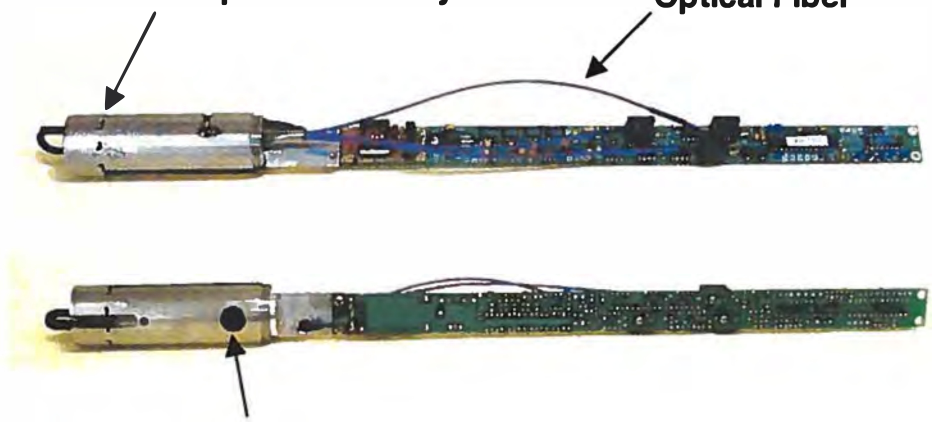


Figure 14. Photographs of the coupled FFD lamp and circuit board subassemblies.

In order to enhance the durability of the coupled FFD lamp and circuit board assembly during sonic deployment, the assembly was rigidly mounted inside a plastic tube that was shock-isolated from the sensor housing and the CPT rod system via springs on both ends of the tube. The springs were selected to provide effective shock-isolation when deployed with either a sonic CPT or a Geoprobe®, which uses impact hammering to drive probes into the subsurface. A shock-isolated system involves putting a soft spring between the element to be isolated and the source of the shock/vibration. The spring and the isolated mass can be idealized as a single-degree-of-freedom (SDOF) oscillator. This idealization is valid provided the base (in this case, the probe body) is much stiffer than the isolating spring. More precisely, the first mode frequency of the base must be much higher than the frequency of the SDOF isolation system.

Since detailed information on the vibration environment was not available for either the sonic CPT or the Geoprobe®, it was necessary to exercise some engineering judgement in selecting the design criteria. The following criteria were used to guide the design:

Maximum Displacement = 0.5 inch. This is the vertical movement the isolated element is allowed from its rest position to maximum excursion. This displacement is allowed in both directions, for a total range of 1.0 inch peak-to-peak. This criterion was based on a judgement that the maximum advance (or "set") of the probe on any given load cycle will be less than 0.5 inch.

Minimum Loading Frequency = 16 Hz. Sales literature published by Geoprobe® specifies an operating frequency of 32 Hz. The sonic CPT was designed for frequencies of 42 Hz to 142 Hz. For an added measure of conservatism, half the low value (i.e., 16 Hz) was used in the design.

Maximum Acceleration of FFD Components = 2 g. With the addition of gravity (in one direction), the total acceleration experienced by the isolated element is 3 g, a rather benign environment for components as small as the FFD. Again the selection of this criterion was an engineering judgement.

Fundamentally, there are only two parameters to select in the design of the isolation system, the SDOF frequency and the "rattle space," or peak displacement of the system. Thus, only two of the three criteria listed above will actually impose limits on the design. A general principle in the design of isolation systems is to select the isolating spring so that it in combination with the isolated mass forms a SDOF system with a frequency no more than one third of the forcing frequency. Based on the criteria stated above, the loading frequency is 16 Hz. The nominal isolation frequency was selected to be 5 Hz. The fundamental vibration frequency of a SDOF oscillator is given by:

$$\omega = 2\pi f = \sqrt{k/m} \qquad (8)$$

where:

ω	=	circular frequency (rad/s)
f	=	frequency (Hz)
k	=	spring stiffness (force/length)
m	=	isolated mass (mass)

This equation, and those following, are derived from the dynamic equilibrium equation of the isolated mass, a second order differential equation with constant coefficients. The maximum acceleration, A_{pk}, of a SDOF oscillator at peak displacement, D_{pk}, (ignoring signs) is given by:

$$A_{pk} = \omega^2 D_{pk} \tag{9}$$

For a 0.5-inch displacement of a 5-Hz oscillator, the peak acceleration is 493 in/s^2, or 1.28 g. This is within the criterion value of 2 g. A SDOF system acting in the same direction as gravity will have a static displacement, δ, under the action of gravity that is purely a function of the acceleration of gravity and the frequency. This must be accommodated in the design, and is given by:

$$\delta = \frac{g}{\omega^2} \tag{10}$$

For a 5-Hz system operating in the earth's gravity, the static displacement is 0.39 inch. This is less than the assumed maximum dynamic displacement, and can be accommodated with a reasonable spring size.

The FFD lamp subassembly, circuit board, and protective tube have a combined weight of approximately 1.25 lb, which is equivalent to a mass of 3.24 x 10^{-3} lb-s^2/in. Using that value in equation 8 and solving for k gives a required total spring stiffness:

$$k = 3.2 \text{ lb/in} \tag{11}$$

Actual implementation of the design requires two springs, one above and one below the isolated module. Thus, the sum of the stiffnesses of the two springs must equal that value. Since the lower spring supports the gravity load of the module, it was selected to be larger than the upper spring. The geometry of the system was designed so that the sensing element of the FFD is centered directly behind the window when at rest in a vertical orientation. The full 0.5-in vertical displacement is allowed in both directions, and both springs are always compressed at least 0.25 in. Again, a conservative approach was used in implementing the springs, which were approximately 2.2 lb/in (lower) and 1.8 lb/in (upper) for a total k = 4.0 lb/in. The extra stiffness beyond the calculated 3.2 lb/in helped to ensure that the insert module did not "bottom out" during deployment.

A photograph of the shock-isolated insert assembly is presented as Figure 15. Not shown is the second spring mounted inside the sensor housing which the lamp subassembly also compresses. The second spring is located at the lamp end of the assembly, so that the insert "rides" between the two springs.

Figure 15. Photograph of the shock-isolated FFD insert module.

3. TEST DESCRIPTION

The objective of the field testing program was to test and evaluate the newly developed vibratory CPT system under rigorous field conditions to determine its suitability for DNAPL characterization at DoE and DoD facilities. Preliminary testing was conducted at two local ARA test sites followed by testing at the Cold Region Research and Engineering Laboratory (CRREL), located in Hanover, NH. This was followed by a one-week testing and demonstration event at the US Army's Camp Edward, located on the Massachusetts Military Reservation (MMR), Cape Cod, MA and a second week at Kelly AFB, San Antonio, TX. Finally, the sonic system was tested at two DoE facilities, the Savannah River Site (SRS) in Aiken, SC and the Hanford Site in Richland, WA. This section discusses the objectives, scope, and results at each of the sites during the field testing and demonstrations.

Several system parameters influence the depth capacity and rate of penetration of the sonic system. These parameters include the eccentric mass offset, rotational frequency, and static (bias) force added to the dynamic force generated by the sonic head. Much of the information gleaned during the field testing was the result of varying these parameters and observing the effect.

Other aspects of the vibratory system that were studied during the course of the field testing included:

- the ability to collect and the quality of soil and groundwater samples obtained with the sonic CPT;
- the effect of vibration on the CPT truck, hydraulic system, electronic equipment, and CPT sensors;
- the force output of the sonic head, including frequency and acceleration measurements; and
- the overall performance of the integrated sonic system.

The following sections discuss these topics as they relate to the individual field testing events.

3.1 LOCAL TEST SITES

3.1.1 OBJECTIVES

The primary objective of the testing conducted at the Vermont test sites was to conduct a controlled startup and break-in period and to evaluate the initial performance of the sonic system. It provided an opportunity to run the system under closely supervised conditions by ARA engineers, and to evaluate problems associated with both the mechanical and instrumentation aspects of the sonic CPT system prior to the full scale testing and demonstration at the DoE and DoD facilities. The secondary objective was to evaluate the effectiveness of sonic CPT in penetrating familiar soil strata at local sites while providing easy access to shop facilities to allow for any needed repairs and modifications to the system.

3.1.2 SCOPE

Vibratory system startup and shakedown testing was conducted first at ARA's New England Division (NED) office / manufacturing facility, located in South Royalton, VT, and then at two different sites located proximate to the office during the period from August 1 through August 7, 1997. The two sites exhibited distinctly different geologies and provided ideal test conditions to begin testing the sonic system.

The vibratory system startup began by slowly and cautiously allowing the hydraulic motors to spin the eccentric masses which were set at the lowest eccentric moment (170° offset angle). The system was allowed to spin for approximately 30 minutes at 100 revolutions per minute (rpm) to allow the grease to thoroughly coat the bearings prior to increasing the speed. The vibratory head was closely monitored for unusual noises and vibrations. Once the initial break-in period was complete, the system's rotational speed was progressively increased through the full operating range.

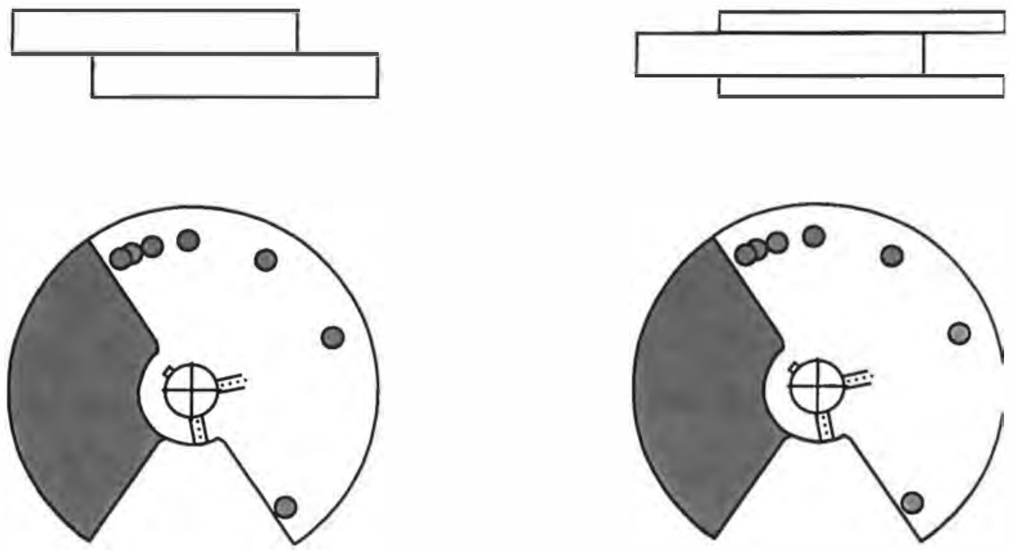
During this preliminary testing, various subsystems were installed and tested. For example, the variable speed control and emergency shutdown systems were tested and set to prevent over-rotation at each of the individual eccentric mass offset angles. The speed control system consisted of a proximity switch and a pulse counter/control unit. This system was vital to safe operation of the vibratory system. Hydraulic flow to the individual motors was set and the auxiliary heat exchanger's thermostatic valve was calibrated to open when the oil temperature reached 130°C. An accelerometer was mounted on the vibratory head to provide a means of quantifying the attenuation in the rod string by comparing the acceleration delivered by the vibratory head and the acceleration experienced by the cone at depth. Finally, the two transducer bolts that were installed during assembly of the vibratory head were wired into the dynamic data acquisition system and tested along with the two accelerometers.

Once these preliminary tasks were complete, the vibratory system was prepared to mobilize to the field for testing under rigorous field conditions. The first site was located on the north end of ARA's property and consisted of clayey sand and silt overlying bedrock at a depth of approximately 30 feet below ground surface (bgs). Using a 'dummy tip' the rod string was advanced into the ground until moderate resistance was encountered at which point the vibratory system was engaged. The frequency was varied during the course of the push, as were the bias load and the eccentric offset. Previous numerical modeling efforts indicate that low frequency and high amplitude are optimal in this stratigraphy. In fact, these settings seemed to work well; however, it was difficult to determine the optimum settings, since resistance to pushing in the static mode was minimal and, in the sonic mode, the rods penetrated the soil faster than the hydraulic cylinders could travel. Two penetrations were completed at this site, both to depth of approximately 40 feet. Standard CPT data were not collected during these shakedown tests.

The second site, located approximately three miles southwest of ARA's office, consisted of uniform fine to medium sands that extend to bedrock at approximately 120 feet. Here, five penetrations were conducted to various depths while varying the rotational frequency, eccentric mass offset angle, and bias load. Model predictions suggest that higher rotational frequency and lower amplitude work better in sands by inducing liquefaction in the sand grains in contact with the rods and at the tip. With this in mind, the focus of the testing here was to use higher frequency and lower amplitude while varying the bias load. Three of these penetrations were advanced using an instrumented cone. Standard CPT parameters were recorded as well as accelerometer and hydraulic force data.

3.1.3 RESULTS

During the preliminary testing of the vibratory head, it became apparent that the design of the eccentric masses was causing a moment force perpendicular to the shaft resulting in excessive loading in the bearings. This resulted in the rapid failure of one set of bearings. To alleviate this problem the eccentric masses were reconfigured by splitting one of them and sandwiching the halves around the other mass as shown in Figure 16. After balancing the masses, the bearings have proven to be robust and well suited for this application. Bearing temperature was carefully monitored throughout the remainder of the testing and found to be less than 30°C above ambient temperature. This is within the acceptable operating range of both the bearings and the grease used as lubricant.



(a) (b)

Figure 16. Preliminary (a) eccentric masses resulted in premature failure of the bearings. The masses were redesigned (b) by splitting one of the masses and sandwiching the two halves around the other mass.

Comparison of the acceleration data from both the accelerometers mounted on the vibratory head and the down-hole accelerometer illustrates that significant attenuation occurs in the soil. This is a function of the type of soil, the length of rod string in the ground, and the length of rod string below the water table. Figure 17 depicts this below.

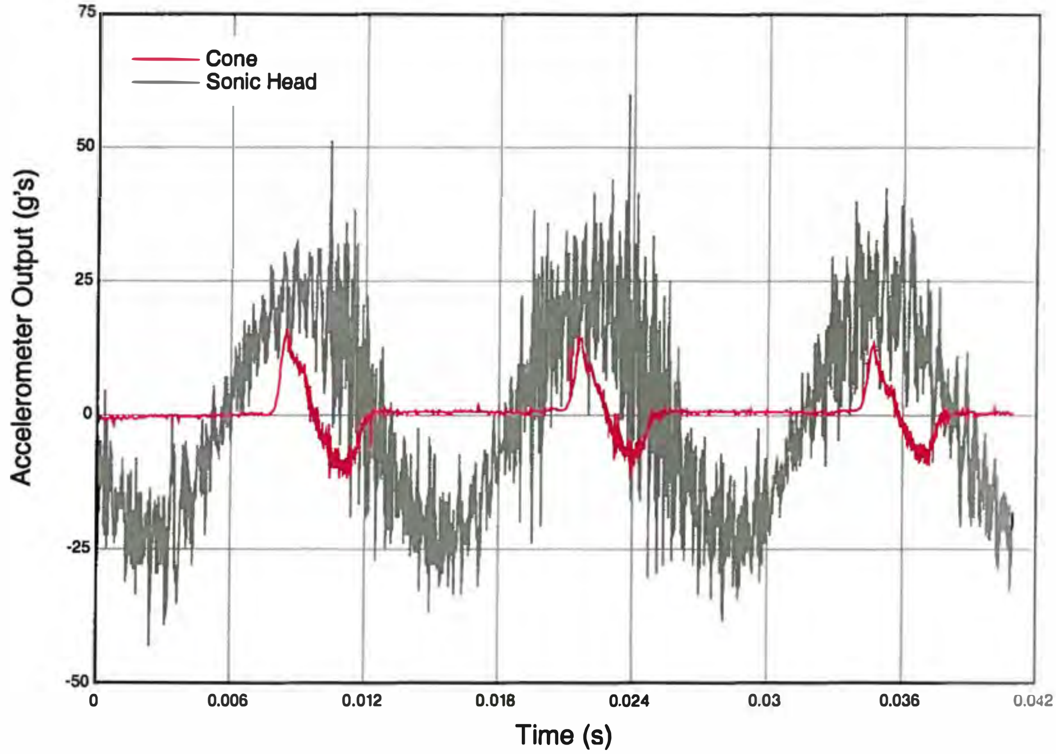


Figure 17. Acceleration in the vibratory head and CPT cone. Comparison of the two traces indicates that approximately one-third of the acceleration delivered to the drive point is attenuated in the soil. The eccentric masses were set to an offset of 157° and the rotational speed was 4600 rpm.

3.2 CRREL

3.2.1 OBJECTIVES

The primary goal of the initial testing conducted at CRREL was to gain experience with the vibratory system at a familiar site known to be difficult to push in using a heavy weight CPT. It provided an opportunity to continue to evaluate any problems associated with both the mechanical and instrumentation aspects of the vibratory CPT system prior to the full scale testing and demonstration at the DoE and DoD facilities. It also provided valuable experience with the use of a soil sampler using the vibratory CPT system and finally, it enabled us to evaluate the new rope thread configuration for the CPT rods.

3.2.2 SCOPE

During the period from 7 August through 15August 1997, ARA conducted seven penetrations using the vibratory system at CRREL. The penetrations were conducted in an area where ARA has had significant previous experience using standard CPT. The near surface geology consists of silty sands with a dense layer at 45-50 feet bgs. During the field testing, parameters such as bias load, frequency, and eccentric mass offset were altered and their effect on the ability to penetrate the formation was evaluated. Soil samples were collected as part of the testing at this site. A typical push at this site is illustrated below in Figure 18.

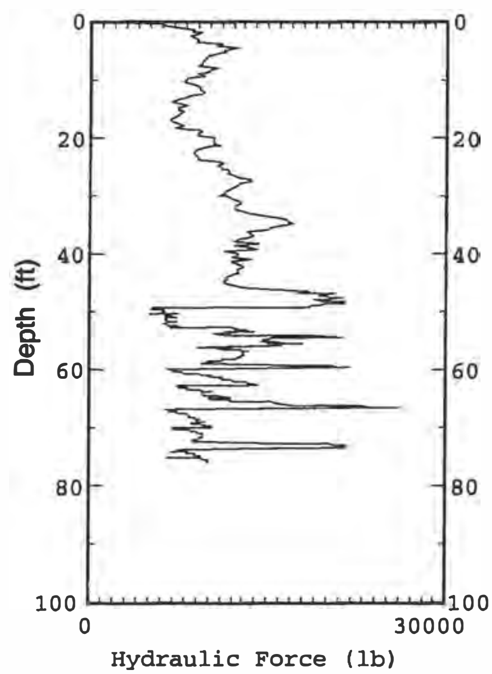


Figure 18. Plot of hydraulic force verses depth typical of the penetrations conducted at CRREL. Note the spikes in the hydraulic force from approximately 50 feet and below indicate the hydraulic force required to penetrate in static mode while the valleys show the force required in sonic mode.

At this location, the rods were pushed to approximately 49 feet bgs in the static mode at which point the hydraulic push force required was sufficient to warrant using the vibratory head. With the eccentric masses set to 143° offset, the penetration continued using the vibratory system. The rotational speed was varied throughout the push, progressively increasing it from 1000 rpm at a depth of 49 feet bgs to 4450 rpm at 72.1 feet bgs while recording the hydraulic push force. At several depths, the vibratory system was turned off and the rod string was pushed statically for comparison purposes as shown in Figure 18.

At a depth of approximately 66 feet after pushing statically, we began to notice significant spring-back when the rod clamp was released in order to add additional rods. Eventually the magnitude of the spring-back increased to about one foot. Upon pulling the rods, we realized that this was the result of the rods bending. Eleven of the rods from the upper thirty to forty feet had permanently deformed, bending in an arc of approximately four feet in radius.

3.2.3 RESULTS

Throughout the course of the testing, a variety of combinations of bias load, frequency, and eccentric mass offset were used. Frequencies between 1700 to 3600 rpm and eccentric mass offsets at 112° and 143° worked better in this formation. However, the near surface (upper 40 feet) geology did not provide adequate lateral support, resulting in enlargement of the hole due to the horizontal vibration of the rods. This ultimately stressed the rods to the point of bending and/or breakage. This led to the modification of ARA's thread design, incorporating 2-inch diameter collars at each coupling and the use of a straight rope thread design. This greatly improved the strength of the couplings with the tradeoff that the increased effective diameter of the rods was more difficult to push in certain formations.

There are two hydraulic pumps on the CPT, one to power the truck hydraulics and one to run the hydraulic motors on the vibratory system. The main hydraulic pump was a constant pressure type, requiring the pump to operate continuously to maintain a hydraulic pressure of approximately 2500 psi within the system. This generated a significant amount of heat that was dissipated by conduction through the hydraulic storage tank and by convection in an auxiliary heat exchanger. The hydraulic pump that powers the vibratory system, conversely, is an on-demand style pump which generates some heat but not nearly as much as the main hydraulic pump. The combined heat load generated by the two pumps exceeded the cooling capacity. To alleviate this, the main hydraulic pump was replaced with an on-demand style similar to that used for the vibratory system. This significantly reduced the heat load, allowing the cooling system to maintain proper operating temperature of the hydraulic fluid.

Another lesson learned during this phase of the testing was the importance of insuring that the rotation of the two eccentric masses was synchronized with each other. This was accomplished by adjusting the helical-cut gears on their respective shafts to assure that the center of mass of each eccentric weight reaches the apex of rotation simultaneously. By doing this the vibratory head ran much smoother hence prolonging the service life of the bearings. The helical timing gears are shown from the top view in Figure 19.

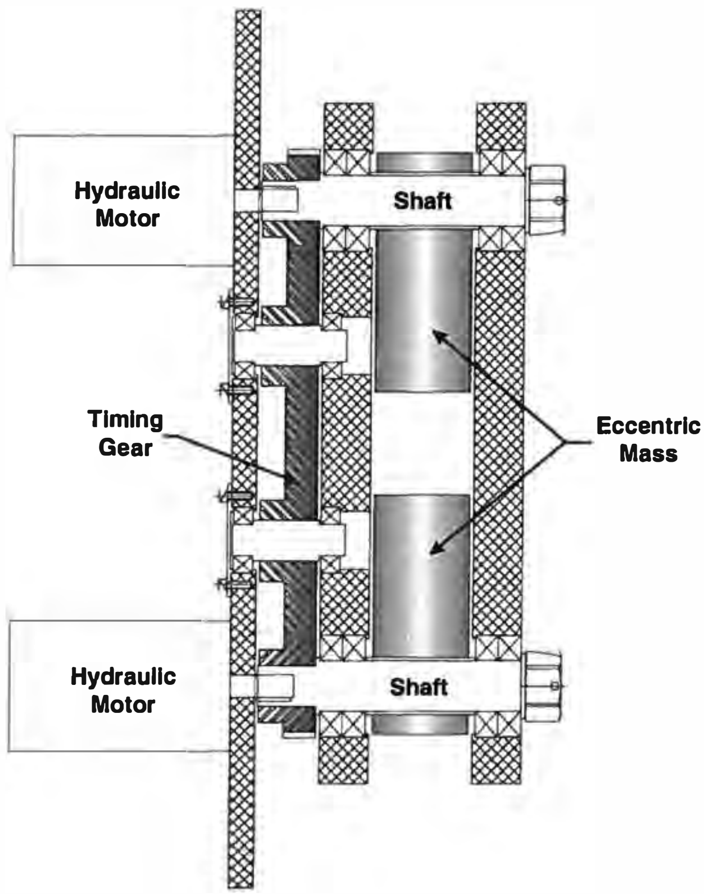


Figure 19. Preliminary testing demonstrated the importance of insuring that the eccentric masses were synchronized. This was accomplished by adjusting the helical-cut gears on their respective shafts to assure that the centroid of each eccentric weight reaches the apex of rotation simultaneously.

3.3 MMR

3.3.1 OBJECTIVES

The objectives of the testing at MMR were to (a) test the vibratory system at a site where the geology is typically difficult to penetrate with standard CPT, and (b) to demonstrate improved CPT capabilities for site characterization and monitoring. The primary objective was to attempt penetration of a dense cobble layer located between 10 and 20 feet below ground surface (bgs) near the LF-1 landfill. This area was selected since previous attempts to perform CPT testing by the WES SCAPS rig resulted in repeated refusal at approximately 20 feet bgs. The second objective was to evaluate the ability to collect soil and groundwater samples using vibratory CPT technology.

3.3.2 SCOPE

Testing at the MMR occurred during the week of August 18, 1997 and was conducted at two different sites exhibiting two distinct geologies. During the test program, ARA completed seven CPT penetrations, collected four groundwater samples, and attempted to collect two soil samples. The first area selected for testing was located along the northwest boundary of the LF-1 landfill. Drilling logs from previous investigations indicated a cemented region at a depth of approximately 20 feet bgs, followed by cobbles and boulders from 20 to 60 feet bgs. The MMR Installation Restoration Program (IRP) geologist described this site as a lateral moraine. Figure 20 illustrates the typical grainsize distribution noted at this site. The second area selected for testing was described as a glacial outwash by the IRP geologist, and was located in the north-central portion of the MMR. Collecting soil and groundwater samples using the sonic CPT was the primary focus at this location. The soil samples that were collected provided vital data for an ongoing remediation program currently underway at the site.

Figure 20. Typical grain-size distribution noted at the MMR site.

A demonstration of the sonic system was held on August 21, 1997 and was attended by representatives from the Army Environmental Center (AEC), Armstrong Laboratory, WES, and the MMR IRP.

3.3.3 RESULTS

The first CPT penetration (MMR-1) was advanced using a dummy tip to a depth of 41.9 feet bgs with the eccentric masses offset to 165°. In general, optimum settings included a bias load of 4000 to 6000 lbs. and an angular velocity of approximately 1700 revolution per minute (rpm). Progress was moderate until the 40 foot depth at which point it was slow but consistent. Since it was nearing the end of the day it was decided to halt the push and change the eccentric mass setting to 112° then continue the push the following day.

With the eccentric masses offset to 112°, a second penetration (MMR-2) was conducted at the same location as MMR-1. At this setting, there was significant lateral vibration of the rods, which seemed to increase as the bias load was increased. This setting did not appear to enhance the ability to penetrate the formation regardless of the frequency selected. The penetration was aborted and the eccentric mass setting was changed to 157°.

MMR-5 was conducted at a new location approximately 5 feet south of the MMR-1 & 2 locations. This penetration was pushed statically to refusal at 54 feet in the static mode where the sonic system was turned on. The eccentric mass setting was 157° during this penetration and the rotational speed was varied from 3600 to 5000 rpm with 4000 rpm being optimal. Penetration was rapid and continued to a depth of 64.5 feet. Static pushing was attempted at 64.5 ft, but refusal was met immediately. At that point, the penetration was aborted to ensure our ability to retract the rods. The vibratory system was required to pull the rod string for approximately two rod lengths; the remaining rods were removed using only the static mode. The hydraulic push force data collected during this penetration are presented in Figure 21.

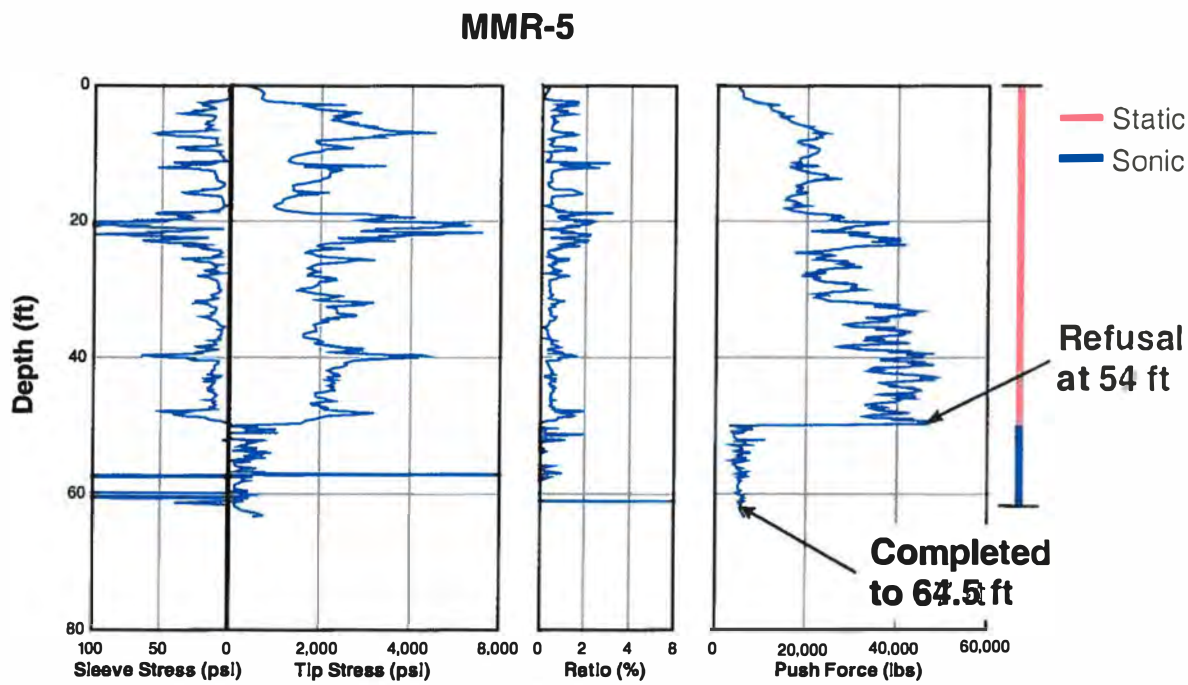


Figure 21. Note the reduced hydraulic push force required from 54 feet to the bottom of the penetration corresponding to the depths that the sonic mode was used.

MMR-6 was conducted approximately 100 feet south of the MMR-5 using an instrumented cone. This penetration was conducted in static mode to a depth of 9.3 feet. From there the CPT cone was pushed both statically and with the sonic system as required to achieve a depth of 56.7 feet. The eccentric mass setting was 157° and the optimal rotational speed was approximately 1700 rpm. The penetration was stopped due to the elevated hydraulic fluid temperature. Problems were encountered with the electrical connector inside the cone during this penetration and were later repaired. Figure 22 illustrates the data collected during this penetration. Note that the tip temperature does not increase significantly due to the vibratory energy.

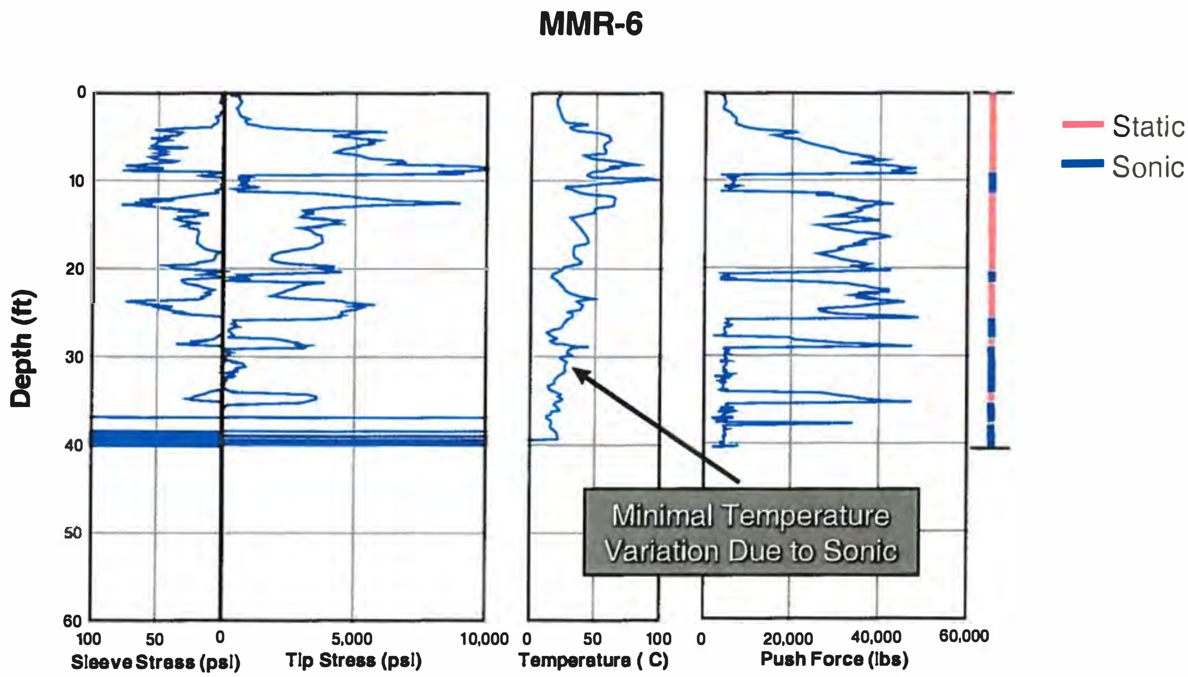


Figure 22. **CPT profiles from the MMR-6 penetration including tip temperature and hydraulic push force. Note the minimal temperature variation due to the vibratory energy.**

MMR-7 was conducted approximately five feet north of MMR-6 and was performed on the day of the demonstration. This was a difficult push, but clearly demonstrated the value of the sonic CPT system. Refusal was met at a depth of nine feet in the static mode; the sonic mode was then employed to reach a depth of 100 feet. The penetration was aborted due to time constraints. The eccentric mass setting was 157° and the optimum rotational speed was approximately 1700 rpm in the shallower portions but increased to 4600-5500 rpm as the rod string approached the 60 to 100-foot interval. With a longer rod string, the system was able to reach resonate frequencies at the higher rotational speeds. Based on the rate of penetration at a depth of 100 feet, the penetration could have gone much deeper. The data collected during this penetration is presented in Figure 23. It clearly illustrates the greatly reduced hydraulic force required to advance the rod string.

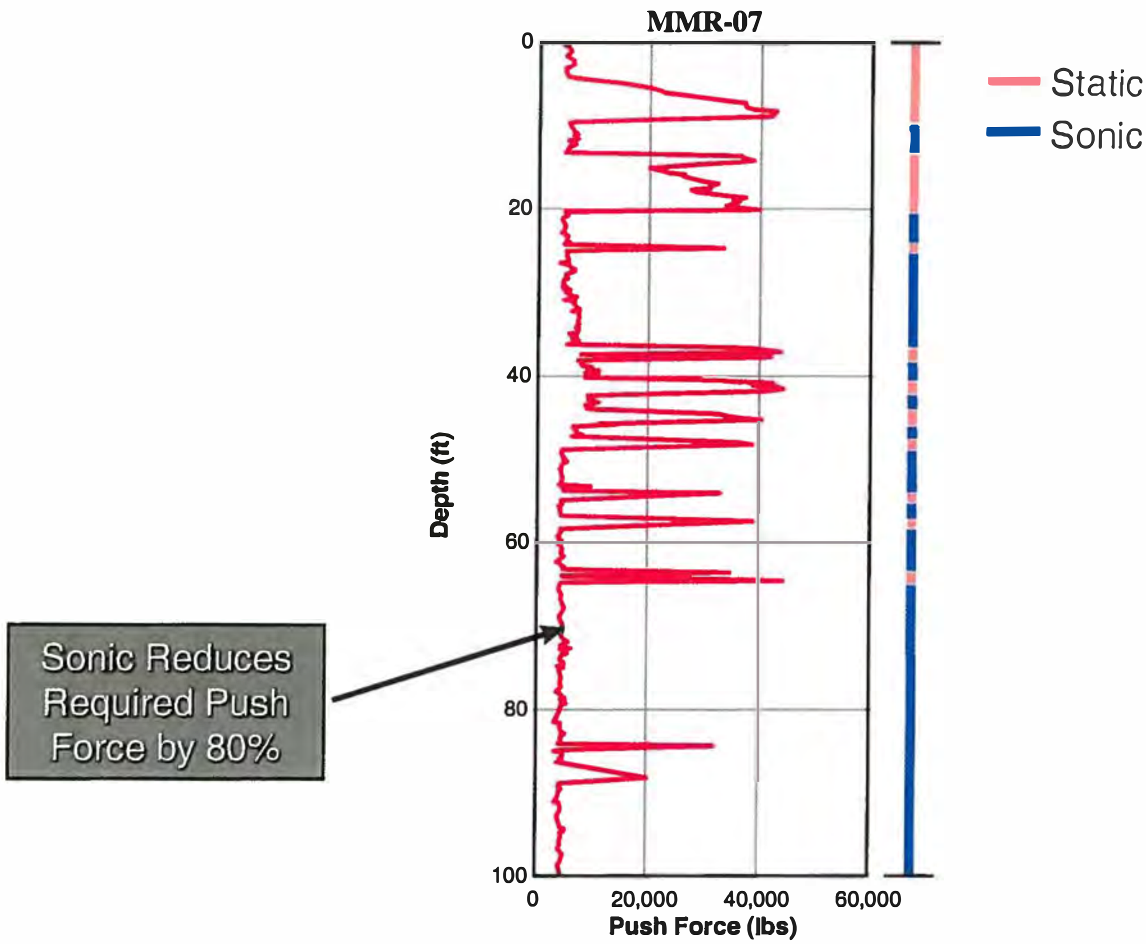


Figure 23. The hydraulic push force during the sonic portions of this penetration was well below 10,000 lbs. The spikes indicate the zones that were conducted in the static mode.

The testing at MMR clearly demonstrated the utility of the sonic CPT system. The results of the WES SCAPS experience at the LF-1 site indicated that only one of "numerous attempts" was successful in penetrating to depths deeper than 20 feet. Using the sonic system, ARA did not meet refusal during any of the five penetration locations and attained a minimum of 42 feet and a maximum of 100 feet bgs at the LF-1 site. Equipment losses were significant during this test program; a CPT cone was lost while retracting from the 100-foot penetration (MMR-7) and two Mostap® soil samplers and 27 CPT rods were lost during the soil and groundwater sampling tasks. The cause was examined and methods to reduce losses were engineered and appear to be successful; however, the sonic CPT will cause higher wear and increase the risk of lost equipment.

3.4 SRS

3.4.1 OBJECTIVES

The primary goal of the SRS field testing program was to evaluate the effectiveness of sonic CPT in reaching the clay/sand soil strata characteristic of the M-Basin with particular emphasis on reaching the green-clay layer at a depth of approximately 160 feet below ground surface (bgs). SRS engineers are anxious to develop an economical method to reach this zone, both to characterize the soils and to begin cleanup efforts of DNAPL contamination known to exist there. The use of the soil sampler with the vibratory system was emphasized during this testing program to demonstrate the utility and robustness of the ARA soil sampler and to provide SRS personnel with soil samples for logging purposes.

A second, but equally important, objective was to conduct a demonstration of the vibratory system for DoE and DoD personnel and representatives from the commercial sector. The goal was to educate the attendees on the utility of vibratory CPT and promote its use as a cost-effective technology for site characterization in difficult geologies.

3.4.2 SCOPE

During the ten-day testing program at SRS, ARA conducted a total of eight penetrations at two different sites. The first test site was at the M-Basin Seepage Area where seven of the eight penetrations were conducted. This site offered challenging conditions with a particularly dense, fine sand layer at approximately 120 feet below ground surface (bgs). The soils consisted of dense, fine to medium sands with little amounts of clay and were characteristic throughout the site. The results from the testing are presented below.

3.4.3 RESULTS

The first penetration, SRS-M-001, was conducted on 29 September 1997. In order to develop a "feel" for the site, a dummy tip was used for this first push rather than risk loosing an instrumented cone. The penetration was advanced to refusal at a depth of 76 feet in static mode before switching to sonic mode. Initially the eccentric mass offset was 157°. The bias load and rotational frequency were varied throughout the operating range without success. Next, the offset was changed to 112° and again the bias load and frequency were varied without success. The eccentric mass offset was switched to 165° and the frequency was adjusted to 6100 rpm, which is the approximate resonate frequency for the installed rod length, without success. Finally, the offset was set at 143°. At this setting progress was made, although slowly (e.g., 0.01feet / min.) at first, the rate began to increase. The optimum frequency was approximately 1600 rpm and the bias force was maintained at approximately 5000 lbs. The hard layer was penetrated at approximately 78 feet bgs, at which point we were able to resume advancement of the rods in the static mode. At a depth of 105.3 feet bgs, another hard layer was encountered requiring the sonic system to penetrate it. Progress continued, switching back and forth between the static and sonic modes, as the lithology changed. Refusal was ultimately encountered at a depth of 117 feet bgs. Since a dummy tip was used for this profile, only the hydraulic push force data were recorded. The profile is presented below in Figure 24.

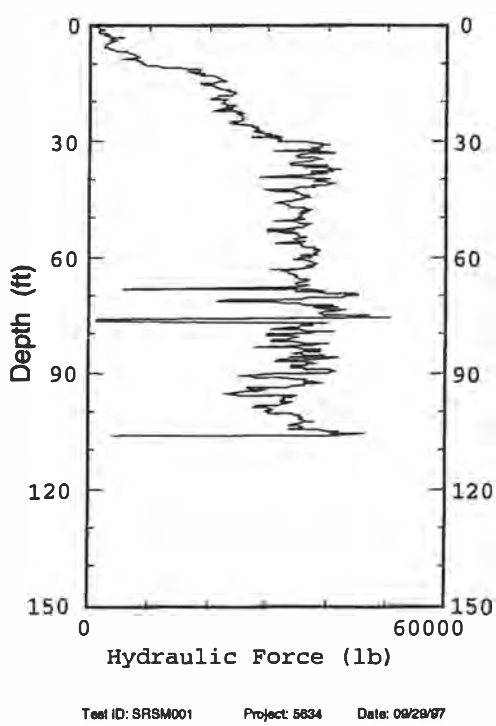


Figure 24. Plot of hydraulic force verses depth at location SRS-M-001.

A second attempt was made to advance the rods further at this location (down the same hole), this time by using a 1.44-inch diameter tip approximately one foot long that transitioned into standard 1.75-inch diameter rods. Using this configuration, a maximum depth of 112 feet bgs was attained. Eccentric offsets of both 143° and 165° were tried with no success. A maximum bias load of 35,000 lbs. was used but yielded no progress. Upon removal of the tip it was noted that it was severely deformed (e.g., "mushroomed") indicating that a significant amount of energy was transferred to the tip during the push.

The next penetration at this site (SRS-M-002) was also pushed using a dummy tip. The rod configuration used here consisted of approximately 50 feet of 1.44-inch diameter rod transitioning into 1.75-inch diameter flush-jointed rods with expanders. Progress was made to a depth of 127.8 feet bgs in the static mode before encountering refusal. With the eccentric offset at 143° and up to 20,000 lb. hydraulic push force, still no progress was made. A final effort was made with the eccentric offset at 72°. The sonic system was run at maximum frequency at this setting (2790 rpm) but still did not exhibit any progress. This penetration was aborted with a maximum depth of 127.8 feet bgs as shown below in Figure 25.

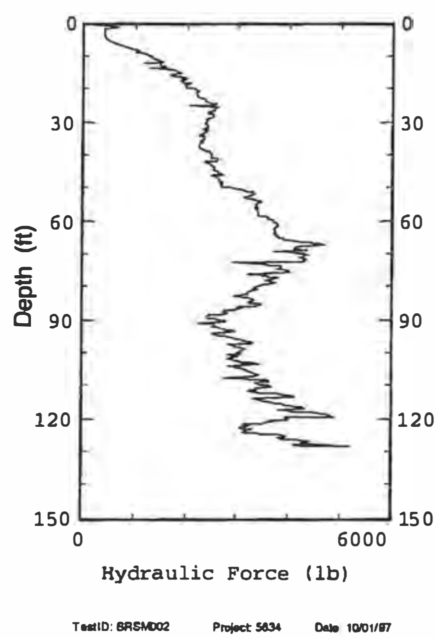


Figure 25. Plot of hydraulic force versus depth at location SRS-M-002.

The goal of the next penetration was to collect a soil sample using ARA's soil sampler. The push began at location SRS-M-003 where penetration continued to a depth of 170.2 feet bgs before encountering refusal in the static mode. The vibratory system was turned on with the eccentric mass offset angle set at 72° and a frequency of 700 rpm. At these settings, penetration continued, piercing a one-foot thick hard layer. Subsequently, static mode was used to continue penetration to a depth of 180.8 feet bgs where refusal was once again encountered. Switching back to the sonic mode, additional depth was gained, reaching a depth of 182.7 using the same settings previously noted. At that point the eccentric offset was switched to 143°. Varying the rotational frequency made only minimal progress. Final refusal was noted at 183.1 feet bgs.

After trying to release the soil sampler release mechanism, we discovered that it had inadvertently released at an estimated depth somewhere between 170-180 feet bgs. The sampler was full and the sample was retrieved and delivered to SRS personnel for logging. Figure 26 illustrates the hydraulic push force profile for this penetration.

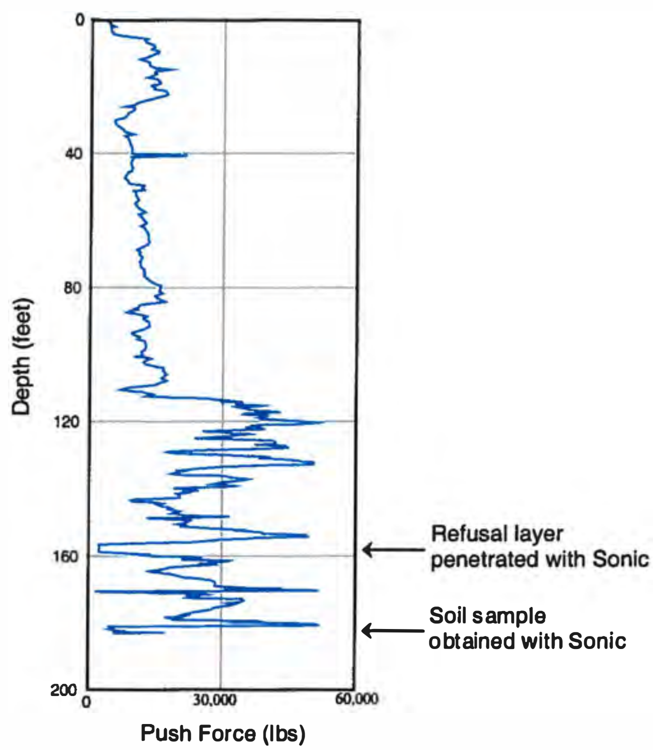


Figure 26. Plot of hydraulic push force as a function of depth at location SRS-M-003. Note the significant reduction in push force required to penetrate the refusal layer at a depth of about 160 feet.

At location SRS-M-004 an instrumented cone was used, switching between static and sonic modes to find optimal combinations of system parameters and to show the distinct advantages of the vibratory system in direct comparison with static pushing. Table 4 lists the depth and the respective frequency and bias load range throughout the profile.

Table 4. Frequency range and bias load as a function of depth required during penetration SRS-M-004.

Depth (ft)	RPM	Bias
12 - 15.3	1700 - 3000	≈ 2500 - 3500
15.3 - 18.3	3700	≈ 4000 - 5000
31.8 - 35.2	3700	≈ 4000 - 5000
35.2 - 38.3	3700	≈ 5000 - 6000
38.3 - 41.5	1700	≈ 3000 - 4000
41.5 - 44.8	1700	≈ 4000 - 4500
61.5 - 61.9	300	500
61.9 - 62.1	600	500
61.9 - 62.1	1200	3000
62.1 - 62.1	600	500
62.1 - 63.3	1200	3000
63.3 - 63.6	2400	1700
63.6 - 64.7	2400	1500
64.7 - 68.2	3800	1200
84.7 - 87.9	1200	≈ 3300 - 4500
82.9 - 91.2	3200	≈ 2000 - 3500
107.8 - 110.6	1200	≈ 4000 - 6000
110.6 - 113.3	3400	≈ 4000 - 8000
114.8	--	Refusal

Figure 27 illustrates the CPT profile and, as noted in previous penetrations, there is a distinct reduction in bias load required to advance the cone while using the vibratory system.

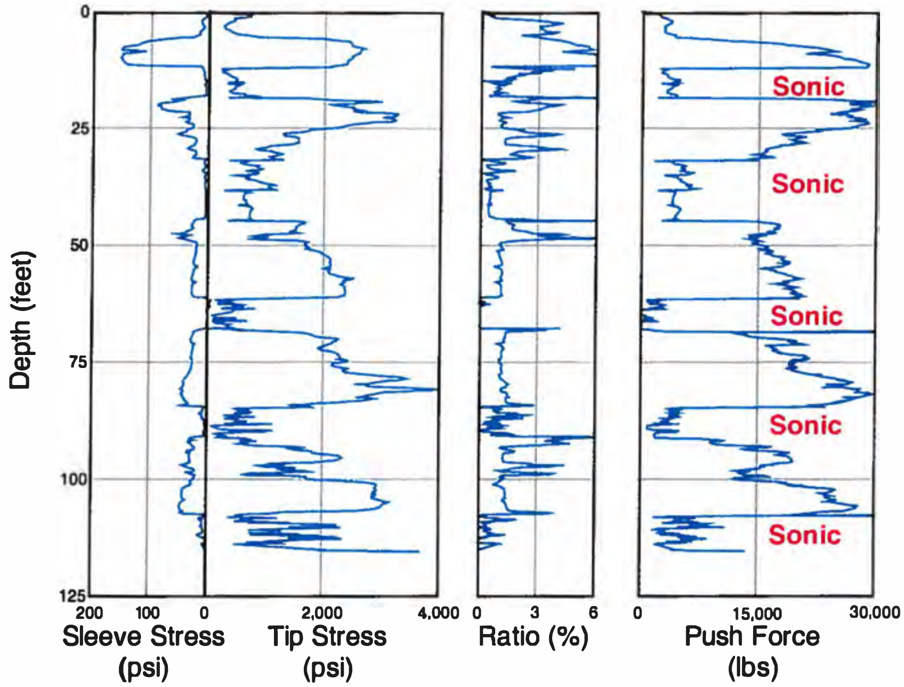


Figure 27. CPT data from SRS-M-004. Note the distinct reduction in tip and sleeve stress as well as the total push force required to advance the sensors into the formation using the sonic system.

The purpose of the next penetration was to demonstrate the robustness of the ARA soil sampler and to evaluate how well ARA's standard V-thread rods worked with the vibratory system. This penetration was performed at location SRS-M-005 and was conducted in static mode to a depth of 111.8 feet bgs where refusal was encountered. Progress continued in the sonic mode to a depth of 114.6 feet bgs with the eccentric masses set at the 143° offset at which point the soil sampler mechanism was released. The soil sampler was advanced another two feet to a depth of 115.4 feet bgs where some very dense material was encountered. In a final effort to continue advancing the sampler, the eccentric weights were set to the 72° offset and the sonic system was run at a frequency of 900 rpm. This had no effect and refusal was recorded at 115.4 feet bgs.

The soil sample retrieved using the ARA soil sampler provided valuable information with regard to the nature of the material that caused refusal at 115.4 feet bgs. From a depth of 114.6 to 115 feet bgs, the soils were described as "*very fine to fine, poorly graded sands with no indication of cementation*". From 115 to 115.4 feet bgs, the soil was described as "*dry, grayish* *tan silt and very fine sand with some friable chunks".* A simple test was performed on some of the dried chunks recovered from the sample to estimate the clay content. This test entailed submerging the fragments in a clear jar of water and observing them for signs of slaking. The sample began to slake within one minute and rapidly disintegrated thereafter. This is indicative of silt; had it been clay, the material would have remained cohesive for a much longer period of time and would not slake.

Several other attempts were made at this location to demonstrate the utility of cutting through the hard zones with a soil sampler. This was successful, although it was slow since we were limited to the length of the soil sampler barrel (e.g., 2 feet). This process could prove much more effective with a wireline sampling system. Another technique involved the use of a 5-foot long, 2-inch diameter thin-walled tube that was modified to thread on to the CPT rods. The idea behind this sampler was again to try to cut through the hard layer; only this sampler had the advantage of removing a larger, continuous sample for logging and/or chemical analysis.

3.4.4 DEMONSTRATION ATTENDANCE

On 8-October, 1997, ARA hosted a demonstration of the vibratory CPT system for representatives of the DoE and DoD as well as from the commercial sector. The demonstration was held at the M-Basin area on SRS and was attended by approximately 50 people throughout the course of the day. Activities began with a presentation of vibratory technology at the SRS employee cafeteria by ARA. Following the presentation, attendees were transported via bus to the site to see the vibratory system in use under rigorous field conditions. Visitors were brought on-board the CPT truck in small groups and given a brief demonstration of the system.

As part of the demonstration, a fully instrumented penetration was conducted using the vibratory system. This penetration was denoted SRS-M-006 and the profile is presented in Figure 28.

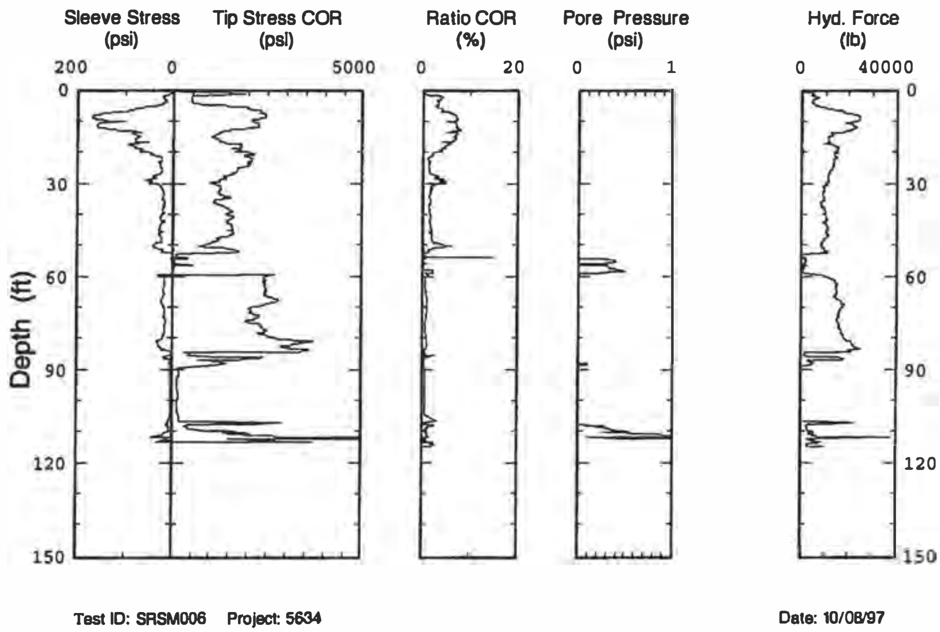


Figure 28. CPT data from location SRS-M-006. Note the two prominent portions at approximately 52 – 60 feet and 90 – 110 feet that show unusually low tip stress and hydraulic force. These two intervals are the result of using the sonic CPT.

The final penetration, identified as SRS-MCB-001, was conducted at the Chemical Basin Area and again was characterized by difficult geological conditions. Due to unfamiliar conditions at this site, a dummy tip was used to minimize the risk involved in pushing an instrumented cone at a new site. At this location, we were able to push in the static mode to a depth of 126.8 feet bgs before encountering refusal. With the use of the sonic CPT system a depth of 150 feet was achieved. Figure 29 illustrates the data from this penetration.

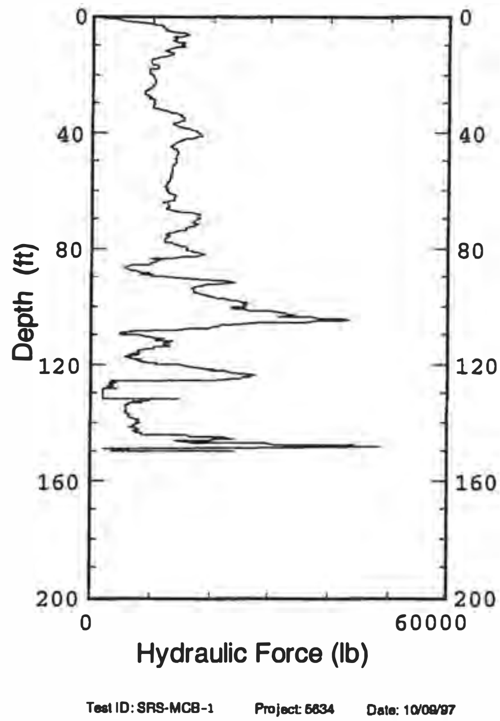


Figure 29. Plot showing the relationship between hydraulic push force and depth at SRS-MCB-001. Note the significant reduction in push force required in the interval between 125 and 134 feet indicating the use of the sonic CPT.

3.5 KELLY AIR FORCE BASE

Kelly AFB, located in San Antonio, Texas, is situated on geologic materials, which are very difficult to penetrate. This difficulty is caused by the presence of gravel in combination with fine-grained materials. The combination of these materials produces a very dense, highly consolidated soil, which is difficult to drill without the use of drilling fluids, or to penetrate using standard, 20-ton CPT testing.

An urgent need exists for an expedient method of investigating the subsurface conditions at Kelly AFB due to the presence of a solvent plume covering a very large area. Based on the difficulty posed to conventional techniques for investigating these soils, it was decided to test the sonic CPT to determine if this technology would provide an improved technique for delineating the plume.

3.5.1 OBJECTIVES

ARA was contracted by the US Air Force to hold a demonstration of the Sonic CPT at Kelly AFB. The work was conducted from June 15th to June 19th, 1998. The objectives of the demonstration were to test the sonic CPT system in a new geologic environment and determine the depth of penetration that could be achieved in that geologic setting.

3.5.2 SCOPE

The Kelly AFB environmental management team hosted the demonstration. Several potential sites were selected for conducting the sonic CPT tests and were prioritized by the demonstration team. Table 5 identifies the locations selected.

Table 5. Test Locations Selected for the Sonic CPT Demonstration

Test Dates	Location
June 15, 1998	Corner of Yarrow and Frontage Road
June 16, 1998	Corner of Burton and Amber
June 16, 1998	Along Yarrow off Military Drive
June 17, 1998	Corner of Hilton and Arron
June 18 & 19, 1998	On Base, in parking lot of Former Metal Plating Facility

A press conference was held on June 17th at one of the sites during a demonstration. Representatives from the base made presentations to various local TV reporters. The types of work that would be conducted during the demonstration included cone testing, water sampling, soil sampling and grouting. The CPT system was tested in both standard and sonic modes. The results from each test location are described in the following section.

3.5.3 RESULTS

In this section, the types of tests attempted at each location are described and a detailed look at the results and the decisions for follow-on testing are presented. The tests are described in chronological order.

CORNER OF YARROW AND FRONTAGE ROAD

The first push was conducted at the corner of Yarrow and Frontage Road with a sacrificial water sampling tip. This tip provided a means of assessing how difficult the soils were to penetrate without risking an expensive instrumented probe. The sacrificial tip was pushed to a depth of 21 feet using the standard CPT push system. At that depth, the sonic energy was applied and the penetration was advanced to 27 feet, where the system met refusal.

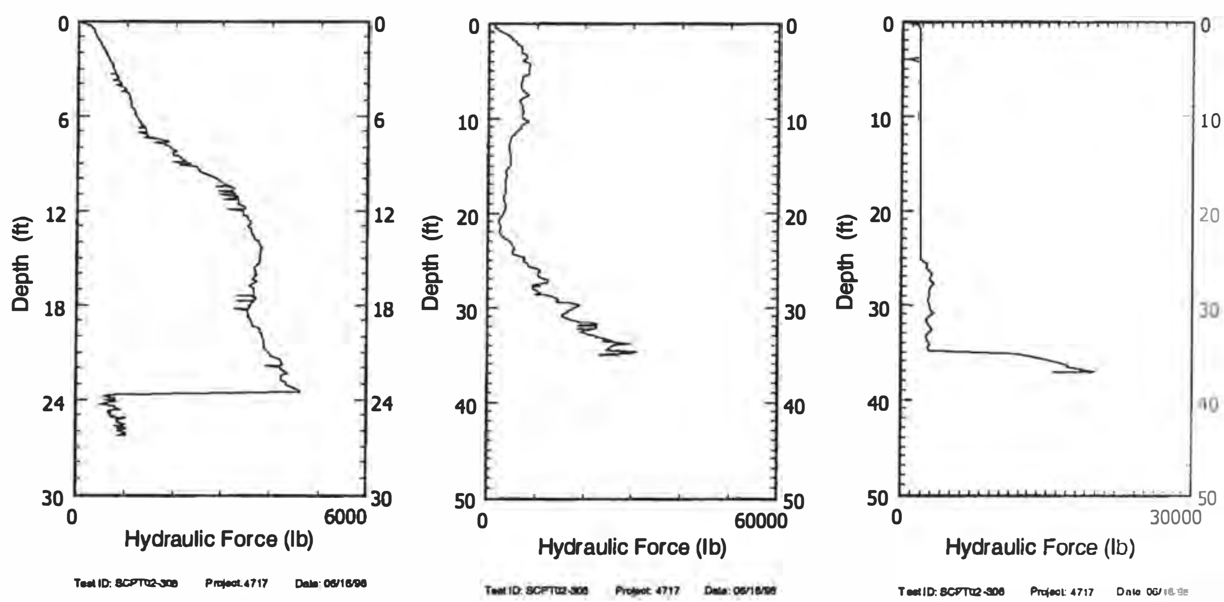
A second attempt was made at this location after moving forward a few feet. This push was made using a solid tip, which allows the operator to cycle the rods up and down to reduce the side friction along the length of the rod string. Using static mode, this attempt met refusal at the same depth as the initial test. The sonic system was applied, and after 0.5 feet of additional penetration, was stopped for reconfiguration. A new setting for the eccentric weights was selected which provided lower dynamic force at a higher frequency. After this change, the system was re-energized and the push continued to 27 feet, where refusal was again met. All holes were grouted upon completion.

CORNER OF BURTON AND AMBER

Using a solid tip, the rod string was advanced to 23.3 feet using standard CPT techniques. The sonic energy was activated and the push extended to 27 feet. Figure 30a plots the push forces required to advance the probe as a function of depth during this push. As shown in the figure, the forces gradually build up as the probe is pushed. The capacity of the rig is reached at 23.3 feet where the push force equals 46,000 pounds. The effect of applying the sonic system can also be seen as the push forces drop significantly after activation at this depth. The sonic CPT met refusal at 27 feet.

For the next penetration, an enlarged tip was used. This opened a larger hole, further reducing the rod friction, which causes refusal. This second push was very successful as shown in Figure 30b, with the push reaching the target depth of 35 feet. As shown in the figure, using the oversized tip and pushing in static mode, the target depth was attained with a maximum force of 31,000 pounds.

The above sounding was followed with a water sampler being delivered down the same hole. A sample was obtained from an interval of 35 to 37 feet bgs. Figure 30c shows the push force required to obtain the sample. As can be seen, the open hole offered little resistance down to the depth of the previous push. At a depth of 35 feet the push force rapidly increases to over 20,000 pounds. Acquiring the water sample completed the desired testing at this location. The hole was grouted after retrieving the equipment.



(a) (b) (c)

Figure 30. Plot of hydraulic force verses depth at the corner of Burton and Amber using (a) a standard sized dummy tip, (b) an oversized tip, and (c) a water sampler. All three pushes were co-located within the same hole.

YARROW OFF MILITARY DRIVE

The CPT rig was moved to the next test location along Yarrow off Military Drive on 16 June, 1998. The first penetration at this location utilized a solid tip. The tip was easily advanced to 29 feet as shown by the low hydraulic force in Figure 31. The rod string was retracted and a water sampler was advanced to 31 feet and opened. The sampler was left in place overnight. For security, the sonic CPT rig was moved to a secure area overnight. During the relocation process the next morning, surface soils were inadvertently allowed to enter the inside of the sample rods, preventing the water bailer from reaching the sample interval. The rods were retracted and the hole grouted. No further attempts were made at this location due to the requirement to meet the press corps at the next location.

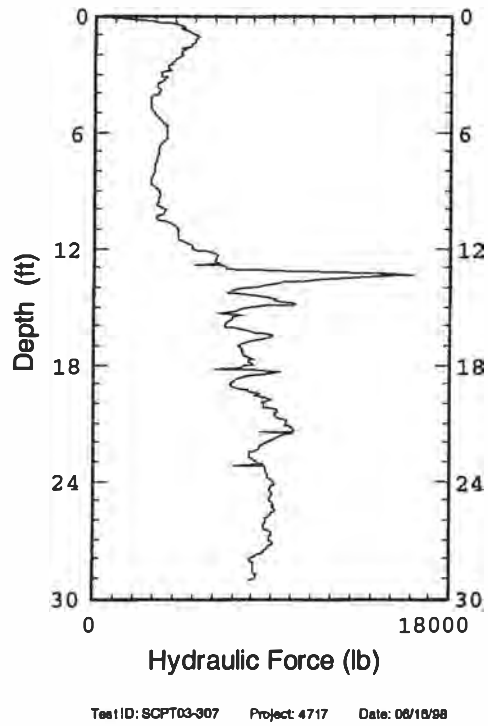


Figure 31. Plot of hydraulic force verses depth utilizing a solid tip from the Yarrow off Military Drive location.

CORNER OF HILTON AND ARRON

At this location two penetrations were completed using solid tips, while the representatives from the press corps were present. A static push was able to reach a depth of 23.7 feet on both attempts. The sonic vibration was applied and the probe was advanced to 24.6 feet. Collection of a soil sample from this layer was attempted to determine the type of material causing the refusal. The soil sampler used was a crowd-out design, where all soils that are not directly below the opening are directed to the outside of the sampler. It was noted in the field that this might not be the best style of sampler for this geology.

The soil sampler was advanced to 24.3 feet and opened. It was advanced in the sampling mode to a depth of 25.2 feet. Upon retraction, approximately 5 inches of sample was removed from the tip. A quick visual description by geologists described the material as a dense formation with the presence of chert. A second soil sample was obtained from a depth interval of 25.2 to 26.8 feet.

Data from a subsequent CPT test performed at this location are shown in Figure 32. Of particular note is the elevated sleeve stress throughout the push. This signifies a high value of friction due to lateral stress and/or cohesive soils. The CPT test was conducted in the static mode to eliminate the potential of losing the instrumented probe. The test met refusal at 22.8 feet.

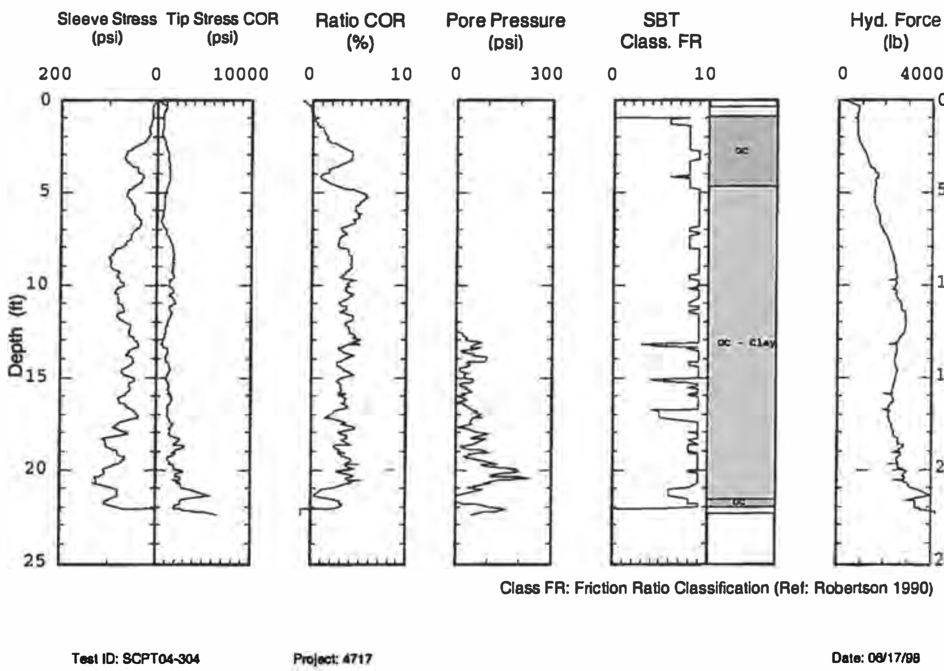


Figure 32. Penetration data from a fully instrumented cone in static mode at the corner of Hilton and Arron. Note the high sleeve stress reading throughout the push. This signifies a high value of friction due to lateral stress and/or cohesive soils.

The soil sampler was lowered down the hole left by the previous penetration in order to obtain a third soil sample from this location. The sampler was statically pushed to 23.6 feet before the sonic head was activated. The sampler advanced an additional 0.3 feet. The sampler was then opened and a soil sample was recovered from 23.9 to 24.4 feet. The materials recovered were similar to the previous samples obtained from this location. The rods were retracted and all holes were grouted to the surface.

PARKING LOT OF FORMER METAL PLATING FACILITY

The last two days of the demonstration were spent at the former Metal Plating Facility on base. All testing was attempted at one location with efforts focused upon maximizing the depth attained. The first test conducted was a conventional piezo-cone sounding. The data from this push are shown in Figure 33. As illustrated, this site is relatively soft from the surface to a depth of 21 feet. At that depth, the soils become very difficult to penetrate as exhibited by the hydraulic force. Refusal was met with the CPT under static conditions at a depth of 26 feet.

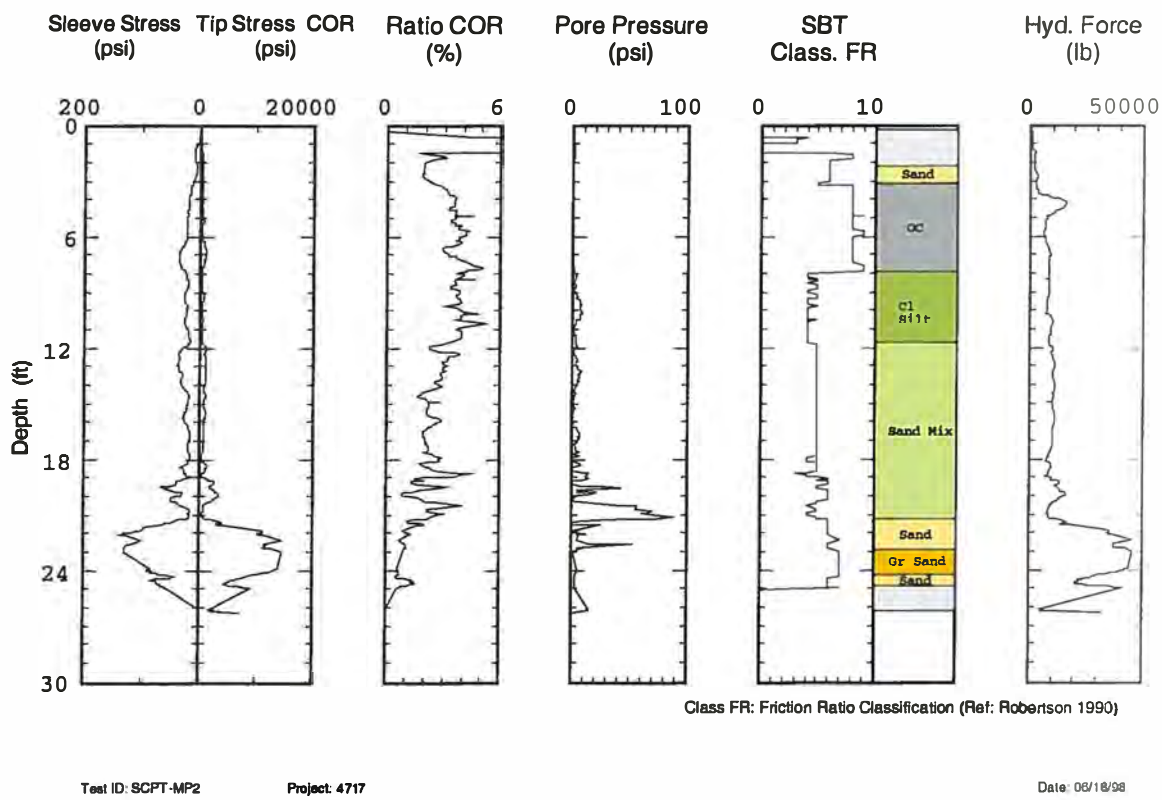


Figure 33. Penetration data at Kelly AFB's former metal plating facility. The data indicate relatively soft soils from the surface to a depth of 21 feet, where the soils become very difficult to penetrate as exhibited by the hydraulic force.

The objective of this test was to collect a soil sample at a depth of 26 feet. The sampler was opened at 26 feet, then advanced to 26.3 feet using static mode. The sampler was retrieved and the sample removed for analysis.

A large diameter solid tip was then pushed using a combination of static and sonic modes. Figure 34 illustrates the hydraulic forces required during this test. Note the presence of a hard layer between 25.5 and 27.5 feet. Three more sampling attempts were conducted at this location with the maximum depth obtained being 32.6 feet.

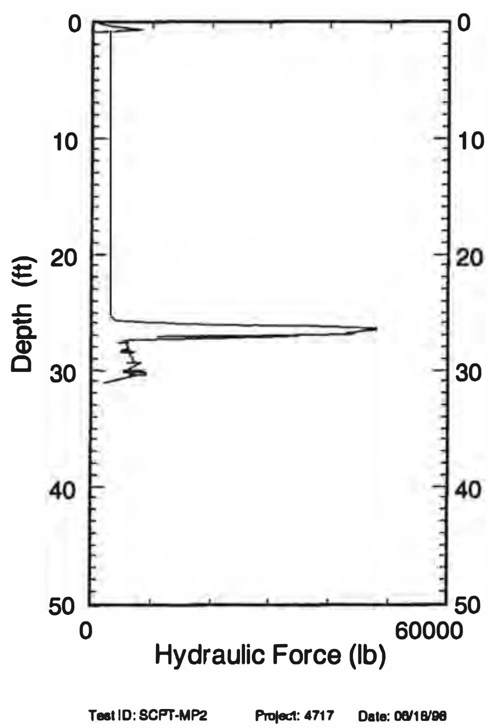


Figure 34. Hydraulic force verses depth from a penetration at the former metal plating facility using an oversized tip. Note the very dense layer penetrated at a depth of 25.5 – 27.5 feet. A combination of sonic and standard CPT was used during this penetration.

The last day of the demonstration focused on extending the depth attained by the sonic CPT. All attempts were conducted using soil samplers. By alternating between static and sonic modes, the ultimate depth achieved was 37.7 feet. As noted by the on site geologists, a drilled hole in the vicinity had hit refusal at this depth as well. Additional investigations are taking place to determine if this material is a hard layer or a local rise in the bedrock. Upon completion of the testing the hole was grouted and the pavement patched.

3.6 HANFORD

The effectiveness of the sonic CPT at a DoE site known to be difficult to penetrate using conventional CPT was evaluated during an eight-day demonstration in April 1999 at the Hanford Site located in Richland, WA. The two main goals of this demonstration were: (1) to evaluate the effectiveness of the sonic CPT in penetrating soil strata which historically have proven difficult or impossible to penetrate with conventional CPT rigs, and (2) to evaluate various CPT instruments and tools during sonic penetration mode to determine if they could survive the vibrational environment. A third goal of the Hanford tests was to evaluate the modified (smaller) eccentric weights to determine their effectiveness.

3.6.1 OBJECTIVES

The objectives for this demonstration were to:

- Determine whether or not the redesigned eccentric weights improved the performance of the sonic CPT system.
- Determine if the sonic CPT could achieve greater depths of penetration than a high push capacity CPT rig using static penetration techniques at the Hanford facility,
- Gather data to evaluate the shock-isolated system ARA developed for enhancing the survivability of delicate instruments such as gamma spectroscopy sensors, and
- Evaluate the ability of the CPT to penetrate difficult formations using soil core barrels and/or samplers.

3.6.2 SCOPE

Prior to beginning the Hanford evaluation, ARA performed additional modeling of the eccentric masses to optimize their geometry, such that their rotational moment of inertia is minimized for net dynamic force output. By reducing the diameter of the weight to 4.0 inches, higher frequencies were achieved by minimizing the torque required of the motors. Previously, the hydraulic motors could not supply sufficient torque to spin the weights at higher frequencies when operated at large eccentricity settings. Figure 35 shows the peak dynamic force generated using the modified weights at various offset angles. The results from preliminary testing of the modified weights showed that the maximum desired frequency of 4,500 rpm could now be attained for all of the weight settings with the exception of the 0-degree offset, which has not yet been tested.

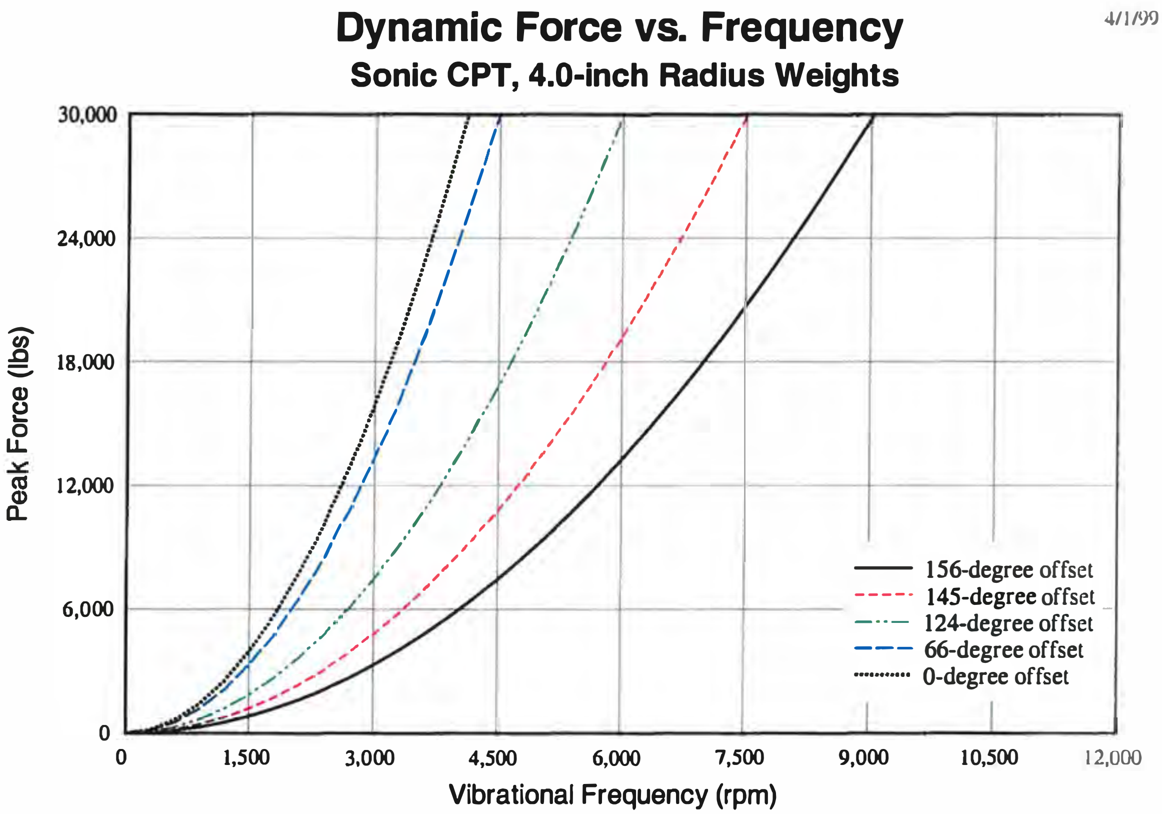


Figure 35. Plot of dynamic force verses frequency for the various eccentric weight settings of the modified weights.

Additional testing was conducted prior to the Hanford field tests to compare the rate of penetration with the eccentric weights set at two different offsets, specifically at the 124° and 156° positions. These two settings were selected based on the success achieved during testing in similar geologic settings at the MMR. Figure 36 and Figure 37 present the data profiles for the two settings, respectively, including the soil classification from a standard CPT penetration conducted adjacent to the sonic CPT profiles.

Sonic CPT Profile
Eccentric Mass Offset = 124°

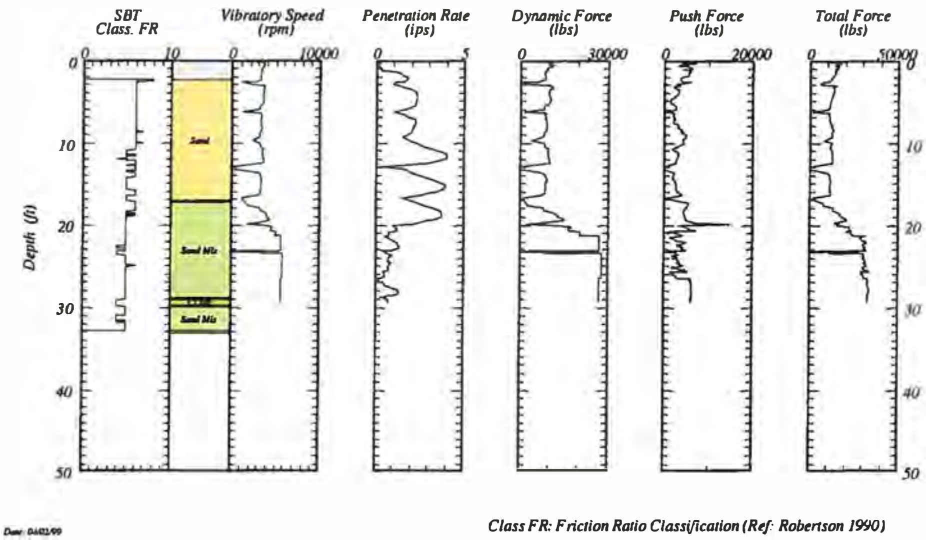


Figure 36. CPT profile showing sonic data collected at Hanford with the eccentric weights set at the 124° position. The soil classification is from an adjacent static CPT penetration.

Sonic CPT Profile
Eccentric Mass Offset = 156°

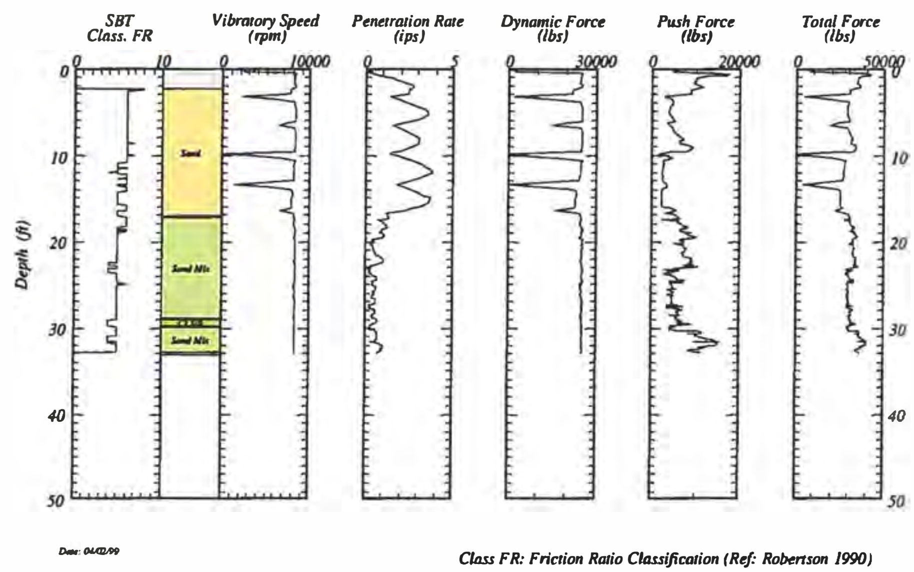


Figure 37. Sonic data collected at Hanford with the eccentric weights set at the 156° position. Again the soil classification is from an adjacent static CPT penetration.

The comparison showed a reduction in the static push force required to advance the rods when compared to the static CPT test. However, the data also indicate that slightly lower average push force was required at the 124° setting when compared to the 156° setting. Also, penetration rates at the two eccentric settings were similar.

During the Hanford evaluation, several locations in the 100, 200 East, and 200 West areas were targeted for testing. The evaluation employed most of the various digital sensors and probes developed throughout this project as well as the analog gamma probe. In the course of the evaluation program, each sensor was monitored before, during, and after deployment to determine if performance was compromised by application of Sonic force.

Soil coring tools used to cut through otherwise impenetrable layers were also evaluated under the rigorous conditions offered at the Hanford Site to determine their applicability, effectiveness and robustness. The tools were open-barrel coring tubes that can be pushed directly using either static or Sonic modes. Different cutting shoe geometries were tested and compared.

CORE BARRELS

To provide a mechanism to "core" through otherwise impenetrable layers, core barrels with a variety of cutting shoes were tested. The core barrels consisted of heavy-duty 1.83-inch diameter flush-joint drill casing (Longyear EW casings cut into 3-foot lengths) with a cutting shoe threaded on at the bottom. Several different styles of cutting shoes were evaluated to determine which was most effective in the soils at Hanford. Figure 38 and Figure 39 present the two ARA designed cutting shoes that were tested. A third style, Longyears standard EW cutting shoe with the cutter ID equivalent to that of the barrel was also tested. The ARA designs evaluate a crowd-in and crowd-out style shoe with ID's smaller than that of the barrel to permit expansion of the soil as it enters the barrel.

This is known as the inside clearance ratio and is defined as:

$$C_i = \frac{D_s - D_e}{D_e} \qquad (12)$$

Where:

C_i= Inside Clearence Ratio

D_s = Inside diameter of Sampling Tube

D_e = Diameter of the cutting edge

Both of the ARA designed cutting shoes have a 3.5% inside clearence ratio.

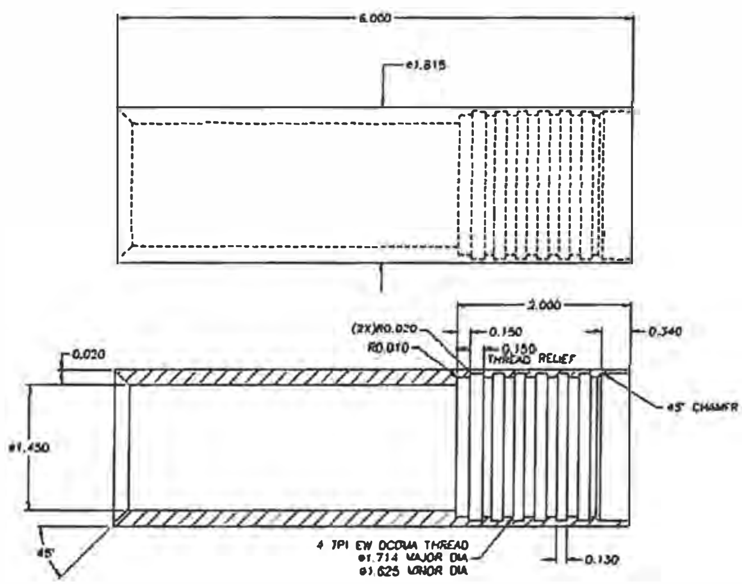


Figure 38. Crowd-In Cutting Shoe with 3.5% Inside Clearance Ratio

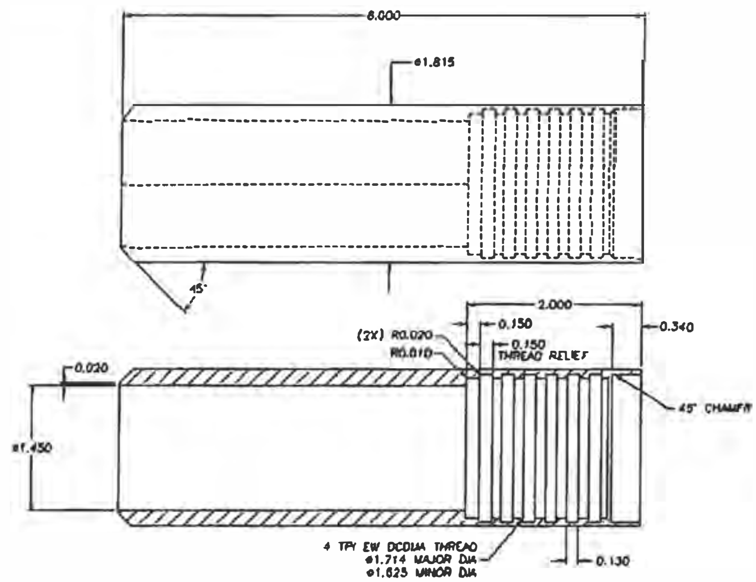


Figure 39. Crowd-Out Cutting Show with 3.5% Inside Clearance Ratio

3.6.3 RESULTS

Testing took place at three locations on the Hanford Site, each with a specific focus. The testing performed at the 100D Area (near the REDOX Test Site) focused on penetration depth in soils consisting of large rocks and cobbles using the sonic head. Pushes performed in the 200East area (B-2-2) involved testing the survivability of down-hole probe instrumentation. Finally, work performed in the 200W area (SX Pit south of the SX Tank Farm) demonstrated the core barrel sampling techniques.

100D AREA

Five penetrations were conducted at the 100D area. The CPT truck was ballasted to provide a static push capacity of 25 tons. The eccentric masses were initially set at the 154° offset angle, which affects the frequency range and amplitude induced by their rotation. Each penetration was initially conducted with a dummy tip, then at selected locations, open barrel drive samplers were used. Upon completion, holes deeper than 18 feet required grouting using cement-bentonite slurry in the 100D area.

The first penetration (B8787) reached static refusal at 6.3 feet. The sonic system was turned on and run at various frequencies ranging from 500-7000 rpm. No additional depth was gained at this location using the sonic CPT system. The hole was dry grouted from the surface prior to moving to the next location.

At the second location (B8788) static refusal was reached at 6.7 feet and, as with the first location, no additional depth was gained with the sonic system. The eccentric weight setting was changed to the 124° setting to determine if lower frequency and higher amplitude would improve the performance. The results showed no further improvement at this location. The dummy tip was severely rounded and deformed when removed from the rod string as shown in Figure 40. It was replaced with an open core barrel with a crowd-out style cutting shoe. Again, no additional depth was achieved.

Figure 40. Photograph showing wear on cone tip. The dummy tip on the left illustrates the severe wear experienced tip due to the high energy delivered by the sonic system and the abrasive nature of the soils. The cone on the right was not deployed.

The third push in this area (B8789) showed more promise. Static refusal occurred at 5.4 feet. Sonic assist achieved an additional 2 feet to a depth of 7.34 feet. The sonic system was run at 2100 – 2300 rpm. The dummy tip was removed and an open-barrel coring tube with a crowd-out cutting shoe was added. This configuration reached refusal at 7.71 feet. Upon pulling the rod, it was found that the core barrel had broken at the upper thread joint and was lost. Figure 41 shows that the barrel broke at the shoulder of the male thread on the up-hole end at the adapter. It also shows that the female portion fatigued on the side of the adapter. A probable scenario is that the sidewall of the adapter fatigued due to bending enough to allow the male thread to snap cleanly at the shoulder.

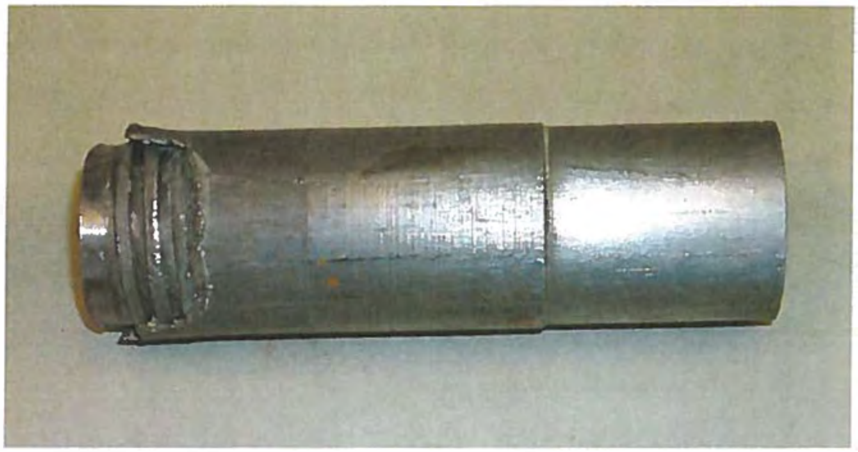


Figure 41. Photo illustrating the breakage of a core barrel. The failure occurred at the shoulder of the male thread on the up-hole end, where it threads into the adapter.

Static refusal was reached at 6.77 feet at the forth penetration location in this area (B8790). The sonic system, with the eccentric weights at the 124° offset, was run at 2000 rpm and the rod string advanced to 13.2 feet. Penetration was smooth so static pushing was again attempted. An additional six inches were gained in the static mode before activating the sonic system once again. The sonic system was run at 2000 rpm to a depth of 23 feet. Penetration was smooth so, static pushing was again tried. Static refusal was reached at 41.7 feet. Sonic refusal was reached at 42.0 feet. The data for this penetration are presented in Figure 42. This hole was grouted with a cement/bentonite slurry.

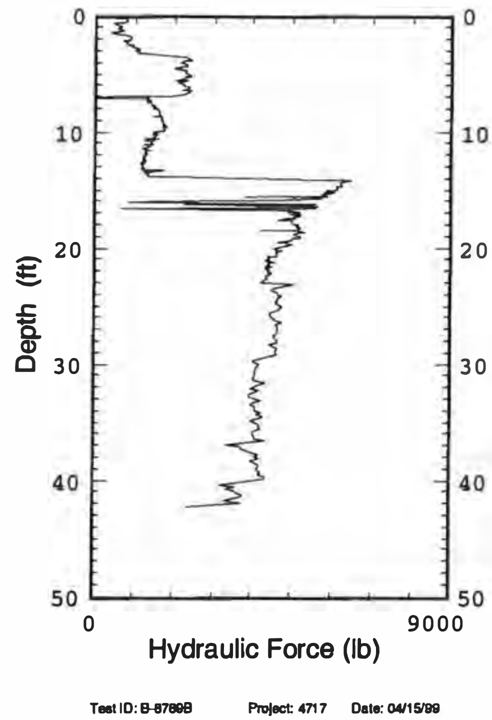


Figure 42. Plot of hydraulic force verses depth at Hanford location B8790. Note the significant increase in hydraulic force required at a depth of 13 feet; the depth at which the operator switched from sonic to static mode.

The last push at this location (B8791) achieved even greater depth. Static refusal occurred at 6.6 feet. The sonic system was used to reach 9.8 feet where penetration became smooth and easy. Static penetration continued reaching a depth of 15.6 feet. The sonic system was reactivated advancing the rodstring to a depth of 20 feet, at which point the sonic system was reactivated allowing a depth of 51.38 feet to be achieved before refusal was met. The data from this penetration are presented in Figure 43. Problems with the data acquisition system at approximately 42 feet prevented data collection from the remainder of the penetration. This hole was grouted with a grout slurry of cement and bentonite.

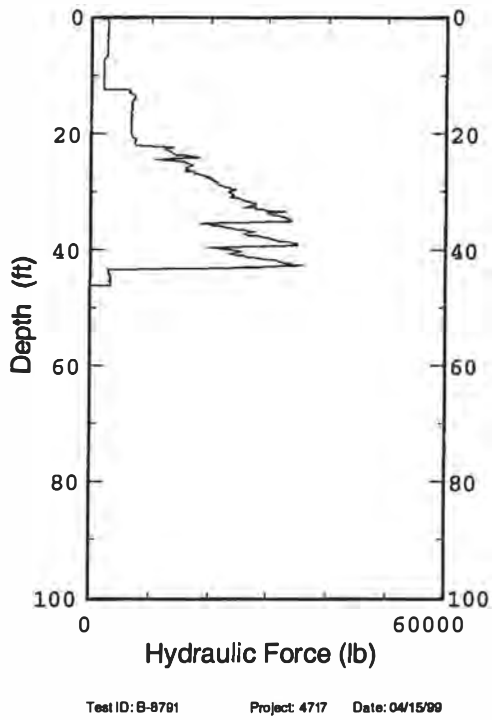


Figure 43. Hydraulic force verses depth for the penetration conducted at location B8791.

200 EAST AREA

Two penetrations were conducted in the 200 East area of the Hanford facility near the 216-b-2-2 trench using the digital cone – SMR – gamma probe. The first penetration was conducted in static mode and did not utilize the sonic system at location B-8807. The second penetration was B-8808, located approximately 10 feet west of penetration B-8807. The digital CPT data and soil stratigraphy obtained from this penetration are presented in Figure 44 and clearly indicate that all the digital sensors functioned properly throughout the deployment. The penetration was conducted in static mode to a refusal depth of 105 feet. At that depth, the sonic head was activated for about 20 minutes and several frequencies were attempted. No significant advancement of the rods occurred during the sonic testing. However, static penetration was then resumed with reduced total friction and the penetration was completed to a depth of 124 feet. The increase in refusal depth suggests that the sonic action reduced the frictional stress on the sides of the rods, permitting the probe to be advanced deeper into the subsurface.

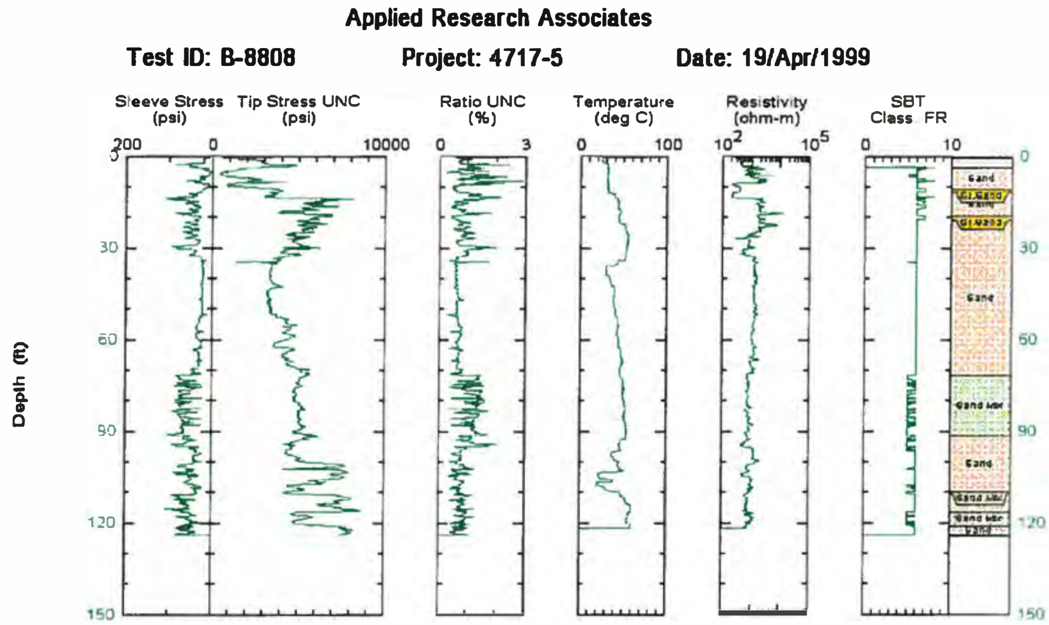


Figure 44. Static CPT data collected at Hanford using the newly developed digital CPT cone and SMR module. Sonic data were recorded at depth beginning at 105 ft.

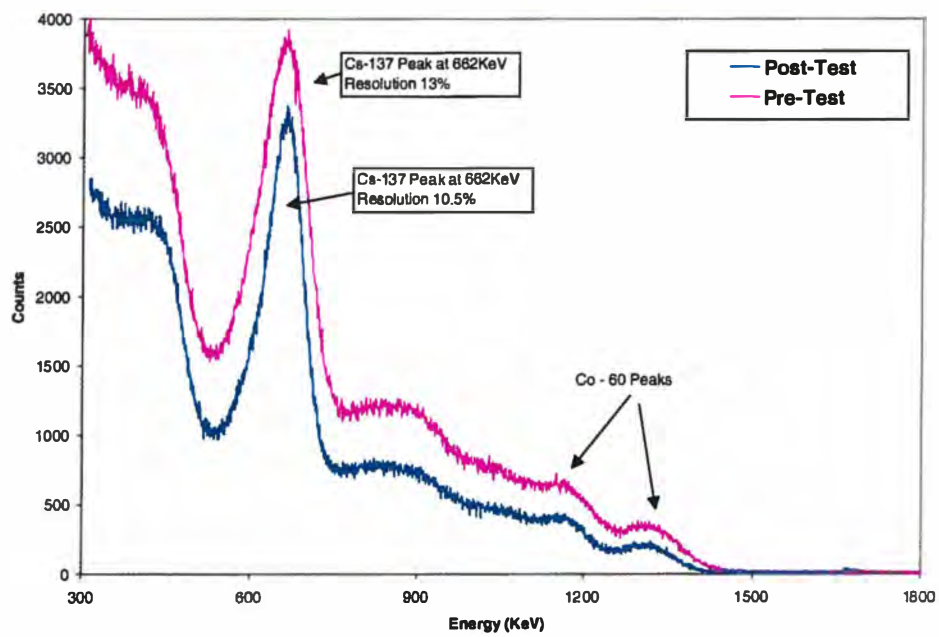


Figure 45. Cesium and cobalt spectra collected with the sonic gamma probe before and after field testing.

The gross gamma log from location B8808 is presented in Figure 46, and indicates many depths at which gamma radiation was detected. It is interesting to note that no contamination or noise was indicated after the sonic unit was activated. After sonic activation at 105 ft, the gamma log was exceptionally quiet (i.e., not responding). Initially, we suspected that the detector had been damaged. However, during retrieval of the rods, it was noted that the gamma signal cable came loose approximately 20 feet before the probe reached the ground surface. Inspection of the connector indicated that it had failed and the wires were broken. It was suspected that the wire and connector junction did not survive the sonic vibrations.

The fact that the gamma detector itself survived the sonic vibrations was confirmed in post-deployment laboratory tests. The results are presented in Figure 45 for a standard Cs-137 / Co – 60 source. The spectrum collected after the fielding effort was nearly identical to the pre-test spectrum. Slightly better resolution (10.5% vs. 3%) was realized in the post-test spectrum for Cs-137 when the long, damaged CPT cable was replaced with a shorter laboratory grade cable.

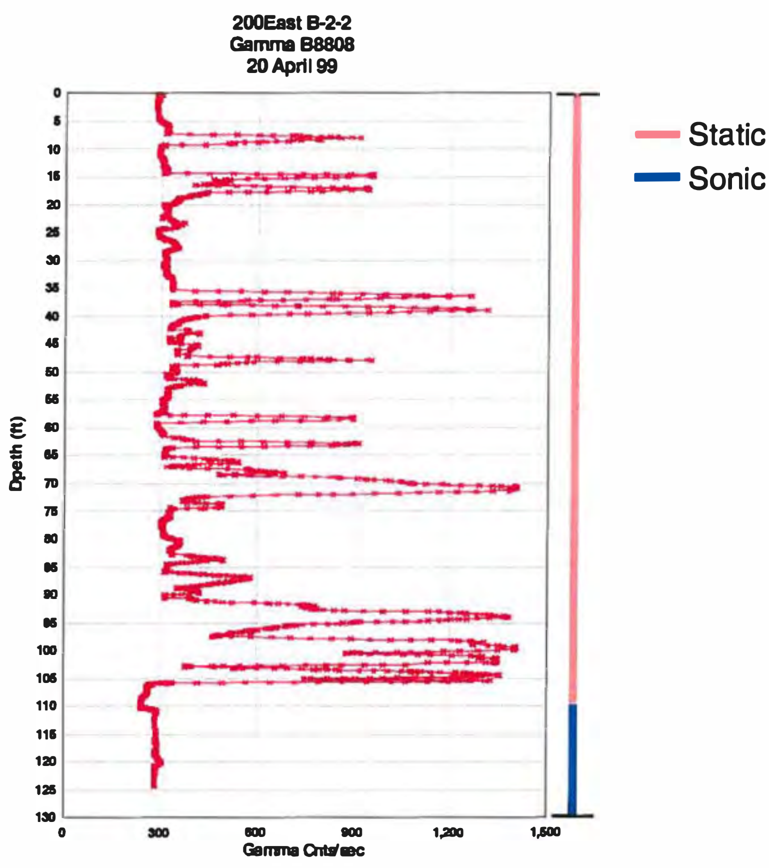


Figure 46. Gamma log from penetration B8808 in the 200 East Area

3.7 PADUCAH

3.7.1 OBJECTIVES

A field evaluation of the Sonic CPT was conducted at the Paducah Gaseous Diffusion Plant (PGDP) located in Paducah, KY. ARA in conjunction with DoE's Savannah River Technology Center (SRTC) performed field testing of the sonic CPT and SRTC's DNAPL tool kit in various geological environments to determine their capabilities.

The objectives of the technology evaluation were to determine if sonic CPT could be used to access the Regional Gravel Aquifer (RGA) at Paducah and to demonstrate the deployment of new technologies in SRTC's DNAPL tool kit using the sonic CPT. The subsurface geological conditions present in the area of the Paducah Gaseous Diffusion Plant typically result in drilling difficulties such as refusal, drill string sticking, etc. Direct Push technology that utilizes low frequency hydraulic hammering has been limited to a depth of approximately 60 feet subsurface. The predominant reason for this drilling refusal has been theorized to be the presence of large rock fragments that make up the RGA which begins at a depth of approximately 55 feet.

3.7.2 SCOPE

The sonic cone penetrometer was tested at two locations at PGDP. The first location, called the Southwest Plume location (SW1), was just outside the west security fence north of Outfall 008. This location was adjacent to a DG-001, which is a boring completed during a previous sitewide investigation (Data Gaps Investigation, 1998).

The second location was located approximately 10-20 feet due north of the TCE unloading pumps located at the southeast corner of the C-400 Building. At this location, two DNAPL detection approaches developed by the DoE's SRTC, the Ribbon NAPL Sampler (RNS), and Raman probe, were tested.

The soundings conducted at these locations encountered the following stratigraphic units:

- Surface Soil/Loess/Fill

- Upper Continental Deposits (UCD)
- Lower Continental Deposits (LCD)

3.7.3 RESULTS

At the Southwest Plume location, the sonic cone penetrometer attempted to penetrate through to the base of the Regional Gravel Aquifer, an expected depth of approximately 105 feet. In static mode, progress continued to a depth of 62.3 feet at which point the sonic CPT was activated. Progress continued into the RGA to a depth of approximately 65 feet before refusal was encountered. During this first attempt, the vibrations caused a failure in the data acquisition system resulting in the loss of all data except depth. Two attempts were made at this location with similar results. The borings were abandoned by grouting to the surface in accordance with the workplan.

The C-400 test location was approximately 10-20 feet north of the TCE unloading pumps present at the southeast of C-400. The RNS was deployed with the cone penetrometer to a depth of 59 ft below ground surface. The deployment of the sampler took approximately 2 hours and it remained in contact with the borehole for approximately 45 minutes. Staining on the sampler showed DNAPL is present throughout the sampled interval with the highest densities located at approximately 10 ft, 25-40 ft, and 50-55 ft. The spotty nature of the staining on the ribbon indicates the DNAPL is in the form of dispersed globules and is not present in pools or strong discrete layers. Unlike conventional sediment sampling and analysis, the RNS provides continuous profile in a borehole.

The Raman system was deployed in an adjacent CPT penetration but unfortunately, due to a defective laser power supply, was aborted at a depth of 12-feet below grade.

3.8 CRREL 2

3.8.1 OBJECTIVES

Field testing of the hardened FFD was conducted during a second visit to CRREL. A Geoprobe® type system, which drives probes into the subsurface by hammering on the top of the rod string, was used for the tests. The Geoprobe® delivery system was selected because it produces the largest shock forces of any direct push technology, and was therefore the most conservative test of short-term FFD survivability. Our goal in this test was not to evaluate the *in situ* response of the FFD to fluorescent contaminants (there are none at CRREL) but rather to evaluate the durability of the sensor.

3.8.2 SCOPE

Two penetrations were conducted in a single day of testing (April 5, 2000) at the CRREL location described previously in Section 3.2 of this report. The first push was discontinued at a depth of less than 3 feet when an impervious obstruction, suspected to be an electrical conduit, was encountered. About 6 feet from the first push location, a second penetration was conducted to a depth of nearly 16 feet. The deployment was discontinued at that depth to ensure that the rod string could be retrieved from the subsurface. In addition to monitoring the FFD sensor response during deployment, a series of controlled laboratory tests were performed before and after the field evaluation to monitor any changes in the system induced by hammering.

3.8.3 RESULTS

INITIAL LABORATORY TESTING OF THE FFD SENSOR

A short series of performance tests were conducted to ensure that the system was working properly prior to field testing. First, the sensor module was repeatedly shaken by hand to ensure that the insert returned to its proper alignment position (relative to the sapphire window) for performing fluorescence measurements. In the course of these tests, we found that it was necessary to polish the inside of the housing to prevent occasional misalignment due to frictional binding of the insert. No binding was observed after polishing the housing.

The FFD sensor was also connected to a 12Vdc power supply and computer to confirm that the three photodiode detector systems were operating properly. ARA's CPT_DAS data acquisition software was modified to accommodate three channels of FFD data. Fluorescent test cards and fuel samples placed against the sapphire window confirmed that fluorescence was being detected on all three channels. The responses were about 20% lower than those measured in the breadboard tests, which is likely due to the more difficult fiber optic termination procedure required for the CPT sensor module. Nevertheless, the sensitivities were adequate for *in situ* detection of fuels and were used as the basis for comparison of sensor response before and after field deployment.

FIELD TESTING OF THE SHOCK-ISOLATED FFD

For the field tests, the FFD was outfitted with a "dummy" (uninstrumented) conical tip and a custom rod interface unit which provided a hammering surface on top of the hollow, cylindrical CPT rods. A string-potentiometer depth gage was attached to the Geoprobe®. The depth gage output was digitized and fed, along with the FFD signals, into the serial port of a portable laptop computer, allowing the three FFD channels to be monitored and recorded in real-time vs. depth. Results for the single deep penetration, conducted entirely in percussive deployment mode, are presented in Figure 47.

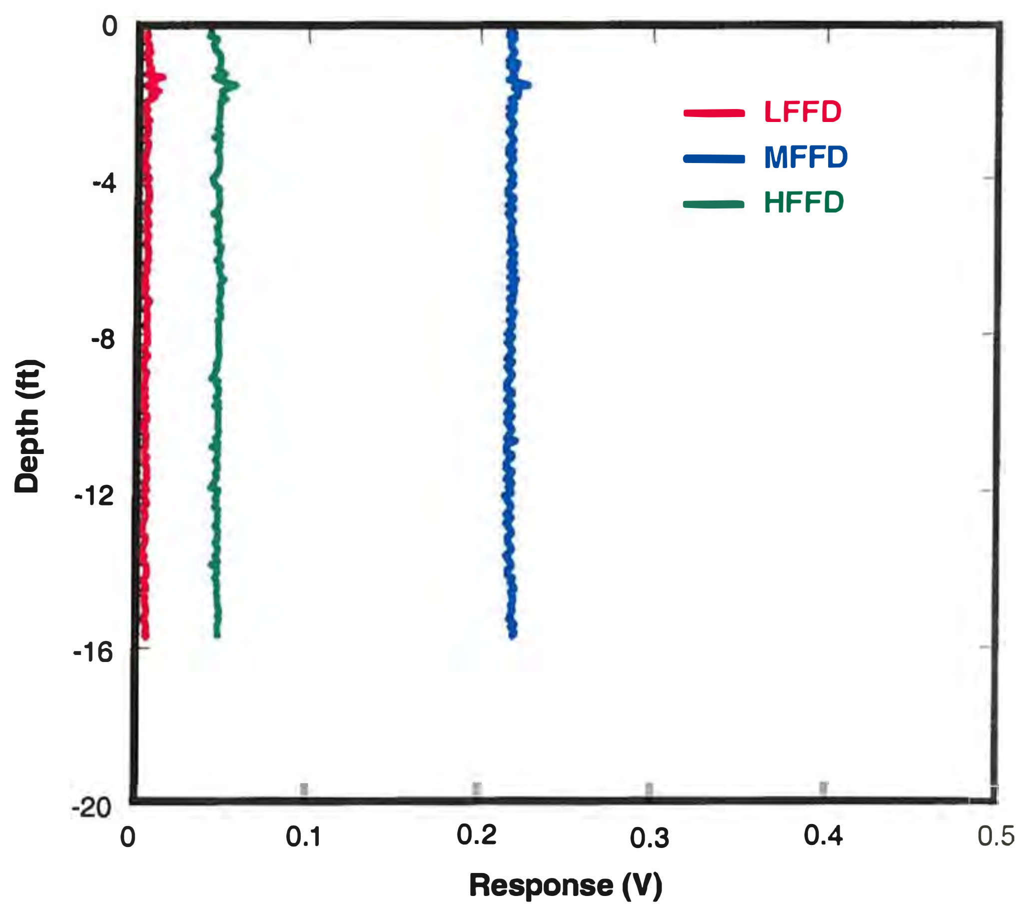


Figure 47. Results for the FFD deployed with a Geoprobe®-type impact system.

For clarity, the three FFD sensor output traces are plotted vs. depth in Figure 47 without baseline correction. The sensor outputs were consistent with one another, showing only a small response at about 2 feet and a slight upward baseline drift at the end of the push (14-16 feet). Because there are no known fluorescent contaminants at the site, the lack of appreciable FFD responses was expected. The consistent output of the FFD sensors during both hammering and nascent periods indicated that the insert module remained within the housing window area throughout the push, and therefore did not travel the full 0.5 inch allowed in the isolation engineering calculations. Indeed, the movement of the insert could not have exceeded 0.25 inch without changing the sensor output due to "shadowing" of the collection optics. It is also noteworthy that appreciable electrical noise was not introduced into the system while hammering. Thus, the FFD can be used to collect data in real-time during percussive, sonic, or other dynamic push methods. The FFD traces in Figure 47 reveal no evidence of sensor malfunction during percussive deployment.

POST FIELD TEST LABORATORY RESULTS

The durability of the FFD sensor was also confirmed in laboratory tests performed a few hours after the field tests. As shown in Table 6, the response of the three FFD sensors to a series of fluorescent test cards and fuel samples did not change significantly after the field tests. Also, mechanical testing of the FFD revealed that the insert module was still centered on the window and "rode" properly when shaken.

Table 6. FFD Laboratory Test Results Before and After Field Deployment

	LFFD (mV)		*MFFD (mV)*		*HFFD (mV)*	
Sample	**Pre-field**	**Post-field**	**Pre-field**	**Post-field**	**Pre-field**	**Post-field**
Gray Card	42	60	131	96	50	54
Tan Card	108	116	158	194	177	108
White Card	536	529	1315	904	655	515
Creosote	27	31	132	147	29	27
Diesel Fuel	157	142	204	179	146	146

Upon completion of the field tests, it was observed that the retaining nut at the probe end of the CPT cable had loosened and an inner connector had been damaged as a result of the strong forces induced by the Geoprobe® hammer. Before the FFD can be used with a dynamic push system, a better nut locking system will need to be developed.

4. CONCLUSIONS

The Scope of Work defining the development of the Sonic CPT was successfully executed. The goal of the sonic CPT development program was to expand the applicability of conventional CPT systems for DNAPL characterization and monitoring in some of the more recalcitrant stratigraphies encountered at DoD and DoE facilities. Under this contract, project success criteria were met and additional technical performance measures were documented. The success criteria for the project were to:

- design, fabricate, and field test a prototype sonic CPT drive system including modified CPT rods and sensors capable of withstanding the vibrational stresses associated with the sonic system,
- develop a shock-isolated gamma radiation probe capable of being deployed with the sonic CPT in tough soils typically encountered at the Hanford Site,
- develop a shock-isolated optical fuel fluorescence detector, and
- demonstrate improved CPT capabilities for site characterization and monitoring at DoE and DoD sites, which historically prove troublesome for conventional CPT.

In addition to meeting these success criteria, the performers:

- generated substantial interest among potential end-users both in commercial and government sectors as a result of the sonic CPT technology demonstrations,
- demonstrated the long-term reliability of sonic CPT system in multiple geologies, and
- demonstrated the deployment of DNAPL characterization tools for the Savannah River Technology Center.

4.1 TECHNICAL PERFORMANCE

The reliability and survivability of sonic CPT drive system were demonstrated in various, difficult-to-penetrate geologic settings including: the US Army's Cold Regions Research & Engineering Laboratory (CRREL); the Massachusetts Military Reserve (MMR); SRS M-Basin; Kelly AFB; and the 100 & 200-Areas at the Hanford Site. In addition, the ability of the CPT rods and sensors to work under the extreme vibrational environment generated by the sonic drive unit was demonstrated.

The performance of the sonic CPT was compared to conventional CPT and was found to improve the achievable penetration depth in all cases. The degree of improvement was found to be a function of soil type with the most notable improvement occurring in coarse- grained sands and gravels such as the glacial deposits found at the MMR. The least amount of improvement was noted in caliche -- cemented soils commonly encountered in the southwest (e.g., Kelly AFB) -- and in silts and fine sand.

The success noted in the coarser grained, cohesionless soils is hypothesized to be the result of the collapse of the "fabric" of these soils. The fabric of a soil refers to the geometric arrangement of the soil particles and is the result of many factors including depositional mechanics and subsequent geologic and engineering stress histories. Once the fabric is disrupted due to the vibrations of the sonic CPT, the grains can rearrange themselves providing adequate displacement volume to allow for the CPT cone and rod string to advance. This, along with the reduction of skin friction along the length of the rod string due to the vibration ultimately resulted in achieving greater depths.

The following sections highlight some additional specific conclusions associated with the sonic CPT and associated equipment in four topic areas: sensors, electrical, mechanical, and operational.

4.1.1 SENSORS

Temperature profiles recorded during penetration indicate that there is not a significant build up of heat at the CPT tip due to sonic vibration as was initially suspected based on the findings of previous sonic drill rigs developed by Water Development Corporation.

Shock sensitive sensors, such as the gamma and FFD sensors, can be adequately isolated to withstand the high accelerations experienced during sonic vibrations or other dynamic methods. Using low-density foam or springs, the gamma crystal/photomultiplier tube assembly can be effectively isolated from shock.

The results from the digital CPT cone and RSMP sensors indicate that the probe survived the sonic vibrations through the use of rigid "potting" epoxy.

4.1.2 ELECTRICAL

The 28-pin electrical connection inside the cone that joins the individual wires from the sensor to the up-hole cable is prone to failure. This connector was eliminated from the cone in later versions and replaced with LEMO® connectors. The LEMO® connector provides a secure, water-tight connection which eliminates failed solder connections and fatigue failure of individual wires using IDC-28 pin type connectors.

The data collected from the instrumented bolts used to secure the bearings within the pillow blocks proved to be inconclusive. Only two of the eight pillow block bolts were instrumented bolts. Both of them were instrumented by drilling out the center of the bolt to accommodate the strain gauges, which removed approximately 1/2 to 2/3 of the cross sectional area of the bolts, significantly reducing their stiffness. The data implies that the six un-instrumented bolts are taking up the load thus reducing the load distributed to the instrumented bolt in a non-linear fashion. There was also an issue with pre-stressing the instrumented bolts, limiting the dynamic range of the sensors (i.e., they were calibrated to zero in a heavily strained state, so the amount of fluctuation is a small part of their potential range).

4.1.3 MECHANICAL

A new rope thread was designed to reduce the likelihood of losing instrumentation when pulling the rod string from the ground with vibratory action. Vibration was required to pull the rod string from the 100 foot depth at penetration MMR-7. This resulted in the loss of the CPT cone that vibrated loose at the cone connection. This connection was the new double-lead rope thread design and although much stronger than standard rods, the high pitch of the thread design tends to loosen while vibrating and pulling simultaneously. A new thread design incorporates a single-lead rope thread which threads into the back of the cone, and a double-lead rope thread on the up-hole end.

Upon completion of the testing and demonstration at the MMR, the sonic system was disassembled and inspected for signs of wear. In general, all internal components, including the bearings, appeared to be in very good condition. Further inspection including detailed measurements of individual components did not reveal any significant wear.

The sonic CPT drive head has proven to be robust and problem free. The bearing design adequately supports the eccentric weights with minimal bearing temperature increase even after prolonged operation. Based on the recent reduction in the size of the weights, the overall size of the head assembly could be reduced to make it more compact and easier to retrofit into standard CPT rigs.

4.1.4 OPERATIONAL

Since the sonic head is so effective at advancing the CPT cone/rod string, there were times when it was not possible to retrieve the rod string using only static pull force. The vibratory system was required to initiate the removal of the rod string. After approximately two rod lengths were removed using the sonic head, the rest could be removed using the static mode. Minor modification of the sonic head's shock-isolation will be required to optimize the ability to use the sonic head in the pull mode.

Quality soil samples can be collected using the Mostap® soil sampler as was demonstrated during testing at CRREL, but the sampler proved to be inadequate for collection of samples in the glacial till deposits. Two Mostap® were destroyed while trying to collect soil samples at MMR. ARA's soil sampler proved robust and survived demanding use at Kelly AFB, SRS, and Hanford.

Several groundwater samples were collected from MMR during the field evaluation effort. The watersampler proved to be a robust design and no problems were encountered while using it in conjunction with the vibratory system.

Production rates using the sonic system are dependent on in situ conditions. Although progress might be slow under difficult conditions, the alternatives (e.g., trial and error strategy with CPT or bringing in a drill rig) cost more in terms of time and money.

The sonic CPT has demonstrated its usefulness in granular soils with matrices that allow for reorientation of the grain structure as the probe is advanced. At MMR, the sonic system was able to advance a 1.75-inch cone to a depth greater than 100 feet in granular soils that consistently stopped a conventional 20-ton CPT rig at 20 feet below ground surface.

The data suggest that, to penetrate soils with tight matrices such as clays, silts, and fine sands, a technique is necessary that will allow removal of soil prior to advancing the probe. The use of an open-barrel tube has not proven useful due to the fact that cuttings tend to fill the sampler as it is pushed down the open hole. A rotary wash technique using a water or air flushing system is one technique that is proven to work in the drilling industry and could be adapted. Another option includes the use of an auger-style sampler to help remove the cuttings and retain them in the sampler as it is replaced.

Based on the results of the week-long demonstration at Kelly AFB, there are potential applications of sonic CPT at locations on and around the air base. The soil conditions are very difficult for conventional CPT to penetrate and it is thought that a combination of heavyweight (30-ton or greater push capacity) and sonic CPT could maximize the applicability of CPT in this geologic setting.

In some soils, pushing a probe down the same hole twice makes it more difficult to advance the rods. This was demonstrated at SRS at location SRS-M-001during the second trip down the same hole. The reason for this is that the formation has consolidated proximate to the hole as a result of the first push and cuttings falling into the pilot hole can not be displaced. Because of this, we found that we were unable to reach the initial depth at this location.

5. RECOMMENDATIONS

Overall the sonic CPT drive head performed well and has proven to be robust and effective in certain soil stratigraphies. However, there are some characteristics, which could be improved:

5.1 SPEED CONTROL

A servo valve with feedback control should be implemented to control hydraulic flow. The proportional valve used for controlling hydraulic flow cannot provide braking to slow down the speed of the rotating masses; it can only regulate power to increase speed. Also, the speed setting will change when the vibration amplitudes are changed. For example, if the operator increases the bias load, the result is increased stiffness of the system, lower vibration amplitude, and increased sonic head speed. At times this will result in unintentional overspeed. If a servo valve with feedback is implemented, speed will be controlled in all conditions providing a safer, more controlled operation.

5.2 OVERLOAD SENSING

The strain gauging on the pillow block bolts should be improved. The overload shutdown circuit relies on a load signal from instrumented bolts located within the sonic drive unit. The bolt outputs do not correspond with predicted outputs for reasons discussed in the Conclusions. More measurements are required to better characterize the bolt transducer signals.

5.3 VIBRATION ISOLATION

Better vibration isolation is also recommended. The vibration isolation system utilizes marshmallow springs. These springs characteristically increase in stiffness as load increases. The use of air springs would provide significantly more vibration isolation and linear response. The current system only provides isolation when pushing, not pulling. Though much more complex, isolation in both directions would be beneficial to the overall operation of the system and could be provided by a well-designed air spring system.

5.4 PENETRATION ENHANCEMENT

A wireline soil sampler would greatly enhance the sonic system by combining the advantages of using a cutting barrel to cut through hard layers with the speed of the wireline system to remove the cuttings. This would eliminate soil from calving into the borehole while tripping in and out, as was experienced during testing. For extremely resistant lithologies, as was experienced at SRS, the utility of a rotary auger system would be useful. Figure 48 illustrates this concept showing the 'paddy bit' closed (a) and open (b).

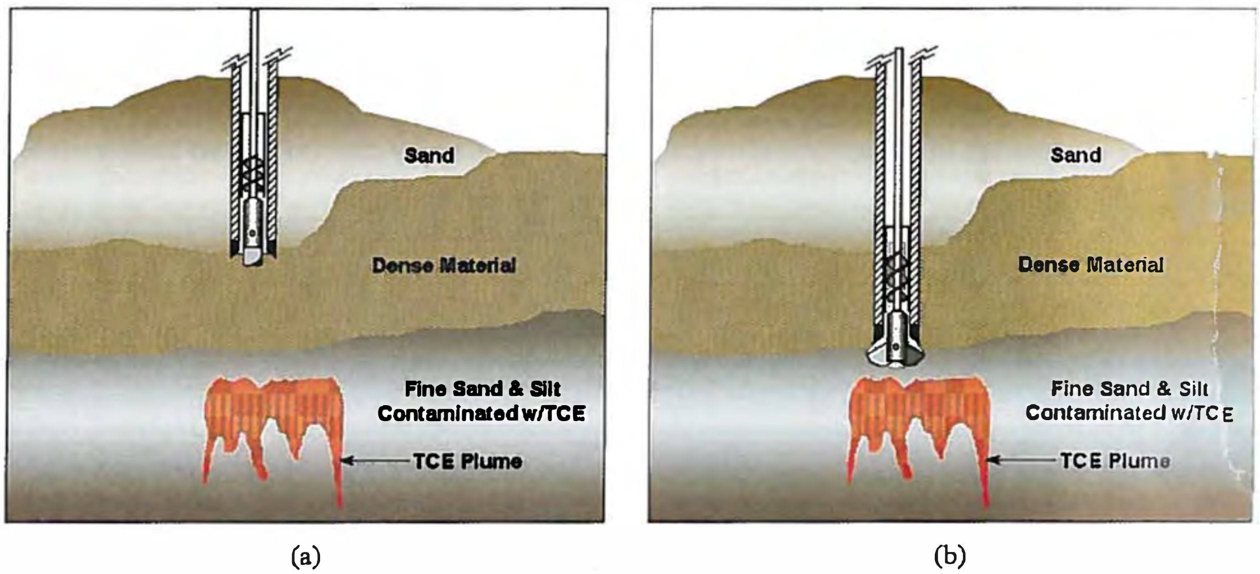


Figure 48. Illustration of an internal auger cutting tool with a 'paddy bit' in both the closed (a) and open (b) configurations. The tool would be deployable through the wireline CPT system to temporarily replace instrumentation while penetrating hard layer.

5.5 CABLES AND CONNECTORS

Although the LEMO® connectors performed well during the sonic tests, the retaining ring loosened during the Geoprobe® deployment. A locking ring system needs to be developed for the crucial probe-to-cable connection. Improved cable connections are also needed for the gamma sensor.