VADOSE ZONE TRANSPORT FIELD STUDY
Cone Penetrometer Tests, ERT, Advanced Tensiometer, And Well Installation at the Sisson and Lu Site

200 EAST AREA, HANFORD SITE, RICHLAND, WASHINGTON

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SISSON AND LU SITE
200 EAST AREA, HANFORD SITE
RICHLAND, WASHINTON

INTRODUCTION

Applied Research Associates, Inc. (ARA), under contract to Battelle installed nine Electrical Resistivity Tomography (ERT) arrays at the Sisson and Lu Site of the Hanford Site, Richland, Washington. In addition to the installation of the ERT arrays, piezocone testing was performed to collect tip stress, sleeve friction, pore pressure, volumetric soil moisture, and soil resistivity values. Six advanced tensiometers and 4 PVC wells were also installed at the site. This report documents ARA's site investigation efforts, test techniques, and analysis of the data for fieldwork conducted from 2 May 2000 to 16 May 2000. Continuous soil sampling was performed using an innovative wireline approach at one location on July 21, 2000. Presented are the field testing methods, data analysis techniques, and a brief discussion of the results.

TEST LOCATIONS

Nine ERT arrays, six advanced tensiometers, and 4 cross borehole access wells were installed using cone penetrometer techniques at the Sisson and Lu Site. Each ERT location and two of the cross borehole locations included complete piezocone testing. Figure 1 shows the location of each installation. The steel cased wells were already present at the Sisson and Lu Site from a previous experiment. Each ERT array consisted of 15 electrodes at 1 meter spacing with the deepest most electrode placed at 62.5 feet (19 meters). The target depths for the advanced tensiometers varied upon location and are stated in Table 1. The cross borehole wells had a target depth of 60 feet, the actual installation depths are also stated in Table 1.

REPORT OUTLINE

Section 2 discusses the CPT equipment, installed equipment, field procedures, and data format. Section 3 describes the methods used to interpret the CPT results as well as a discussion of a typical CPT profile from the Sisson and Lu Site. Section 4 presents the summary and conclusions and Section 5 list the references.

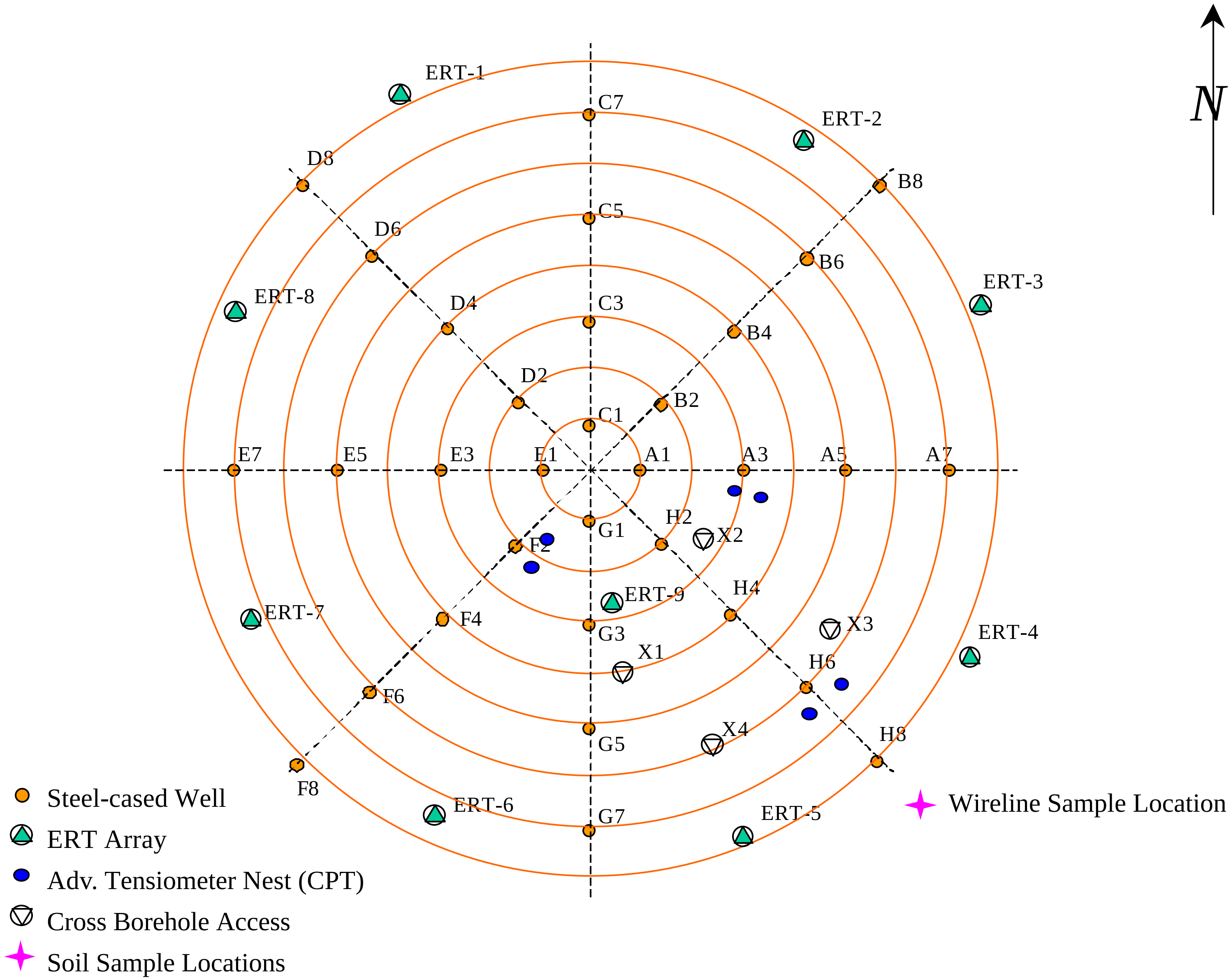


Figure 1. CPT Test locations at the Sisson and Lu Site.

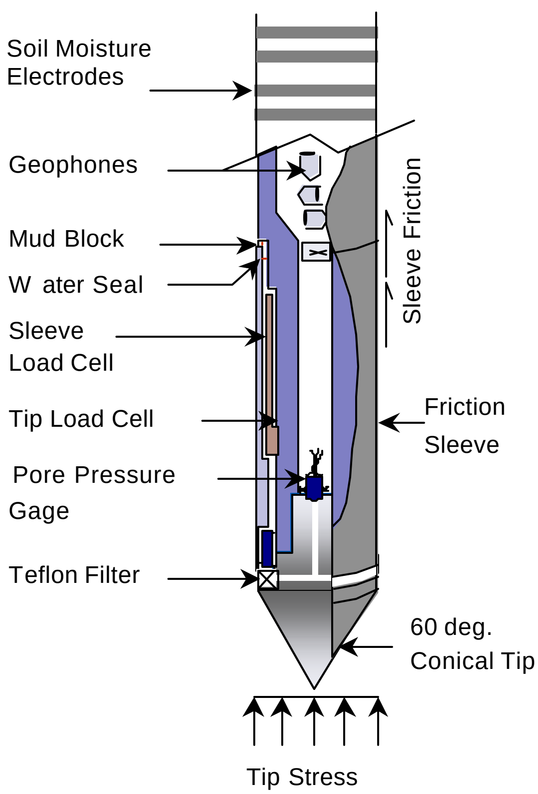
Table 1. Summary of Data from CPT at Sisson and Lu Site.

Location	Well #	LLNL Label	Final Depth (ft)	Cone Datafile
ERT-1	C3083	ERT-I	62.5	502Y0003C.DAT
ERT-2	C3084	ERT-A	62.5	511Y0006C.DAT
ERT-3	C3085	ERT-B	62.5	511Y0003C.DAT
ERT-4	C3086	ERT-C	62.5	502Y0007C.DAT
ERT-5	C3087	ERT-D	62.5	510Y0007C.DAT
ERT-6	C3088	ERT-E	62.5	510F0005C.DAT
ERT-7	C3089	ERT-F	62.5	510Y0003C.DAT
ERT-8	C3090	ERT-G	62.5	510Y0001C.DAT
ERT-9	C3091	ERT-J	62.5	511Y0001C.DAT
TEN-A3-27	C3092		24.4	
TEN-A3-20	C3093		18.1	
TEN-H6-36	C3094		9.2	
TEN-H6-19	C3095		17.6	
TEN-F2-19	C3096		18.4	
TEN-F2-31	C3097		16.2	
X1-well	C3098		51.6	
X2-well	C3099		54.40	516Y0001C.DAT
X3-well	C3100		50.40	515Y0004C.DAT
X4-well	C3101		53.10	

SECTION 2
TESTING EQUIPMENT AND PROCEDURES

INTRODUCTION

The electric cone penetrometer test (CPT) was originally developed for use in soft soil. Over the years, cone and push system designs have evolved to the point where they can now be used in strong cemented soils and even soft rock. ARA's penetrometer consists of an instrumented probe that is forced into the ground using a hydraulic load frame mounted on a heavy truck with the weight of the truck providing the necessary reaction mass. The probe has a conical tip and a friction sleeve that independently measures vertical resistance beneath the tip as well as frictional resistance on the side of the probe as a function of depth. A schematic view of ARA's penetrometer probe is shown in Figure 2. A pressure transducer in the cone is used to measure the pore water pressure as the probe is pushed into the ground (Piezo-CPT).



The probe also included ARA's soil moisture/ resistivity/ temperature (SMRT) module. The SMRT module was used to develop continuous profiles of volumetric soil moisture and resistivity at each of the ERT locations. The resistivity data helped initiate the ERT analysis algorithms. The CPT sensors also provided stratigraphy information for the analysis.

Figure 2. Schematic of ARA's Penetrometer Cone

PIEZO-ELECTRIC CONE PENETROMETER TEST

The cone penetrometer tests were conducted using the ARA penetrometer truck. The penetrometer equipment is mounted inside a van body attached to a ten-wheel truck chassis with a diesel engine. Ballast in the form of weights is added to the truck to achieve an overall push capability of 50,000 lbs. Penetration force is supplied by a pair of large hydraulic cylinders bolted to the truck frame.

A 15-cm^2 penetrometer probe (which has 1.75-inch diameter, 60° conical tip, and a 1.75-inch diameter by 6.5-inch long friction sleeve) was used on this project. This probe size is in conformance with ASTM D3441 (Ref.1). The shoulder between the base of the tip and the porous filter is 0.08 inch long as shown in Figure 2. The penetrometer is advanced vertically into the soil at a constant rate of 48 inches/minute, although this rate must sometimes be reduced as hard layers are encountered. The electric cone penetrometer test is conducted in accordance with ASTM D3441.

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

Soil Moisture/Resitivity Sensor

The soil moisture / resistivity/ temperature module connects directly behind the piezocone and produces a profile of each measurement during the penetration. The ARA developed soil moisture probe uses a Resonant Frequency Modulation (RFM) approach to determine the soil moisture content and dielectric constant (K_d). This approach consists of installing a custom PC board in the CPT probe which is then interfaced with standard CPT equipment, eliminating the need for specialized measurement equipment. An advantage of this approach is that cable distances are unlimited as all conditioning and processing of the signal occurs downhole, eliminating the effect of cable length induced signal attenuation.

The RFM approach uses the probe and surrounding soil to determine the resonant frequency of an oscillator. The RFM circuit frequency varies from 150 MHz in air to approximately 75 MHz in tap water. The basic principle of the probe is that a portion of the soil between two rings in contact with the soil will form part of an electronic circuit that has a frequency of:

$$f = \frac{1}{2p\sqrt{\mathrm{LC}}} \tag{1}$$

where: L = inductance and

C = capacitance

The capacitance has two components that set its value: 1) fixed parameters of the probe that equal a constant "C_k," and 2) a value that changes with the surrounding soil moisture, C_v. The combination of C_k and C_v will change by ≈30 pf from air to water with the soil moisture probe (SMP).

The final equation relating the frequency of oscillation of the circuit to the capacitance of the soil is:

$$f = \frac{1}{2p\sqrt{\mathrm{L}(\mathrm{C}_K + \mathrm{C}_v)}} \tag{2}$$

A critical choice in a soil moisture probe is the frequency at which the system operates. At low frequencies, the electrical conductivity of the soil can have a significant influence on the measured dielectric. In addition, examination of work by other researchers indicated that as the measurement frequency is increased, the soil conductivity influence on the measured value is greatly reduced (Refs. 4, 5 and 6). Calculations demonstrating the influence of soil conductivity on the measured soil dielectric as a function of measurement frequency are plotted in Figure 3. Calculations were conducted for two different pore fluid conductivities and for a 20 MHz and 100 MHz measurement system. For a soil with a very low pore fluid conductivity, the 100 MHz and 20 MHz calculations are almost identical. However, for a high conductivity fluid, the 20 MHz calculation shows a large reduction in apparent dielectric due to the conductivity effect. These calculations indicate that measured soil dielectric constant at 100 MHz is much less affected by conductivity than at 20 MHz. This effect was used as the basis for selecting an operating frequency of greater than 100 MHz as the design frequency.

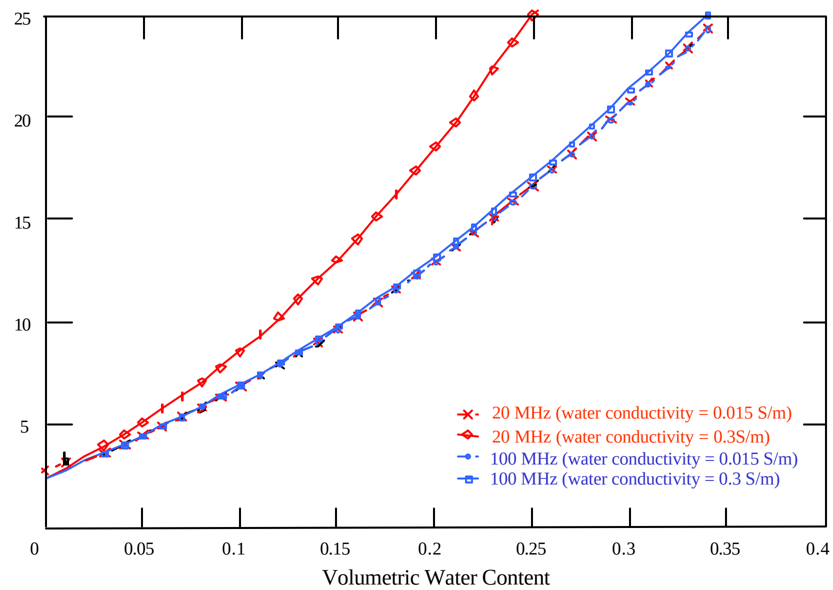


Figure 3. Calculation of soil dielectric at 20MHz and 100MHz for two pore water conductivities.

The capacitance based soil moisture sensor operates at 150 MHz reducing the effects of soil type on the measurement. The probe measures a shift in the high frequency signal as it passes through the soil near the surface of the module. It has been demonstrated that this capacitance shift is proportional to the soil moisture content.

The resistivity measurement uses the outer two rings of the moisture module to apply the current and the inner rings to measure the resistivity. The measurement principal exploited by resistivity surveying is the electrical contrast between different geological materials. Resistivity can be used to locate mineral deposits, water, and other soil features of interest. It can also be used to measure salinity, since salt increases electrical conductivity. The electrode array operates at a frequency of 30-40 Hz to avoid soil polarization effects.

Data Acquisition Collection

Electronic data acquisition equipment for the cone penetrometer consists of signal conditioning and digitizing boards within the probe and a data acquisition computer with a graphics monitor within the CPT truck. Analog signals are amplified and filtered at 1 Hz before being digitized in the probe. Once a second, the data acquisition computer polls the probe for its data. The digitized data are then read into memory and written to the internal hard disk for future processing. Upon completion of the test, the penetration data are plotted. Zip® disks containing the data are brought to ARA's Pacific Northwest Branch in Richland, Washington, for analysis and preparation of report plots.

Saturation of the Piezo-Cone

Penetration pore pressures are measured with a pressure transducer located behind the tip in the lower end of the probe. Water pressures in the soil are sensed through a 250 micro-inch porous polyethylene filter that is 0.25-inch high and 0.202-inch thick. The pressure transducer is connected to the porous filter through a pressure port as shown in Figure 2. The pressure port and the filter are filled with a high viscosity silicone oil.

For the pressure transducer to respond rapidly and correctly to changing pore pressures during the penetration, the filter and pressure port must be saturated with oil upon assembly of the probe. A vacuum pump is used to de-air the silicone oil before use and also to saturate the porous filters with oil. The probe is assembled with the pressure transducer facing upwards and the cavity above the pressure transducer is filled with de-aired oil. A previously saturated filter is then placed on a tip and oil is poured over the threads. When the cone tip is screwed into place, excess oil is ejected through the pressure port and filter, thereby forcing out any trapped air. The high viscosity of the silicone oil coupled with the small pore space in the filter prevents the loss of saturation as the cone is pushed through dry soils. Saturation of the cone can be verified with a calibration check at the completion of the penetration. Extensive field experience has proven the reliability of this technique.

Calibration Verifications

Many factors can effectively change the calibration factors used to convert the raw instrument readouts, measured in volts, to units of force or pressure. As a quality control measure, as well as a check for instrument damage, the load cells and the pressure transducer are routinely verified in the field. Verifications are completed with the probe ready to insert into the ground so that any factor affecting any component of the instrumentation system will be included and detected during the calibration.

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

Each instrument is verified using a specially developed computer code that displays the output from the reference device and the probe instrument in graphical form. During the verification procedure, the operator checks for linearity and repeatability in the instrument output. At the completion of each verification, the computer calculates the needed calibration factors using a linear regression algorithm. If the verification regression is within 2 percent of the calibration, then the instrument is operating properly and the calibration retained. At a minimum, each probe instrument is verified at the beginning of each field testing project. Verifications are also performed to confirm the proper operation of any instrument if any damage is suspected.

Penetration Data Format

As shown in Figure 2, the piezo-cone probe senses the pore pressure immediately behind the tip. Currently, there is no accepted standard for the location of the sensing element. ARA chose to locate the sensing element behind the tip since the filter is protected from the direct thrust of the penetrometer and the measured pore pressure can be used to correct the tip resistance data (discussed in the next section) as recommended in Reference 2. The magnitude of the penetration pore pressure is a function of the soil compressibility and, most importantly, permeability. In freely draining soil layers, the measured pore pressures will be very close to the hydrostatic pressure computed from the elevation of the water table. When low permeability soil layers are encountered, excess pore pressures generated by the penetration process cannot dissipate rapidly and this results in measured pore pressures, which are significantly higher than the hydrostatic pressures. Whenever the penetrometer is stopped to add another section of push pipe, or when a pore pressure dissipation test is run, the excess pore pressure may begin to dissipate. When the penetration is resumed, the pore pressure quickly rises to the level measured before the penetrometer was stopped. This process causes some of the spikes that appear in the penetration pore pressure data.

Pore Pressure Correction of Tip Stress

Cone penetrometers, by necessity, must have a joint between the tip and sleeve. Pore pressure acting behind the tip decreases the total tip resistance that would be measured if the penetrometer was without joints. The influence of pore pressure in these joints is compensated for by using the net area concept (Ref. 2). The corrected tip resistance is given by:

$$q_T = q_c + u\left[1 - A_n/A_T\right] \qquad \textbf{(2.3)}$$

where: q_T = corrected tip resistance (psi)

q_c = measured tip resistance (psi)

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

A_n = net area behind the tip not subjected to the pore pressure (1.95 in^2)

A_T = projected area of the tip (2.405 in^2).

Hence, for the ARA cone design, the tip resistance is corrected as:

$$q_T = q_c + u(.1890) \qquad \textbf{(2.4)}$$

Laboratory calibrations have verified Equation 2.2 for ARA's piezo-cone design.

A joint also exists behind the top of the sleeve (see Figure 2). However, since the sleeve is designed to have the same cross sectional area on both ends, the pore pressures acting on the sleeve cancel out. Laboratory tests have verified that the sleeve is not subjected to unequal end area effects. Thus, no correction for pore pressure is needed for the sleeve friction data.

The net effect of applying the pore pressure correction is to increase the tip resistance. Generally, this correction is only significant when the measured tip resistance is very low.

Numerical Editing of the Penetration Data

Any time that the cone penetrometer is stopped or pulled back during a test, misleading data can result. For instance, when the probe is stopped to add the next push rod section, or when a pore pressure dissipation test is run, the excess pore pressures will dissipate towards the hydrostatic pore pressure. When the penetration is resumed, the pore pressure rises very quickly to the pressures experienced prior to the pause in the test. In addition, the probe is sometimes pulled back and cycled up and down at intervals in deep holes to reduce soil friction on the push tubes. This results in erroneous tip stress data when the cone is advanced in the previously penetrated hole.

To eliminate this misleading data from the penetration profile, the data is numerically edited before it is plotted or used in further analysis. Each time the penetrometer stops or backs up, as apparent from the depth data, the penetration data is not plotted. Plotting of successive data is resumed only after the tip is fully re-engaged in the soil by one tip length of new penetration. In addition, each time the probe stops, the previous 0.5 inch of penetration data is filtered out. This filter is required to remove data that was recorded while the operator was in the process of stopping the probe. This algorithm also eliminates any data acquired at the ground surface before the tip has been completely inserted into the ground. The sleeve data is similarly treated and this results in the first data point not occurring at the ground surface, as can be seen in the tip and sleeve profiles in Figure 4. These procedures ensure that all of the penetration data that is plotted and used for analysis was acquired with the probe advancing fully into undisturbed soil.

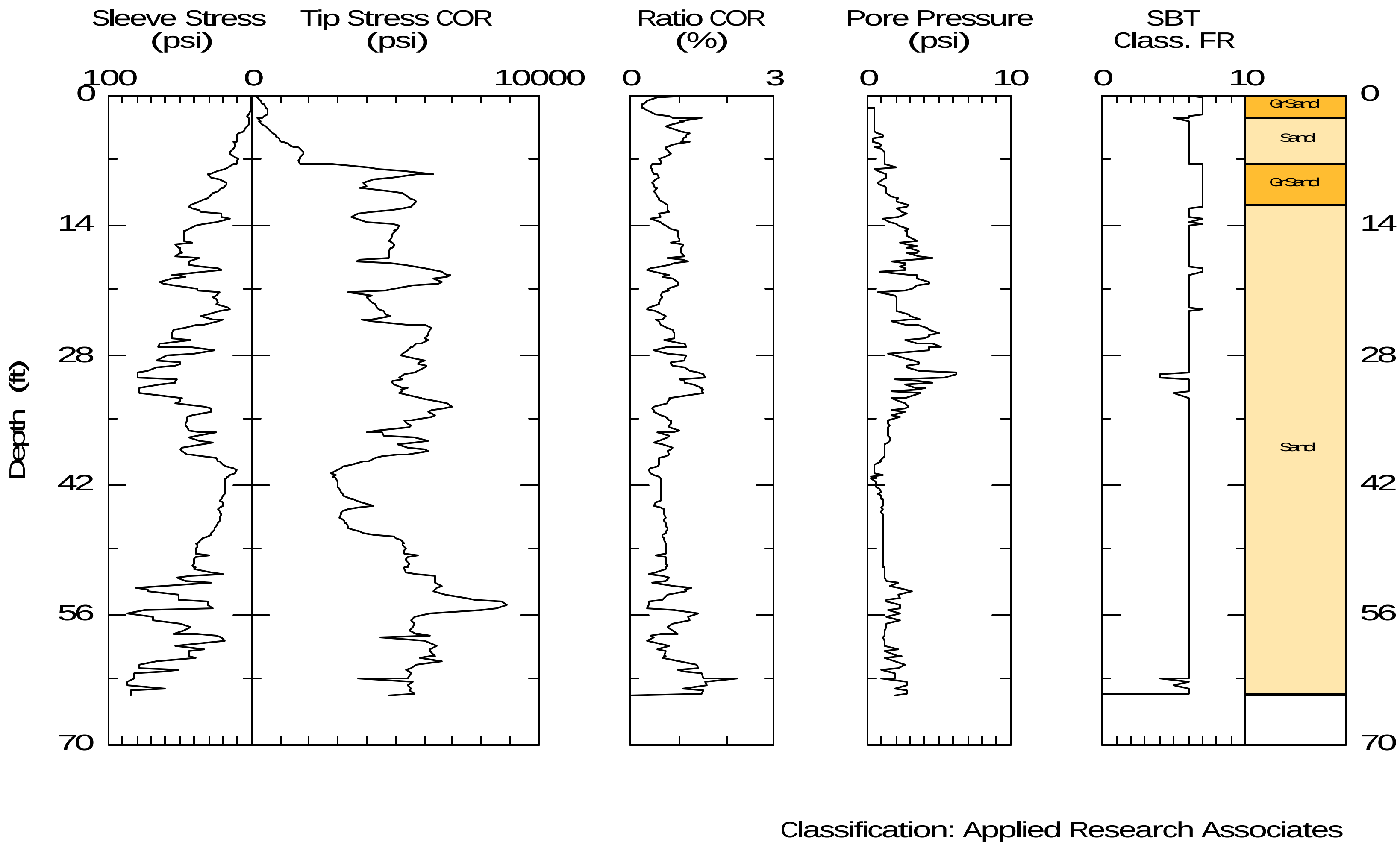


Figure 4. CPT Profile for ERT-03 at the Sisson & Lu Site.

ELECTRICAL RESISTIVITY TOMOGRAPHY ARRAYS AND INSTALLATION

To address the need for better site characterization and long term monitoring issues, a number of techniques have been pursued. A monitoring technology that is gaining acceptance is Electrical Resistivity Tomography (ERT). The ERT approach uses arrays of electrodes placed surrounding a region of interest to monitor resistivity changes that occur in the soils over time. The resistivity changes are typically due to the infiltration of water or the removal of a contaminant. To date, most ERT surveys have used drill rigs to install the ERT electrode arrays. This approach has been less than satisfactory because adequate coupling of the electrode to the media has been difficult to obtain and the cost of installing the electrodes has been prohibitive. For example, at the Hanford site the cost to install electrodes in a radioactive contaminated site using a drill rig is in excess of $1000 per foot, whereas with the CPT the cost is less than $100 per foot. The high cost of the drilling has limited the use of ERT at many sites. Under funding from the DOE, ARA has developed methods to install Electrical Resistivity Tomography (ERT) arrays with the cone penetrometer.

The CPT measurements of soil moisture and resistivity made during the installation of the arrays can be used to improve the ERT analysis. In general, electrical resistivity tomography data are analyzed using finite element model methods that solve the inverse problem by minimizing an objective function made up of iterates of a forward model and the data collected. The algorithm will find an acceptable minimum value of the objective function that satisfies some explicit criteria set forth by the user and determined by the nature of the data. An initial guess of the site resistivity is needed, and it can be shown that the better the initial guess, the more likely the inversion technique will find the optimal solution. Since CPT gives measurements of the resistivity of the site with depth, it is hypothesized that a better solution will be obtained by inputting a CPT profile as the initial starting condition.

At the Sisson & Lu site, eight ERT arrays were installed in a ring around the perimeter of the area eight meters from the center. An additional ERT array was installed in the proximity of the injection well. Figure 1 shows the ERT locations. The 15 individual electrodes per array are spaced one meter apart with the deepest electrode at 62.5 feet (19 meters). Table 2 shows the wiring for each electrode.

Table 2. Wiring colors for each electrode of the ERT arrays.

Electrode Depth (m)	Wire color
5	Gray
6	White/orange
7	Orange
8	Brown
9	Purple
10	White/red
11	Red
12	White/gray
13	Yellow
14	White/blue
15	Blue
16	White
17	Green
18	White/black
19	Black

The ERT arrays were installed by first pushing the piezocone to a depth of 65 feet collecting tip, sleeve, pore pressure, soil moisture, resistivity, and temperature data. The piezocone was removed form the hole and two inch outer diameter rods with an ERT disposable tip were pushed back down the same location. At 62.5 feet the penetration was stopped and the ERT array was lowered through the rods and latched into the ERT tip at the bottom. The two inch rods were then removed from the hole leaving the disposable tip and ERT array in place.

The ERT arrays were completed by grouting with a slurry mixture of portland cement. The grout mixture was pumped into the grout tube of the ERT arrays where it was dispersed into the hole through openings in the grout tube.

ADVANCED TENSIOMETER DESIGN AND INSTALLATION

Idaho National Engineering and Environmental Laboratory (INEEL) has developed an Advanced Tensiometer for measurement of soil water potential at depths greater then previously achievable. This is accomplished by placing the pressure transducer at depth. The approach reduces thermal variations as well as permits the tensiometer to be installed at any depth. In cooperation with ARA, the advanced tensiometer designs were modified for direct push installation using CPT techniques. This approach not only saves on installation costs, but also improves accuracy as the screen section is in direct contact with the soil and not placed in a silica flour matrix as would be case with a drilled installation approach.

The body of the advanced tensiometer is constructed of sintered stainless steel to allow capillary tension (soil suction) to be measured by a pressure gauge internal to the unit. A pushing tip is attached to the bottom of the sintered cylinder to install the advanced tensiometer by direct push methods. The upper end of the advanced tensiometer threads to two inch diameter schedule 80 PVC. The PVC extends to the ground surface and allows maintenance of the unit and access to the pressure gauge. The advanced tensiometer is shown in Figure 5.

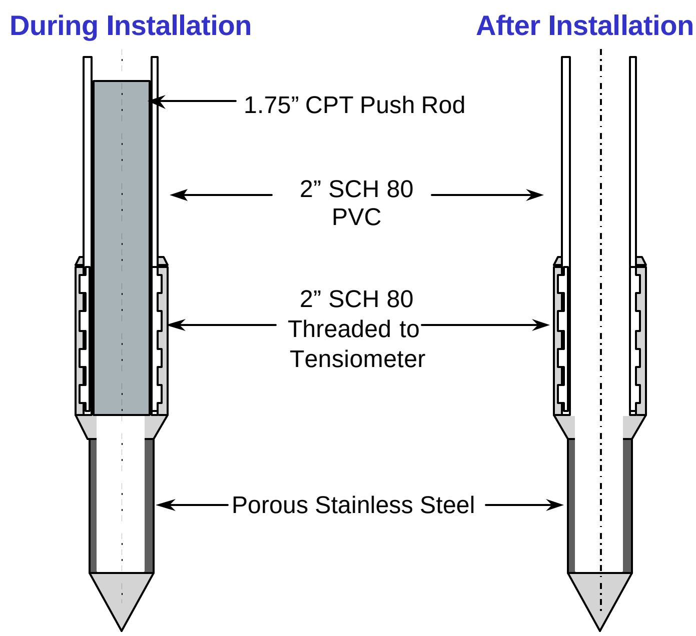


Figure 5 . Schematic of INEEL's Advanced Tensiometer.

Installation of the advanced tensiometers required pre-pushing the location with a dummy tip and 1.75" rods to open the hole and reduce side friction on the PVC during installation. The advanced tensiometers were installed by placing the 1.75" rods inside the PVC, with the end of the rods seated on a rim in the threaded section of the tensiometer. This method focuses the push force on the metal tip of the push string. Since the location was initially pre-pushed with 1.75" rods and the PVC has a 2" outer diameter, there is still a fair amount of side friction on the PVC. This side friction limits the amount of force that can be used to reach the desired depth. The installation of the tensiometers at the Sisson and Lu site did not reach the target depth on each of the locations due to high side friction and failure of the PVC. The friction on the sides of the PVC creates tension in the PVC and pulls the PVC joints apart. Refusal was called when the push forces reached levels that could damage the PVC casing.

The advanced tensiometers have since been redesigned to aid in reducing the side friction on the PVC. Previous CPT experience shows that the use of expanders, two inch sections on the push rods of slightly larger diameter, reduces the side friction during pushing. The original design has the threaded section of the advanced tensiometer at the same outer diameter as the PVC casing. Adding an expander to the threaded section of the advanced tensiometer will open the hole slightly, reducing the side friction on the PVC. Tensiometers of this new design will be installed at the Sisson & Lu site with the goal of reaching the target depths.

PVC CROSS BOREHOLE MONITORING WELLS

Another Geophysical technique that has been used on other projects and is gaining acceptance for environmental monitoring purposes is cross-borehole radar. The approach uses PVC wells which permit the transmission of radar signals from a source to an antennae lowered into an adjacent well. By lowering both the source and the antenna, a picture of the subsurface between the wells can be created.

The cross borehole wells are constructed of a stainless steel tip which attaches to 1 meter lengths of 2 inch schedule 80 PVC. The installation of the cross borehole wells followed the technique described above for the advanced tensiometers. Each location was pre-pushed to open the hole before the PVC casing was inserted. Greater depths were reached installing the borehole wells than the tensiometers because of the well tip was a slightly larger diameter than the PVC. The tip for the wells had a diameter of 2.25”, greater then that of the PVC itself. This opened the hole just enough to reduce side friction on the PVC and allow depths of greater than 50 feet to be reached.

The final cross borehole well, X1, was installed using a clear schedule 80 PVC rather than the traditional white. This was done to permit a video camera to be lowered down the well to make images of the soils that the well penetrated. This information can be used to look at soil grain size, color, contamination staining, and moisture movement. Videotapes of the borehole were made by personnel from INEEL.

CONTINUOUS SOIL SAMPLING

CPT methods were also employed for soil sampling at the Sisson and Lu Site. One meter outside well number H8 (see Figure 1) continuous soil sampling was conducted with the wireline sampler from 13 feet to 55 feet. Each sample collected was 1 inch in diameter and 1 foot in length. A dummy tip was initially pushed to 13 feet. The dummy tip was then withdrawn and the sampling unit lowered in its place as shown in Figure 6. The unit was pushed 1 foot and the sample retrieved to ground surface. This procedure with the sampler was repeated to a depth of 55 feet. Each sample was bagged and labeled for laboratory analysis.

CPT soil sampling is a minimally invasive procedure for collecting soil samples. The only disturbance to the site is a 2 inch diameter hole which is grouted upon completion. Only the soil collected in the sample is retrieved so no waste is generated which will need disposal. The sampling process from set up on site to grouting of the penetration, including collecting 42 samples, was completed in less than 4 hours.

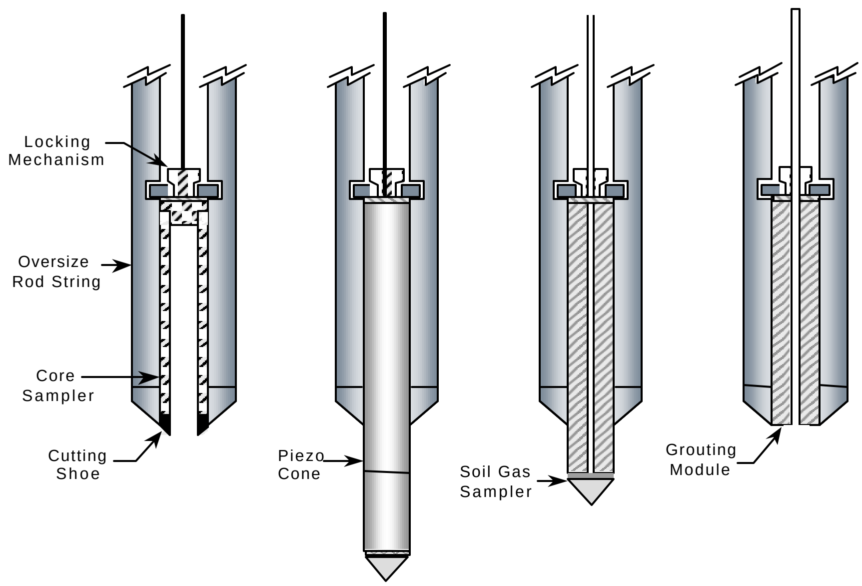


Figure 6. CPT Wireline Tool with Soil Sampler, Piezocone, Gas Sampler, and grout tools.

SECTION 3
DISCUSSION OF P-CPT TEST DATA

OVERVIEW

Presented in this section is a detailed discussion of a typical Piezo-Electric Cone Penetrometer Test (P-CPT) profile and the CPT derived soil stratigraphy. The methods used to determine the soil type information from the CPT are also discussed.

LOCATION OF THE SITE WATER TABLE

Generally, the static water table at a given site can be identified from the penetration pore pressures, since it will be equal to the hydrostatic pore pressure in freely draining soil layers. When no such layers are present at a site, pore pressure dissipation tests can be performed to determine hydrostatic pressures at depth. At the Sisson & Lu site, the water table is typically deeper than 200 feet and therefore was not encountered during any of the penetrations. Pore pressure measurements were still made to look for perched water table layers and to correct the tip stresses for any pore pressure generated by the penetration process.

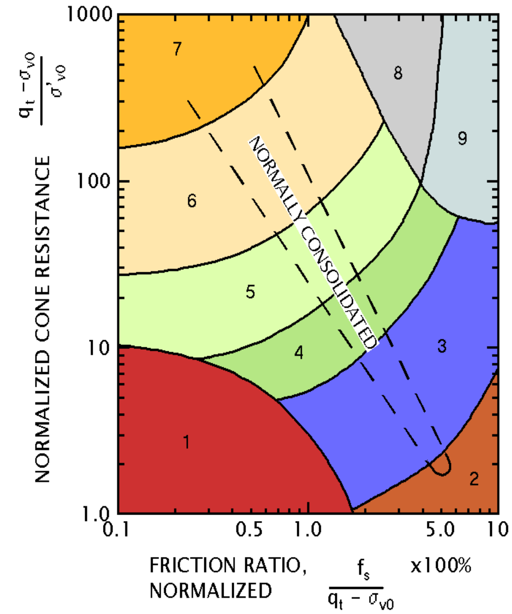
SOIL CLASSIFICATION

The tip resistance, friction ratio, and pore pressure values from CPT profiles can be used to determine a soil stratigraphy profile. Plots of normalized tip resistance versus friction ratio and normalized tip resistance versus penetration pore pressure can be used to determine soil classification (Soil Behavior Type, SBT) as a function of depth. Both methods of soil classification are based on empirical charts developed by Robertson (Ref. 2). Since the groundwater table in the Sisson & Lu site is deeper than the final depth of any penetration conducted as part of this project, only the friction ratio soil classification approach was used. The friction ratio soil classification is determined from the chart in Figure 7 using the normalized corrected tip stress and the normalized friction ratio of f_{SN}.

Zone		Q_t/N	Description
1		2	Sensitive, Fine Grained
2		1	Organic Soils-Peats
3		1.5	Clays-Clay to Silty Clay
4		2	Silt Mixtures-Clayey Silt to Silty Clay
5		3	Sand Mixtures-Silty Sand to Sandy Silt
6		4.5	Sands-Clean Sand to Silty Sand
7		6	Gravelly Sand to Sand
8		1	Very Stiff Sand to Clayey Sand *
9		2	Very Stiff, Fine Grained *

(*) *Heavily Overconsolidated or Cemented*

Normalized Friction Ratio Classification Chart



(Ref. Robertson, 1990)

Figure 7. Normalized Friction Ratio Classification Chart.

The normalized tip resistance is defined as:

$$q_{NT} = \frac{q_T - \sigma_{vo}}{\sigma'_{vo}} \qquad \textbf{(3.2)}$$

The normalized friction ratio is defined as:

$$f_{SN} = \frac{f_s}{q_T - \sigma_{vo}} \, x\,100 \qquad \textbf{(3.1)}$$

where: fs = sleeve friction

q_T = corrected tip resistance

σ_{vo} = total overburden stress

σ'_{vo} = effective overburden stress

The intersection point of the q_T and f_{SN} values normally falls in a classification zone. The classification zone number corresponds to a soil behavior type (SBT) as shown in Figure 7. At some depths, the CPT data will fall outside of the range of the classification chart. When this occurs, no data is plotted and a break is seen in the classification profile. This occasionally occurs at the top of a penetration as the effective vertical stress is very small and produces normalized cone resistances greater than 1000.

The classification profiles are very detailed due to the high sampling rate of one sample every 2 cm (0.8 in) for CPT profiles. Frequently significant variability in soil types over small changes in elevation can be observed in the profiles. To provide a simplified soil stratigraphy for comparison to standard boring logs, a layering and generalized classification system was implemented. A minimum layer thickness of one foot was selected. Layer thicknesses are determined based on the variability of the soil classification profile. The layer sequence is begun at the ground surface and layer thicknesses are determined based upon changes in the standard deviation of the soil classification number. Whenever an additional 6-inch increment deviates from the previous increment, a new layer is started, otherwise, this material is added to the layer above and the next 6-inch section is evaluated.

The soil type for the layer is determined by the mean value for the complete layer. The nine types are classified as shown in the legend of Figure 7. Again, a more detailed classification can be determined from the classification profile plotted just to the left of the layering in ARA's cone plots. The layering provides a summary of the soil stratigraphy.

TYPICAL P-CPT PROFILE

A typical penetration profile from the Sisson & Lu site is presented in Figure 8. The soil profile represented in this figure is from the installation of ERT at location ERT-09. This location is closest the injection point near the center of the site and is typical of the ten piezocone penetrations conducted at the Sisson & Lu Site. The figure presents plots of the tip stress, sleeve stress, friction ratio, pore pressure, soil behavior type (soil classification number from Figure 7), and a simplified soil stratigraphy. The second page of Figure 8 presents the soil moisture profile, the resistivity profile and the temperature of the probe during the penetration. This temperature value is the result of frictional heating on the probe and is used for temperature corrections of various sensors. It is not the actual temperature of the soils and should not be used as such, unless the probe is stopped and allowed to equilibrate with the soil environment.

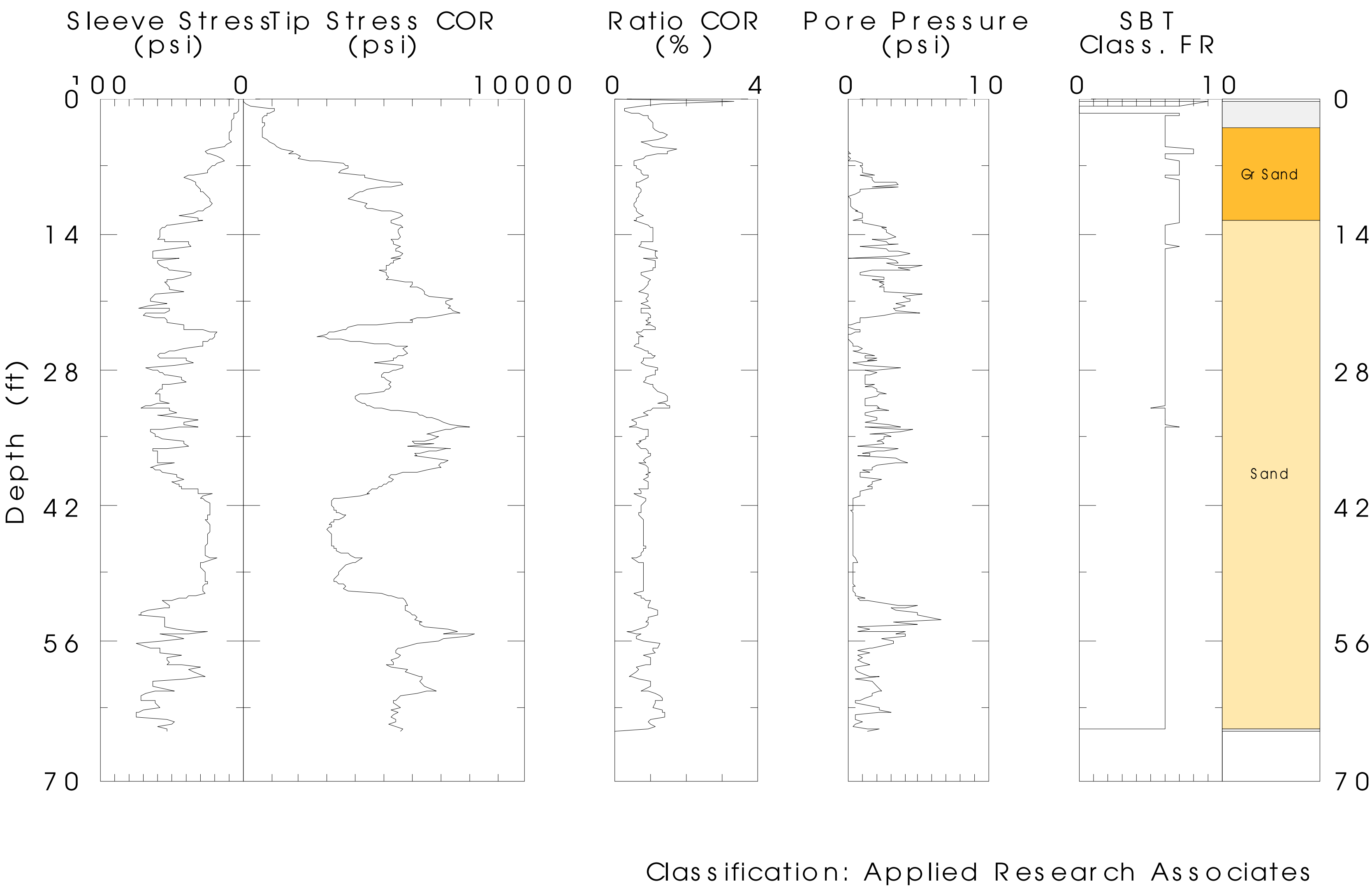


Figure 8. CPT Profile of Location ERT-09.

Test ID: ERT-9 C3091 Date: 11/May/2000

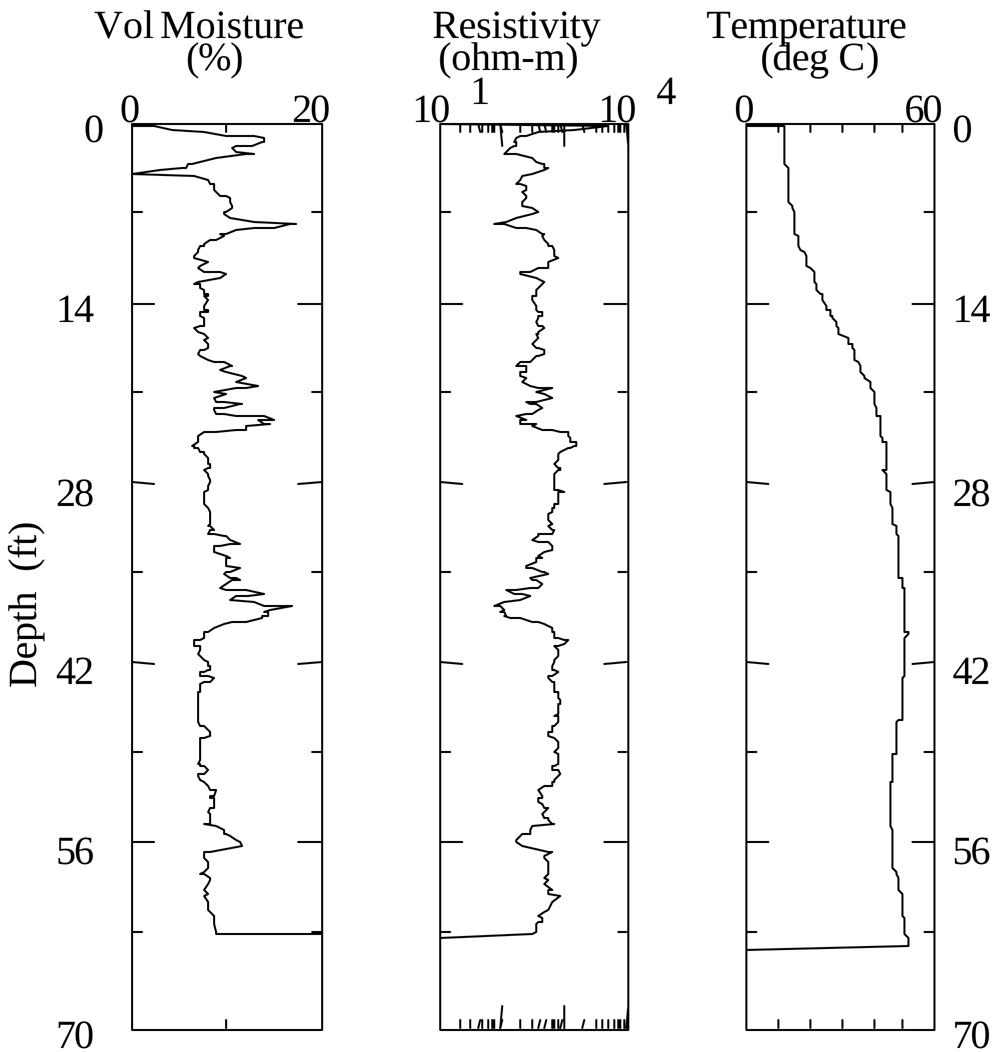


Figure 8. CPT Profile of Location ERT-09, Continued.

The soils at the Sisson and Lu site typically classify as a gravely sand material down to a depth of 13 feet and then transition to a sand material for the remaining of the profile. Although the soil log on the right edge of Figure 8 does not show additional layers, the tip stress and sleeve profiles do offer some additional information about the soil materials encountered during the penetration. The tip stress gradually increase from 6 to 9 feet and then remains constant at around 6,000 psi. until a depth of 18 feet. This material has properties of a typical sand. The friction ratio is approximately 1 while the soil moisture averages 7.5% and the resistivity is 400 Ohm-m. Beginning at 18 feet the tip stress increases to 8000 psi at a depth of 20 to 22 feet and then reduces to 2,500 psi at a depth of 24 feet. The sleeve stress displays the same trends over this depths range. Since the tip and sleeve stress are moving together the friction ratio is remaining constant indicating that the soil material type is constant over the region, but the density and strength of the material are changing. The moisture also increases in this layer to an average of 13%. This is the upper wet region that is found in all the profiles.

The next layer from 24 feet to 32 feet is similar to the previous layer from 10 to 18 feet. The tip stress is again approximately 6,000 psi and the friction ratio is 1. The moisture content has returned to 7.5% and is constant over the layer. The resistivity has increased slightly to a value of 700 ohm-m. The increase in the resistivity is likely due a small change in the mineralogy or grain size of the sand.

The lower wet zone extends from a depth of 32 feet to approximately 41 feet. This layer again has tip stress value of 8,000 psi, similar to the upper wet region. The moisture content of this layer is approximately the same as the upper region at 14%. The resistivity in this layer drops from the layers above and below due to changes in the moisture content.

The tip stress reduces at 41 feet to a value of 3,500 psi and maintains that value until 51 feet. This layer is also a sand, although not a dense as the layers immediately above. The moisture of this layer is typical of the profile at 7%. At 51 feet until the bottom of the penetration at 65 feet the tip stress averages 6,000 psi and the friction ratio is consistent around 1. The moisture content and resistivity are both constant at around 7% and 600 ohm-m respectively, expect for the region from 54 to 56 where the moisture increases slightly to around 11%. The resistivity reduces in this same region due to the increase moisture content.

SITE WIDE CROSS-SECTIONS

As stated previous section, the data from penetration ERT-9 was typical of the other penetrations. To display this aspect, all the penetrations conducted at the 8 meter range have been laid out in a linear manner. These plots are done in terms of elevation so that the layering is correct. Figure 9 presents the fence plot for tip stress. The lower tip stress region 41 to 51 feet is consistent in all penetrations as shown by the lower blue region. The materials on either side of this layer are much stronger as exhibited by the red and yellow regions. As anticipated, the layering is predominantly horizontal and fairly consistent across the site.

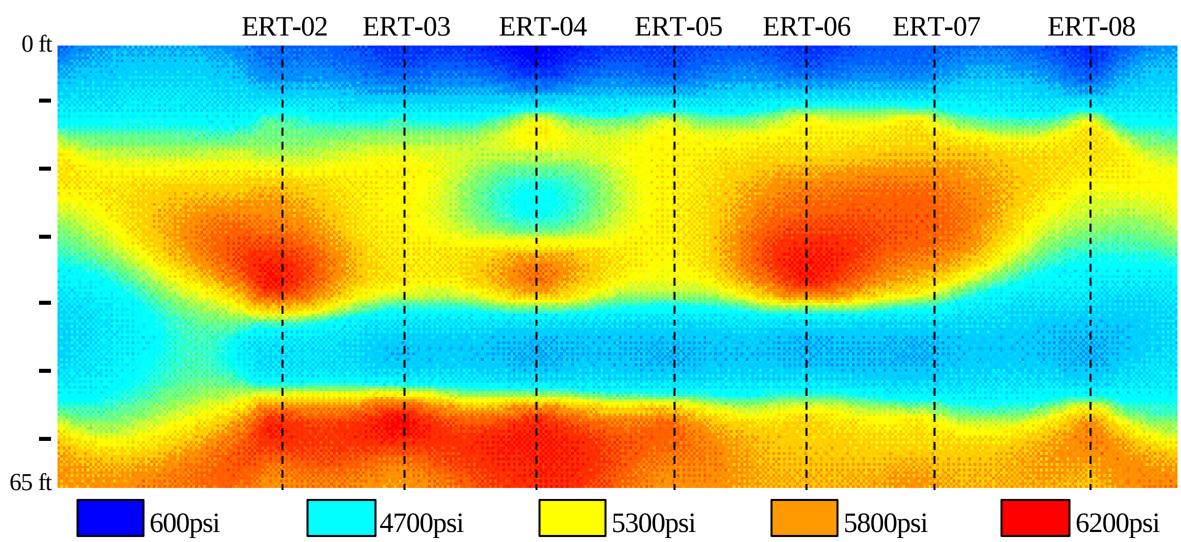


Figure 9. Tip Stress Map of CPT Penetrations on the Perimeter of the Sisson and Lu Site.

Figure 10 present the same type of layout for soil moisture. Again the site layering is strongly evident in this type of layout. The regions of higher moisture that were discussed in the previous section can be seen in these figures. The upper wet region is from 18 to 24 feet and is consist at approximately 12% across the site. This region is a little difficult to see in Figure 10 due to the interpolation scheme used. The lower wet region extends from 32 to 38 feet and again is more strongly noted as the large red region in Figure 10. The small wet layer at a depth of 54 to 56 feet is also present on this figure as the yellow region across the bottom of most of the profiles.

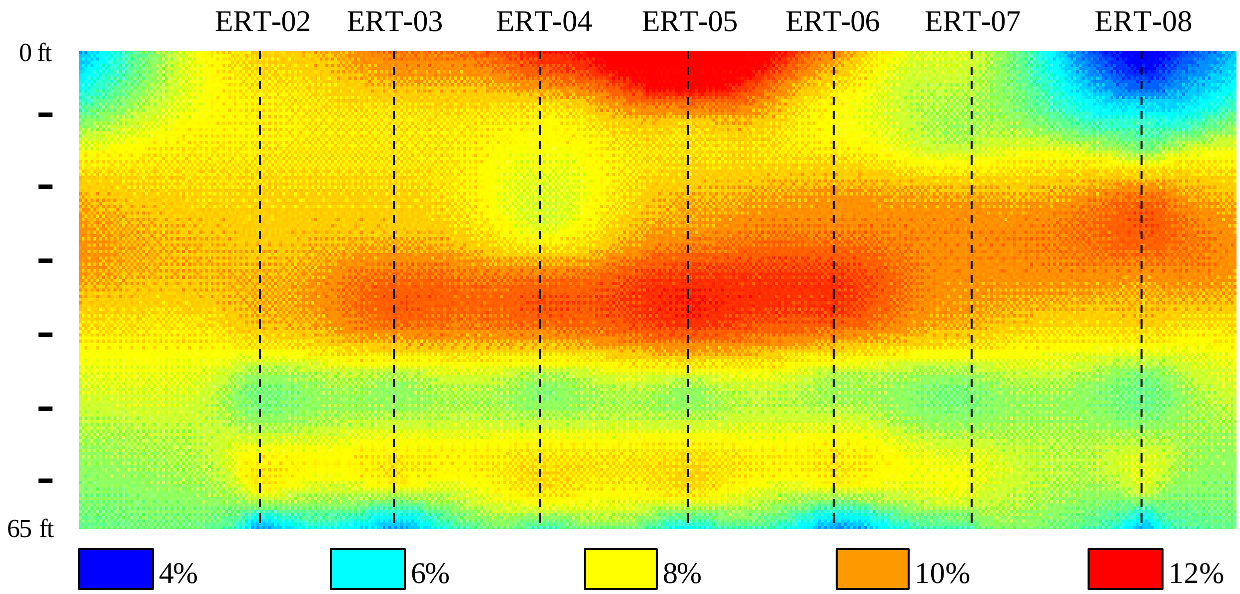


Figure 10. Soil Moisture Map of CPT Penetrations one the Perimeter of the Sisson and Lu Site.

The final fence plot presented is the resistivity plot in Figure 11. The resistivity results again shows that the site layering is predominately horizontal and fairly consistent between the all the penetrations. The highest resistivity region is the lower layer from 42 to 51 feet. This layer is presented as red in the plot. Similar resistivity values were detected in the upper regions (20 to 30 feet) of penetrations 2, 3, 4, and 5 but not in penetrations 6, 7 or 8.

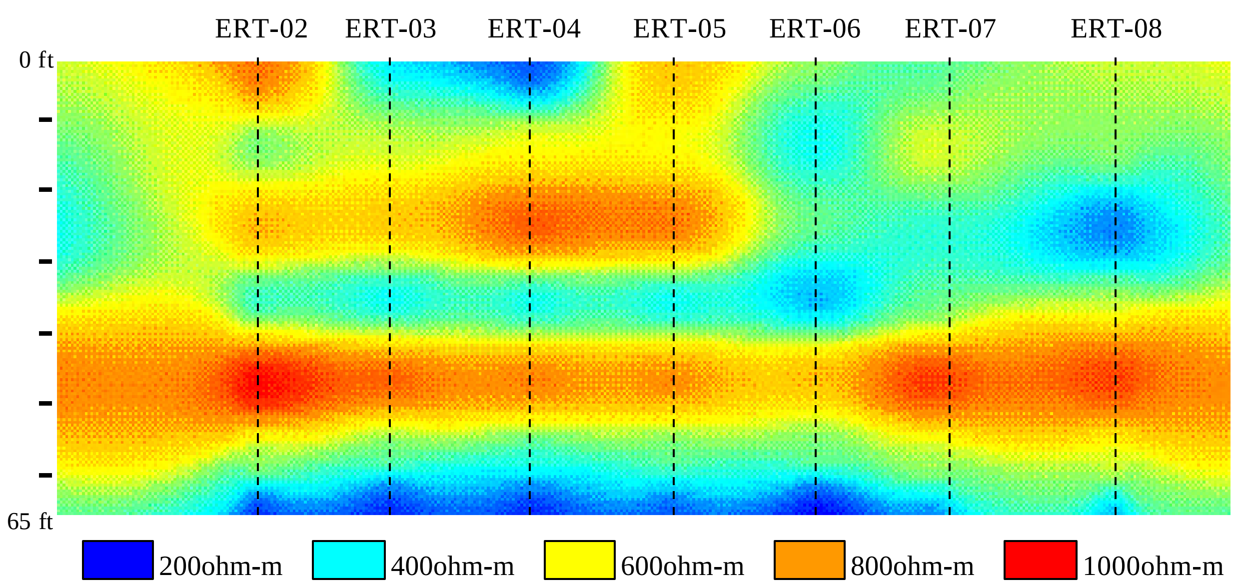


Figure 11. Resistivity Map of CPT Penetrations on the Perimeter of the Sisson and Lu Site.

Finally a set of cross sections plots has been made considering the center profile (ERT #9). This fence plot includes ERT-08, ERT-09 and ERT-05. Many of the same trends present in the fence plots are present in this plot. Cross-sections for tip stress and soil moisture are presented in Figure 12 and Figure 13 respectively.

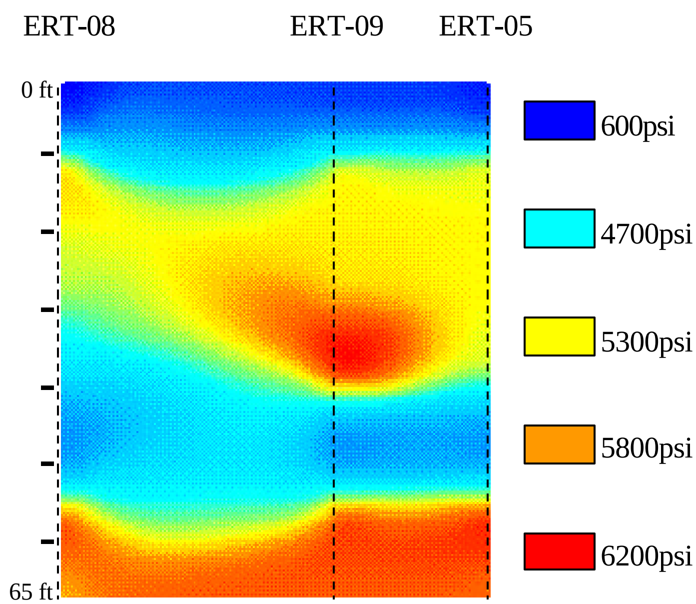


Figure 12. Cross Section of Sisson and Lu Site using ERT-08, ERT-09, and ERT-05.

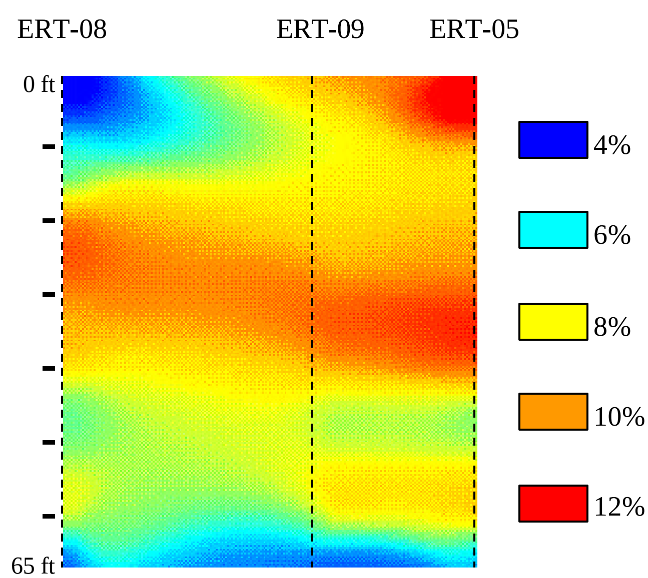


Figure 13. Soil Moisture Cross Section at Sisson and Lu Site using ERT-08, ERT-09, and ERT-05.

Soil Moisture Evaluation

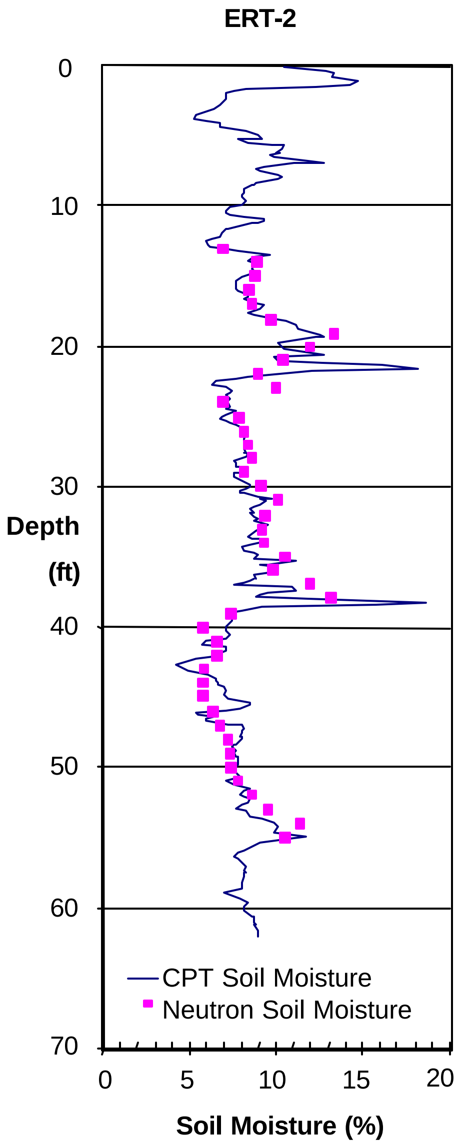


Figure 14. Comparison of CPT Soil Moisture Measurement and Neutron Probe Measurement.

A comparison between the CPT dielectric based soil moisture measurements and the neutron soil moisture measurements made in the steel wells was conducted. Both profiles were referenced to the top of the casing to ensure that both sensors were looking at the same depths. Figure 14 presents a comparison profile of the CPT data and the neutron data. The profiles compare very favorable as the various wet layers detected by the neutron probe are also detected by the CPT method. Some small depth shifts still appear in the data, but the general comparison is quite strong.

A correlation plot was made using all the soil moisture data from the CPT penetrations and the neutron data. This plot is presented in Figure 15. Although the correlation coefficient is not as strong (0.66) as desired, the slope of the line is very close to 1 as it should be for two sensors reading the same parameter. The coefficient is reduced due to scatter that is present in the field data and likely influenced by minor depth offsets in the two data sets.

In general the CPT sensor provides comparable readings to the neutron logs at the Sisson and Lu Site. Although the CPT has more detailed, it does not have the flexibility of being able to monitor changes over time without additional penetrations. Strings of soil moisture probes can be installed at the site and left in place to measure soil moisture over long periods of time. The advantage of this is that the manual labor required in making the neutron measurement is eliminated and the soil moisture probe can be polled from a computer automatically any time data is desired.

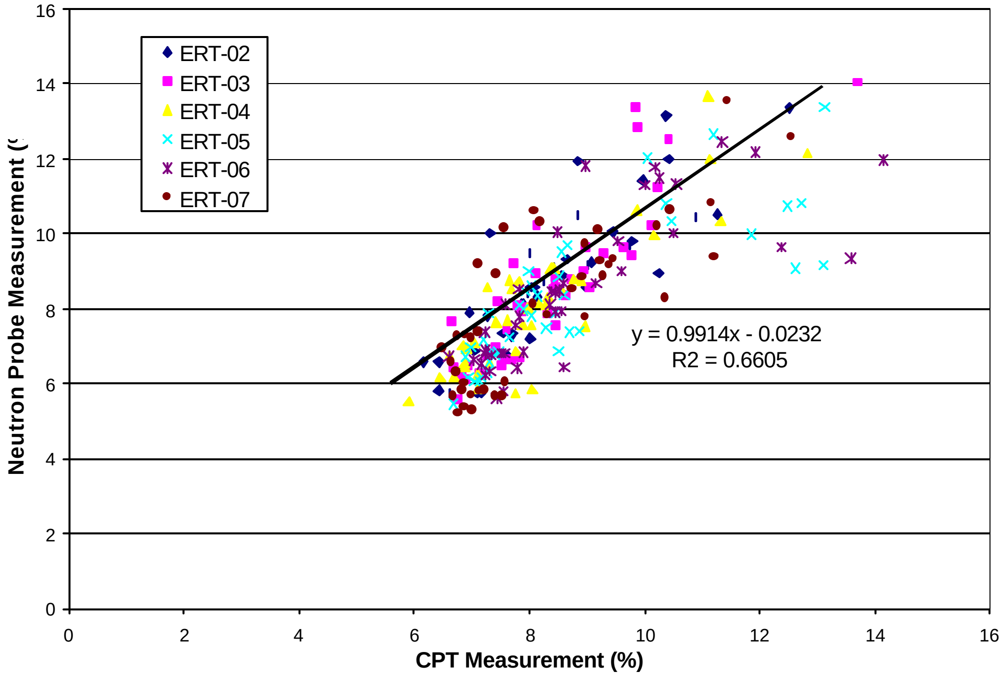


Figure 15. Correlation Plot of CPT Measurements and Neutron Data.

SECTION 4
SUMMARY AND CONCLUSIONS

As described previously in this report, a variety of Vadose Zone monitoring equipment was installed at the site using innovative Cone Penetration Techniques. This work included installing 9 ERT arrays, 6 tensiometers, and 4 cross-hole radar wells. All the ERT wells reached the desired depth of 62.5 feet. The 6 tensiometers were much more difficult to install and several did not reach the target depth or were damaged during the installation process. Although we had success with this tensiometer design at a previous site on the Hanford reservation, modification to the design is required to reach the desired depths for the installations at the Sisson and Lu site. The new design needs to expand the hole above the filter section to reduce friction loading on the PVC. This design has been fabricated and two additional installations are anticipated in the next month. Installation of the cross-borehole wells also did not reach the target depth, but were deep enough that they were able to capture the moisture movement through the soil horizons. The well tip used for these installations does incorporate an expander to reduce the friction on the PVC sections and was the reason for the deeper installations. The site geology at 52 to 55 feet consists of a dense material that caused the termination of these well installations prior to damage of the wells.

In addition to the monitoring equipment installation, 10 CPT penetrations were conducted to gather stratigraphy and initial soil moisture and resistivity information. This data has been prepared and presented in this report. Details of each profile are contained in Appendix A. These data sets were consistent and clearly show the horizontal layering present at the site. The data sets were also used in the ERT analysis as part of the ground truth and baseline data controls.

Finally, a continuous soil core was also collected using a new wireline CPT sampling system. This tool was very successful in collecting a 1-inch by 12-inch long sample from the ground with minimal disturbance. Recovery on all samples was greater than 80 percent with most samples ranging from 90 to 100 percent. Continuous samples can be quickly sampled using this approach and the hole grouted upon retraction of the rods. It is anticipated that additional soil sampling will be conducted using this technique at future experiments near the Sisson and Lu site.

In summary, the use of CPT techniques to install the vadose zone monitoring equipment was successful and proved to be a very economical approach. Typically CPT costs are only 10 percent of the cost of drilling techniques at the Hanford Site. This cost saving can have a large impact on most projects. Future deployments of these types of vadose monitoring approaches should again consider CPT for the installation process as a means to reduce costs as well as increase instrument coverage.

SECTION 5

LIST OF REFERENCES

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Appendix A. Piezocone Data