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Use of the Cone Penetration Test for Geotechnical Investigations at the Savannah River Site

Site Geotechnical Services Department

Westinghouse Savannah River Company
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Use of the Cone Penetration Test for Geotechnical Investigations at the Savannah River Site

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List of Acronyms, Symbols, and Keywords

A	Area
AL	Altamaha
APSF	Actinide Packaging and Storage Facility
ASTM	American Society for Testing and Materials
B_q	Pore pressure parameter
C_c	Compression index of a soil
CG	Congaree
COR	Corrected
CPT	Cone Penetration Test, a.k.a. Cone Penetrometer Test
CR	Compression ratio
DB	Dry Branch
e_o, E_o	initial void ratio of a soil
FHWA	Federal Highway Administration
GC	Green Clay
GWT	Groundwater table
HTF	H Tank Farm
ITP	In-Tank Precipitation
KASS	K-Area Soil Stabilization Program
M	Earthquake magnitude
MPa	Megapascal (1 MPa = 10.467 tsf)
N_k, N_q	Bearing capacity factors
N-value	Number of blows to drive a standard penetration sampler one foot
OYO™	suspension logger for obtaining shear wave velocity measurements
ϕ'	Effective friction angle of a soil
p_o	Total overburden pressure
Q_c, q_c	Measured tip resistance
Q_{c1}, q_{c1}	Measured tip resistance normalized to one tsf overburden pressure
Q_T, q_T	Tip resistance corrected for pore water pressure
RTF	Replacement Tritium Facility
σ	Standard deviation
σ', σ_{vo}'	Effective overburden pressure
SPT	Standard Penetration Test
SRS	Savannah River Site
ST	Santee
S_u	Undrained shear strength
τ	Shear stress
tsf	tons per square foot
TCI	Tan Clay Interval
TR	Tobacco Road
UD	Undisturbed sample boring
Vs	Shear wave velocity
WES	Waterways Experiment Station
WH	Warley Hill
WSRC	Westinghouse Savannah River Company
wt	weight

Use of the Cone Penetration Test for Geotechnical Investigations at the Savannah River Site

Introduction

The primary objective in designing any geotechnical exploration program is understanding the geological framework and the engineering properties which define the subsurface conditions. This is the reason for, and thus the mission of, the Site Geotechnical Services Department at the Savannah River Site (SRS); in essence, to obtain, concentrate, and use the knowledge and experience of subsurface conditions at the SRS to the benefit of all geotechnical activities.

A philosophy as to how exploration programs are designed and implemented has developed over the past several years as site geologic and geotechnical experience has grown. The Cone Penetration Test (CPT, ASTM D3341) has become a reliable and very useful tool and has become a part of this philosophy.

The first consideration for determining the scope of an exploration program is to define the required data and analyses to support the foundation design. Based on these requirements, a field program is devised taking into account the required information, the quantity and quality of existing data, and anticipated field conditions. As shown in Plate 1, a typical geotechnical program follows a series of logical steps by which the program is modified as the field program evolves.

One of the goals is to utilize as much of the existing subsurface data as possible. In general, if an area is already well characterized both in terms of stratigraphy and engineering properties, the ratio of borings to CPTs will be relatively low. In a relatively new or unexplored area, however, that ratio would be higher. Currently we do not have hard and fast guidance for the ratio of borings to CPTs. It is primarily based on judgment. For this reason, exploration programs for large projects are usually implemented in phases. The objective of a typical Phase 1 is to perform reconnaissance of the subsurface conditions and estimate preliminary engineering properties. The CPT is predominantly used for this purpose. Information acquired during this phase is used to identify where additional field work may be required based on the foundation requirements and structure locations. Once the layout of the proposed facility is finalized, a Phase 2 program may then consist of a combination of CPT soundings, SPT/UD borings, as well as other techniques. Laboratory

analysis of soil samples, and/or more sophisticated field tests, will generally be required to further define the subsurface conditions and obtain site specific soil properties for design.

This White Paper will further describe the use of the CPT as it relates to traditional geotechnical evaluations. This White Paper will not address the many uses and applications of CPT technology to environmental investigations.

History of CPT Use at the SRS

The CPT has a long and distinguished history in geotechnical engineering. It was introduced in modern form in Holland in the 1930s and is sometimes referred to as the "Dutch Cone Test". It came to the USA via the University of Florida in 1965, became an ASTM standard in 1975, and its use here has since grown steadily. Countless papers have been written which describe or discuss the CPT or data therefrom. From this research and experience, we now have powerful and reliable equipment to obtain quality CPT data, theories to interpret the data, and design methods for use of the data. Much of this is presented in the latest book devoted to the CPT (Lunne, et al. 1997).

Use of CPT technology at the SRS has progressively increased since the early 1990s in response to addressing the aforementioned objectives project by project. This progressive evolution of CPT use at the SRS can be traced from four specific geotechnical programs, in chronological order.

1st, 1989-1992: Work in K-Area, as part of the Reactor Restart effort (1989-1991) and the K-Area Soil Stabilization (KASS) Program (1991-1992). These programs focused on the characterization and stabilization of soft sediments in the subsurface. The CPT was used primarily as a reconnaissance tool for locating these soft soil zones.

2nd, 1992-1993: The Replacement Tritium Facility (RTF). This program involved the assessment of subsurface conditions beneath the RTF. Of particular interest here was the use of CPT for stratigraphy and the initial efforts to develop a SRS site-specific liquefaction relationship. It was during the latter stages of this program and the initial stages of the subsequent ITP program that we employed the services of the Waterways Experiment Station (WES) (Olsen, 1993) to review our CPT procedure (WSRC, 1998) for modification recommendations.

3rd, 1993-1995: The In-Tank Precipitation Facility (ITP). This program involved the assessment of subsurface conditions beneath existing waste tanks in the H-Area. CPT soundings were used for similar reasons as the KASS program, but were also used to estimate soil properties established from correlations between boring and CPT pairs. The CPT provided a quick and efficient technique for obtaining in-situ measurements under environmentally challenging conditions. Particular application for defining stratigraphy was recognized during this program as well. Stratigraphic relationships developed from CPT/SPT data pairs during this program were carried forward to investigate the balance of the H Tank Farm (HTF).

4th, 1995-1996: The F-Area Geotechnical Characterization. This program represented the first initiative to characterize the subsurface conditions for an entire operating area as opposed to a specific facility. This program consisted of compiling and qualifying numerous geotechnical reports and further supplementing this information with an exploration program consisting of primarily CPT soundings, supplemented by borings. For this investigation, some 98 existing quality borings, 12 new borings and 40 new CPT soundings were used to define the engineering stratigraphy and determine average soil properties throughout the F-Area.

As these and other various geotechnical projects have been performed at the Savannah River Site, thirty-nine CPT soundings have been paired with adjacent SPT and UD borings and subsequent laboratory testing. Over time, these CPT and laboratory data pairs has given us a better understanding of how to use the CPT relative to conventional borings and have allowed us to more efficiently design a field program. In addition to the data pairs, a significant amount of laboratory testing has been done at the SRS. For example, Plate 2 contains a table which lists the number and type of laboratory testing done for RTF, ITP/HTF, and F-Areas alone. Plate 3 compares average laboratory index test properties from the F- and H-Areas. These plates illustrate not only the similarity in index properties by engineering layer identified by the CPT but the vast amount of data available to draw upon. Plate 4 is a summary of the thirty-nine pairs, while Plate 5 shows their distribution throughout the SRS. Twenty-four of these data pairs are in F- and H-Areas. Four CPT-SPT data pairs from F-Area are shown in Plate 6. What is demonstrated in Plate 6 is the consistency between the SPT N-value and the CPT tip resistance. What is significant, however, is the level of detail that the CPT affords over the SPT, particularly in stratifying these sites.

Several particularly important advantages of the CPT technology, as practically applied at the SRS, have been recognized and thus used to further enhance the quantity and quality of geotechnical exploration at the SRS. Those advantages being:

- Continuous or near continuous data
- Excellent repeatability and reliability of data
- Time and cost savings (See Plate 7) allowing for acquisition of more high quality data

At the SRS the primary uses of the CPT are: to establish stratigraphy, soft zone identification, and estimation of specific engineering soil properties for design. Each is discussed in the following sections.

Stratigraphy

The evaluation of existing structures under a loading condition requires that a reasonable model of the subsurface conditions be constructed for analysis. For the SRS, this typically applies to sediments within the upper 200 feet. Therefore, subsurface conditions must be measured in terms of material properties such as soil type and strength to develop these

models. Other factors for defining these subsurface conditions depend on the lateral continuity of determined layers and detection of intermittent compressible layers generally observed in the range of 115-145 feet deep at the SRS. For large or complicated structures obtaining such data usually translates into additional exploration.

The CPT offers several advantages over traditional drilled borings for determining site specific stratigraphy. These include:

- More penetrations due to lower cost and less field time as compared to traditional drilled borings
- Higher vertical resolution due to nearly continuous measurements
- Highly repeatable measurements within similar material types or layers because of standard and automatic testing and data acquisition methods
- Multiple measured parameters including tip stress, sleeve stress, friction ratio, pore pressure, and shear wave velocity for resolving material characteristics
- Detection of layers of special interest, including very thin, loose, or compressible layers which can be used to determine target intervals for further adjacent sampling and subsequent laboratory testing.

Several soil classification systems have been developed over the years. From the early work by Begemann (1965) and Schmertmann (FHWA, 1978) to the pioneering work of Douglas and Olsen (1981) and Robertson and Campanella (1983a and 1983b). Other classification systems attempted to relate tip stress and sleeve stress with pore pressure (Jones and Rust, 1982; Baligh, et al., 1980; Senneset and Janbu, 1985). Robertson, et al. (1986) is believed to be the first attempt to relate all three parameters with soil classification. Since it has been recognized that tip and sleeve stress are affected by overburden pressure, researchers have attempted to account for this by normalizing the tip stress (Olsen, 1984; Douglas et. al. 1985; Olsen and Farr, 1986; Robertson, 1990; and Olsen and Mitchell, 1995). With the advent of the seismic piezocone, Robertson et. al. (1995) suggested a classification system based on normalized tip resistance and the ratio of low-strain shear modulus to CPT tip resistance.

It is important to note that all of the above classification systems were based on different data sets from various locations. They are therefore general and only provide a guide to soil type and behavior. All need to be adjusted or can be adjusted based on local knowledge at a particular site, area, or region. However, all are consistent in that sands are easily identified by high tip resistance, low friction ratio, and low pore pressure. Clays, on the other hand, are identified by reduced tip stresses, but more importantly, by high friction ratio and high excess pore pressures. Currently at SRS, we relate the CPT data directly to the results of the conventional borings and laboratory tests. We do not use an intermediate classification step.

As a result of using the CPT at the SRS, engineering stratigraphy can be developed to a fine level. An example of this is included as a subsurface cross-section developed for the Actinide Packaging and Storage Facility (APSF) located in the northeast corner of F-Area (See Plate 8). On this section, both continuous and non-continuous SPT borings are shown along

with adjacent CPT measurements of tip resistance and sleeve friction. The higher vertical resolution of the CPT is obvious. More importantly, the continuity of measurements between penetrations makes the technique useful for defining stratigraphy. Additionally, Plate 6 shows an example of engineering layers identified by utilizing the tip resistance, friction ratio, and the pore pressure measured by the CPT.

Developing engineering stratigraphy from CPT measurements is done by dividing the subsurface section into like units vertically but also units which can be correlated horizontally between CPT soundings. Once this is established, appropriate testing to determine engineering properties can be done. This has proven to be a strong application for the CPT because it provides high vertical resolution that can be used as an indicator of changing subsurface conditions. A typical deep CPT sounding in the center of the SRS penetrates between 160 to 200 feet deep and usually refuses on the dense sands of the Congaree formation. Such a sounding may penetrate as many as seven geologic formations or members.

The nature of the geology in the Carolina Coastal Plain setting results in vertical and horizontal facies changes over variable distances. In very general terms, most geologic formations are associated with some difference in lithology or material type that can be related to a change in depositional environment. Local geology is determined primarily from samples, geophysical log signatures and geologic maps and cross-sections where a relative depth for the geologic units can be determined. These changes in material type can be correlated directly to CPT measurements. Plate 9 is used to illustrate this point.

Plate 9 shows two CPT soundings in the center of the SRS and nearly two miles apart. The CPT on the left-hand portion of Plate 9 (CPT-36) is in F-area, while the one on the right (CPT-19) is in H-area. The stratigraphic geology for each of the areas is also shown. The geologic layers have been further subdivided into engineering layers, based on the CPT signature supplemented with borehole data. The shallowest geologic formation is the Altamaha formation. It consists predominantly of well graded clayey sands. CPT measurements are generally noted as high tip and sleeve resistance measurements with high friction ratios.

The underlying Tobacco Road formation generally coincides with a reduction in tip resistance. However, the lithologic similarity between the Tobacco Road and Altamaha can result in high friction ratios as well, making this a difficult contact to determine. As shown on Plate 9, the Tobacco Road formation in F-area was subdivided into two engineering layers while in H-area, it's subdivided into three layers based on local conditions. In F-Area the CPT signature is very clear between the two Tobacco Road layers. It is most evident in the friction ratio, which ranges from 2 to 6% in the upper, and is fairly constant at less than 1% in the lower layer. In the upper layer q_t is somewhat erratic (also noted in the SPT N-values) while in the lower layer q_t is generally increasing somewhat linearly (also noted in the SPT N-values).

The underlying Dry Branch formation is more sandy than the Tobacco Road formation but also contains layers of clayey sands and clays ranging in thickness' from a few inches to tens of feet. The transition into this

formation is generally noted by an increase in tip resistances and reduced friction ratios resulting from the sediments becoming more sandy. As shown on Plate 9, the Dry Branch formation is subdivided into five engineering layers in F-Area and four layers in H area. In H-Area the upper Dry Branch is subdivided into two layers. The difference is clearly shown in the q_t measurements (also noted in the SPT N-values), with the upper layer about 100 tsf and the lower layer being about 250 tsf. Friction ratios are relatively constant at less than 1%. However, the lower layer is more uniform. The Tan Clay member is very distinguishable between the upper and lower sands, with a low q_t (about 50 tsf) and a higher friction ratio (2%), and a much higher pore pressure response. The lower Dry Branch is also easily distinguishable from the upper Tan Clay by a sharp increase in q_t (50 tsf to over 100 tsf) and a sharp decrease in pore pressure (8 tsf to hydrostatic). Note, the SPT N-value trend also shows an increase within this unit.

The Santee/Tinker formation has been the subject of numerous geotechnical investigations. This geologic unit contains varying amounts of limestones and carbonate rich sands and muds. It is also the most variable geologic formation due to the complex depositional and post-depositional history. Simply put, the Santee is represented by the carbonate bearing sediments while the Tinker is represented by the stratigraphically equivalent sand facies. Where the Tinker formation is present, the contact between the Dry Branch and Tinker is obscured by the lithologic similarities. This can be observed in the H-area CPT on Plate 9. The upper ten feet of the Santee/Tinker section contains Tinker formation sands which have very similar CPT characteristics as the overlying Dry Branch sands (q_t of about 200 tsf and a friction ratio of less than 1%), although the friction ratio is somewhat more uniform than the Lower Dry Branch. The SPT N-values are also much higher. Determining this geologic contact was based on correlations with adjacent SPT borings, where a subtle gradational change was noted, as well as correlation with regional wells and geophysical logs. The lower Santee is much more erratic (also noted by the SPT N-values) but is generally characterized by a higher friction ratio and a higher pore pressure than the upper Santee. Where penetrations have reached deep enough, the Warley Hill (denoted Green Clay on Plate 9) formation can be determined typically from lower and more uniform tip resistances with resulting high friction ratios and pore pressures. This formation is generally less than 20 feet thick but is used frequently as a basal unit for the engineering stratigraphic section.

It is interesting to note that in general, the CPT results and the SPT N-values follow a very similar trend. Thus, both methods are consistent. However, unlike the CPT, the SPT N-values may mask thin, loose or compressible zones. This can be due to a number of reasons including the sampling interval, the SPT procedure itself, or neglecting the number of hammer blows in the first six inches on an 18 inch sample. To reinforce this observation, note the plotted N-value points from FB-9 and how these compare with the CPT-24 tip resistance in Plate 6. Loose layers near the bottom of the CPT sounding are not identified by the boring.

Another important note is the location of selected, or "pin-point", undisturbed samples as shown on the section as blocks within the CPT curves in Plate 8. With the CPT, these lenses (in this case the loose or

compressible zones) are easily identified and thus, targeted for sampling and laboratory testing. On the non-continuous SPT borings, several of these loose or compressible zones would have been missed.

The role of the CPT in stratigraphy identification is emphasized in a recent case history at the SRS. The APSF lies in the northeast corner of F-Area. As previously described, F-Area was the focus of an attempt to characterize an entire operating area under one field investigation. This investigation included CPTs, borings, and laboratory testing. Stratigraphic layers were determined based on the CPT results and engineering properties were determined for each layer based on laboratory testing results. The properties were determined conservatively and assigned to the particular geologic layer within F-Area, regardless of the location. Subsequently, forty-five CPTs were pushed and ten additional SPT borings were drilled at the APSF site. Based on these CPTs, the stratigraphy was concluded to be nearly identical (See Plate 8 F-Area Separations stratigraphy versus APSF engineering units). Thus, the soil properties previously determined for F-Area should also be comparable. A confirmatory drilling and laboratory testing program is currently being performed for the APSF. Average field and index properties for the confirmatory APSF program are compared to the original properties determined for F-Area in Plate 10. This plate shows excellent confirmation of the CPT's ability to identify similar stratigraphy and thus allow correlation of soil properties to be made. It illustrates that within the same geologic environment, similar stratigraphy subjected to the same geologic processes, will generally translate to similar soil properties. This is the fundamental basis of the subsurface exploration program philosophy at the SRS.

Soft Zone Identification

Of particular importance at the SRS is the detection of soft zones usually encountered at depths exceeding 100 feet. These zones have been characterized from previous investigations as SPT "weight of rod" intervals, lost circulation zones, or a CPT tip resistance less than 14.4 tsf (WSRC, 1991). The basis for the tip resistance of 14.4 tsf is discussed in Plate 11. "Weight-of-rod" advancement can be a misleading indicator of a soft soil zone. At depth, the weight of the rods alone is imparting a significant stress on the soil at the sampler location. For instance, at a depth of one hundred twenty feet, the weight of the rods alone acting between the soil and the end area of the SPT spoon sampler would be approximately 30 tsf (See Plate 12). Adding the weight of the hammer would increase this pressure to over 35 tsf.

On the other hand, the CPT has provided valuable information within these zones. The multiple parameters measured by the CPT indicate the presence of material where a mud rotary boring may lose circulation in the interval resulting in no recovery of material. One application in CPT technology which has recently been used at the SRS is the CPT sampler. In soft intervals where traditional drilling techniques have generally failed to adequately recover such soft materials, the CPT sampler has proved numerous times to have a nearly perfect recovery rate. The success rate is probably due to the push technique and no induced drill fluid pressure. The

technique can best be described as a "piston" type sampler, which also helps obtain the high recovery rate. This type of "piston" sampler has been in use since the early 1960s (SGI, 1961). These samples, however, are best suited for index testing and visual soil classification. Disturbance issues and the use of a smaller diameter sample must be resolved (possibly by a comparative testing program) prior to their use for other types of strength or compressibility testing.

Engineering Properties

Engineering properties of particular interest for subsurface evaluation are; shear wave velocity, static and dynamic soil strength, consolidation characteristics, and liquefaction potential. Each is discussed in the following paragraphs.

In the past 10 to 15 years the seismic cone has become a very useful tool to measure shear wave velocity reliably and economically. At the SRS, shear wave velocity measurements have been made from seismic crosshole testing, the OYO™ suspension logger, and from the seismic CPT. Plate 13 shows comparisons of shear wave velocity measured from these three different tools; crosshole survey, CPT, and the OYO™ suspension logger; 13A shows the crosshole and CPT downhole shear wave velocity in K-Area, 13B shows the crosshole and CPT downhole shear wave velocity at RTF, 13C shows the crosshole and CPT downhole shear wave velocity at ITP, and 13D shows the OYO™ and CPT downhole shear wave velocities at ITP. In general, the results show excellent agreement between all three methods at various sites across the SRS. Slight differences may be attributed to the local site variability. For shallow shear wave velocity determination, the CPT is preferred since it is considerably less time consuming and can be performed in multiple locations allowing for the variability across a site to be assessed.

The long term static strength of a soil is determined by a measure of the drained or effective stress friction angle. Correlations have been developed for the determination of the drained friction angle for cohesionless soils based on the tip resistance of the CPT. One such relationship developed by Robertson and Campanella,(1983), is shown in Plate 14. This relationship was used to estimate the drained friction angles for the soil strata at the ITP Facility in H-Area. Plate 14 also presents a comparison of the average laboratory determined drained friction angle and the corresponding average CPT derived drained friction angle. With the exception of the Tobacco Road 2 layer the drained friction angles determined by the CPT with global correlations compare well to those determined in the laboratory. As more data becomes available, the trend in the Tobacco Road 2 layer may be better explained.

As a part of the RTF and ITP investigations, site specific dynamic strength and volumetric strain relationships were developed from 53 laboratory stress-controlled cyclic triaxial tests (for more detailed discussion see WSRC, 1995). The results of these laboratory tests were correlated with adjacent CPTs to relate the CPT tip resistance and friction ratio to cyclic stress ratio (Plate 15a) and to relate volumetric strain to the factor of safety against initial liquefaction (Plate 15b). These curves were

developed with some conservatism and were reviewed and accepted by a peer review panel. The conclusions from these investigations were that by utilizing these curves and the near continuous data the CPT affords, the liquefaction potential and subsequent dynamic settlement at the SRS can be more reliably assessed using CPT data than using SPT data. The use of the CPT for earthquake engineering applications has been gaining wide acceptance in the industry over the last 10 to 15 years and was recently underscored in a paper by Dr. Jim Mitchell (Mitchell, 1998). Mitchell writes *"Experts… reviewed the 'simplified procedure' for liquefaction potential evaluation and concluded that the CPT should be adopted as a primary tool for determining soil stratigraphy and liquefaction resistance."*

The state of stress in the soil plays a significant role in the behavior of a structure. For example, the degree of consolidation, or past stress history of the soil has a significant influence on estimated structure settlements. At the SRS, this is particularly true of the loose or compressible zones below a depth of about 100 feet. In this regard, use of CPT parameters is still evolving. However, to collect samples in these intermittent compressible layers at the SRS, the CPT "piston-type" sampler has recently been utilized. These samples are excellent for laboratory determination of index properties such as moisture content, grain size distribution, and plasticity of the material. Correlations developed during the H- and F-Area investigations relate these three properties to the compression index, C_c (See Plate 16). Once the index tests are measured, the compression index and the initial void ratio can be estimated from the correlations shown.

An example of the use of these correlations was performed on a recent sample obtained using the CPT sampler at APSF. Index properties as well as a one-dimensional consolidation test were performed in the laboratory on this sample. Each index property was used to arrive at a compression index and initial void ratio based on the F-Area correlations on Plate 16. The table at the bottom of the Plate indicates that there is excellent agreement between the laboratory derived compression ratio ($C_c/1+e_o$) and the compression ratio derived from the correlations shown on Plate 16.

We have also employed statistical tools to compare the CPT parameters in each of the various geological formations as found in the heavily tested F- and H-Areas. Generally, we found very good statistical agreement (See Plate 17) between sets of CPT data previously identified from the same formation. This has enhanced our confidence in the CPT as a means of transferring experience from one site to another. It also supports the usefulness of using the CPT to help carry stratigraphy from one site to another.

It is important to note that the use of engineering properties from one site to another is a task which requires a great deal of engineering judgment and care. The use of pure statistics to determine the similarity can be a futile effort due to one major obstacle; geology. Ralph Peck once wrote *"Because nature is infinitely variable, the geological aspects of our profession assure us that there will never be two jobs exactly alike."* (Dunnicliff, 1991). Thus, although statistics play a role in our assessment of the subsurface conditions at the SRS, engineering judgment and geologic knowledge play a larger role.

Concluding Comments

The CPT has enhanced our capability to perform subsurface exploration at the SRS and to allow a more reliable comparison of nearby sites from an engineering standpoint. The key attributes contributing to this capability are:

- Continuous or near continuous data
- Excellent repeatability and reliability of data
- Time and cost savings allowing for acquisition of more high quality data

Over the years, as experience with the CPT and the SRS geology has increased, the ratio of borings to CPTs has no doubt decreased. This is not to say that borings are less important than they have been, rather it speaks more to the advancement in CPT technology and the use of the "pin-point" sampling philosophy which makes fewer borings necessary. Since field costs alone for conventional drilling methods are approximately three to four times that of the CPT on a per foot basis, the CPT offers the ability to obtain much more coverage of a site under investigation for a given budget. While there will always be a need for soil borings and laboratory testing, the amount should decrease with increased use of the CPT. However, knowledge about the subsurface conditions will increase. This has been commonly recognized as far back as 1978 (FHWA); *"Although engineers with much CPT experience in a local area sometimes conduct site investigations without actual sampling, in general one must obtain appropriate samples for the proper interpretation of CPT data. But, prior CPT data can greatly reduce sampling requirements."*

A large amount of site specific investigation data is continually being assembled and evaluated at the SRS. Advancements in CPT technology will be considered for use at the SRS as their effectiveness for evaluating the subsurface conditions becomes evident. When coupled with the philosophy presented herein of;

(a) similar stratigraphy in the same geologic environment will result in generally similar engineering properties,
(b) the CPT provides a presently unrivaled tool for the accurate and economical assessment of general site stratigraphy, liquefaction assessments, and site specific engineering properties, and
(c) the use of "pin-point" sampling, guided by prior CPT sounding profiles, provides the visual and laboratory 'anchor' for the interpretation of CPT data,

the Site Geotechnical Services Department ongoing site exploration efforts has the objective of providing the needed geotechnical design information in the most timely and economical manner currently possible at the SRS. As demonstrated herein, the CPT plays an important role in meeting this objective.

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Plates

GENERIC INVESTIGATION PROGRAM

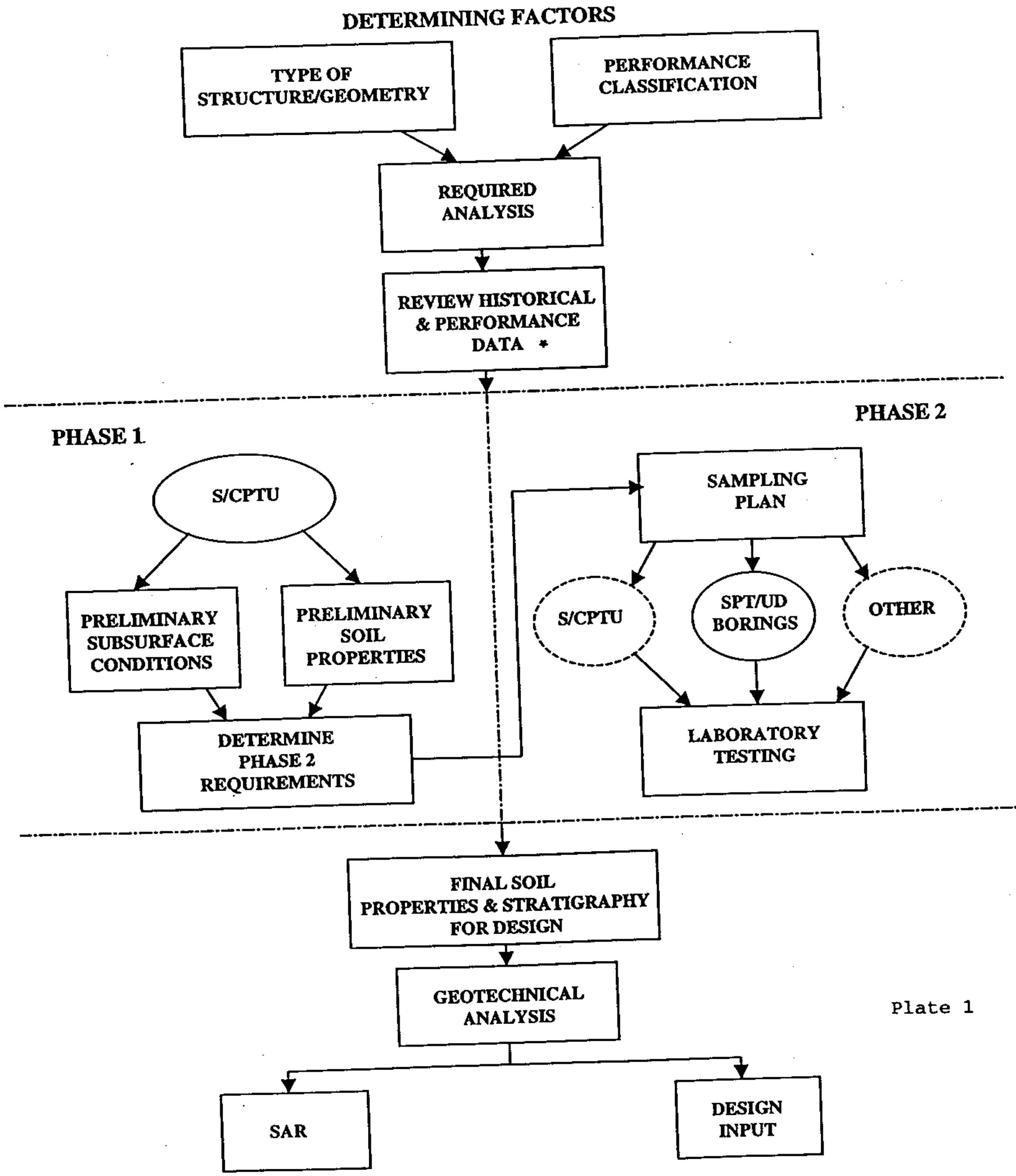


Plate 1

* Note — Typically some pre-preliminary boring data or existing knowledge of the geology is necessary to know if/how to effectively use the CPT (can one penetrate deep enough, need boring rig support, etc.).

Summary of Laboratory Testing for F- and H-Areas

Index Testing

Type of Test	Number of Tests
Atterberg Limits Testing	535
Grain Size Distribution Testing	914
Hydrometer Testing	270
Unit Weight Testing	351
Moisture Content Testing	1316
Specific Gravity Testing	330

Static Strength and Compressibility Testing

Type of Test	Number of Tests
Consolidated Drained Triaxial Test	60
Consolidated Undrained Triaxial Test	64
Unconsolidated Undrained Triaxial Test	38
Consolidation Test	135

Dynamic Strength and Volumetric Strain Testing

Type of Test	Number of Tests
Stress Controlled Cyclic Triaxial Tests	53
Volumetric Strain Measurements	35

Includes the F-Area Characterization, ITP/HTF Investigation, and RTF Investigation.

Plate 2

Plate 3 - Statistical Summary for Selected Properties

Unit	Property	F-Area Mean	F-Area STD	F-Area N	H-Area Mean	H-Area STD	H-Area N	F- & H-Areas Combined Mean	F- & H-Areas Combined STD	F- & H-Areas Combined N
Upland	%Sand	65.9	12.9	97	61.8	16.6	37	64.7	14.1	134
	%Fines	33	12	97	37.8	16.8	37	34.3	13.7	134
	Clay	18.2	9.9	6	24.98	13.9	28	23.8	13.6	34
	LL	37.7	8.99	76	75.9	20	29	48.3	21.5	105
	PL	21	4.3	76	28.7	6.7	29	23.1	6.2	105
	PI	16.7	7.2	76	47.2	16.6	29	25.1	17.3	105
	SG	2.67	0.05	18	2.67	0.03	32	2.67	0.04	50
	MC	15.7	4.5	85	21.8	4.8	21	16.9	5.2	106
	DD	102.7	-	1	98.6	4.7	4	99.4	4.8	5
	WD	116.6	3.6	5	120.5	4	24	119.8	4.2	29
Tobacco Road	%Sand	77.3	15.2	135	82	6.8	22	77.9	14.5	157
	%Fines	22.6	15.3	135	17.9	6.8	22	22	14.5	157
	Clay	14.9	13.8	13	11	6.9	7	13.5	11.8	20
	LL	36.1	11.3	71	37.2	5.9	6	36.2	10.9	77
	PL	22.4	4.1	71	19	1.5	6	22.1	4.1	77
	PI	13.7	10.2	71	18.2	5.2	6	14.1	10	77
	SG	2.68	0.05	21	2.66	0.04	13	2.68	0.05	34
	MC	19.6	6.1	89	22.3	2.8	8	19.8	6	97
	DD	101.6	7.1	4	107.7	-	1	102.8	6.7	5
	WD	117.1	9.8	18	126.4	4.2	5	119.1	10	23
Dry Branch	%Sand	65.5	30.2	73	81.3	10	93	74.3	22.7	166
	%Fines	34.5	30.2	73	18.5	10	93	25.6	22.7	166
	Clay	24.3	21.3	9	14.1	7.5	71	15.2	10.3	80
	LL	84.1	39.3	56	48.8	15.9	53	66.9	35	109
	PL	35.1	16.9	56	20.9	4	53	28.2	14.2	109
	PI	49	30	56	27.8	15.1	53	38.7	26.1	109
	SG	2.68	0.04	18	2.68	0.04	77	2.68	0.04	95
	MC	41.8	20.5	79	24.9	6.8	43	35.9	18.8	122
	DD	88.9	15	7	101.8	7.3	18	98.2	11.4	25
	WD	114.6	9.7	17	123.7	8.3	65	121.8	9.3	82
Santee	%Sand	67.3	17.8	59	69	20.2	96	68.4	19.3	155
	%Fines	30	15.1	59	29.1	19.6	96	28.7	18	155
	Clay	23.1	12.5	15	20.4	17	64	20.9	16.3	79
	LL	40.9	12.7	38	63.1	29.4	43	52.7	25.6	81
	PL	21.6	4.9	38	23.1	5.9	43	22.4	5.5	81
	PI	19.4	9.9	38	40.1	28.9	43	30.4	24.5	82
	SG	2.69	0.05	14	2.67	0.05	68	2.67	0.05	82
	MC	29.2	8.5	32	34.1	13.4	56	32.2	12.1	88
	DD	91.5	12.8	4	87.1	12.7	42	87.9	12.7	25
	WD	116.5	6.9	9	113.1	8.4	55	113.5	8.2	64

Contains laboratory tests from the F-Area Characterizatrion and the ITP/HTF Investigation only.

Legend of Terms and Symbols	
%Sand	Percent material larger than .07mm
%Fines	Percent material smaller than .07mm
Clay	Percent material smaller than .005mm
LL	Liquid Limit of a material, %
PL	Plastic Limit of a material, %
PI	Plasticity Index of a material, % PI=LL-PL
SG	Specific Gravity
MC	Moisture Content, %
DD	Dry Density of a material, lbs/ft^3
WD	Wet Density of a material, lbs/ft^3
Mean	Average value of the population
STD	Standard deviation of the population
N	Number of samples

Area	Boring ID	CPT ID	Project
H-Area	HSPT-18	HCPT-18	In-Tank Precipitation Facility
	HSPT-20	HCPT-20	"
	HSPT-14	HCPT-14	"
	HBOR-23	HCPT-23	"
	HLWF-B2	HLWF-C2	Latewash Facility
	B-13	HRTF-C4	Replacement Tritium Facility
	B-2/B-14	HRTF-C7	"
	B-15	HRTF-C11	"
	B-1	HRTF-C15	"
	HTEF-B3	HTEF-C9	Tritium Extraction Facility
	HTEF-B2	HTEF-C21	"
L-Area	L1008A/B	LCPT-C18	L-Reactor Seismic Qualification Program
	L202/L205	LCPT-C5	"
	LBSN-B12	LCPT-C12	L-Basin Geotechnical Investigation
	L201	LCPT-C4	"
K-Area	K1003A	KC2	K-Reactor Seismic Qualification Program
	K1006	KC10	"
	K1008B	KR2C	"
	K1012C	KR12A	"
	K1013B	KR9	"
G-Area	MWD-12	MWD-C2	WSRC Corporate Initiative-Site Characterization
	MWD-13	MWD-C1	"
	MWD-14	MWD-C4	"
	MWD-15	MWD-C6	"
F-Area	FSEP-B6	FTNK-C6	F-Area Geotechnical Characterization Program
	FSEP-B8/8.1	FSEP-C8	"
	FSEP-B13/13.1	FSEP-C13	"
	FTNK-B16	FTNK-C16	"
	24114F-1	FTNK-C4	"
	FB-1	F235-C2	"
	FB-2	F235-C4	Actinide Packaging and Storage Facility
	*FB-3	C-10	"
	FB-4	C-9	"
	*FB-5	C-1	"
	*FB-6/15	C-36	"
	FB-7	C-16	"
	*FB-11/13	C-14	P-Reactor Seismic Qualification Program
P-Area	P1002	PC-4	"
	P1003	PC-6	

* Comparisons presented in Plates 6 and 8.

Plate 4 - SPT/CPT Data Pairs

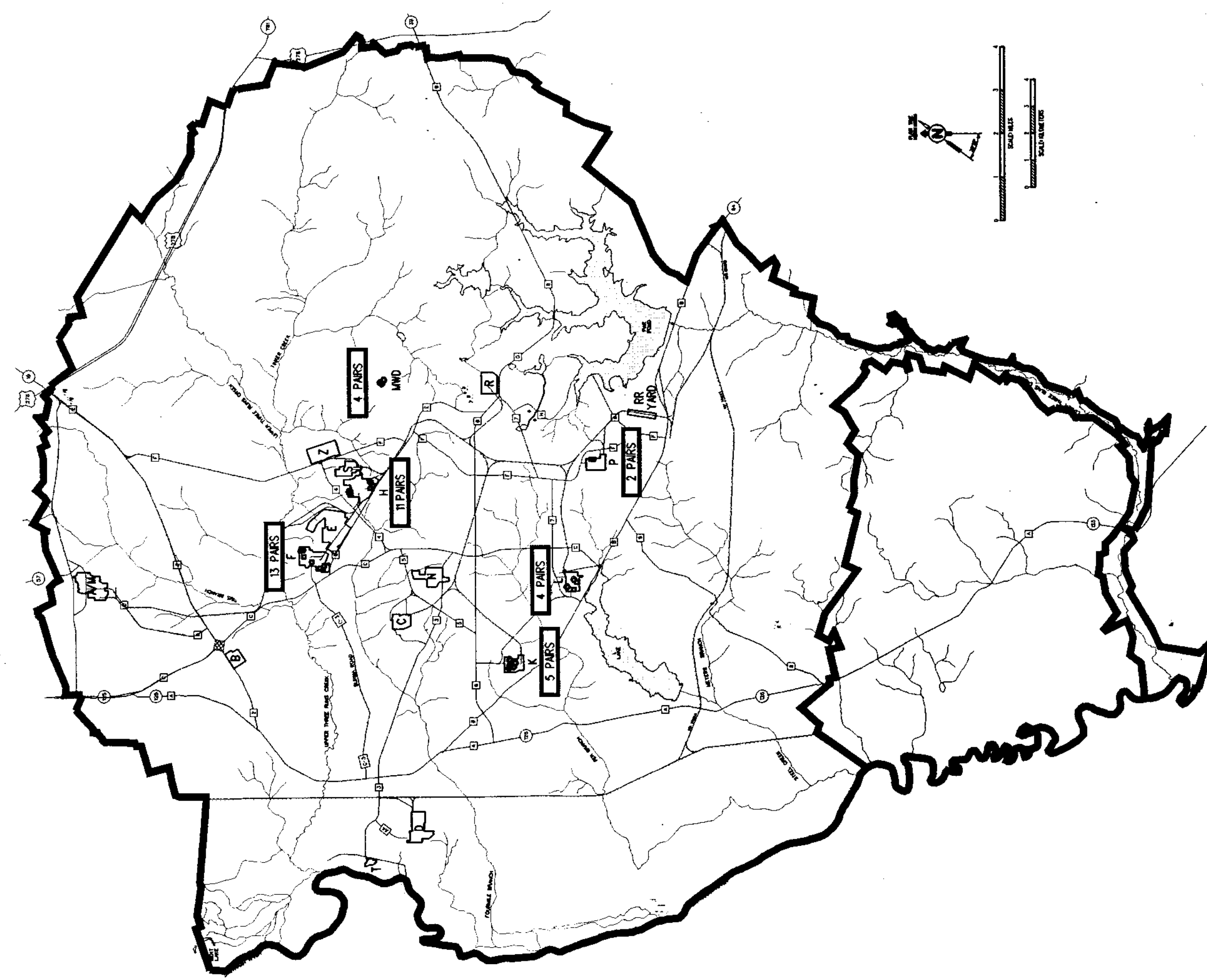
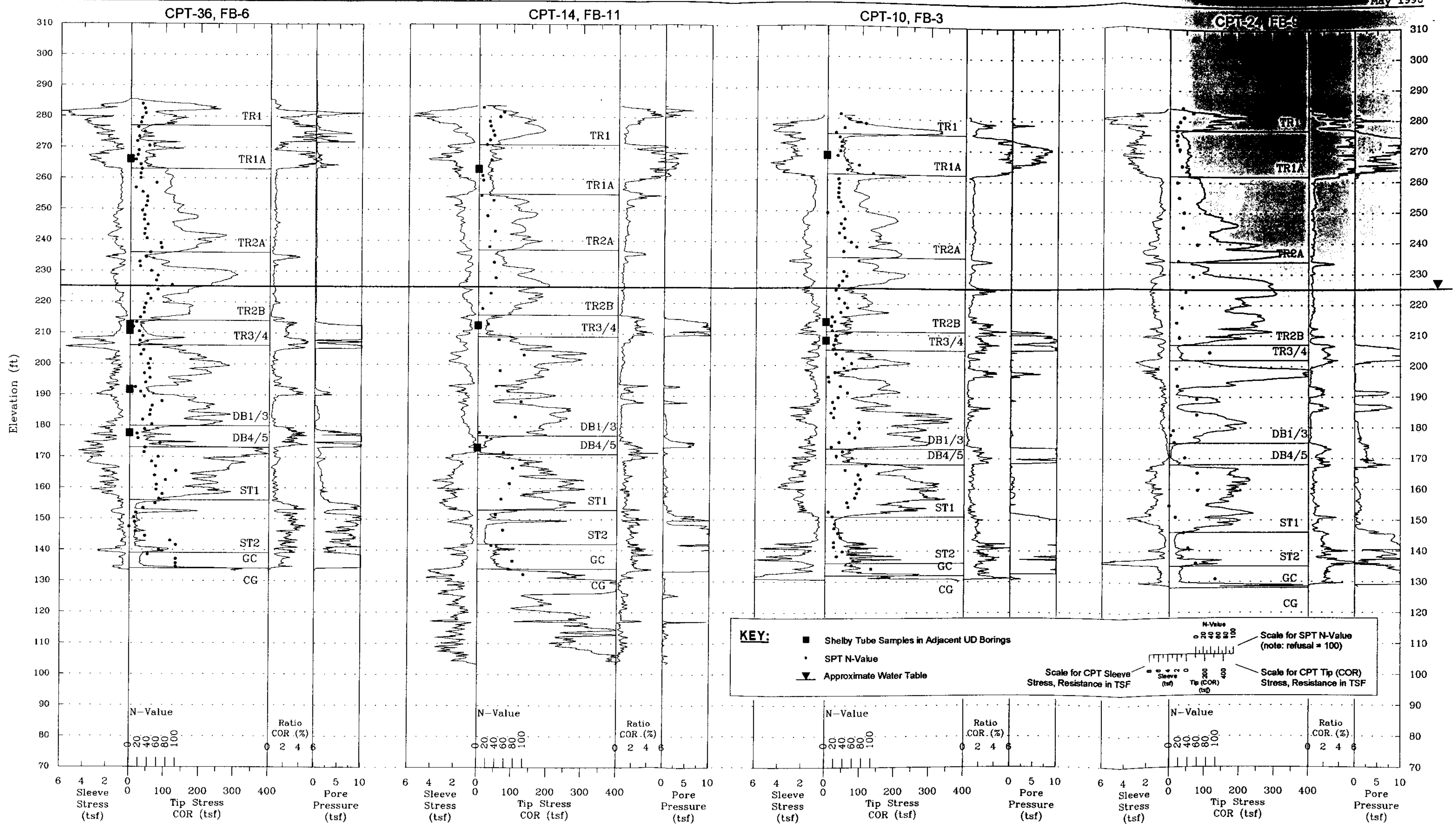


PLATE 5.   Distribution of SPT/CPT Data Pairs across the SRS.


CPT-36, FB-6
CPT-14, FB-11
CPT-10, FB-3
CPT-24, FB-9
Elevation (ft)
TR1
TR1A
TR2A
TR2B
TR3/4
DB1/3
DB4/5
ST1
ST2
GC
CG
N-Value
Ratio COR (%)
Sleeve Stress (tsf)
Tip Stress COR (tsf)
Pore Pressure (tsf)
KEY:
Shelby Tube Samples in Adjacent UD Borings
SPT N-Value
Approximate Water Table
Scale for SPT N-Value (note: refusal = 100)
Scale for CPT Sleeve Stress, Resistance in TSF
Scale for CPT Tip (COR) Stress, Resistance in TSF

	Green Field					Operating Area					RBA (Rad Area)				
	Duration	Sub $	Osight $	Total$	$/ft	Duration	Sub $	Osight $	Total$	$/ft	Duration	Sub $	Osight $	Total$	$/ft
150' SPT Continuous	5 days	4600	3250	7850	52.33	6 days	5600	3900	9500	63.33	10 days	13100	6500	19600	130.67
150' SPT on 5' CTR's	4 days	2200	2600	4800	32.00	5 days	3200	3250	6450	43.00	9 days	8823	5850	14673	97.82
150' SCPTU	1 day	2752	650	3402	22.68	1 day	2873	650	3523	23.49	1 day	3197	650	3847	25.65
150' CPTU	1/2 day	2163	325	2488	16.59	1/2 day	2284	325	2609	17.39	1 day	2608	650	3258	21.72

CPT Notes:

1. 25' water table assummed
2. Does not include permitting time
3. Continuous oversight cost calculated at $ 65.00/ hour
4. Does not include General Site Overhead
5. Operating area includes 1 hour of stand-by per day at $150 per hour
6. RBA operations includes 3 hours of stand-by per day at $150 per hour due to HP monitoring CPT rods as they are withdrawn from ground
7. Does not include CPT reporting fees @ $600/project
8. Does not include mob/demob fees, @ $400/project/rig
9. Includes pre and post push equipment calibrations
10. CPT Subcontractor is Level 1 Procurement w/full QA Program
11. Includes abandon grouting costs

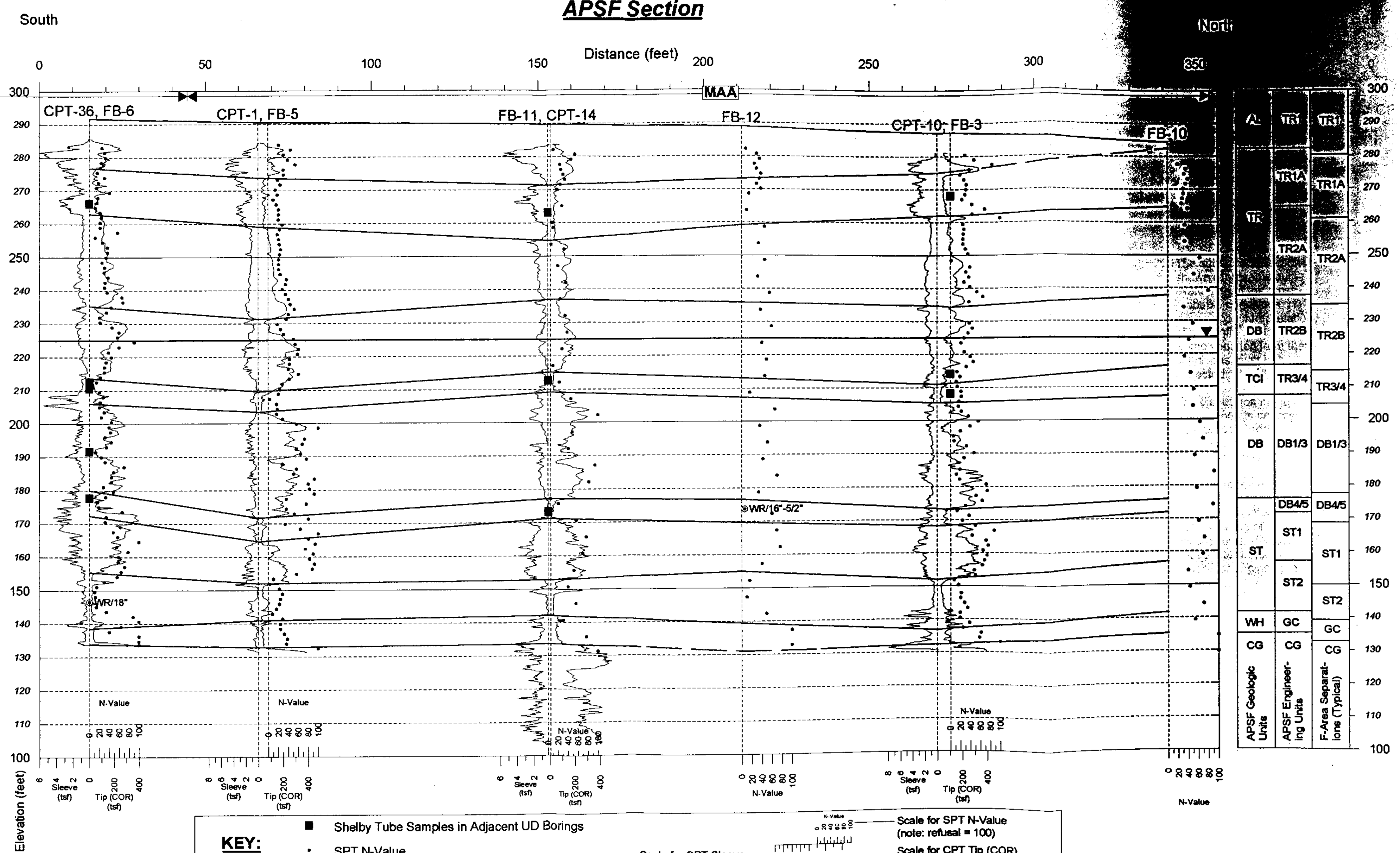
Drilling Notes:

1. 25' water table assummed
2. Mud rotary drilling
3. Does not include permitting time
4. Skip pan service required for borings within operating areas and RBA @ $100/day
5. Continuous oversight cost calculated at $ 65.00/ hour
6. Does not include General Site Overhead
7. Operating area includes 1 hour of stand-by per day at $250 per hour
8. RBA operations includes 3 hours of stand-by per day at $250 per hour due to HP monitoring the drill string & testing split-spoon samples for RAD
9. Costs include field boring log
10. Does not include mob/demob fees @ $1200/project/rig
11. No undisturbed sampling (only split spoon)
12. Includes abandon grouting costs

Note: As of January 1998

Plate 7 Per foot conventional drilling and CPT cost comparison.

APSF Section



Notes:

1. All CPT and SPT Borings Projected to N-S line at E55014
2. The subsurface section shown represents our evaluation of the most probable conditions based upon interpretation of presently available data. Some variation from these conditions must be expected.
3. The discussion in the text of the report is necessary for a proper understanding of the nature of the subsurface material.
4. The use of the geologic formation designation of soils encountered is used for ease of description and should not be interpreted as a textural or engineering description.

KEY:

- ■ Shelby Tube Samples in Adjacent UD Borings
- • SPT N-Value
- ▼ Approximate Water Table

Scale for SPT N-Value (note: refusal = 100)

Scale for CPT Tip (COR) Stress, Resistance in TSF

Scale for CPT Sleeve Stress, Resistance in TSF

d:/gelinas/cpt/white.pap/sect-2j.grf 05/22/98
uses apsfsect.xls sheet section2

PLATE 8

ENGINEERING STRATIGRAPHY AND PROPERTIES

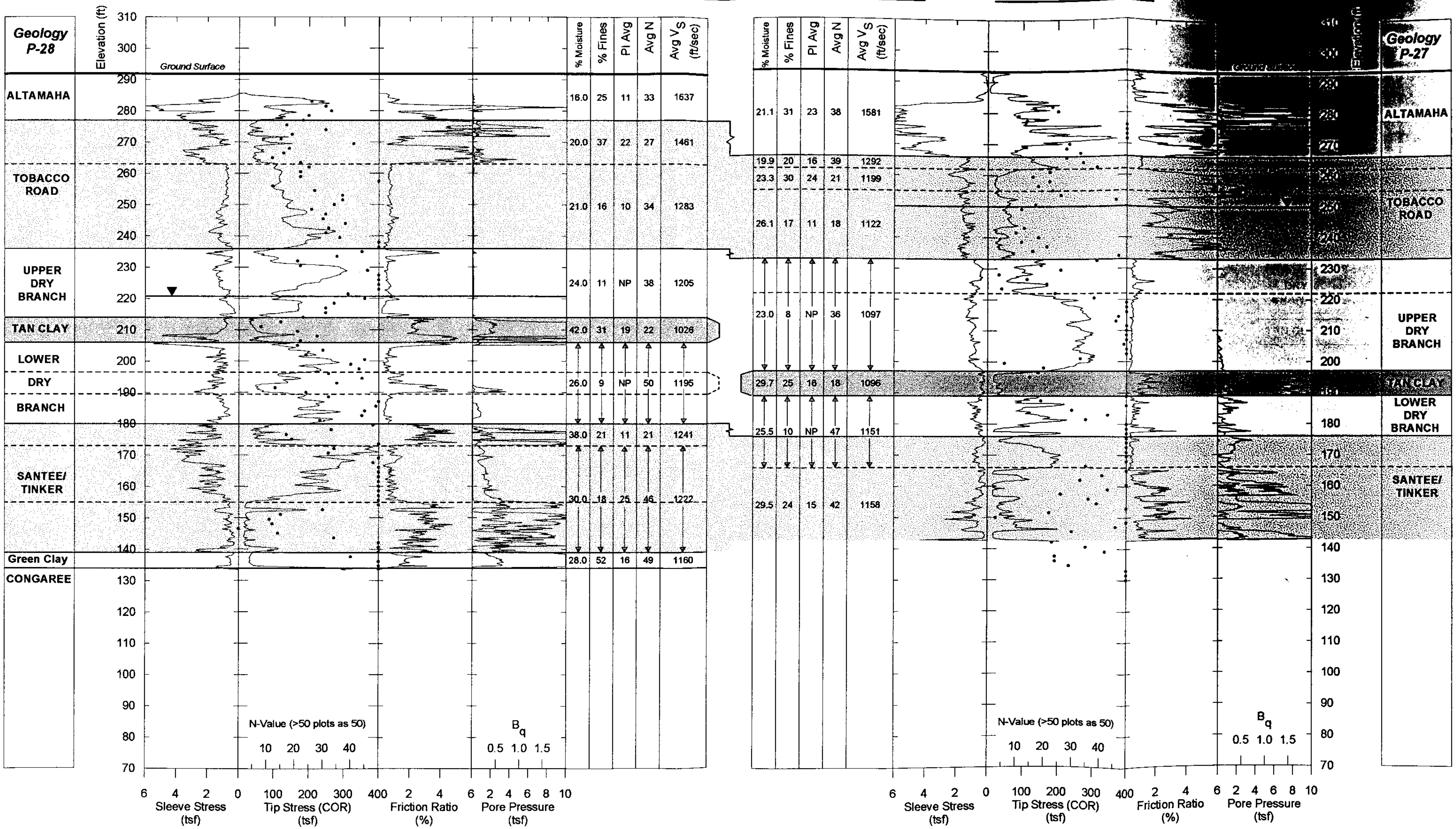


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PLATE 9

Plate 10 - Comparison of APSF and F-Area Soil Properties

Description	Source	Fill	TR1	TR1A	TR2A	TR2B	TR3/TR4	DB1/DB3	DB4/DB5	ST	GC
SPT N-Value (blows/foot)	F-Area Report	23	25	25	28	36	18	33	15	47	21
	APSF Data	-	33	27	34	38	22	50	21	48	49
Qc/N	F-Area Report	4.9	3.7	4.8	5.2	5.5	3.1	5.1	4.1	2.8	2.7
	APSF Data	-	3.7	2.5	4.1	4.1	1.7	3.9	3.1	2.8	3.8
Shear Wave Velocity (ft/sec)	F-Area Report	978	1455	1348	1256	1254	1074	1157	1140	1353	1675
	APSF Data	-	1637	1461	1283	1205	1026	1195	1241	1222	1160
Qc (tons/foot²)	F-Area Report	112	91	120	147	201	55	172	61	131	58
	APSF Data	-	142	68	136	154	37	188	52	137	79
Friction Ratio (%)	F-Area Report	2	4	2	2	1	2	1	2	2	2
	APSF Data	-	2	4	1	1	2	1	2	1	2
Percent Fines (%)	F-Area Report	25	33	30	17	19	64	14	22	29	39
	APSF Data	-	25	37	16	11	31	9	21	18	52
Percent Clay (%)	F-Area Report	21	18	33	10	8	40	12	20	24	3
	APSF Data	-		26	11	-	23		15	16	32
Mean Grain Size (mm)	F-Area Report	0.22	0.23	0.12	0.27	0.36	-	0.34	0.29	0.22	0.11
	APSF Data	-	0.20	0.16	0.28	0.31	0.23	0.38	0.23	0.17	0.09
Plasticity Index (%)	F-Area Report	15	17	14	10	18	58	19	28	18	47
	APSF Data	-	11	22	10	NP	19	NP	11	25	16
Liquid Limit (%)	F-Area Report	32	38	36	33	41	96	44	48	40	83
	APSF Data	-	30	46	33	NP	54	NP	45	49	32
Water Content (%)	F-Area Report	13	15	19	17	22	51	27	39	29	32
	APSF Data	-	16	20	21	24	42	26	38	30	28

From the F-Area Characterization Report and the APSF Investigation CPTs 1-17, 36,37,44 and Borings FB-1 through FB-12

Plate 11 SOFT ZONE CPT TIP RESISTANCE CRITERIA

The criterion used at the SRS to determine the presence of a soft zone is a continuous 2-foot thick layer of material with a CPT tip resistance (q_t) of less than 15 tons per square foot (tsf). This criteria was originally established for the work performed at K area for the Reactor Restart in the early 1990s (WSRC, 1991).

The original criteria was 200 pounds per square inch (psi), which is 14.4 tsf. We have since rounded this value up to 15 tsf. As stated in the above reference, this value would be roughly equal to that expected from a normally consolidated medium plastic clay at the depth in question (about 115 to 145 feet below ground surface in K area).

The theoretical basis for the above criteria is as follows, from bearing capacity theory:

$$Q_T = N_k S_u + p_o \qquad (1)$$

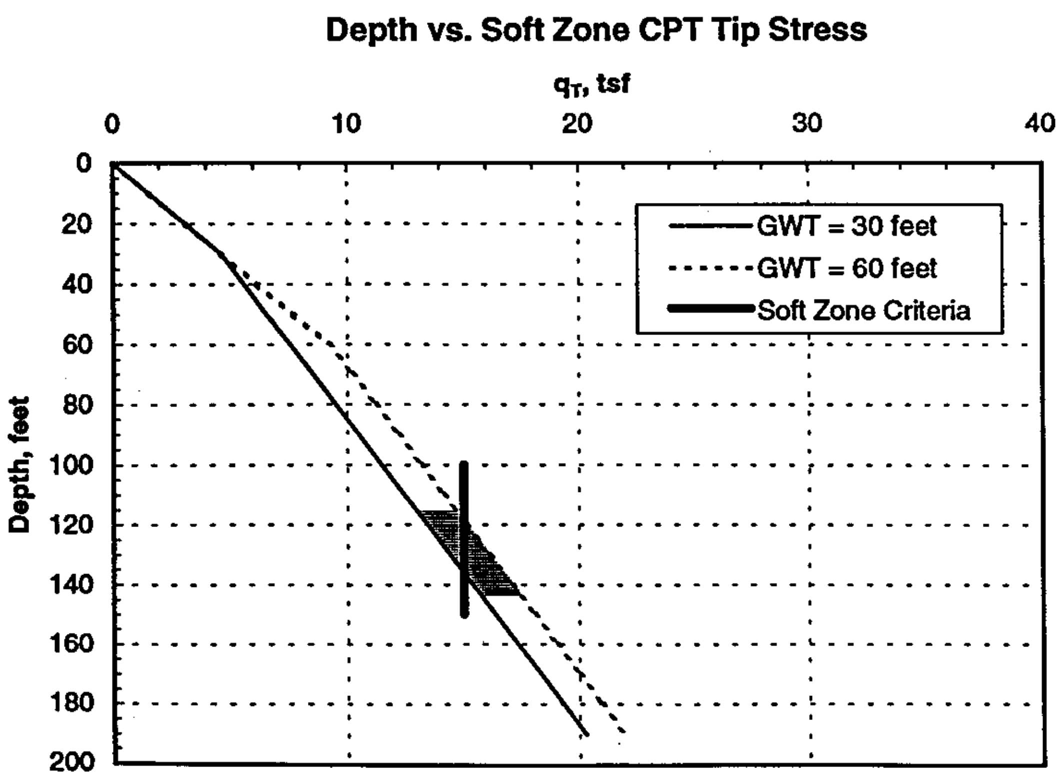
Where: S_u = undrained shear strength
q_t = corrected cone tip resistance
p_o = the total overburden pressure
N_k = constant that varies between 10 and 20, (a bearing capacity factor, assumed to be 10 for normally loaded clays)

The shear strength is then computed from the following relationship (Jamiolkowski, 1985) proposed for normally loaded, marine clays of low to medium plasticity:

$$S_u \,/\, p_o' \sim 0.23\ (+/-\ 0.04) \qquad (2)$$

Where: p_o' = effective overburden pressure

The CPT q_t is plotted below for groundwater depths of 30 and 60 feet below the surface assuming a soil wet unit weight of 110 pcf, S_u / p_o' ~ 0.2, and N_k = 9.



Note that when comparing Plate 11 with Plate 12, the SPT is not capable of measuring soft zones below 40' (wt. Hammer + rods) and 60' (wt. rods).

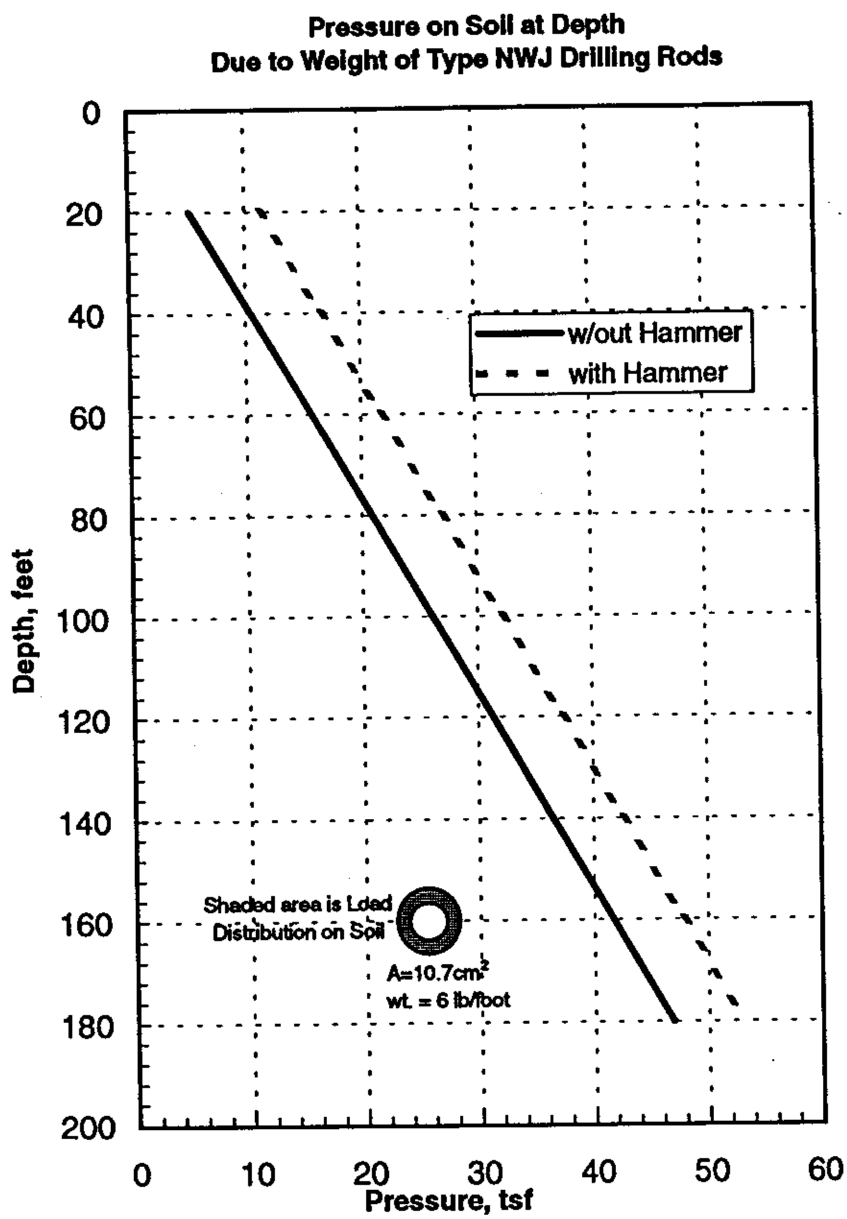

Pressure on Soil at Depth
Due to Weight of Type NWJ Drilling Rods
Depth, feet
0
20
40
60
80
100
120
140
160
180
200
Pressure, tsf
0
10
20
30
40
50
60
w/out Hammer
with Hammer
Shaded area is Load Distribution on Soil
A=10.7cm²
wt. = 6 lb/foot

Plate 12

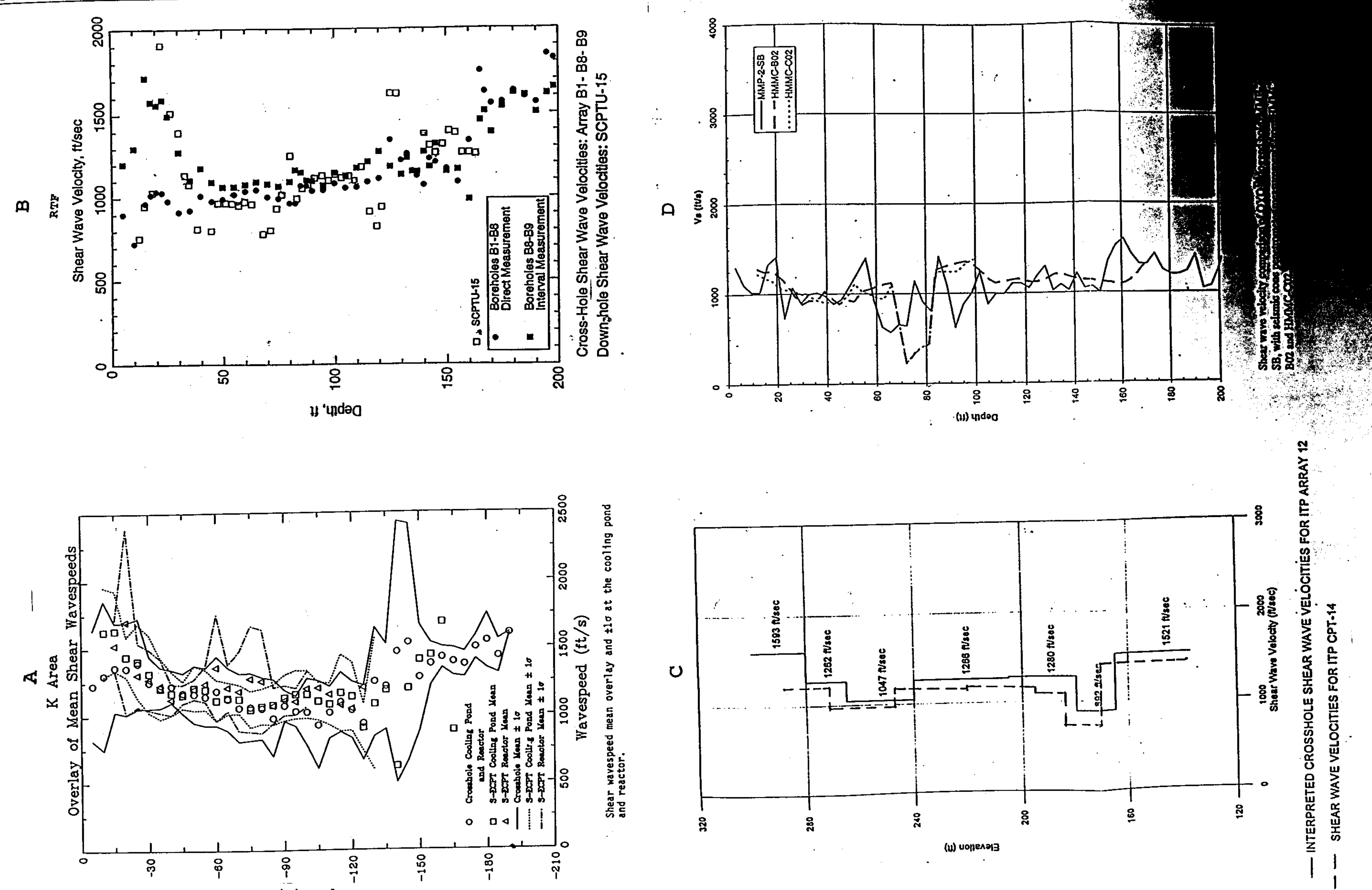
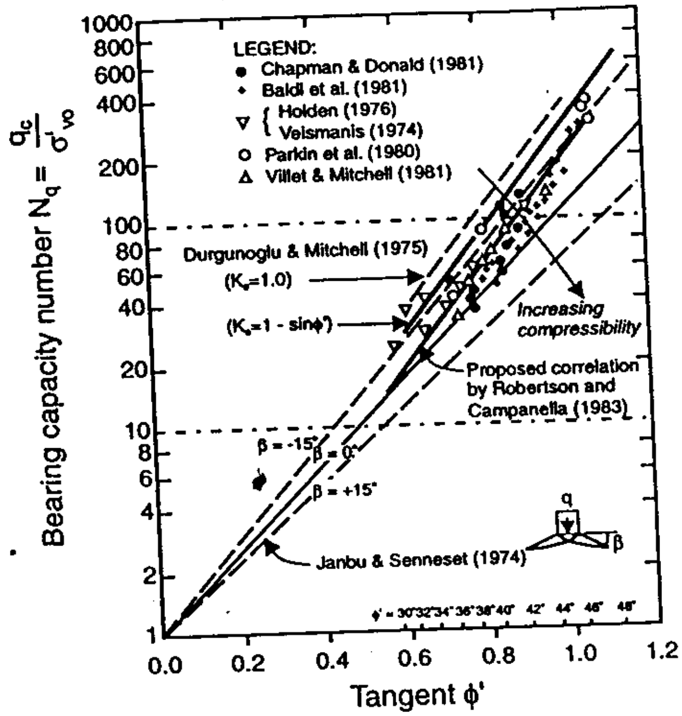
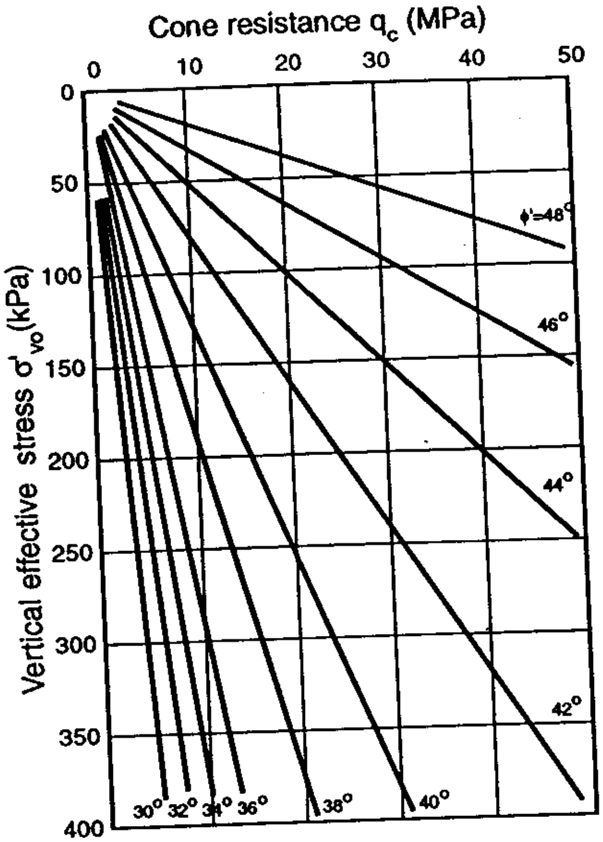


Plate 13 Shear Wave velocity comparisons



A Relationship between bearing capacity number and friction angle from large calibration chamber tests (after Robertson and Campanella, 1983b).

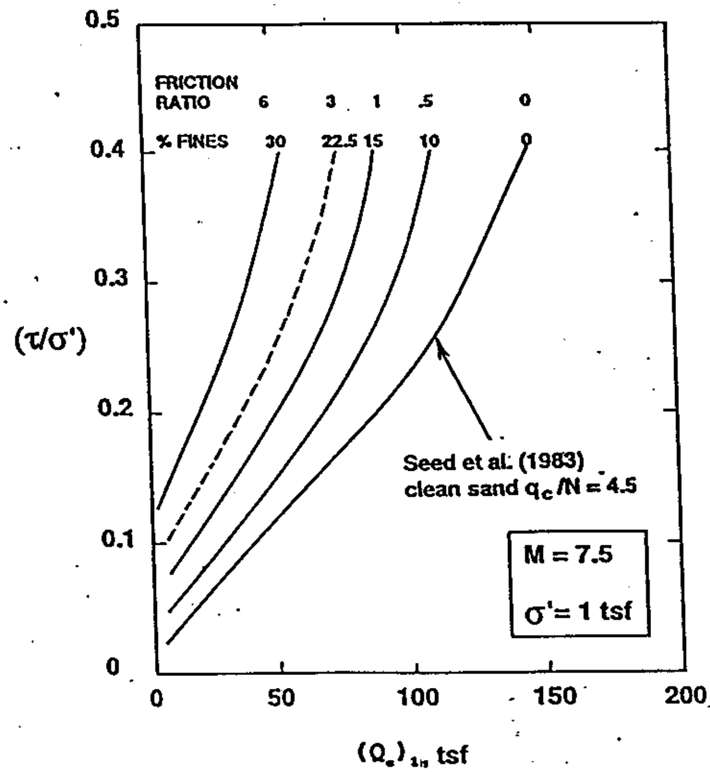


B σ'_v, q_c, ϕ' relationships (after Robertson and Campanella, 1983b).

C

Unit	Laboratory Average Friction Angle	CPT Average Friction Angle
Fill	37	36
Tobacco Road Layer 1	34	32
Tobacco Road Layer 2	29	37
Tobacco Road Layer 3/4	33	30
Dry Branch Layer 1/3	34	37
Dry Branch Layer 5	29	30
Santee	34	34

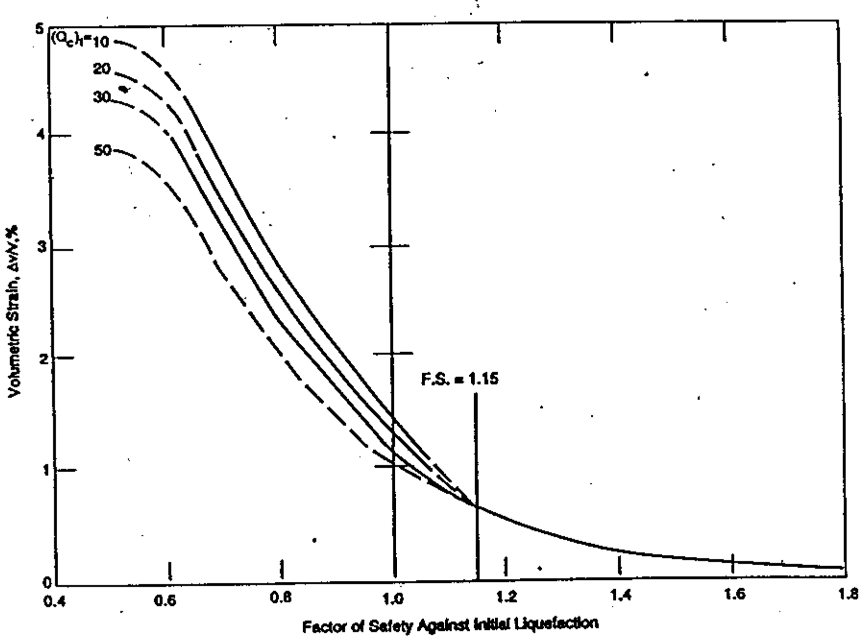
Plate 14 Relationships for determining effective friction angle.



A

Proposed correlation for ITP between modified cone tip resistance and friction ratio with the cyclic stress ratio required for initial liquefaction in the field.

(WSRC, 1995)

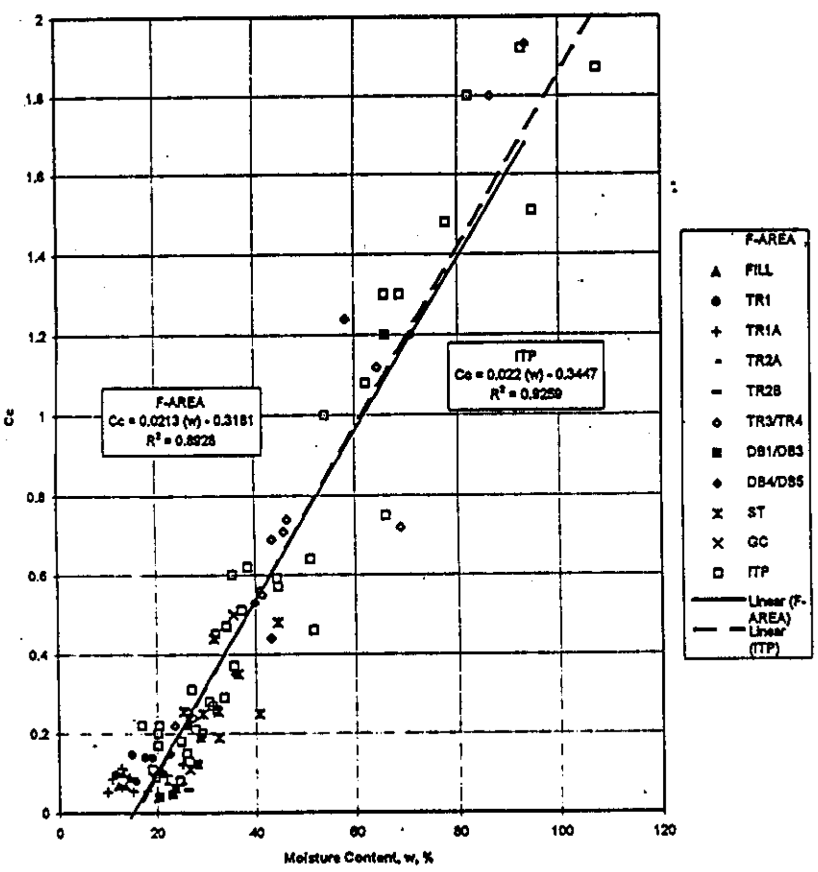


$$FS = (\tau/\sigma')_{seismic\ analysis} / (\tau/\sigma')_{from\ above\ (A)}$$

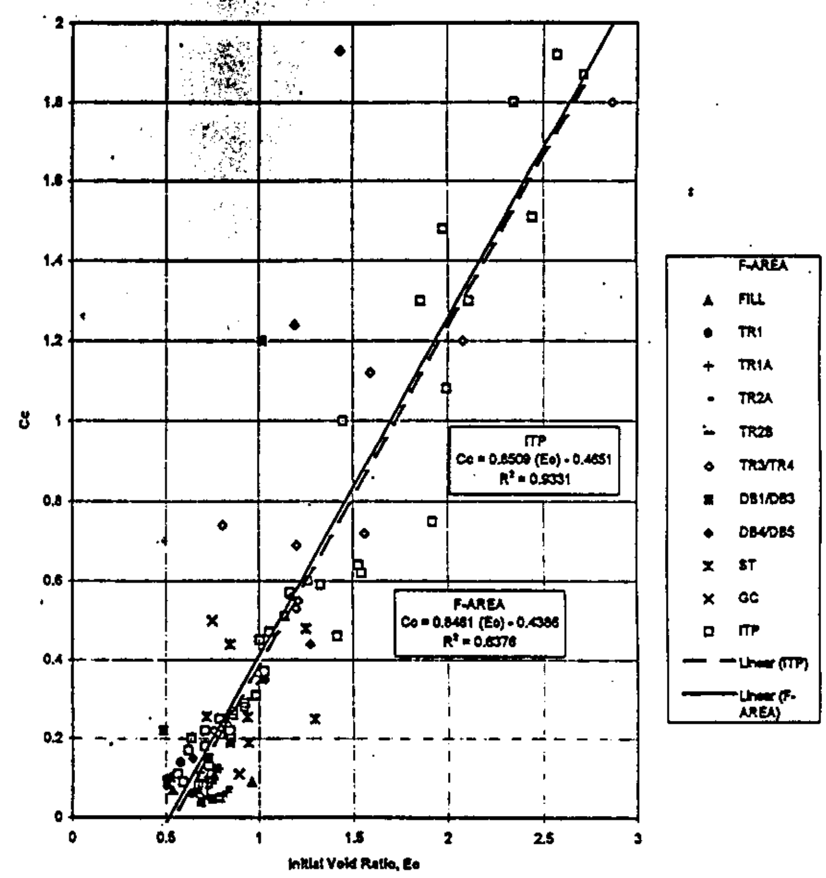
B Volumetric strain expressed as a function of factor of safety against initial liquefaction.

(WSRC, 1995)

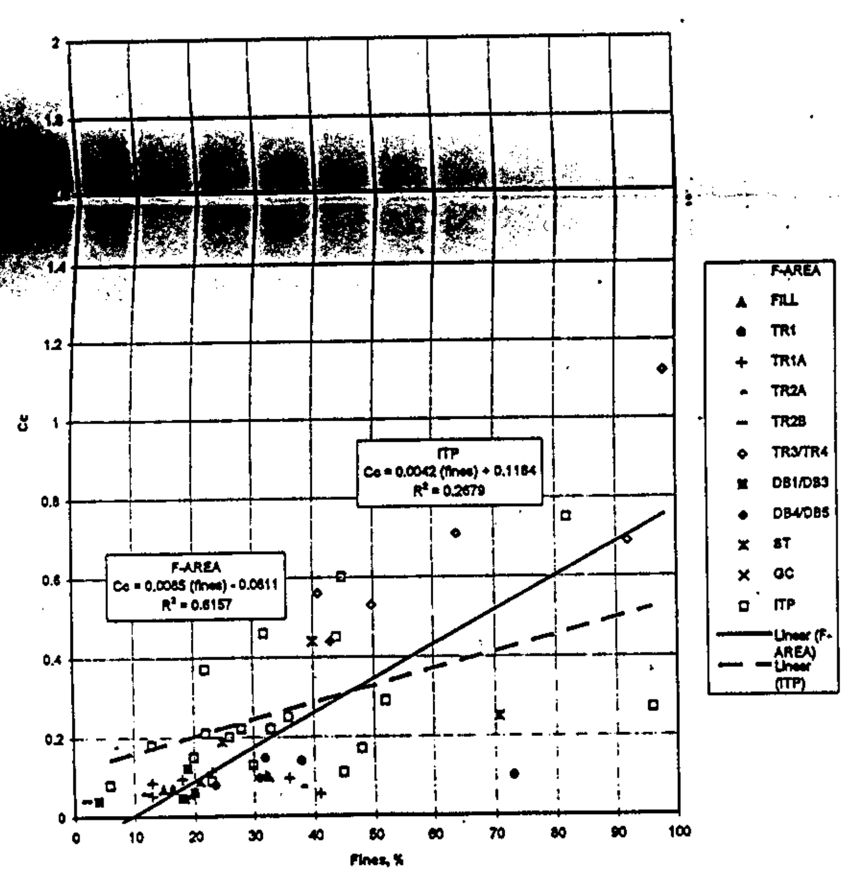
Plate 15 Relationships for determining liquefaction potential and resulting dynamic settlement.



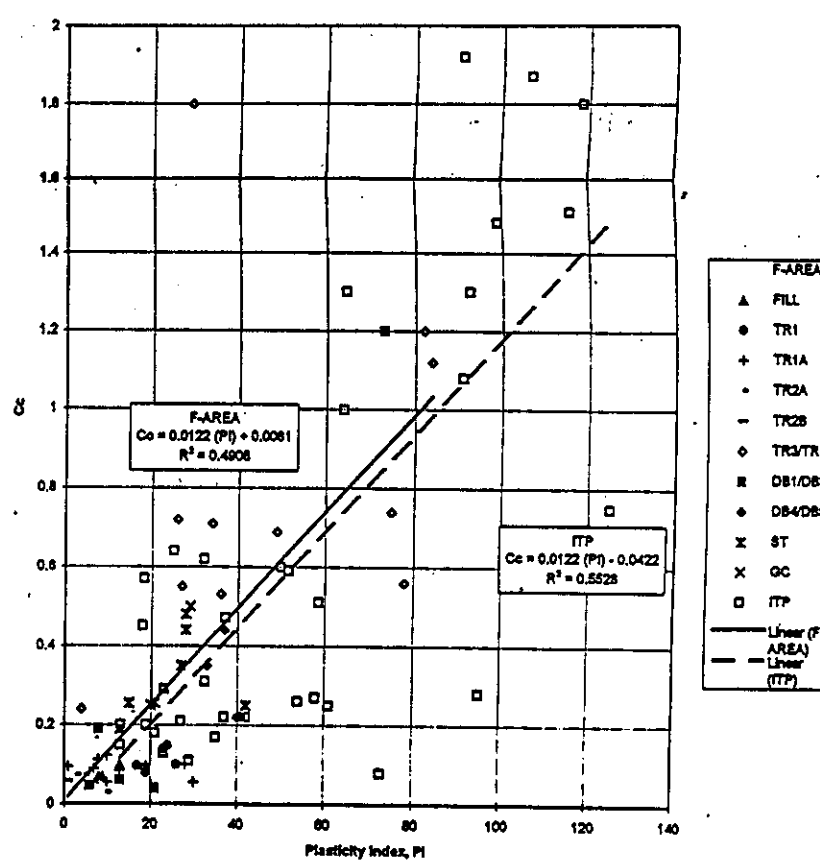
A Compression Index versus Moisture Content for F-Area and ITP



B Compression Index versus Initial Void Ratio for F-Area and ITP



C Compression Index versus Percent Fines for F-Area and ITP



D Compression Index versus Plasticity Index for F-Area and ITP

Laboratory Data on sample obtained using the CPT

MC, %	Fines, %	PI, %	Cc in Lab	Eo in Lab	CR Lab
25	51.7	24	0.26	0.59	0.16

$CR = C_c/(1+E_o)$

Compression Ratio from Index Properties and F-Area Correlations

MC,%	Fines,%	PI,%	Cc Calc.	Fig.	Eo Calc. (Fig. B)	CR Calc.
25			0.21	A	0.77	0.12
	51.7		0.36	C	0.94	0.18
		24	0.30	D	0.87	0.16

$CR = C_c/(1+E_o)$

Plate 15 Site specific relationships for estimating consolidation parameters.

Plate 17 - Statistical Summary for CPT Data

Unit	Property	F-Area			H-Area			F- & H-Areas Combined		
		Mean	STD	N	Mean	STD	N	Mean	STD	N
Upland	Sleeve Resistance, tsf	2.77	1.58	10,949	2.26	1.32	15,318	2.47	1.46	26,267
	Friction Ratio, %	3.3	2.1	10,949	3.7	2.4	15,318	3.5	2.3	26,267
	Tip Resistance, tsf	105	59	10,949	88	65	15,318	95	63	26,267
Tobacco Road	Sleeve Resistance, tsf	1.87	0.98	17,736	1.16	0.8	4,388	1.73	0.98	22,124
	Friction Ratio, %	1.3	1.1	17,736	0.8	0.7	4,388	1.2	1.0	22,124
	Tip Resistance, tsf	171	71	17,736	169	61	4,388	171	69	22,124
Dry Branch	Sleeve Resistance, tsf	1.29	0.94	14,005	1.02	0.58	20,404	1.13	0.76	34,409
	Friction Ratio, %	1.4	1.2	14,005	1.3	1.4	20,404	1.3	1.3	34,409
	Tip Resistance, tsf	139	99	14,005	153	102	20,404	147	101	34,409
Santee	Sleeve Resistance, tsf	1.64	2.01	9,901	1.17	1.03	21,850	1.32	1.43	31,751
	Friction Ratio, %	1.8	1.7	9,901	1.6	1.2	21,850	1.7	1.4	31,751
	Tip Resistance, tsf	109	100	9,901	102	95	21,850	104	96	31,751

Legend of Terms and Symbols

Sleeve Resistance, tsf	Resistance of soil along cone sleeve
Friction Ratio, %	(Sleeve Resist./Tip Resist.(x100)
Tip Resistance, tsf	Resistance of soil on cone face
Mean	Average value of the population
STD	Standard deviation of the population
N	Number of samples

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