

Evaluation of Cone Penetration Testing (CPT) for Use with Transportation Projects

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16. Abstract Cone Penetration Testing (CPT) has many advantages as a means for subsurface investigation. CPT consists of pushing a steel cone into the ground and recording the penetration resistance using sensors. Pore pressure, shear wave velocity and other measurements can also be taken using CPT. Several states have incorporated CPT into their subsurface investigation programs and the Ohio Department of Transportation (ODOT) has funded this project as a first step toward routine use of CPT in Ohio. CPT soundings were completed at 20 sites throughout Ohio and the data were correlated with corresponding data obtained from standard penetration and laboratory testing. Clear correlation trends for the 17 different ODOT soil types were not obtained and a larger database is needed to improve the correlations. Guidelines for CPT machine operation and data analysis are presented. Existing correlations for engineering parameters are also discussed. CPT is expected to become a useful tool for ODOT subsurface exploration work and provide considerable cost savings over the long term.					
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SYMBOLS

α	= area ratio of the cone (A_n/A_c)
A	= area; pore pressure parameter
A_c	= projected area of the cone
A_n	= cross-sectional area of load cell or shaft
A_s	= area of friction sleeve
B_q	= pore pressure parameter [= $(u_2 - u_o)/(q_t - \sigma_{vo})$]
c'	= cohesion (effective stress)
c	= coefficient of consolidation
c_h	= horizontal coefficient of consolidation
c_v	= vertical coefficient of consolidation
C_c	= compression index
D_{10}	= particle size at 10% finer (by weight), similar expressions for D_{50} , D_{60} , and D_{90}
e	= void ratio
e_o	= initial void ratio
E_s	= Young's Modulus
f	= unit skin friction resistance
f_s	= unit sleeve friction resistance
f_t	= sleeve friction corrected for pore pressure effects
F_s	= total force acting on friction sleeve
F_r	= normalized friction ratio [= $f_s/(q_t - \sigma_{vo})$]
g	= acceleration due to gravity [= $9.81 \text{ m/s}^2 = 32.2 \text{ ft/s}^2$]
I_c	= soil behavior type index
k	= coefficient of permeability
k_h, k_v	= coefficient of permeability in horizontal, vertical directions
L	= length
LL	= liquid limit
N	= number of blows in SPT (last 12 in.)
N_k	= cone factor
N_{ke}	= cone factor
N_{kt}	= cone factor
$N_{\Delta u}$	= cone factor
N_{60}	= N corrected for 60% energy
p_a	= reference stress [= $100 \text{ kPa} = 0.1 \text{ MPa} = 1.06 \text{ tsf}$]
q_c	= measured cone resistance
\bar{q}_c	= average cone resistance
q_{c1}	= normalized cone resistance
q_n	= net cone resistance = $(q_t - \sigma_{vo})$
q_t	= corrected cone resistance = $q_c + (1 - \alpha)u_2$
Q_c	= total force acting on cone
Q_t	= normalized cone resistance = $(q_t - \sigma_{vo})/\sigma'_{vo}$
Q_{tn}	= normalized cone resistance = $\frac{q_t - \sigma_{vo}}{p_a} \left(\frac{p_a}{\sigma'_{vo}}\right)^n$
R_f	= friction ratio = $f_s/q_t * 100\%$
s_u	= undrained shear strength
S_t	= sensitivity
t	= time
t_{50}	= time for 50% dissipation of excess pore pressure

T	= time factor
T_{50}	= time factor at $U = 50\%$
u	= pore pressure
u_o	= <i>in situ</i> pore pressure
u_2	= pore pressure measured behind cone
u_i	= pore pressure measured at time $t = 0$
u_n	= pore pressure at time t
Δu	= excess pore pressure
U	= average degree of consolidation
V_s	= shear wave velocity
w	= water content
z	= depth

GREEK

γ	= unit weight
γ'	= buoyant unit weight
γ_d	= dry unit weight
γ_w	= unit weight of water
Δ	= change
μ	= Poisson's ratio
v	= penetration rate
ρ	= density
σ_v, σ'_v	= vertical stress (total, effective)
$\sigma_{vo}, \sigma'_{vo}$	= overburden stress (total, effective)
ϕ, ϕ'	= friction angle (total, effective)

ABBREVIATIONS

ASCE	= American Society of Civil Engineers
ASTM	= American Society for Testing and Materials
CPT	= Cone Penetration Test
CPTU	= Cone Penetration Test with Pore Pressure Measurement (Piezocone Test)
FC	= Fines Content
GSD	= Grain Size Distribution
GWL	= Ground Water Level
IRTP	= International Reference Test Procedure
LL	= Liquid Limit
NC	= Normally Consolidated
OC	= Overconsolidated
OCR	= Overconsolidation Ratio
ODOT	= Ohio Department of Transportation
OGE	= ODOT Office of Geotechnical Engineering
PI	= Plasticity Index
PL	= Plastic Limit
SCPTU	= Seismic CPTU
SBT	= Soil behavior type
SPT	= Standard Penetration Test

UNIT CONVERSIONS

Stress/ Pressure

1 kPa	20.885 psf
	0.14503 psi
	0.0104427 tsf
	1000 MPa

1 MPa	20855 psf
	145 psi
	10.443 tsf
	0.001 kPa

1 psi	6.8948 kPa
	0.0068948 MPa
	144 psf
	0.072 tsf

1 psf	0.04788 kPa
	4.788×10^{-5} MPa
	0.00694 psi
	5×10^{-4} tsf

1 tsf	95.76 kPa
	0.09576 MPa
	13.889 psi
	2000 psf

Force

1 kN	224.81 lb f
	0.1124 t f
	0.22481 kip

1 lb f	0.004448 kN
	0.0005 t f
	.001 kip

1 t f	8.896 kN
	2000 lb f
	2 kip

1 kip	4.448 kN
	1000 lb f
	0.5 t f

Length

1 m	3.28084 ft
	39.37 in

1 ft	0.3048 m
	12 in

1 in	0.0254 m
	0.083 ft

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CHAPTER 1. INTRODUCTION AND BACKGROUND TO RESEARCH

1.1 GENERAL

In an effort to increase the capabilities and efficiencies of their subsurface exploration program, the Ohio Department of Transportation (ODOT) purchased a cone penetration test (CPT) machine. The purpose of this report is to provide ODOT district geotechnical engineers (DGEs) and the engineers and geologists in the Office of Geotechnical Engineering (OGE) with information required to successfully use CPT for subsurface exploration. Routine use of CPT will give ODOT a valuable new investigation tool and is also attractive due to the potential savings of time and money relative to current investigation methods.

The first year of ODOT CPT operations was conducted for research purposes. This report will describe the research program and the results obtained, and how ODOT can continue to use CPT for subsurface investigations associated with future highway projects in Ohio.

1.2 OVERVIEW

This report will present information collected with regard to use of CPT by ODOT. The report is divided into the following chapters: 1) introduction to concepts and history of CPT, 2) literature review, 3) methods for successful completion of a CPT project, including procedures followed for the research program, 4) presentation of research data with discussion of available correlations and interpretations, 5) suggestions for use of CPT for subsurface exploration, and 6) conclusions and recommendations.

1.3 INTRODUCTION TO CPT TECHNOLOGY

A cone penetration test is conducted by continuously pushing an instrumented cone into the ground at a constant rate of displacement. The following primary measurements are made during this procedure: tip resistance, sleeve friction resistance, cone inclination, and pore pressure. Depending on the specific cone, other measurements are also possible such as temperature, shear wave velocity and groundwater quality. According to Lunne et al. (1997), CPT has three main applications for site investigation:

- To determine subsurface stratigraphy and identify materials present
- To estimate the geotechnical parameters
- To provide results that can be used directly for geotechnical design

The cone is attached to a string of rods that are continuously added as the cone is pushed into the ground. Figure 1.1 shows the main components of a cone penetration test: the electric penetrometer, a hydraulic push system with rods, a data transmission cable inside the rods, a depth recorder, and a data acquisition unit.

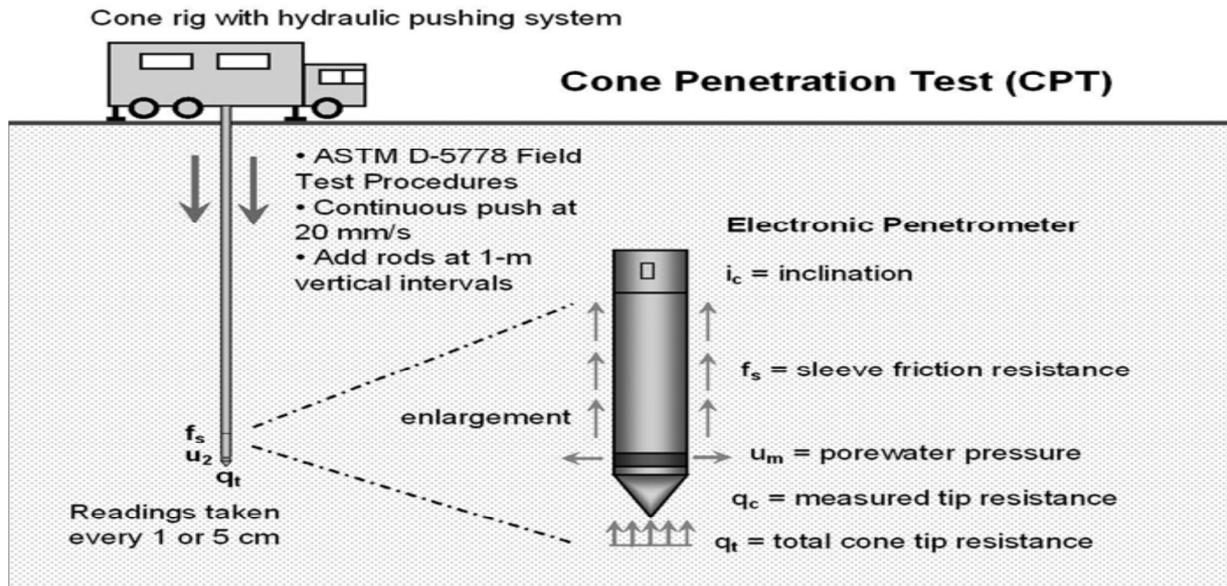


Figure 1.1. Overview of the CPT test (Mayne, 2007).

Cone penetration testing is often used as a replacement for conventional rotary drilling and standard penetration testing (SPT). In other cases, CPT is used to supplement conventional site investigation methods. CPT has the following advantages over conventional drilling (Mayne 2007):

- Continuous or near continuous data with depth
- Repeatable and reliable penetration data
- Cost savings (due to time savings)
- Less disruption to environment
- Multiple and simultaneous measurements with depth
- Soil properties obtained in natural state

The disadvantages of the CPT include:

- Soil samples are not typically obtained
- Less research is available with regard to CPT data as compared to SPT data
- Difficulty to push cone through hard materials
- High cost of equipment

In many cases, CPT is used alongside rotary drilling to overcome these disadvantages. According to A.P van den Berg (2008), a 30 ft. CPT sounding costs approximately \$6-9/ft. and takes about 15-20 min to complete, whereas a 30 ft. SPT hole costs approximately \$12-24/ft. and takes about 60-90 min to drill.

Cone penetration testing systems are classified into three main groups: mechanical cone penetrometers, electric cone penetrometers, and piezocone penetrometers. Mechanical CPT was the first type of cone penetration system and is shown in Figure 1.2. A mechanical cone is pushed using an inner and outer rod, with the cone tip attached to the inner rod. These rods are pushed either continuously or discontinuously into the ground. The force needed to push the entire mechanical cone

is measured using a manometer at the ground surface, which gives the total resistance. The inner rod with the cone tip is then pushed independently to measure the tip resistance. The difference between these measurements is the sleeve friction resistance. According to Lunne et al. (1997), the mechanical penetrometer is still used due to its robustness, simplicity and low cost. This method is suitable for homogeneous soils without sharp variations in cone resistance, but is unsuitable for highly stratified or soft soils. Mechanical CPT was originally invented by the Dutch, which is why these types of cones are often referred to as Dutch cones.

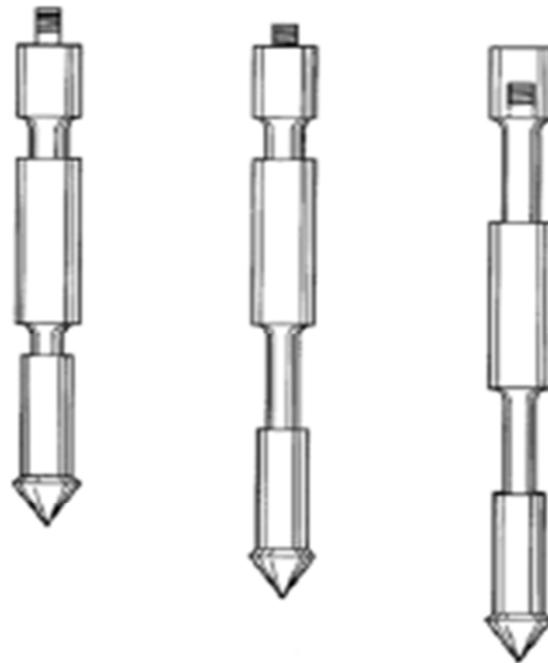


Figure 1.2. Mechanical CPT or Dutch cone (Mayne 2007).

The electric cone penetrometer represents a significant improvement over the mechanical system. The electric cone penetrometer is pushed into the ground hydraulically at a constant rate (2 cm/sec) using a single set of rods. The cone collects data at 2 cm intervals for cone tip resistance, q_t , and sleeve friction resistance, f_s . An inclinometer is also used to measure deviation from vertical during a sounding. The piezocone penetrometer is a further improvement on the electrical penetrometer because it can also measure pore water pressure, u_m . Figure 1.1 shows an example of an electric piezocone penetrometer and Figure 1.3 shows the basic internal schematic diagram. In this system, strain gauges measure the required forces and a pressure transducer measures the pore pressure. The cone in Figure 1.3 also contains a geophone for shear wave velocity testing. The data is sent to a data acquisition unit in the CPT machine via an electric cable passing through the inside of the rods. An electric piezocone penetrometer test is sometimes referred to as a CPTU.

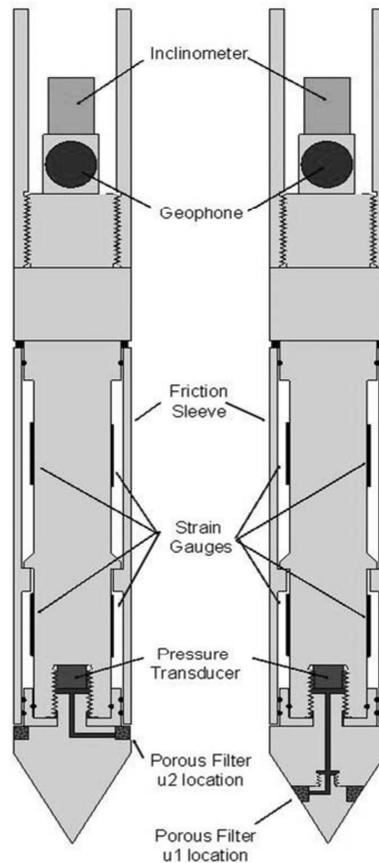


Figure 1.3. Internal schematic of an electric cone penetrometer (Mayne 2007).

The two cones in Figure 1.3 are the same except for the location of the pore pressure measurement (i.e., porous filter). The cone on the right-hand side has the filter at the u1 location; midway along the cone tip. The cone on the left-hand side has the filter at the u2 location; in between cone tip and the friction sleeve, or the shoulder. The u2 location is generally preferred; however, there is no standard for the correct location for pore pressure measurement (Lunne et al. 1997). Other possible sensors for a cone include (Robertson and Cabal 2010):

- Geophone
- Temperature
- Pressuremeter
- Camera (visible light)
- Radioisotope (gamma/neutron)
- Electrical resistivity/conductivity
- Dielectric
- pH
- Oxygen exchange (redox)
- Laser/ultraviolet fluorescence (LIF)
- Membrane interface probe (MIP)

Common dimensions for cone penetrometers are shown in Figure 1.4. Typical cones have a 60° apex angle at the tip. The two common cone section areas are 10 cm² and 15 cm², with the 15 cm² cone now gaining popularity because more internal sensors can be accommodated (Mayne 2007) and it can be pushed through harder soils. Measured cone tip resistance, q_c , and sleeve friction resistance, f_s , are calculated as:

$$q_c = \frac{Q_c}{A_c} \quad (1.1)$$

$$f_s = \frac{F_s}{A_s} \quad (1.2)$$

where Q_c is the measured force acting on the cone; A_c is the projected area of the cone; F_s is the measured force acting on the friction sleeve; and A_s is the sleeve surface area. Although cone tip resistance, q_c , is measured during testing, a corrected cone tip resistance, q_t , is used for data analysis. The equation for this corrected value is:

$$q_t = q_c + u_2(1 - a) \quad (1.3)$$

where a is the cone area ratio, which is the cross sectional area of the load cell or shaft divided by the projected area of the cone tip. Equation 1.3 is an important correction for tip resistance and also highlights the general preference for the u_2 pore pressure measurement. This correction was developed when CPT was used for deep water investigations because the cone tip resistance did not equal the surrounding pore water pressure (Lunne et. al 2007).

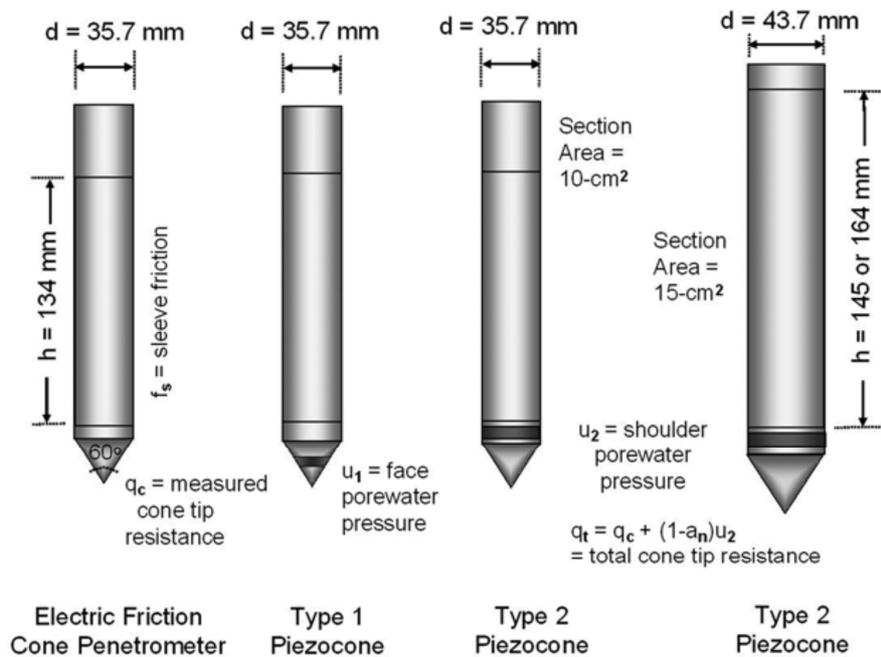


Figure 1.4. Dimensions of standard 10 and 15 cm² cone penetrometers (Mayne 2007).

Many different types of systems are used to push CPT cones into the ground. Figure 1.5 illustrates several land-based pushing machines. Cone penetration testing is not limited to land use and pushing systems are also available for over-water use, such as rigs mounted on marsh buggies, barges,



a.



b.



c.



d.

Figure 1.5. Examples of land-based CPT machines: a) Track mounted (A.P van den Berg), b) Truck mounted (ConeTec Investigations), c) Rotary drill mounted (Gregg Drilling), and d) Portable ramset for CPT (Gregg Drilling) (Robertson and Cabal 2010).

or open-water platforms. In most cases, the weight of the CPT machine itself is used to provide the reaction needed to push the cone into the ground. If the machine weight is insufficient, additional reaction can be obtained using temporary weights added to the machine or from ground anchors. A 20 ton reaction force can typically allow for a penetration depth of 30 m (Lunne et al. 1997). One instance in which a rotary drill can be used in conjunction with CPT is where greater penetration depths are needed. In such cases, a rotary drill can auger down to a specified depth, and then the CPT is pushed in the same hole to greater depths. The same procedure can be conducted if a hard stratum is encountered during a sounding. In this instance the CPT is advanced until refusal, and then retracted. A rotary drill then augers through the hard layer and the CPT sounding resumes until the desired depth is reached.

1.4 PURPOSE OF THIS REPORT

The ODOT OGE primarily uses conventional drilling and laboratory testing to perform subsurface investigations. These methods have been successful, although there are certain disadvantages. The cost and time required to perform these operations are high, conventional drilling does not produce continuous data, and there are certain geologic and environmental restrictions. ODOT recognized these limitations and thus has begun to use CPT to supplement their conventional subsurface investigation and testing program. The purpose of this report is to provide an overview of CPT procedures as well as correlations between CPT and conventional drilling data to allow the OGE to gain confidence with CPT technology. Although extensive work has been previously conducted to determine correlations for CPT data, no correlations are available for Ohio soils and the modified AASHTO soil classification system. This report will attempt to provide ODOT engineers and geologists with information needed to use CPT in an efficient manner for future transportation projects.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

Cone penetration testing has been developed and used for decades. The bulk of early CPT work was completed in Europe and CPT was used for pile design as early as 1932 (Lunne et al. 1997). Today, some state DOTs are using CPT to enhance their subsurface exploration programs. One of the drawbacks of CPT as compared to SPT is the lack of reliable correlations with soil properties. With the increased use of CPT in the U.S., this is becoming less of an issue due to the extensive research that has been conducted to correlate and interpret CPT data.

Chapter 2 summarizes several publications that deal with current CPT correlations and interpretations and discusses research that has been completed to further enhance CPT programs. This chapter outlines possible applications for CPT ranging from pile design to ground modification and also discusses possible sources of error for CPT measurements. The chapter is organized according to publication source. The first two sources, Lunne et al. (1997) and Mayne (2007), are especially comprehensive and should be consulted along with this report. Most of the literature outlined in this chapter can be found on file with the OGE.

2.2 COMPLETE CPT GUIDES

2.2.1 CONE PENETRATION TESTING, NCHRP SYNTHESIS 368, MAYNE 2007.

The National Cooperative Highway Research Program (NCHRP) published this manual in 2007. The manual covers many of the same topics as Lunne et al. (1997) with updates on correlations that have been developed. This manual can be downloaded online for free and is available in the OGE.

2.2.1.1 HOLE CLOSURE

At the majority of sounding locations for the current research project, no closure methods were used and the sounding hole closed on itself. If permanent closure is needed, sounding holes are backfilled with grout as illustrated in Figure 2.1. The three images on the left show closure methods for use after the cone has been retracted and the two on the right display methods that use a sacrificial tip. The sacrificial tip is left in the hole and grout is pumped through the rods as they are retracted from the ground.

2.2.1.2 SOIL PARAMETER EVALUATIONS

2.2.1.2.1 UNIT WEIGHT

Unit weight is an important soil parameter. Figures 2.2 and 2.3 show correlations and equations for soil unit weight. Figure 2.2 gives saturated unit weight versus shear wave velocity for CPT in clay. Unit weight increases consistently with increasing shear wave velocity and is shown as a function of depth from 1 to 100 m. Figure 2.3 shows a correlation for dry unit weight of sand as a function of normalized tip stress. The tests for Figure 2.3 were run in a calibration chamber where the conditions were closely controlled. The equation in Figure 2.3 requires the effective overburden stress, and thus the unit weight. To use this equation, an initial estimate of unit weight is needed and successive iterations should be conducted until the change in the normalized tip stress, q_{T1} , is small. Figure 2.4 shows unit weight versus sleeve friction and specific gravity for a variety of soil types. This correlation is useful if the soil specific gravity can be reliably estimated.

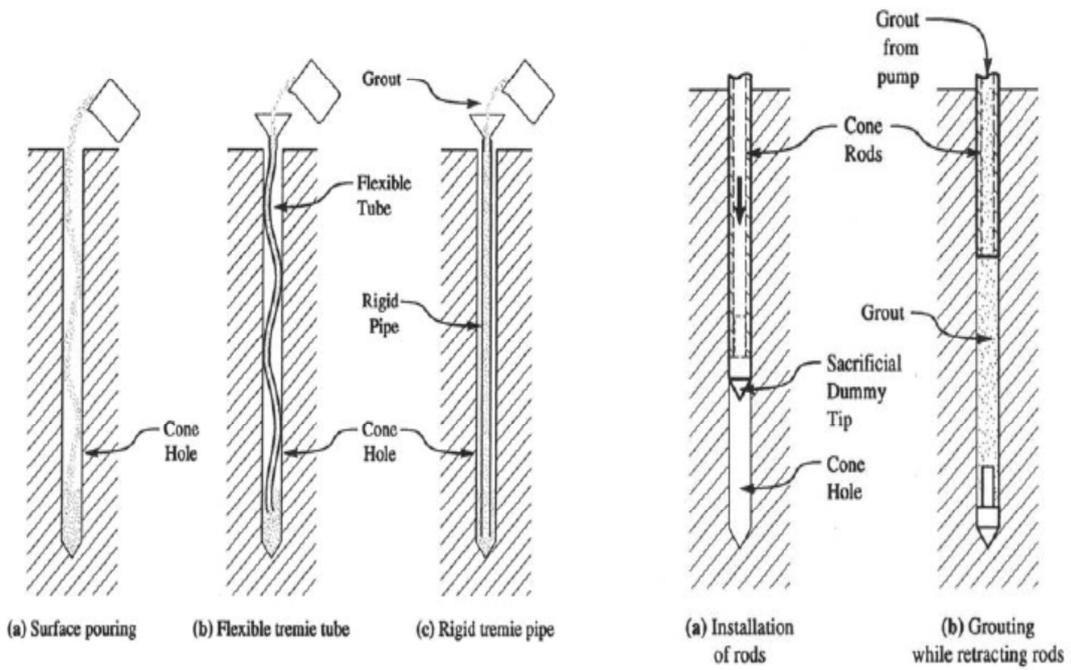


Figure 2.1. Hole closure methods (Mayne 2007).

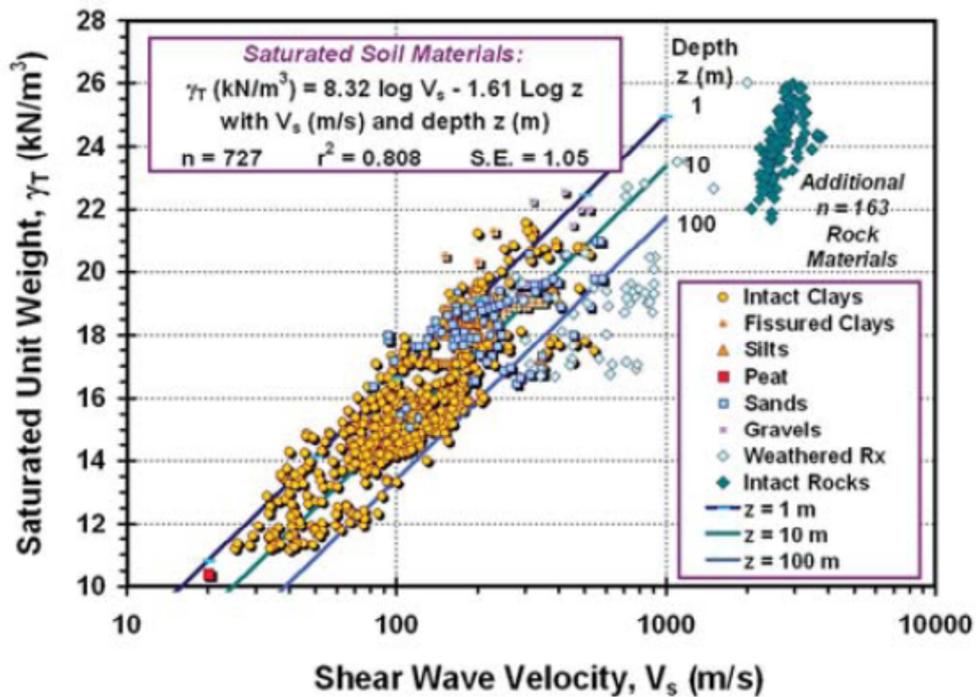


Figure 2.2. Saturated unit weight determination from shear wave velocity for clays (Mayne 2007).

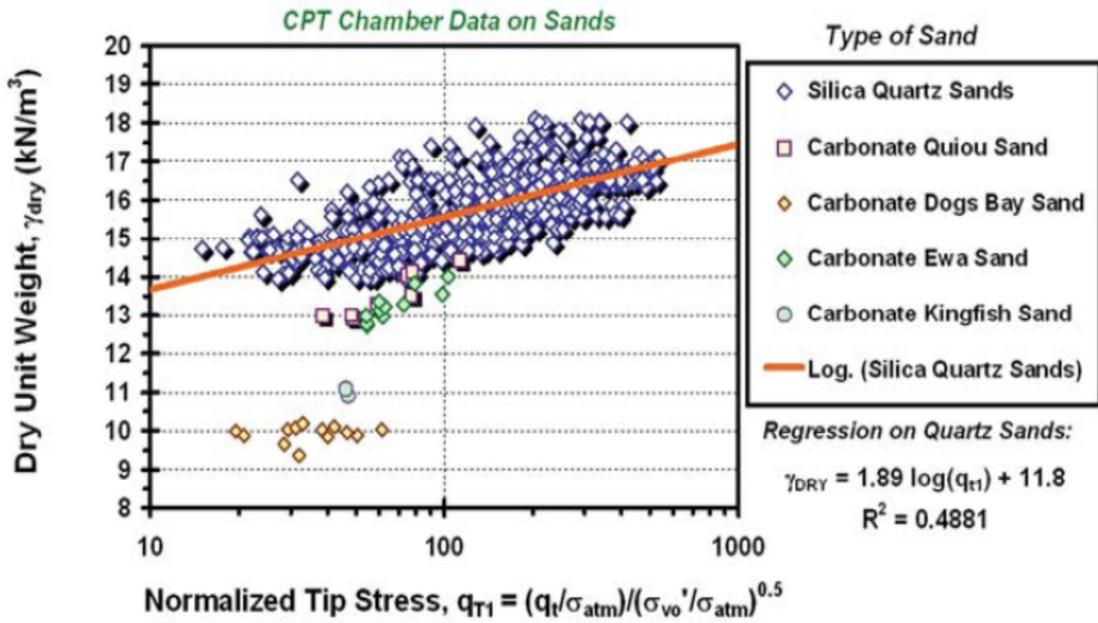


Figure 2.3. Dry unit weight determination from normalized tip stress (Mayne 2007).

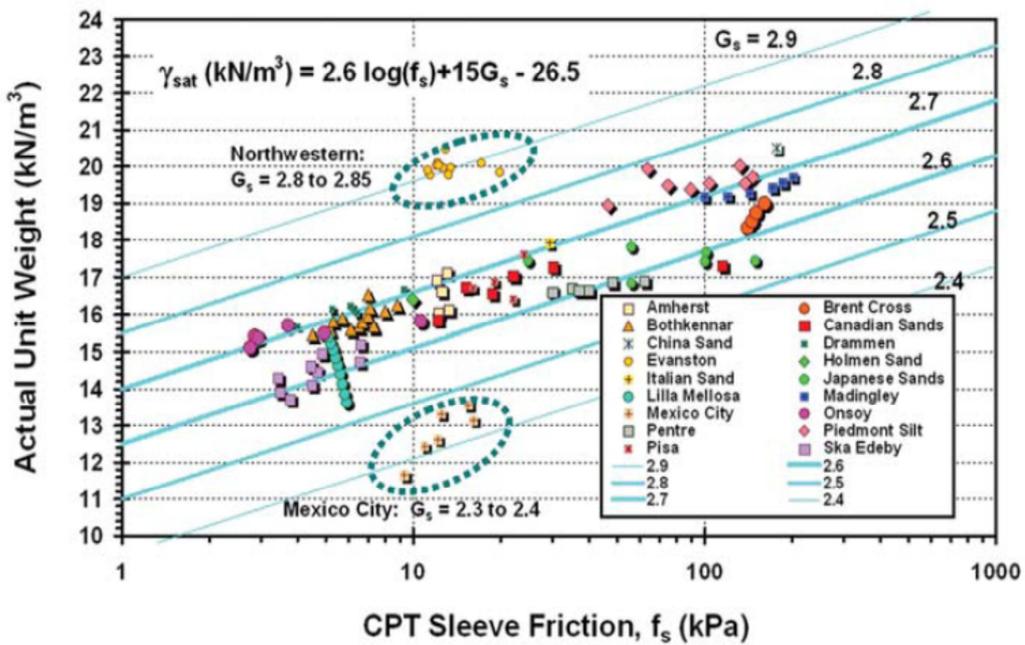


Figure 2.4. Unit weight estimation from sleeve friction and specific gravity of solids (Mayne 2007).

In the above figures, γ_T is saturated unit weight, V_s is the shear wave velocity, z is depth below ground surface, γ_{DRY} is the dry unit weight, σ'_{vo} is effective overburden stress, σ_{atm} is atmospheric pressure (1 atm = 101.3 kPa = 14.7 psi), and G_s is specific gravity.

2.2.1.3 DIRECT APPLICATION OF CPT RESULTS

2.2.1.3.1 CONE PENETRATION TESTING FOR SHALLOW FOUNDATIONS AND EMBANKMENTS

According to a study from Mayne (2007), the two main applications for CPT by U.S. DOTs are investigations for embankment stability and bridge foundations. In both cases, CPT is first employed to define subsurface stratigraphy and groundwater conditions. The data is then processed to provide numerical results. Mayne's NCHRP manual explains how to calculate bearing capacity and settlements for spread footings, as well as settlements and time rate of consolidation for embankments. This section will discuss the calculation of bearing capacity (BC) for shallow foundations using CPT data directly.

For shallow footings on sand, Schmertmann (1978) presents a relationship between ultimate bearing capacity, q_{ult} , and corrected cone tip resistance, q_t , (shown in Figure 2.5) for the following conditions of foundation embedment depth (z_e) and width (B):

- When $B > 0.9$ m (3 ft), embedment $z_e \geq 1.2$ m (4ft)
- When $B \leq 0.9$ m (3 ft), embedment $z_e \geq 0.45$ m (1.5 ft) + $\frac{1}{2} B$

For measured cone tip resistance $20 \leq q_t \leq 160$ tsf, the ultimate bearing capacity stress can be estimated as:

$$\text{Square footings: } q_{ult} = 0.55 \sigma_{atm} \left(\frac{q_t}{\sigma_{atm}} \right)^{0.785} \quad (2.1)$$

$$\text{Strip footings: } q_{ult} = 0.36 \sigma_{atm} \left(\frac{q_t}{\sigma_{atm}} \right)^{0.785} \quad (2.2)$$

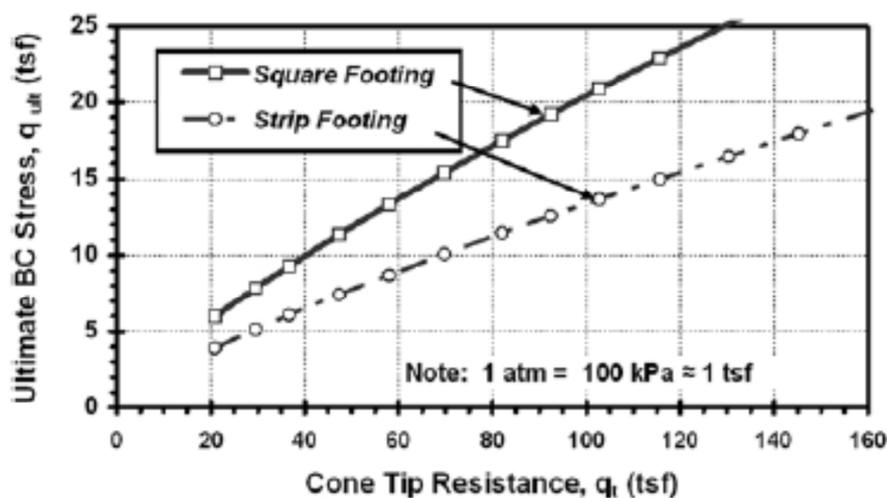


Figure 2.5. Relationship between ultimate bearing stress and cone tip resistance in sands (Mayne 2007).

For shallow footings on clays, Tand et al. (1986) defined parameter R_k as follows:

$$R_k = \frac{q_{ult} - \sigma_{vo}}{q_t - \sigma_{vo}} \quad (2.3)$$

where σ_{vo} is the overburden stress. R_k depends on the embedment ratio (H_e/B), where H_e = depth of embedment. Figure 2.6 presents the plot for determination of R_k .

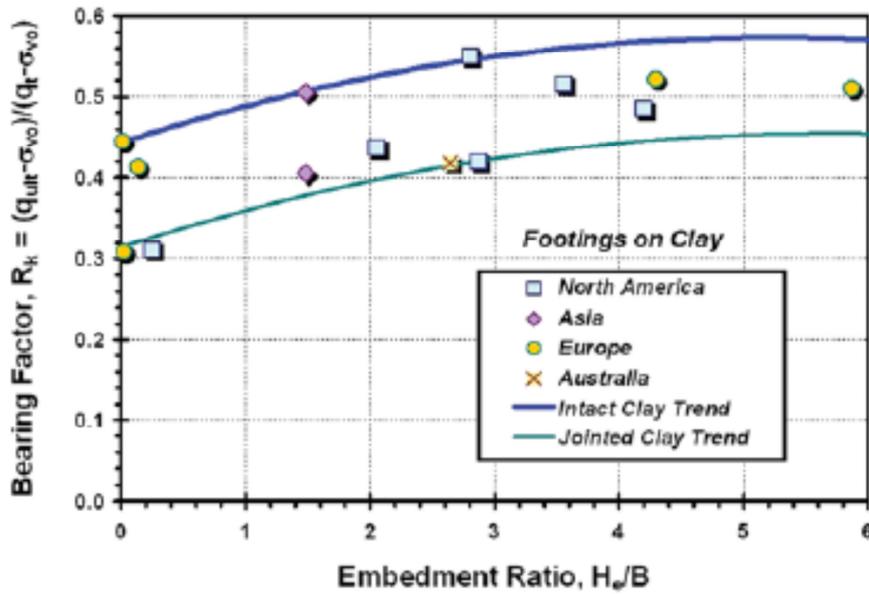


Figure 2.6. CPT method for determination of ultimate bearing stress on clay (Mayne 2007).

2.2.1.3.2 APPLICATIONS TO PILES AND DEEP FOUNDATIONS

The Mayne (2007) manual includes several methods for direct use of CPT data to determine pile capacity. The method that will be discussed herein is the Laboratoire Central des Ponts et Chaussées (LCPC) method for driven and drilled piles. This method relies mostly on q_c for the determination of both unit skin friction, f_b , and unit tip resistance, q_b . The ultimate bearing capacity for piles is calculated as:

$$q_{ult} = q_b + f_b \quad (2.4)$$

where:

$$q_b = k_c * q_c \quad (2.5)$$

and k_c is a reduction factor obtained from the pile type and ground conditions (average = 0.35 ± 0.2). Table 2.1 provides k_c factors for the LCPC method. Figures 2.7 and 2.8 present summary graphical approaches for calculation of unit side resistance for clays and sands.

Table 2.1. k_c factors for unit tip resistance in LCPC method. (Mayne 2007)

Soil Type	Nondisplacement Pile	Displacement Type Pile
Clay and/or Silt	0.40	0.55
Sand and/or Gravel	0.15	0.50

Simplified approach by Frank and Magnan (1995); Bustamante and Frank (1997).

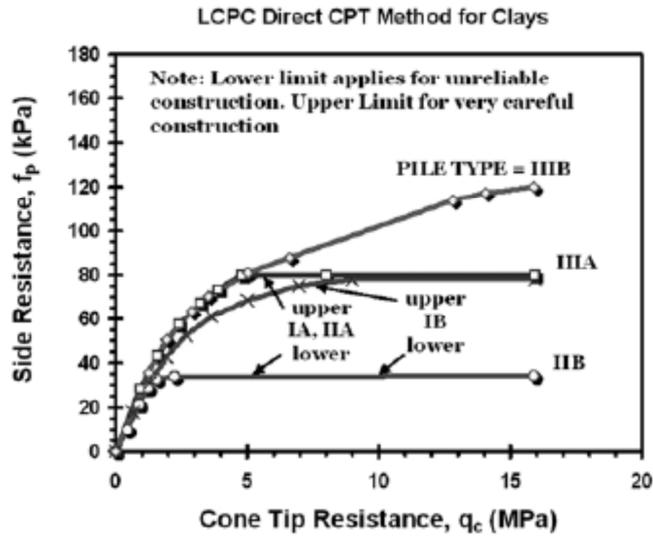


Figure 2.7. LCPC method for evaluation of pile side resistance in clays (Mayne 2007).

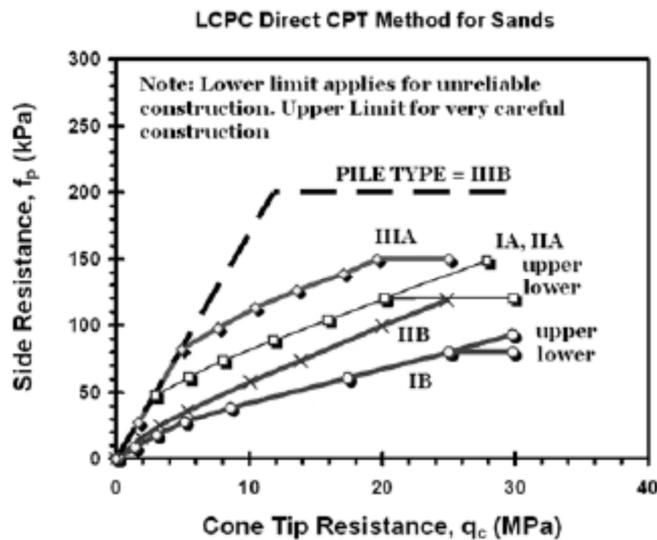


Figure 2.8. LCPC method for evaluation of pile side resistance in sands (Mayne 2007).

2.2.2 CONE PENETRATION TESTING IN GEOTECHNICAL PRACTICE, LUNNE ET AL. 1997

Lunne et al. (1997) is one of the most complete references on CPT and includes the following topics:

- Introduction to CPT technology
- Equipment and procedures
- Checks, corrections and presentation of data
- Standards and specifications
- Interpretation of CPT/piezcone data
- Direct application of CPT/CPTU results
- Use of additional sensors
- Geoenvironmental applications of CPT
- Examples

This section discusses factors that affect CPT measurements and corrections.

2.2.2.1 FACTORS EFFECTING CPT RESULTS

Pore pressures can affect the tip resistance and sleeve friction in saturated soils. Due to the inner geometry of a cone penetrometer, pore pressure will act underneath the cone tip and at the “shoulders” of the cone near the friction sleeve. These areas A and B , shown in Figure 2.9, are unequal and this causes the measured tip resistance to be in error. To account for this effect, a correction factor α is used in Eq. 1.3 to give the corrected cone tip resistance, q_t . This correction is most important for soft fine grained soils because large pore pressures can be generated during a sounding. The difference between q_c and q_t is generally small for sands.

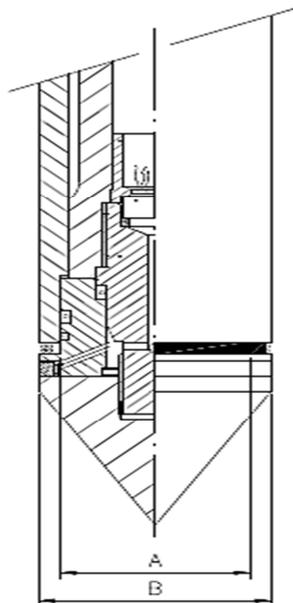


Figure 2.9. Unequal areas of a cone penetrometer (A.P. v.d. Berg Machinefabriek 2009).

Temperature can also have a significant effect on cone measurements due primarily to a possible shift in zero load readings. Most modern load cells have temperature compensation but in soft clays with low tip resistance, temperature may still be a factor. There are two ways temperature effects can be avoided:

- Make sure that the zero readings taken at the beginning and end of the test are at the same temperature as in the ground, and
- Mount a temperature sensor in the cone and correct the measured results based on laboratory calibrations.

Wear of the cone is a large factor that can affect measurements during a sounding. ASTM D5778 outlines tolerances for wear of the cone tip and friction sleeve. If these tolerances are exceeded, measurement errors can be as high as 10% (Lunne et al. 1997). Cone calibration should be completed every three months. It is important that the same cone tip and friction sleeve be used for calibration that will also be used for field soundings.

Soil characteristics also affect CPT measurements. *In situ* stresses, and in particular the horizontal effective stress, have a dominant effect on cone resistance. Therefore, knowledge of the stress history is very important, but may not be known for a given site. Excavations, open boreholes, overconsolidation, or compaction may affect the horizontal stress of the soil and thus change the cone resistance, giving an incorrect measurement. Consideration of stress changes on a site is important for accurate measurements and interpretation of data.

One of the major applications of CPT is for the determination of site stratigraphy. Although CPT has been proven to yield accurate subsurface profiles, certain types of stratigraphy may cause measurement errors. The distance over which the cone senses an interface increases with material stiffness. For soft soils, the zone of influence can be as small as 2-3 cone diameters, but for stiff soils this zone can be as large as 10-20 diameters (e.g., 40-90 cm for a 15 cm² cone). Therefore, cone resistance can respond more locally for soft materials. Hard layers (sands) may need to be at least 750 mm thick for the cone resistance to reach its full value, whereas soft layers (clays) as thin as 100 mm can be fully detected. Thus, care should be taken when interpreting a thin sand layer between two soft clay layers. The friction sleeve averages measurements over 16 cm (6 in) so it will tend to smooth out any effects of thin layers.

The rate of cone penetration is a constant 2 cm/sec as established by ASTM D5778 and deviation from this rate will induce error in the measurements. A tenfold increase in rate causes a 10-20% increase in tip resistance for stiff clays and a 5-10% increase for soft clays (Lunne et al. 1997). Pore pressure measurements will also be affected by changing the penetration rate. The penetration process is generally assumed to be undrained for clays and drained for sands. If the rate is reduced, fine-grained soils will more closely approach a drained condition.

2.2.3 GUIDE TO CONE PENETRATION TESTING, ROBERTSON AND CABAL 2010

Although the manual of Robertson and Cabal (2010) does not provide new correlations, the presentation is more straightforward. The CPeT-IT program, described in Chapter 3, obtains many of its equations from this manual. Figure 2.10 is a risk-based flow chart for various site characterization methods. Table 2.2 lists the applicability and usefulness of *in situ* tests. In this table, the electric SCPTU is used by ODOT. This chart can be a useful tool to develop a site exploration program based on needed parameters or known soil types. The remainder of the Robertson and Cabal (2010) manual reviews equations and applications presented in Lunne et al. (1997) and Mayne (2007).

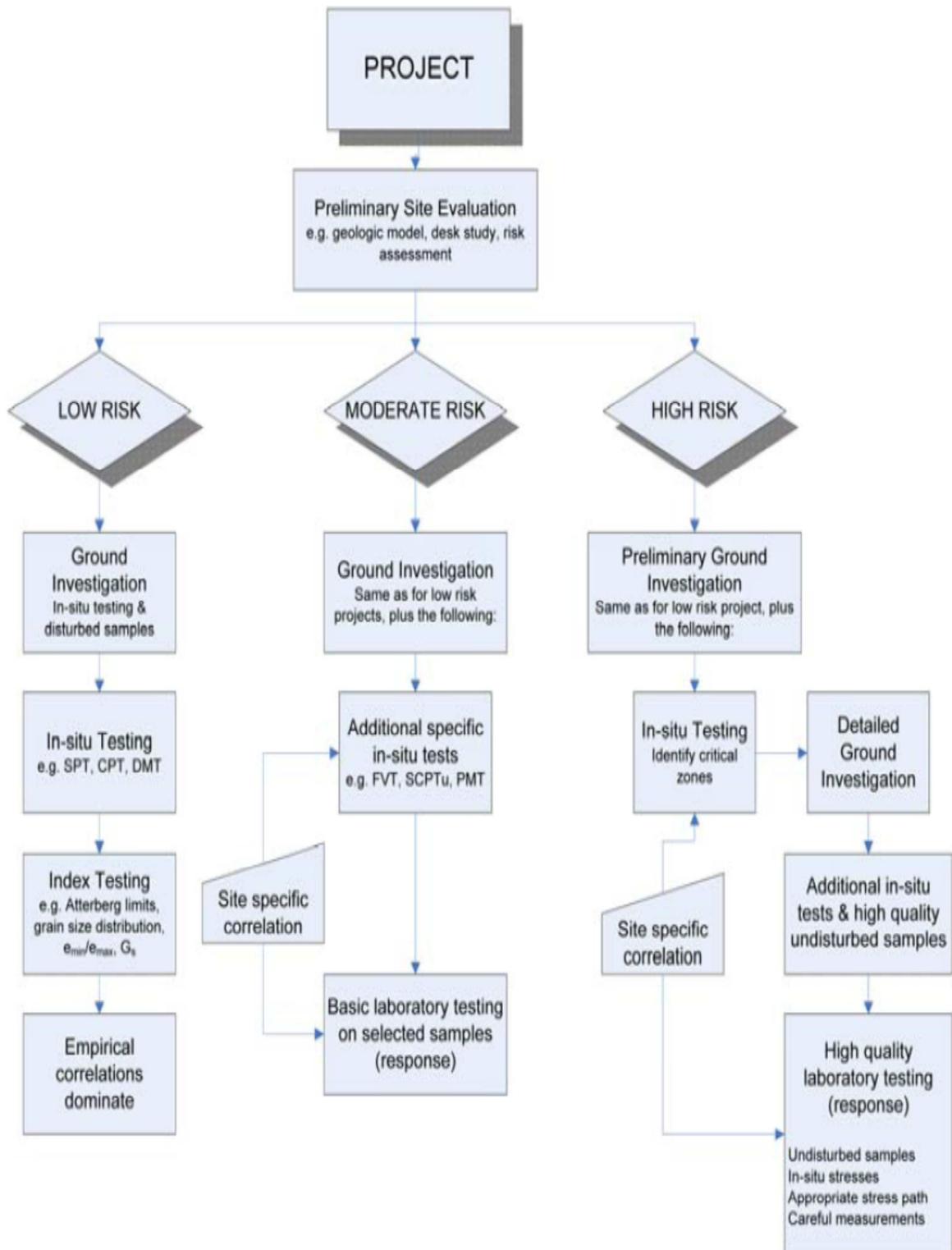


Figure 2.10. Risk-based flowchart for site characterization (Robertson and Cabal 2010).

Table 2.2. Applicability and usefulness of *in situ* tests (Robertson and Cabal 2010).

Group	Device	Soil Parameters											Ground Type									
		Soil type	Profile	u	ϕ^1	s_u	I_p	m_v	c_r	k	G_p	σ_h	OCR	σ_c	Hard rock	Soft rock	Gravel	Sand	Silt	Clay	Peat	
Penetrometers	Dynamic	C	B	•	C	C	•	•	•	C	•	C	•	•	•	C	•	B	A	B	B	B
	Mechanical	B	A/B	•	C	C	B	C	•	C	•	C	•	•	•	C	•	C	A	A	A	A
	Electric (CPT)	B	A	•	C	B	A/B	C	•	B	B/C	B	•	•	•	C	•	C	A	A	A	A
	Piezoelectric (CPTU)	A	A	A	B	B	A/B	B	A/B	B	B/C	B	C	•	•	C	•	•	A	A	A	A
	Seismic (SPT/SCPTU)	A	A	A	B	A/B	A/B	B	A/B	B	A	B	B	•	•	C	•	•	A	A	A	A
	Flat dilatometer (DMT)	B	A	C	B	B	C	B	•	B	B	B	B	C	C	•	•	•	A	A	A	A
	Standard penetration test (SPT)	A	B	•	C	C	B	•	•	C	•	•	•	•	•	C	•	B	A	A	A	A
	Resistivity probe	B	B	•	B	C	A	C	•	•	•	•	•	•	•	C	•	•	A	A	A	A
	Pre-bored (PBP)	B	B	•	C	B	C	B	C	•	B	C	C	C	C	•	•	B	B	B	A	B
	Self boring (SBP)	B	B	A ¹	B	B	B	B	A ¹	B	A ²	A/B	B	A/B ²	•	•	B	•	B	B	A	B
Others	Full displacement (FDP)	B	B	•	C	B	C	C	•	A ²	C	C	C	•	•	C	•	B	B	A	A	
	Vane	B	C	•	A	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
	Plate load	C	•	•	C	B	B	C	C	A	C	B	B	B	•	•	B	B	B	A	A	
	Screw plate	C	C	•	C	B	B	C	C	A	C	B	•	•	•	•	•	•	A	A	A	
	Borehole permeability	C	•	A	•	•	•	B	A	•	•	•	•	•	•	•	•	A	A	A	A	
	Hydraulic fracture	•	•	B	•	•	•	•	C	•	C	•	B	•	•	•	•	•	•	•	•	•
	Crosshole/downhole/surface seismic	C	C	•	•	•	•	•	•	A	•	B	•	•	•	•	•	A	A	A	A	

Applicability: A = high, B = moderate, C = low, • = none
 ϕ^1 = Will depend on soil type; ¹ = Only when pore pressure sensor fitted; ² = Only when displacement sensor fitted.
 Soil parameter definitions: u = *in situ* static pore pressure; ϕ^1 = effective internal friction angle; s_u = un drained shear strength; I_p = density index; m_v = constrained modulus; c_r = coefficient of consolidation; k = coefficient of permeability; G_p = shear modulus at small strains; σ_h = horizontal stress; OCR = overconsolidation ratio; σ_c = stress-strain relationship

2.3 CORRELATIONS AND INTERPRETATIONS

2.3.1 SOIL UNIT WEIGHT ESTIMATION FROM CPT, MAYNE ET AL. 2010

This paper was presented at the Second International Symposium on Cone Penetration Testing (CPT '10) conference and discusses a new method for determination of soil unit weight from CPT. Unit weight is an important property because it is frequently used in CPT correlation parameters. Figure 2.11 shows total unit weight versus the estimated unit weight given by Eq. 2.6. Similar to previous methods, Eq. 2.6 requires the specification of overburden stress and iteration is therefore needed.

$$\gamma_t = 1.81 \gamma_w \left(\frac{\sigma'_{vo}}{\sigma_{atm}} \right)^{0.05} \left(\frac{q_t - \sigma_{vo}}{\sigma_{atm}} \right)^{0.017} \left(\frac{f_s}{\sigma_{atm}} \right)^{0.073} (B_q + 1)^{0.16} \quad (2.6)$$

where γ_w is unit weight of water (= 62.4 pcf = 9.81 kN/m³), and B_q is the normalized excess pore pressure defined by:

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{vo}} \quad (2.7)$$

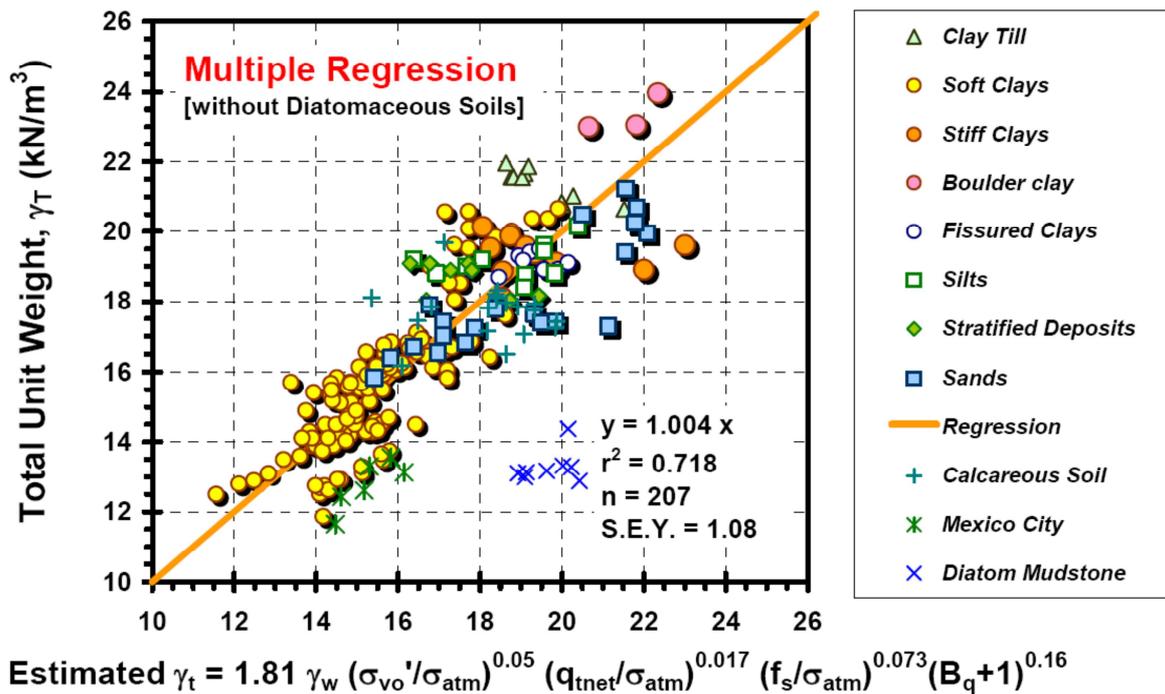


Figure 2.11. Multiple regression relationship for total unit weight (Mayne 2010).

2.3.2 INTERPRETATION OF THE CPT IN ENGINEERING PRACTICE, BEEN ET AL. 2010

This paper was also discussed at CPT '10 and presents several cases where the use of established CPT interpretation methods is not adequate for soil classification. Current correlations and

interpretations mainly classify soils into two types: sand and clay. Testing in clay is assumed to be undrained and testing in sands is assumed to be drained. Two of these cases are discussed below.

The first case involves a site that contained elastic silts. Figure 2.12 shows the soil behavior type (SBT) plot for a large number of CPT measurements. Most of the data points fall in region 3 on the plot, which is characteristic of clays. Only a small fraction of the data falls in regions 4 and 5, which is characteristic of silts.

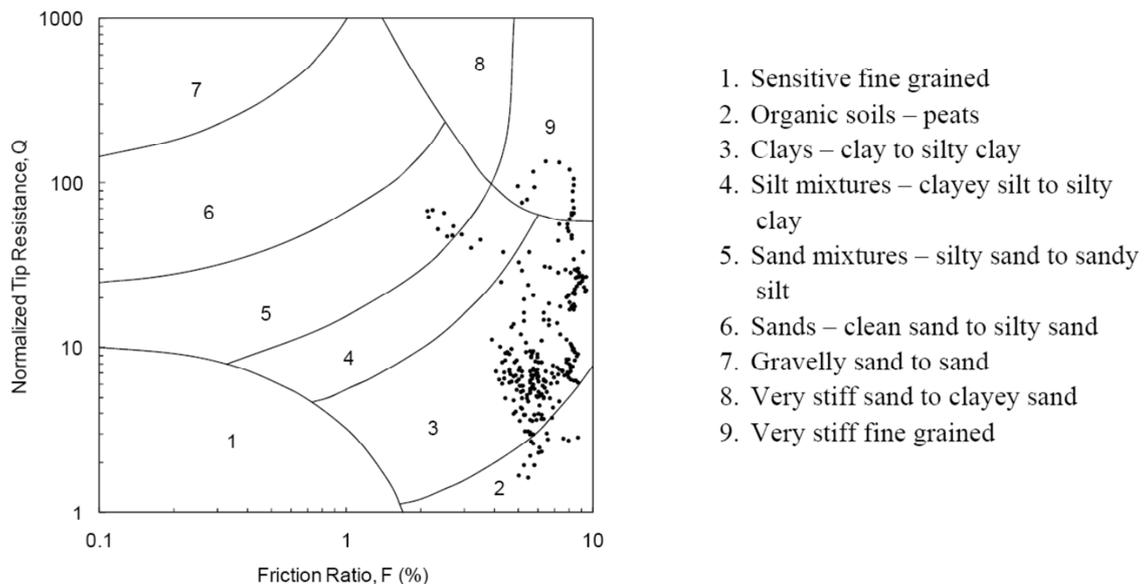


Figure 2.12. Site-specific CPT data shown on the Robertson (1990) soil behavior type diagram (Been et al. 2010).

For this site, many other correlations were also investigated and the following conclusions were reached:

- Undrained clay-like behavior was observed in laboratory tests and was correctly identified by the CPT, but the CPT was incapable of showing that the material was silt, rather than clay.
- The estimated value of N_{kt} of 16 or less to determine undrained shear strength is within the band of expectation for CPT in stiff clays.
- CPT primarily produces shearing of the soil and its use to estimate modulus is limited, to some degree, on how well modulus and undrained shear strength are related.
- Estimation of soil stiffness using CPT empirical correlations is not recommended in a new area or for a new soil without prior experience.

A second site was located offshore and contained a 140 m thick silt deposit. Essentially three layers are indicated in the index test profiles in Figure 2.13. Figure 2.14 displays the SBT chart for the same materials. Although large scatter is observed in the SBT chart, SPT conducted on the same site indicated that only silt was present.

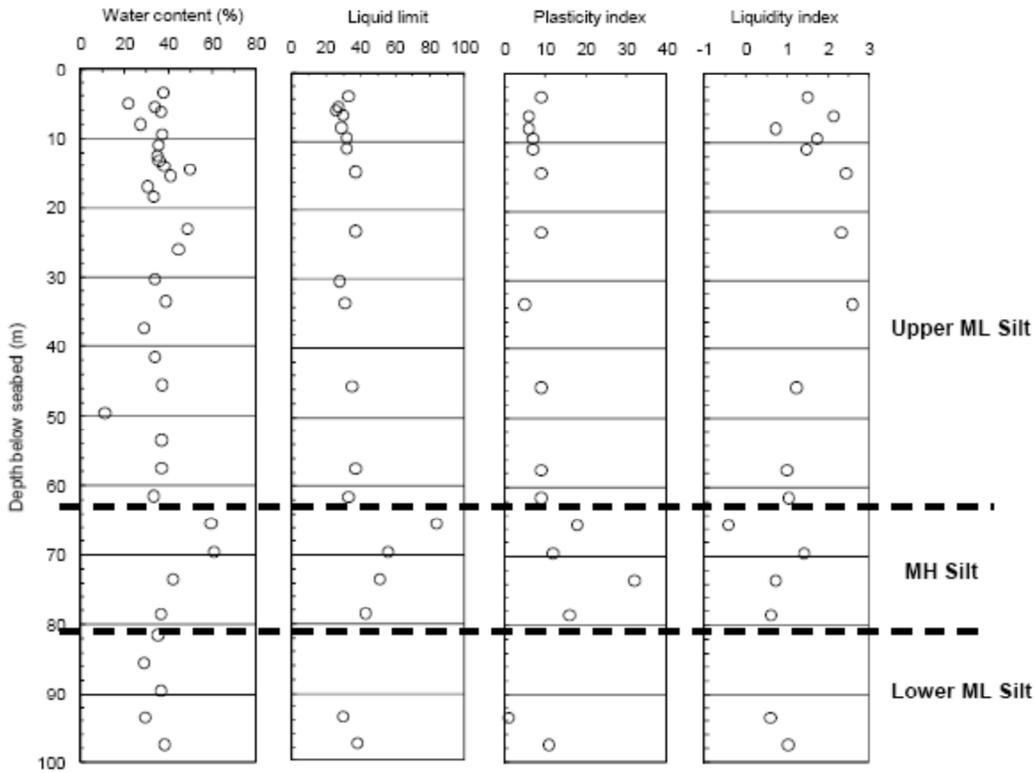


Figure 2.13. Soil index properties at marine silt site (Been et al. 2010).

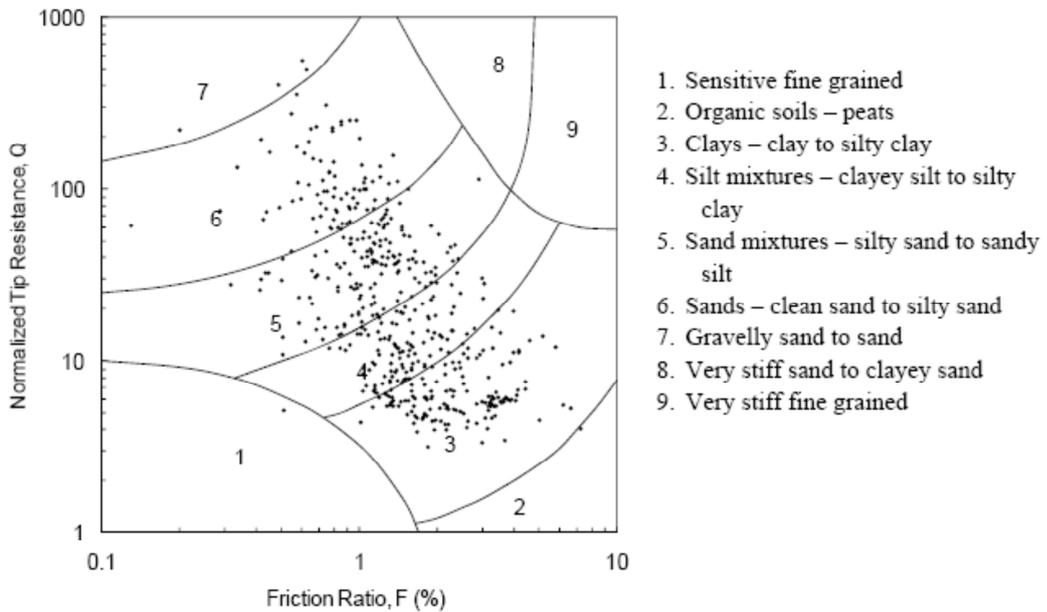


Figure 2.14. Data for marine silt on the Robertson (1990) soil behavior type diagram (Been et al. 2010).

The following conclusions were reached for this site:

- CPT cannot be used in isolation and requires an appropriate program of sampling and related testing to confirm the selected soil parameters
- Soil modulus would not have been well predicted from the CPT data and CPT should not be generally used to determine parameters through indirect correlations.
- This site was particularly challenging for characterization based on CPT data because of the layering and the silty soils.

This paper illustrates the difficulties in using CPT methods for silts. Silt is prevalent throughout Ohio, so care must be taken to ensure proper identification. It is recommended to augment CPT with conventional drilling and laboratory testing in such cases.

2.4 CONCLUSIONS

A large number of papers and guideline documents are available on CPT and go into considerably more depth than this report. The Proceedings from CPT '10 is another excellent resource. CPT is a sophisticated technology that requires considerable knowledge and experience to become proficient in its use. This chapter only provides a brief overview of CPT. ODOT engineers and geologists who are using CPT should consult other available resources as needed on an ongoing basis.

CHAPTER 3. METHODS

3.1 INTRODUCTION

Chapter 3 describes CPT procedures in detail, including necessary procedures before, during and after a CPT sounding using the ODOT CPT machine. This chapter also includes the procedures used for Phase II of the CPT research program.

3.2 PRE-TEST PROCEDURES

This section describes the steps that need to be completed before a CPT sounding can begin, including site selection criteria and issues that must be considered prior to arrival at a field site.

3.2.1 SITE SELECTION PROCESS FOR RESEARCH

Site selection was the first step in Phase II of the CPT research program. ODOT has a data management system that archives completed projects (Falcon) and this database was first used to locate potential testing sites. If a field site had subsurface information obtained within the past 10-15 years then it qualified as a potential site for the research program. As well as using Falcon, the ODOT District Geotechnical Engineers (DGEs) were asked for potential sites in their respective districts. Many DGEs identified sites that had been previously investigated and also needed additional exploration for future construction. An initial list of sites was developed and field testing began in June 2009. As testing was completed at sites around the state, additional sites were added to the list to provide needed soil types and to fill in the database.

Several factors were considered in the selection of research test sites. A primary criterion was the availability of high quality SPT and laboratory test data from previous subsurface investigation. Sites with pile driving information were also seriously considered. Priority was given to the most recently investigated sites. The DGEs also identified sites that were recently investigated but still needed additional testing.

3.2.2 SITE SELECTION PROCESS FOR DGEs

CPT can be used in many different capacities within ODOT. Described in Chapter 5, these uses are as follows:

- Before conventional drilling to guide subsequent operations
- After conventional drilling to augment the investigation
- Concurrently with conventional drilling
- Instead of conventional drilling

Robertson and Cabal (2010) outlined the uses for *in situ* testing methods such as CPT based on risk (Figure 2.10). For low risk projects, *in situ* logging tests (CPT) and index testing on disturbed samples combined with conservative design criteria are often appropriate. For moderate risk projects, these can be supplemented with additional *in situ* testing such as seismic CPT or vane shear tests, combined with basic laboratory testing to make site specific correlations. For high risk projects, these screening methods can be used to identify potentially critical zones that should be further investigated using high quality sampling and laboratory testing. Concepts similar to Figure 2.10 should be considered when deciding if CPT should be used for a given ODOT project. Additional considerations are expected soil types and ease of access. If a given site is suitable for conventional drilling then, more than likely, CPT can also be used unless a hard stratum is present.

3.2.3 SITE RECONNAISSANCE

Once a given site was chosen as a likely candidate for CPT research, reconnaissance was conducted to assess suitability for testing. During site reconnaissance, it is important to note potential hazards such as low clearance for wires, branches, or structures, and any access issues such as steep slopes or brush, soft ground, and right-of-way concerns. Also, since the CPT arrives on a low boy trailer, a suitable location for unloading the CPT machine needs to be identified. If the CPT machine must be unloaded on the roadway, maintenance of traffic (MOT) will be required. MOT will also be needed if the soundings are located on the roadway itself. Each of these items is addressed in the Site Reconnaissance Form provided in Appendix B. This form should be filled out before the CPT machine arrives on-site and should include a sketch of the project area. Photos should be taken to document initial conditions so that any preexisting damage is not attributed to CPT operations. Photos are also needed to indicate issues that are not clearly identified on the reconnaissance report. Following review of the reconnaissance report and making the necessary arrangements, the CPT machine can be transported and on-site testing can begin.

3.3 FIELD TESTING PROCEDURES

The following sections describe the on-site CPT procedures. This includes setting up a test, running a test, clean up, and tasks associated with finishing a testing program. The A. P. van den Berg manuals for the CPT machine provide additional details. Copies of these manuals should be kept in the cabin of the CPT machine and new operators should thoroughly review these manuals prior to operating the CPT machine.

3.3.1 OPERATING THE CPT CRAWLER

The CPT machine weighs over 23 tons and is a very expensive piece of equipment, so care must always be taken during operations. In particular, an operator must be aware of the surroundings and any possible obstructions or hazards when moving and operating the crawler.

3.3.1.1 STARTING THE CRAWLER

The first step is to start the machine. Located on the back left corner (if looking at the rear of the machine) is a large metal key that must be turned clockwise to turn on the batteries. Nothing on the CPT machine is operational when this key is in the “off” position. After turning this key, the next step is to go into the cabin and power on the on screen computer and the engine. Figure 3.1 shows the ignition switch and engine gauges and Figure 3.2 shows the control panel of the crawler with the Human Machine Interface (HMI). To start the engine, the operator must first turn the key and wait for two lights (red and orange) on the top of the LCD screen to illuminate and then turn off (these lights are not illuminated in Figure 3.1). When the lights turn off, the engine can be started. Currently the LCD screen shows battery voltage, engine hours, engine temperature, and engine RPM. This display can be changed using the arrows located beneath the screen. The rabbit and turtle switches are used to adjust engine RPM. If the remote control is activated (described below), engine RPM can no longer be controlled with this switch and must be controlled using the remote.

The next step after starting the ignition is to activate the HMI. Table 3.1 explains the function of each of the buttons and knobs on the control panel. The first step in tracking (i.e., driving) the CPT machine is to turn knob 27 to the “1” position. Button 40 will then illuminate (blue) and should be pressed. After pressing this button, the blue light will no longer be illuminated and in about 45 seconds, knob 27 will illuminate. No further action can be taken until the white light inside knob 27 is illuminated and it should remain illuminated for the duration of operation.



Figure 3.1. Ignition switch panel inside cabin of CPT machine.

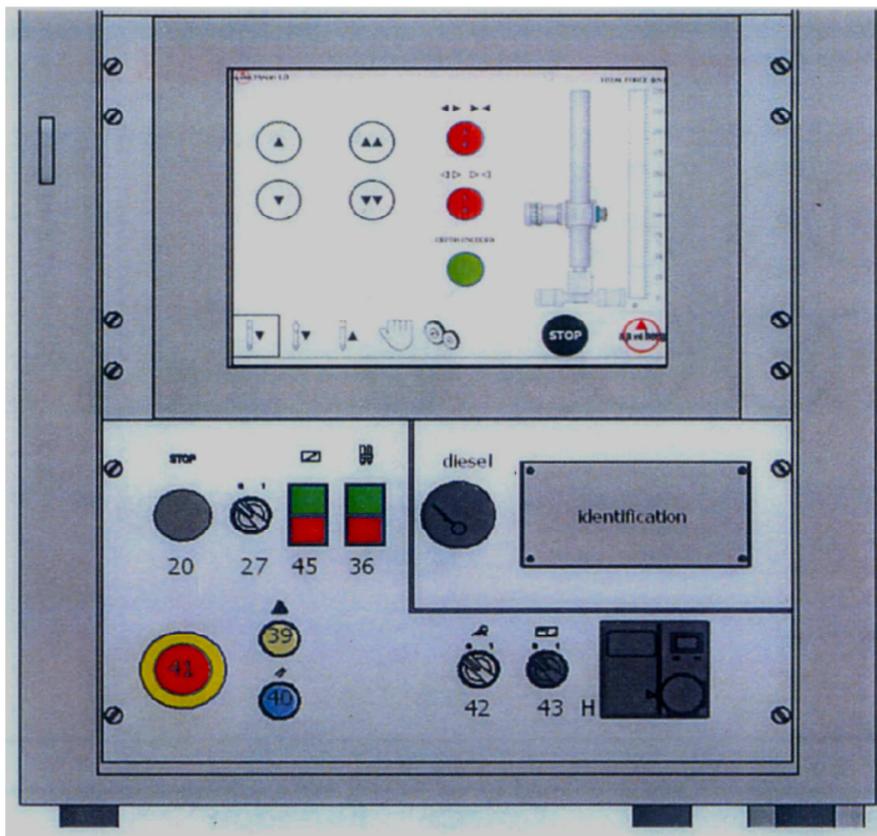


Figure 3.2. Control panel inside cabin of CPT machine (A.P. v.d. Berg Machinefabriek 2009).

Table 3.1. Description of functions for CPT control panel.

Number	Component	Function
20	Mushroom head pushbutton	Stop hydraulic movement
27	Switch turned left (0 position) Switch turned right with light on (1 position)	Control system off Control system on
36	Button, green pushed with light on in middle Button, red pushed	Hyson controls engaged Hyson controls disabled
39	Orange light	Warning light for foot sensor
40	Pushbutton with blue light	Reset emergency switch
41	Red emergency mushroom pushbutton	Emergency stop
42	Switch in 0 position Switch in 1 position	Underfloor light on Underfloor light off
43	Switch in 1 position Switch in 0 position	Inverter on Inverter off
45	Button, green pushed with light on in middle Button, red pushed	Remote control enabled Remote control disabled
H	Heater/Fan switch and dial	Controls heat temp and fan speed

3.3.1.2 DRIVING AND DEPLOYING JACKS

To be able to track the CPT crawler, the remote control and tracks need to be activated. This is done by pressing the green portion of button 45. This activates the remote control which operates the jacks and tracks of the crawler. Once this button is pushed, no further action is needed on the HMI or control panel and all control is now assigned to the remote control unit. Figure 3.3 shows a diagram of the remote control unit and Table 3.2 describes the functions of the various buttons and switches. To turn the remote on, push button R22. The remote is now able to control the crawler.

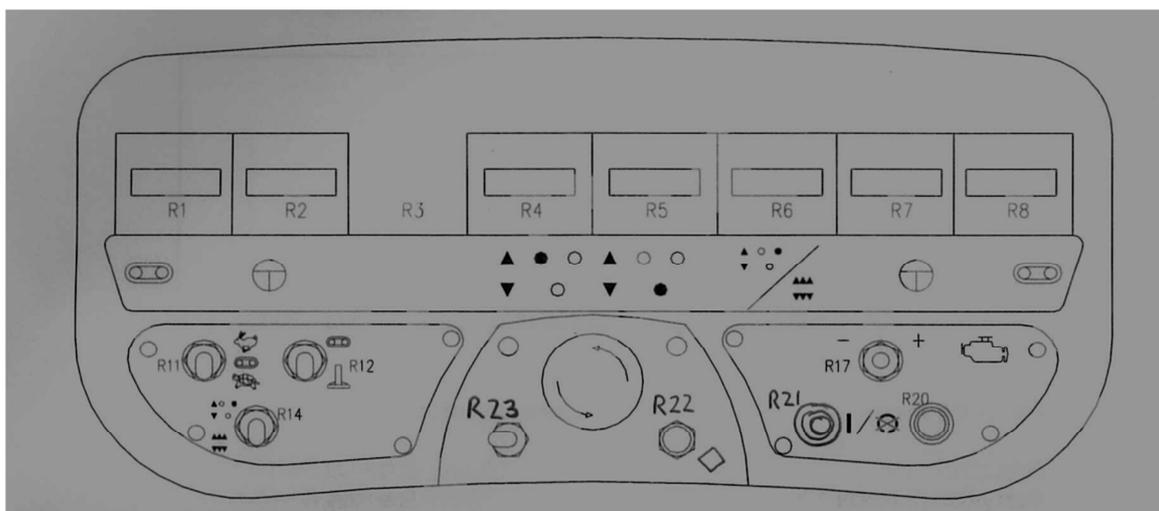


Figure 3.3. Diagram of remote control unit for CPT machine (A.P. v.d. Berg Machinefabriek 2009).

Table 3.2. Description of remote control components.

Number	Function
R1 & R2	Controls left track, push up for forward, back for reverse
R4	Controls from left jack
R5	Controls back jack
R6	Controls front right jack/control for moving all jacks at once
R7 & R8	Controls right track, push up for forward, back for reverse
R11	Controls speed of tracks, rabbit for high speed, turtle for low speed
R12	Toggle up to activate tracks, toggle down to activate jacks
R14	Toggle up to move individual jacks using R4-R6, toggle down to move all jacks at once using R6
R17	Toggle towards + to increase engine RPM's, - to decrease
R20	Turns engine off
R21	Restarts engine of stalled or turned off (ignition key must be turned on)
R22	Power Button, press to activate remote
R23	Controls engine power, toggle to change power by 10%

The front of the crawler contains the door and the engine is at the rear. Thus, when looking out the front, the operator presses R1, R2, R3, and R4 forward to move the machine forward. Left and right are at the orientation of the operator looking out the front door. To move the crawler, toggle switch R12 needs to be in the forward position. **It is strongly advised to move the crawler while outside the cabin because of the generally low visibility inside.** When moving the crawler, the RPM should be between 1800 and 2300. The steepest slope the CPT can ascend is roughly 2H:1V. It is important to note the conditions of all slopes before tracking the CPT in the project area to ensure adequate traction for the machine.

To activate the jacks, R12 should be in the downward position. If moving all jacks at once, toggle switch R14 should be down and switch R6 is used to control the jacks. To move individual jacks, toggle R14 should be up and switches R4-6 are used. A level bubble is attached to the work bench below the HMI and can be used to level the entire machine. It is common practice to lower all jacks so the tracks are off the ground while outside the cabin and then to proceed inside the cabin to completely level the machine by adjusting individual tracks while watching the bubble.

The steepest ground on which the CPT machine can be leveled is an 8° slope (roughly 7:1 or 14%). Figure 3.4 shows a method for leveling the machine on such a slope. Flatter ground makes for an easier CPT leveling process and this should be considered when selecting sounding locations.

3.3.2 PREPARING FOR CPT SOUNDING

Once the machine is level, several steps need to be completed before the cone is pushed. Certain steps described below, such as cone calibration, do not need to be completed before every sounding.

3.3.2.1 PREPARING CABIN FOR TESTING

Prior to conducting a CPT sounding, there are several key components that need to be set-up in the cabin. The red portion of button 45 (on the control panel) should be pushed and the green portion of button 36 then pushed to activate the Hyson. The Hyson controls the hydraulic system that is used to

push a cone into the ground. Figure 3.5 shows the Hyson in the lowest position. The Hyson is controlled by the HMI and the hand lever located below the work bench under the control panel. Figure 3.6 shows the HMI screen and Table 3.3 provides a description of functions for the HMI icons. The hood over the Hyson must be raised in order to have maximum clearance during testing. The hood can be raised using the Hyson itself. The operator must ensure that the hood is fully raised before the locking screws are tightened.

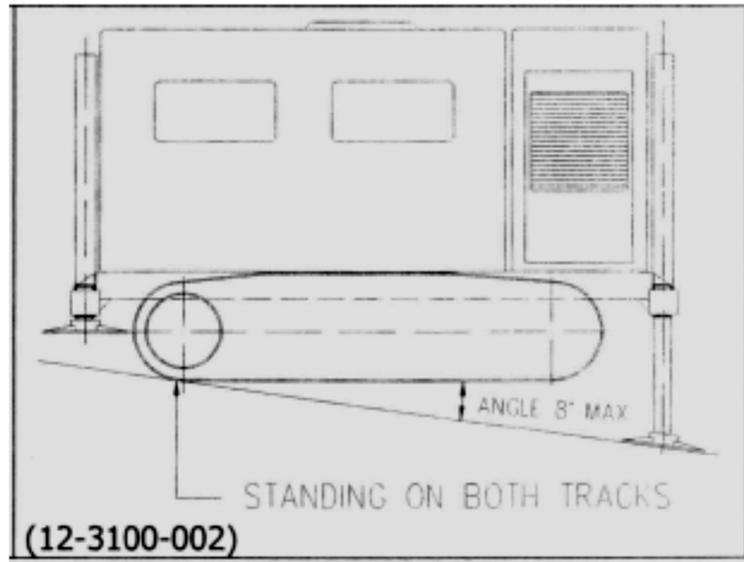


Figure 3.4. Method for leveling the CPT machine on steep ground (A.P. v.d. Berg Machinefabriek 2009).



Figure 3.5. Hyson in lowest position.

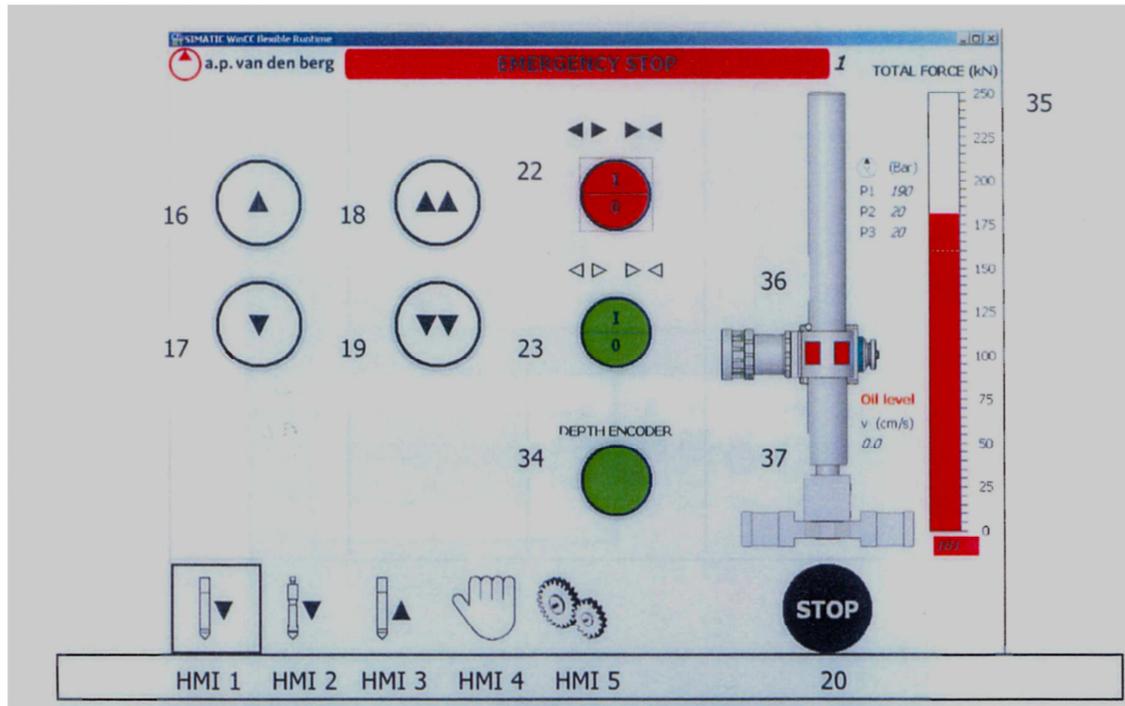


Figure 3.6. Human Machine Interface (HMI).

Table 3.3. Description of functions for HMI.

Number	Component	Function
16	Push Button	Hyson up slow
17	Push button	Hyson down slow
18	Push button	Hyson up fast
19	Push button	Hyson down fast
20	Push button	Stop Hyson
22	Push button red Push button green	Upper clamp not active Upper clamp active
23	Push button red Push button green	Lower clamp not active Lower clamp active
HMI 1	Push button	Automatic testing for 1 meter strokes
HMI 2	Push button	Automatic testing for <1 meter strokes
HMI 3	Push button	Automatic pulling for 1 meter strokes
HMI 4	Push button	Manual control
HMI 5	Push button	Service
HMI 6	Push button (not shown)	Seismic testing
34	Push button green Push button red	Depth encoder enabled Depth encoder disabled
35	Indicator black Indicator red	Total force on Hyson (kN) < 160 Total force on Hyson (kN) > 160
36	Indicator red Indicator grey	Upper clamp engaged Upper clamp inactive
37	Indicator red Indicator grey	Lower clamp engaged Lower clamp inactive

Once the hood is locked in position, the next step is to set up the data acquisition system on the work bench. A flat screen LCD computer monitor can be connected to the data acquisition system and attached above the HMI screen, which makes the system data easier to read when a cone is being pushed.

3.3.2.2 HYSON OPERATION

This section describes the operation of the Hyson. The Hyson is controlled by the HMI and the hand lever below the control panel. All button/indicator numbers are shown in Figure 3.6 and are described in Tables 3.2 and 3.3. HMI 5 should be pressed to move the Hyson manually. The Hyson can now be moved up and down using the hand lever, and also using buttons 16-19. Buttons 16 and 17 move the Hyson at a slow speed (< 2.5 cm/s) and buttons 18 and 19 move the Hyson at a faster speed (> 10 cm/s). Button 22 is pressed to open and close the upper clamp. When the upper clamp is closed, indicator light 36 will turn from gray to red. Button 23 works the same for the lower clamp. HMI 1 is used during testing and automatically moves the Hyson up and down at 1 meter intervals at a speed of 2 cm/s (± 0.5 cm/s) as per ASTM D-5778. HMI 2 is rarely used but this button automatically moves the Hyson at intervals less than 1 m. HMI 3 is used when pulling a CPT string up from a completed sounding. For this operation, it is acceptable to use the faster speed (> 10 cm/s). The HMI shutdown button is HMI 5. After completing a seismic test, HMI 6 should be pressed. This will show the screen to deploy the pneumatic hammer. It is important to carefully monitor the gauges and pressures indicated on the HMI screen. High values or rapid changes may indicate a problem and all operations should cease until the problem can be corrected.

3.3.2.3 VACUUM CHAMBER OPERATION AND DESCRIPTION

Figure 3.7 shows the vacuum pump and chamber. The vacuum chamber is used to de-air the porous filter and the pore pressure measurement cavities inside the cone. These parts measure pore pressures while a cone is pushed into the ground. Accurate pore pressure measurements can only be obtained if the cone is saturated prior to use.



Figure 3.7. Vacuum pump and chamber.

Silicone oil is used to de-air a cone inside the vacuum chamber, as shown in Figure 3.7. Water or glycerin or a combination of all 3 fluids can also be used; however, silicone oil is preferred because it has a higher viscosity than water or glycerin. This increases de-airing time but also better maintains cone saturation while pushing through unsaturated materials. The level of silicone oil in the chamber must be above the porous filter at all times during the de-airing process.

Plastic filters need to be placed in the vacuum chamber for at least 24 hours prior to use, whereas sintered steel filters need at least one week in the vacuum chamber to completely de-air. Thus, an operator must plan ahead to make sure there are filters in the vacuum chamber at all times. It does not negatively affect the filters to be in the vacuum chamber for extended periods (weeks or months). A cone with a saturated filter element in place should be left in the vacuum chamber until no more air bubbles are seen in the silicon oil. This takes about 20-30 minutes. If possible, it is recommended to leave cones in the vacuum chamber overnight. While cones are in the vacuum chamber, it is important to make sure the chamber is properly secured such that it does not overturn. If the chamber falls over with the cone inside, silicone oil may penetrate and ruin the sensors inside the cone.

Vacuum is created using the vacuum pump. The red hose is connected from the pump to the valve with the handle on the vacuum chamber. With the valve open, the vacuum pump should remain on until no more air bubbles are seen in the silicone oil.

The plastic filters are discarded after each use. The sintered steel filters may be re-used but need to be cleaned with a sonic bath after each sounding. The sonic bath is located under the rod rack in the CPT cabin. Multiple passes through the sonic bath may be necessary to completely clean sintered steel filters. As such, plastic filters are generally recommended for CPT work.

3.3.2.4 PREPARING THE CONE FOR TESTING

The type of cone used by ODOT is a seismic piezocone ELCI-CFY20-15, manufactured by A.P. Van den Berg. In addition to measuring tip and sleeve resistance, a seismic piezocone is capable of measuring pore pressure and shear wave velocity. Each cone is stored in a case that protects against damage during transport. Before a cone is stored after use, it should be cleaned and inspected for wear and damage to keep it in proper working condition. Table 3.4 gives recommended maintenance intervals for various equipment checks and calibrations.

Figure 3.8 illustrates the components of a cone below the friction sleeve and Table 3.5 describes the part numbers for A.P. Van den Berg cones (for ordering spare parts). Each of these components must be in good condition; otherwise dirt and water may damage the load cells and electronics inside the cone. Two plastic centering rings are placed around the pore pressure filter to ensure a correct fit during filter placement and the cone is placed into the vacuum chamber for de-airing (see previous section). Once the cone is de-aired, it is removed from the vacuum chamber and a protective membrane (e.g., condom) is placed over the cone tip. The membrane covers the pore pressure element to maintain saturation before the cone is pushed into the ground.

Table 3.4. Calibrations and checks for CPT equipment (Robertson and Cabal 2010).

<i>Maintenance</i>	<i>Start of Project</i>	<i>Start of Test</i>	<i>End of Test</i>	<i>End of Day</i>	<i>Once a Month</i>	<i>Every 3 months</i>
<i>Wear</i>	<i>x</i>	<i>x</i>			<i>x</i>	
<i>O-ring seals</i>	<i>x</i>			<i>x</i>		
<i>Push-rods</i>		<i>x</i>			<i>x</i>	
<i>Pore pressure-filter</i>	<i>x</i>	<i>x</i>				
<i>Calibration</i>						<i>x</i>
<i>Computer</i>					<i>x</i>	
<i>Cone</i>					<i>x</i>	
<i>Zero-load</i>		<i>x</i>	<i>x</i>			
<i>Cables</i>	<i>x</i>				<i>x</i>	

Table 3.5. Part numbers for A.P. Van den Berg cones.

Part Number	Component
77510090	O-ring
77511005	Quad ring
0101150A	Lip seal
0101320A	Centering ring
0101088A	Pore pressure filter
0101098A	Filter centering ring
0101130A	Cone tip

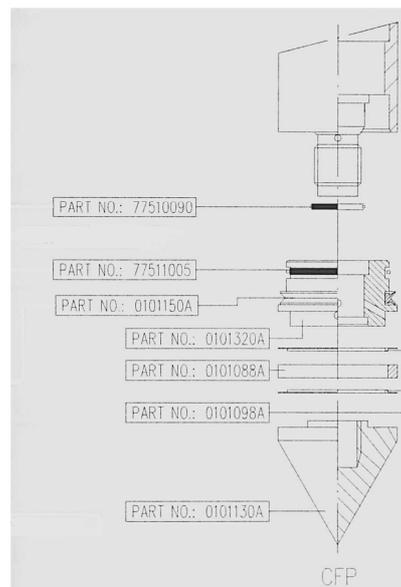


Figure 3.8. Schematic of A.P. Van den Berg CPT cone (A.P. v.d. Berg Machinefabriek 2009).

If shear wave velocity measurements are planned, the seismic module is connected to the cone with the protective cover screwed onto the end of the cone. The operator must make sure that the cover is screwed on **before** the four screws that hold the module in place are tightened along the cover. Otherwise the seismic module will be sheared off at the connection with the cone. The seismic trigger should then be connected to its cable on the outside of the cabin and placed on the front jack. Figure 3.9 shows the seismic trigger on the CPT machine. The cable for the trigger is located in the white box on outside front of the machine. It is important to make sure that when the trigger is attached, the words “trigger up” are pointing upward (Figure 3.9).

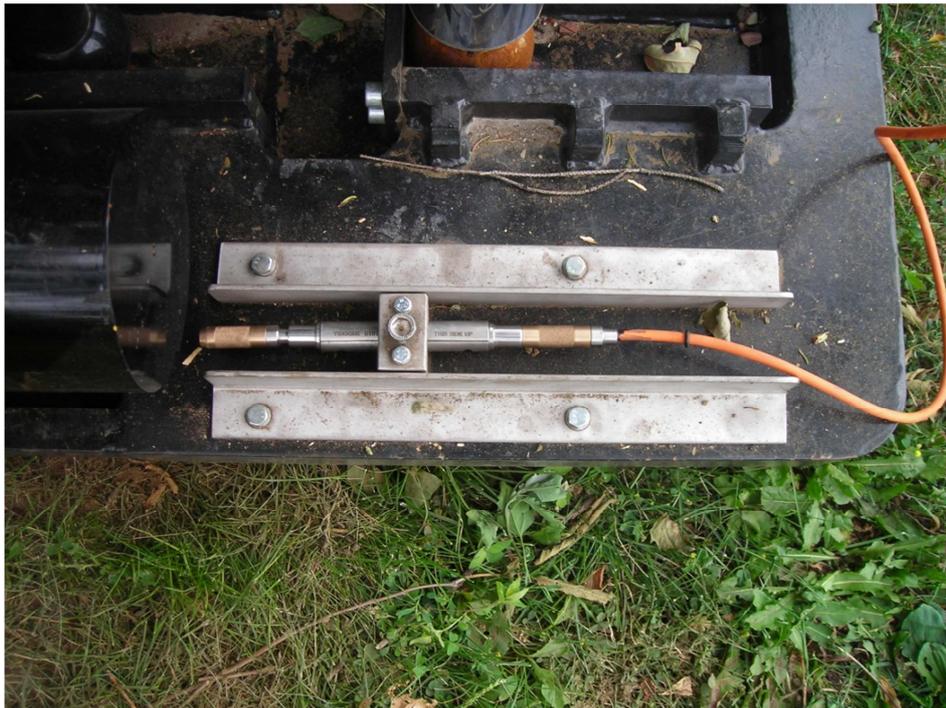


Figure 3.9. Seismic trigger on outside of CPT machine.

The orange data transmission cable is attached to the cone and passes through the piece of rod connected to the friction reducer. The cone is then screwed onto the friction reducer. During this process, the operator must make sure that the orange cable is also turning so that it does not become twisted inside. The cone is attached to a string of friction reducer and rod and is carefully placed through the hole in the cabin floor. The Hyson should be at its highest position during this time. Figure 3.10 shows a photograph of the cone and rod assembly at this point. The Hyson can now be lowered and the orange cable can be strung through the upper clamp and connected to the cable running through the remaining rods. The first rod in the rack is now connected to the CPT string and the cone should sit for 15 minutes to “warm up”. At this point the cone is ready to be pushed, but the sounding information needs to be first entered into the data acquisition system.



Figure 3.10. CPT string with cone below floor level.

3.3.2.4 GONSITE! PREPARATION

The software for the data acquisition system is called GOnsite! Before starting a test, all pre-sounding information needs to be entered into GOnsite! Figure 3.11 shows the opening screen which can be accessed by clicking the icon for GOnsite! on the home screen of the data acquisition system. All options in GOnsite! are listed at the bottom of the screen.

To create a new project, click the project button, or F2. To enter the new project information, click the “New” option and a screen will pop up. After entering the necessary information, click “ok” and then click “cancel” to return to the home screen. The next step is to open the project and prepare for the sounding. Click on the “Testing” button or hit F1 and a blank testing screen will appear. From here, hit the “Select” option and you will be taken to the screen shown in Figure 3.12. The top right corner shows all the projects. The most recent project created will be the project selected. Select the desired project and then click on the box with “1” in the bottom left corner to choose the first test. The blank testing screen is again displayed but now the project information and test number are shown at bottom left. The cone number should be shown in the left corner of the status bar portion (Figure 3.13),

as well as information on the seismic modules. If both seismic modules are connected, the cone portion of the status bar should have the following information: I-CFXYP20-15 090304 I-Seismic ISO90404 I-Seismic2nd 999999B. The numbers will change for different cones. If the cone section is blank when the cones are connected, GOnsite! should be restarted. All connections should be checked if the problem persists. Once the test is open, click "Edit" and a display box will appear. Enter information for the test and click "ok". At this point, the cone is ready to push into the ground.

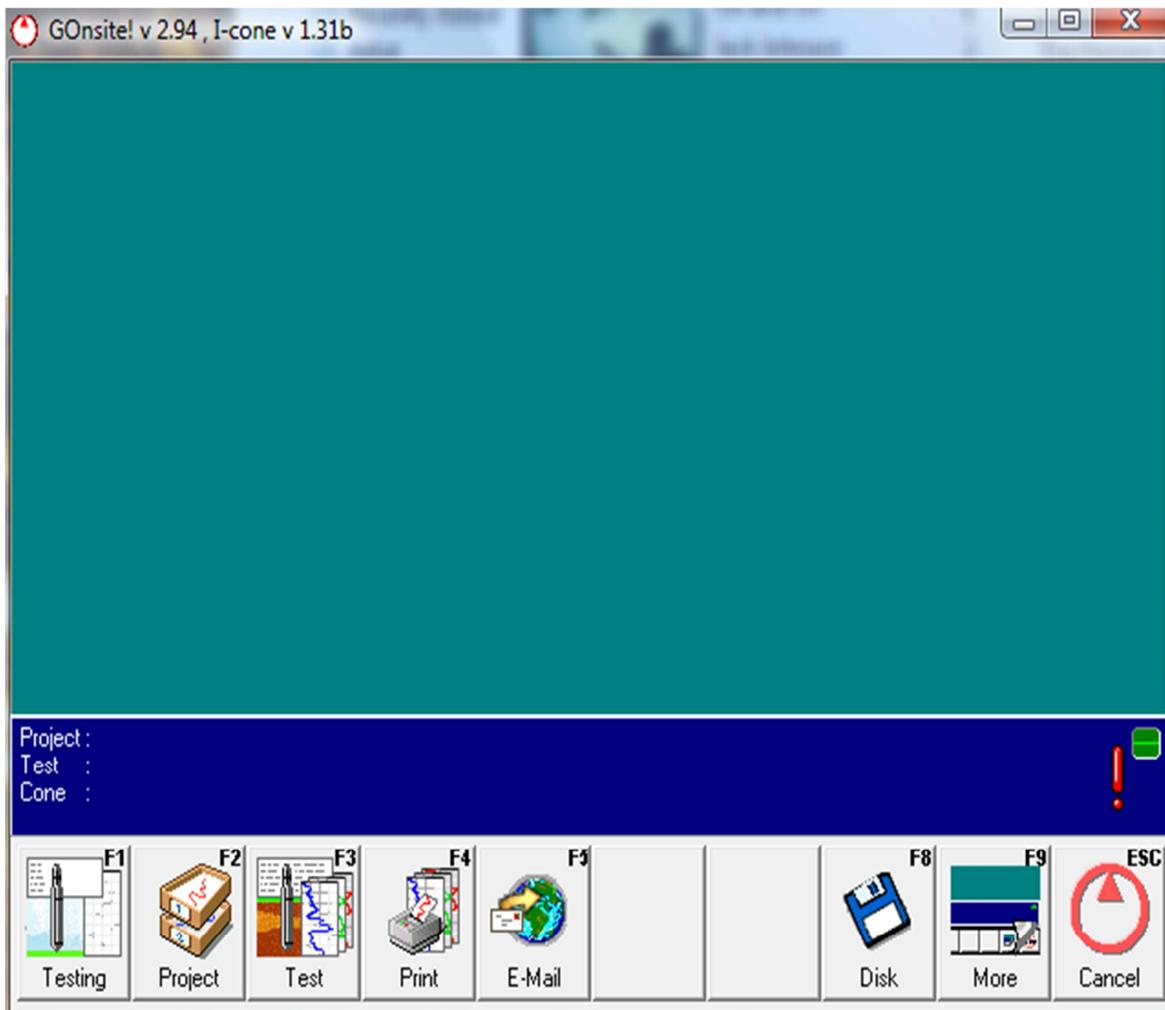


Figure 3.11. Opening screen of GOnsite!.

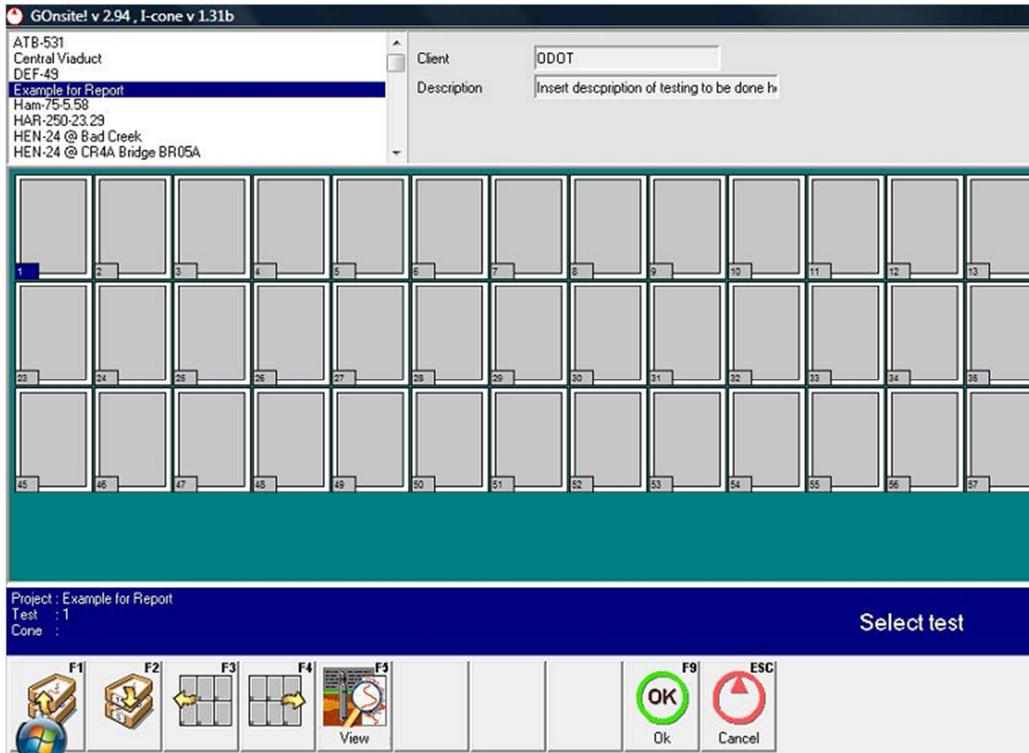


Figure 3.12. Test selection screen for GOnsite!.

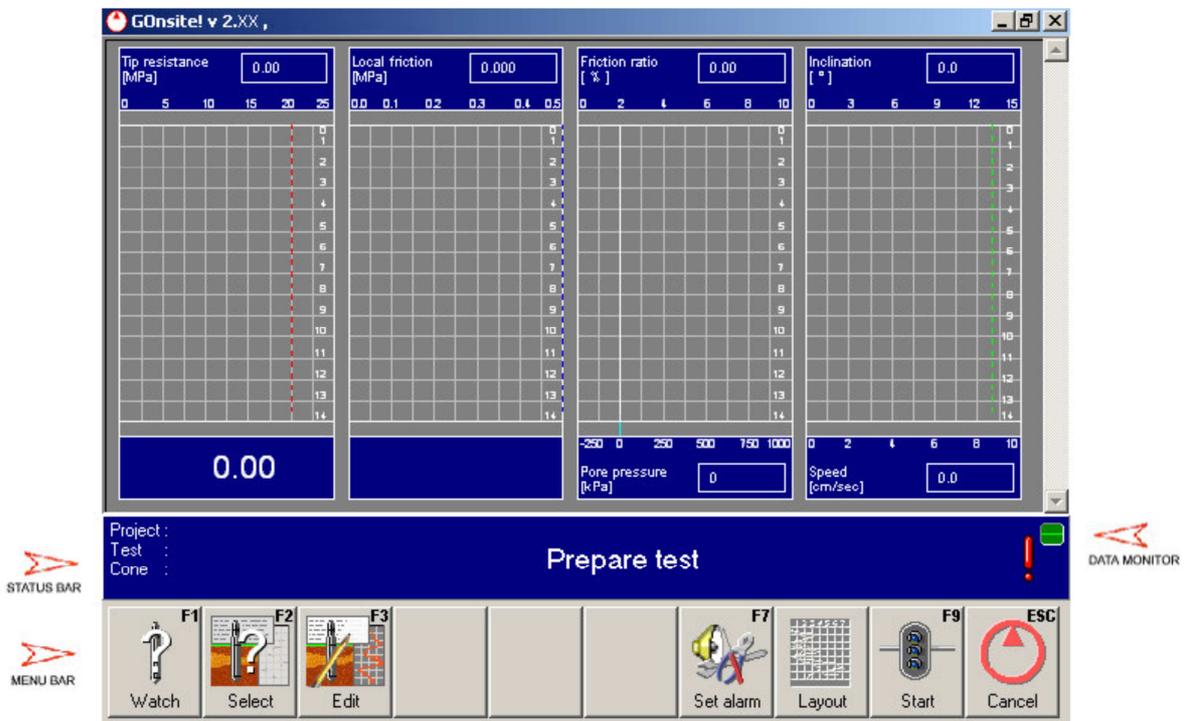


Figure 3.13. Testing screen for GOnsite!.

3.3.4 PUSHING A CONE

Once the CPT string is connected and placed through the cabin floor and GOnsite! is set-up, the CPT sounding can begin. The Hyson is moved to a reasonable starting location and the upper clamp is engaged with the cone as close to vertical as possible. To start the test, push F9 or click the start button and the zero readings will be displayed. **Make sure that the cone is completely unloaded (i.e., not touching anything) before it is pushed into the ground so that the “zero” load will be correct.** After the start button is pressed, every reading on the screen should be zero. If the cone is loaded before the test starts all measurements will still default to zero, thus introducing error in the subsequent load measurements. In order to obtain correct depth measurements, move the cone a few inches above the ground surface and slowly advance the cone using the manual hand control until the tip resistance changes by 0.01 MPa. The test can then be started. Table 3.6 lists the ASTM standards for CPT. These standards should be consulted in addition to this report.

Table 3.6. ASTM standards for CPT.

ASTM Standard	Name
ASTM D5778-07	Standard Test Method for Electronic Friction Cone and Piezocone Testing of Soils
ASTM D6067-10	Standard Test Practice for Electronic Piezocone Tests for Environmental Site Characterization
ASTM D7400	Standard Test Method for Downhole Seismic Testing

The cone should show less than 0.5° inclination when the test begins. If pushing begins at a higher inclination, the inclination will likely continue to grow and the test will have to be terminated prematurely to ensure that the cone and rods are not damaged. There is also an option to zero-out the inclination once a test is started (consult the GOnsite! manual). This would be beneficial if a test is started on a slope intentionally (i.e., the CPT machine is not leveled prior to pushing) so that the measured inclination is a true deviation from the starting inclination of the cone. In general, however, vertical CPT soundings are recommended.

For the first one-half to one meter of a CPT sounding, it is advisable to use manual controls to ensure the cone starts out correctly. The operator should check to see if all readings on the data acquisition screen are changing. If any of the values appear to be frozen, something is wrong and the test should be terminated. Once the cone is advanced about a meter and all the data looks reasonable (low inclination and responsive tip resistance and sleeve friction), automatic pushing can begin. As the cone moves downward, it is very important that readings are continuously monitored. The operator must be ready to terminate the test at any point due to certain conditions such as high hydraulic pressure, high inclination, or large tip resistance. Once the desired depth is reached, “stop” should be clicked on GOnsite!. Do not click “stop” on the window that shows zero-loading tip, sleeve, and pore pressure measurements until the cone is completely out of the ground and unloaded. The zero readings before and after should then be compared to ensure that the cone was not damaged. If the before and after readings are not close, calibration of the cone should be checked. The following section will describe additional tests that can be performed when the advancement of the cone is paused.

3.3.5 PORE PRESSURE DISSIPATION TEST

Cone advancement may be stopped at any point to conduct a pore pressure dissipation test. A dissipation test is used to determine the coefficient of consolidation and soil permeability in the horizontal direction. Once the cone is stopped, the rod is unclamped and the dissipation symbol is clicked on the GOnsite! screen, or F1 pressed on the keyboard. There should be no time delay between stoppage of the cone and the start of the test. During the test, pore pressure is recorded with time automatically and the maximum pressure should be noted by the operator. The percent pore pressure dissipation, U , is defined by:

$$U = \frac{u_i - u_t}{u_i - u_o} \times 100\% \quad (3.1)$$

where: u_t = pore pressure at time t

u_o = equilibrium pore pressure *in situ*

u_i = pore pressure at start of dissipation or maximum value reached

A dissipation test should continue until the measured pore pressure decreases to at least one-half of the maximum ($U = 50\%$). The time corresponding to $U = 50\%$, t_{50} , is needed for analysis. In clayey soils, t_{50} can range from 10 minutes to 12 hours and complete dissipation can take 24-36 hours. Therefore, it may be necessary to terminate a dissipation test early in some cases. Once 50% dissipation is recorded, the test can be completed by clicking "stop" to return to the home screen. In non-cohesive soils, running a dissipation test until no change is observed (> 10 minutes) can be used to indicate the location of the groundwater table in the absence of vertical flow conditions. This pore pressure is the equilibrium pressure, and if divided by the unit weight of water, will give the depth of the cone below the ground water table.

Figure 3.14 shows the results of a dissipation test in silty clay. The pore pressure initially increased from an initial value of 340 kPa to a maximum of 740 kPa at 44 sec and then slowly dissipated. This increase may indicate that the pore pressure filter was unsaturated. In Eq. 3.1, u_i is equal to 740 kPa for this test. Figure 3.15 shows the results of a dissipation test in sandy soil. In this case, the initial pore pressure was negative (due to dilation of the soil during CPT) and then increased to an equilibrium pore pressure $u_o = 99$ kPa. This dissipation test was completed at a depth of 12.24 m. Dividing u_o by the unit weight of water gives a pressure head of 10.09 m. Therefore, assuming no vertical flow, the depth of the groundwater table below surface is 12.24 m – 10.09 m = 2.15 m (7.05 ft).

3.3.6 SEISMIC TESTING

ASTM D 7400 describes the requirements for a downhole seismic test. Analysis of seismic test data is described in Section 3.5.3. A seismic test can also be performed at any time during a sounding. The cone is stopped and the rods should be unclamped at the desired depth. On GOnsite!, F3 should be pushed or the seismic icon clicked, and HMI 6 should be pushed to activate the screen for seismic testing.

Three types of seismic tests (shear left, shear right, and compression) can be performed. The shear left and shear right tests produce s-waves, and the compression test produces p-waves. The shear left/right tests are conducted multiple times during a sounding to determine the s-wave velocity profile for a soil stratum. Likewise, multiple compression tests conducted over depth will give the p-wave velocity profile. Velocity profiles can be used to determine a variety of different soil parameters. Once the type of test is chosen (shear left, shear right, or compression), the gain is adjusted. A higher gain will make the signal more responsive but also introduces more noise. Generally, a lower gain should

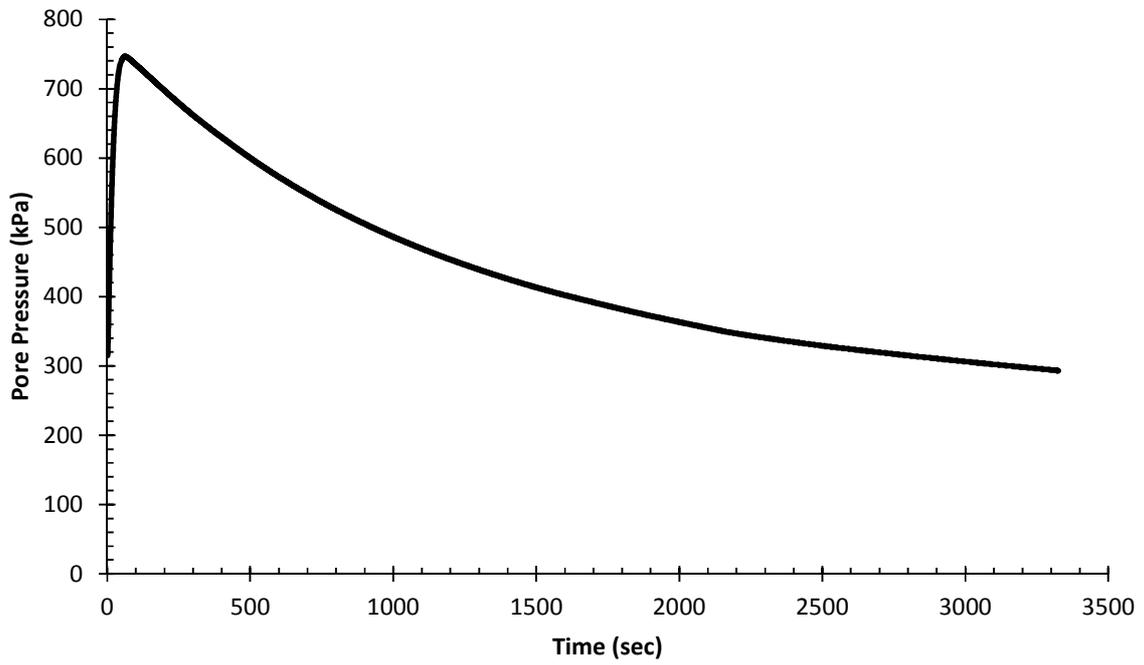


Figure 3.14. Dissipation test in silty clay.

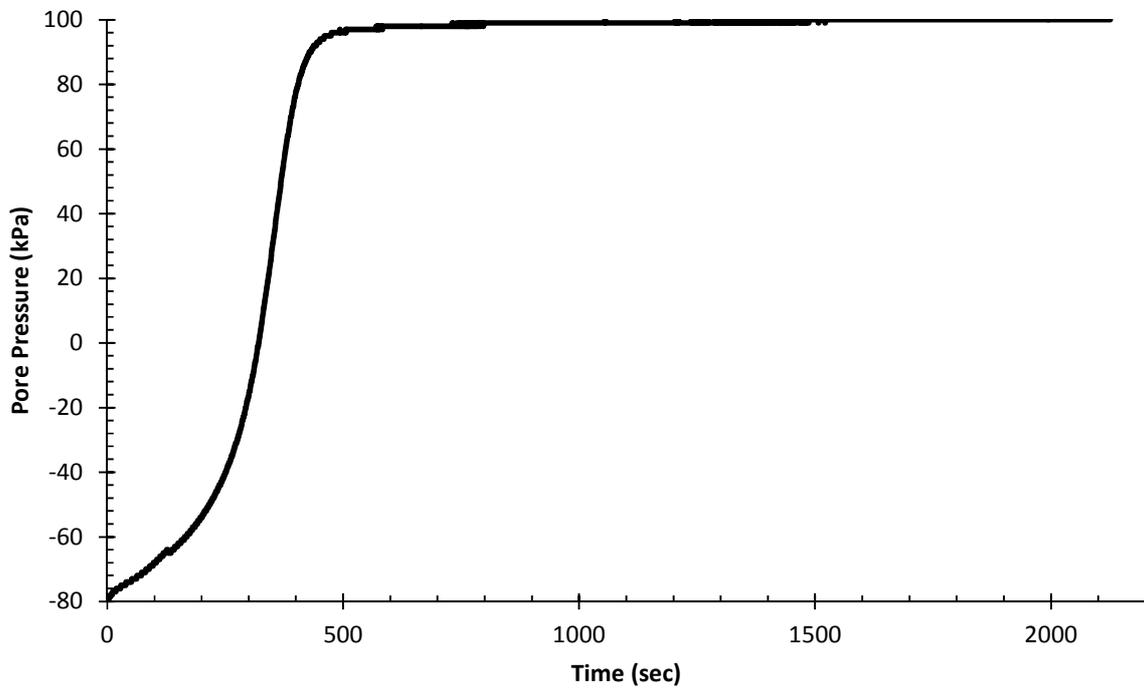


Figure 3.15. Dissipation test in sandy soil.

be used for the shear wave tests than for the compression wave test (ASTM 2009). The gain can be adjusted at any time and it is common to adjust the gain after a test to produce a better wave. Once the gain is set, the pneumatic hammer should be “armed” by pressing F1. The corresponding button on the HMI screen is then pressed to release the hammer. Figure 3.16 shows the seismic hammers located on the front load beam under the CPT machine.



Figure 3.16. Seismic hammers under CPT machine.

Figure 3.17 shows shear wave data from a successful seismic test. The smaller waves are noise and the large wave shows when the signal arrives at the piezocone. Not every test will produce a good signal, and it is the responsibility of the operator to determine if a test is acceptable or needs to be repeated. If a wave is acceptable the test should be “accepted”, otherwise the test should be “deleted”. At each depth, three waves should be repeated or “stacked”. Stacking waves amplifies the primary signal and removes most of the noise. Therefore, 9 tests should be performed at each depth (3 shear left, 3 shear right, 3 compression). The shear left and shear right waves should be mirror images of each other. This is helpful to determine the arrival time at the cone and that a successful test was performed. After tests are completed at a given depth, F9 is pushed to stop the seismic test operations. Do not hit “cancel” because this will delete all the seismic tests that were just conducted. Seismic testing should be conducted at 0.5-1.5 m (2-5 ft) depth intervals to produce a good shear wave velocity profile.

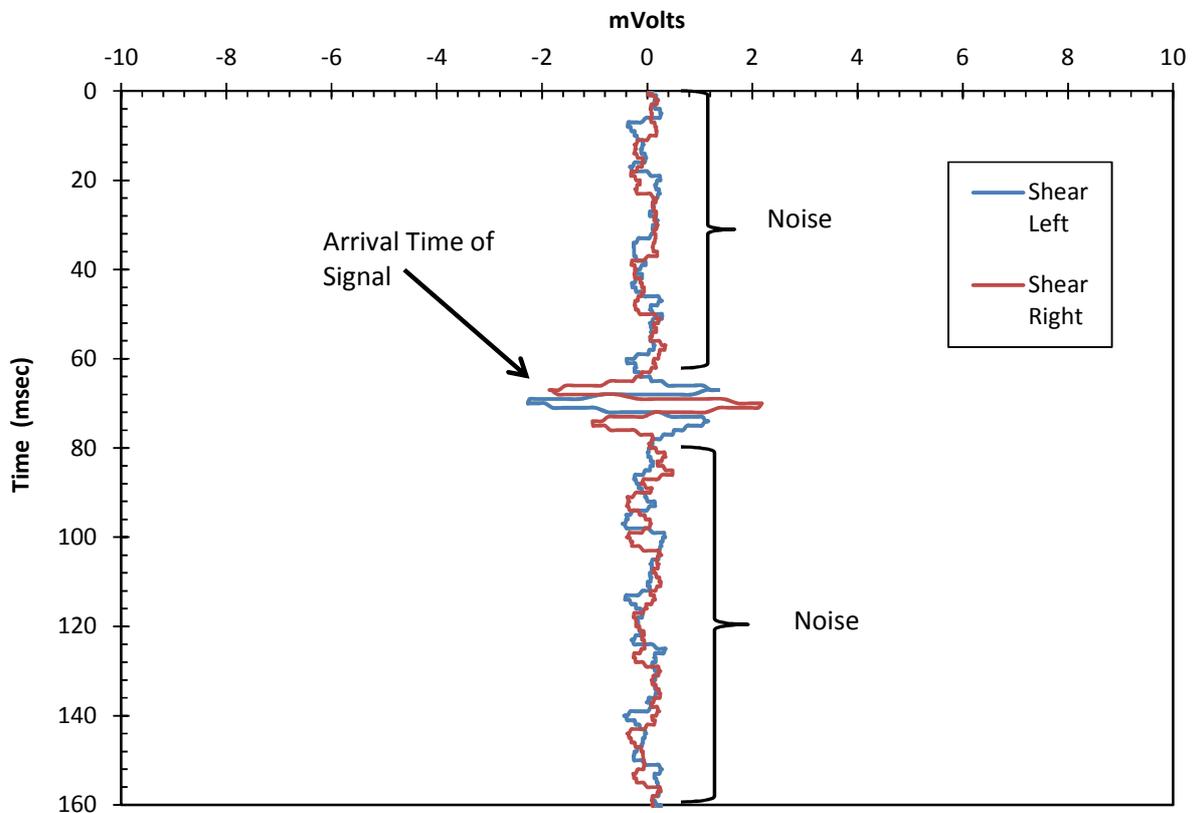


Figure 3.17. Data from a successful shear wave velocity test.

3.3.7 TESTING INTERVALS

The depths and intervals for pore pressure dissipation and seismic tests should be estimated, if possible, before starting a CPT sounding. Typical intervals for dissipation tests are 10 m or one test per soil layer. More tests may be needed for critical soundings. In these cases, pushing a continuous CPT (no stopping for dissipation or seismic tests) can be used to identify the depths for specific testing. Figure 3.18 shows a site where critical zones may be missed. The sounding indicates four primary layers. The upper layer consists of medium dense silty sand, followed by dense sand, sandy silt, and very stiff silt and clay. Examination of the tip resistance, friction ratio, and pore pressures helps to identify these layers. However, the locations of these layers are not known a priori. After completion of the first sounding, the depths for dissipation and seismic tests can be specified. In this case, dissipation tests would probably be conducted at the midpoint of each layer (2.5 m, 3.75 m, 7.5 m, and 10 m). Seismic tests should be completed at 1 m intervals over the entire depth of the sounding.

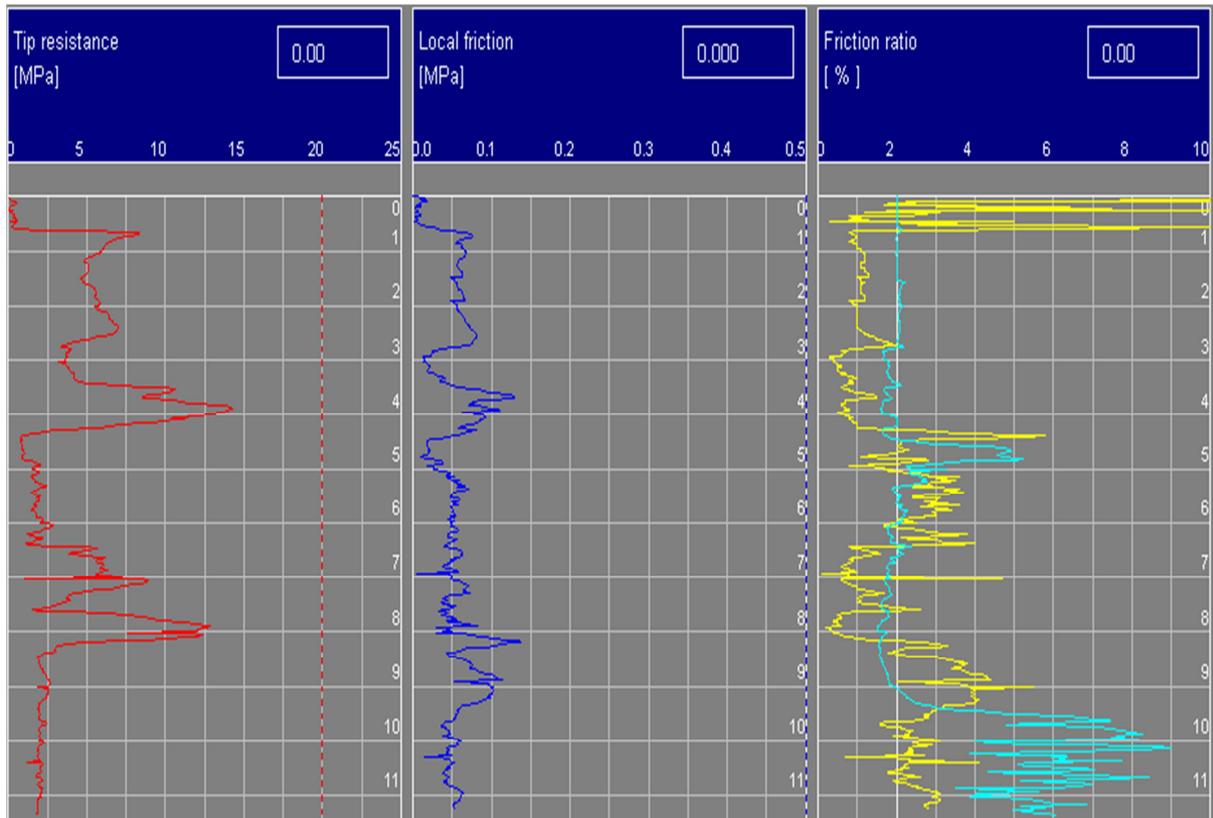


Figure 3.18. CPT subsurface profile showing four primary layers.

3.3.7 ADDITIONAL COMMENTS ON TESTING

A CPTU cone, including the porous filters, must be de-aired before the cone is pushed into the ground. There are, however, circumstances where desaturation can be problematic. When pushing the cone through unsaturated clay or dense silty sand, suctions created in the soil can desaturate the pore pressure sensing system (Robertson 2009). The use of more viscous silicone oil is helpful, but this does not eliminate the problem in all cases. Another difficulty with the pushing a saturated cone through stiff overconsolidated clay or dense sand is that negative pore pressures can cause small air bubbles to come out of solution in the silicon oil and therefore desaturate the filter. If the cone is then pushed through softer fine grained soil with high pore pressures the cone will resaturate, but this process takes time and can produce a sluggish response in measured pore pressures. If this process occurs many times during a sounding, the pore pressure profile may be difficult to interpret. For this reason, other methods should be considered to identify the static pore pressure profile (e.g., dissipation tests, piezometers).

An electric cone will likely be damaged if it is pushed through pavements or very hard soils. To avoid this problem, a dummy cone (i.e., solid steel cone with no instrumentation) should be used to push through such materials. A dummy cone cannot be used to push through concrete layers (such as a concrete subbase) and coring will be needed. A dummy cone can also be used to push through layers of gravelly soil.

3.3.8 TEST INTERPRETATION

The operator should be able to identify the general soil types encountered during a sounding. The following rules of thumb are helpful for this determination:

- coarse soils have a high tip resistance and a low sleeve friction
- fine soils have a low tip resistance and high sleeve friction
- negative pore pressures are typical for coarse soils
- high positive pore pressures are typical for fine soils
- very low tip resistance (< 0.8 MPa) is often observed for organic soils

3.4 TEST ANALYSIS AND CPT DATABASE

This section describes the research work that was performed to analyze CPT data and develop correlations for ODOT. Information from conventional drilling (conducted previously) was available for each CPT research field site. Therefore, a boring log and, in most cases, laboratory test data was available for comparison. This section describes the procedures that were used to match conventional and CPT data for each sounding. The process used to develop data correlations is also described. Data handling and presentation issues are covered in Section 3.5.

3.4.1 BUILDING A DATABASE OF RESULTS

An Excel workbook was created for each CPT sounding in the research program. Using the GO4! software program, the gorilla data files were imported into Excel (using keystroke ctrl+x) to more easily analyze the CPT data. The workbook for each test consists of 2 or more worksheets. The first worksheet contains test information such as date, sounding number, and operator. The second worksheet contains the test data and is organized as shown in Table 3.7. Additional data, such as for seismic or dissipation tests, was placed in subsequent worksheets.

Table 3.7. Excel data columns for CPT data.

Column	Data	Units
A	Test depth	m
B	Cone resistance	MPa
C	Local friction	MPa
D	Pore pressure u ₂	MPa
E	Speed	cm/s
F	Inclination X	deg
G	Inclination Y	deg
H	Inclination	deg
I	Time	sec

Once each Excel workbook was created, data from conventional drilling boring logs and laboratory tests were added in several new columns. Table 3.8 shows the complete list of column headings, including additional data such as such as coefficient of consolidation, over consolidation ratio, and friction angle.

Table 3.8. Excel data columns for complete data.

Column	Description	Symbol, Units
A	Test depth	m
B	Test depth	ft
C	Test depth (from surface)	ft
D	Cone resistance	q_c , MPa
E	Local friction	f_s , MPa
F	Pore pressure	u_2 , MPa
G	Speed[131]	cm/s
H	Inclination X[9]	deg
I	Inclination Y[10]	deg
J	Inclination[8]	deg
K	Time[12]	sec
L	Corrected total cone resistance	q_t , MPa
M	Friction ratio	R_f
N	Normalized cone resistance	Q_{T1}
O	Normalized friction ratio	F_r
P	Pore pressure ratio	B_q
Q	Normalized cone resistance	Q_{tn}
R	ODOT classification	class
S	SPT corrected	N_{60}
T	Hand penetrometer	tsf
U	Physical characteristics (%)	aggregate
V		coarse sand
W		fine sand
X		silt
Y		clay
Z	Liquid limit	LL
AA	Plastic limit	PL
AB	Water content	w_c
AC	Specific gravity	G_s
AD	Initial void ratio	e_o
AE	Initial dry density	γ_D , lb/ft ³
AF	Unconfined compressive strength	Q_u , lb/ft ²
AG	Loss on ignition	%
AH	Friction angle	ϕ , deg
AI	Cohesion,	c , psi
AJ	SBT index	I_c
AK	Soil behavior type	SBT

Section 3.4.2 describes the depth correction procedures for Column C. Column L uses the following equation:

$$q_t = q_c + u_2(1 - a) \quad (3.2)$$

where a is the area ratio of the cone (= 0.65 for a 15 cm² cone) and q_c and u_2 are obtained during CPT and imported into Excel directly from Go4!. Column M calculates the friction ratio R_f as:

$$R_f = \frac{f_s}{q_t} \times 100\% \quad (3.3)$$

where f_s is the sleeve friction. Columns N through Q are taken from spreadsheets created by the software program CPeT-IT and will be explained in Section 3.5.2.4. The equations are:

$$Q_{t1} = (q_t - \sigma_{vo}) / \sigma'_{vo} \quad (3.4)$$

$$F_r = f_s / (q_t - \sigma_{vo}) \times 100\% \quad (3.5)$$

$$B_q = (u_2 - u_o) / (q_t - \sigma_{vo}) \quad (3.6)$$

$$Q_{tn} = \frac{q_t - \sigma_{vo}}{\sigma_{atm}} * \left(\frac{\sigma_{atm}}{\sigma'_{vo}} \right)^n \quad (3.7)$$

$$n = 0.381 I_c + 0.05 \frac{\sigma_{atm}}{\sigma'_{vo}} - 0.15 \quad (3.8)$$

$$I_c = \sqrt{(3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2} \quad (3.9)$$

where: σ_{vo} = overburden stress
 σ'_{vo} = effective overburden stress
 u_2 = pore water pressure measured at shoulder location
 u_o = equilibrium pore pressure
 I_c = soil behavior type index

To calculate Q_{tn} , I_c should be calculated using Eq. 3.9 and Q_{t1} as obtained from Eq. 3.4. The value of n is then calculated using Eq. 3.8 and this I_c value. Once n is calculated, solve Eq. 3.7 for Q_{tn} . The process is then repeated starting with Eq. 3.9 and substituting Q_{tn} for Q_{t1} until Δn is less than 0.01 for successive iterations. The overburden stress, σ_{vo} , and effective overburden stress, σ'_{vo} , were calculated using unit weights given in Table 3.9 and a user-defined ground water depth in CPeT-IT. Column AK for soil behavior type (SBT) is described in Section 3.5. The remaining data were entered directly from boring logs and laboratory test results.

Table 3.9. Soil unit weights used for CPT data analysis (Lunne et al. 1997).

Soil Unit Weight		
SBT	(lb/ft ³)	(kN/m ³)
1	111.4	17.5
2	79.6	12.5
3	111.4	17.5
4	114.6	18
5	114.6	18
6	114.6	18
7	117.8	18.5
8	120.9	19
9	124.1	19.5
10	127.3	20
11	130.5	20.5
12	120.9	19

3.4.2 DEPTH CORRECTION

A GPS point was collected at each CPT sounding site. Each of these GPS points was corrected and exported as a .dbf file using GPS Pathfinder Office 3.10. These files give elevation, latitude, and longitude at the ground surface for each sounding. If the surface elevation for corresponding CPT soundings and conventional borings were different then the surface elevation of the CPT was adjusted such that depths could be directly compared. For instance, if CPT sounding C-005-0-09 was at surface elevation 897.2 ft and SPT borehole B-005-0-09 was at 898.6 ft, then the first number in column C would be 1.40 ft. and all the depths of the CPT log are adjusted accordingly. The GPS typically has an error of ± 0.5 ft. Therefore, no correction was made if the difference in elevation was less than 0.5 ft.

3.4.3 BORING LOG AND LABORATORY DATA

Once the Excel spreadsheets were corrected for surface elevation, information from boring logs and laboratory tests were entered at the correct depth (i.e., corresponding row on the spreadsheet). Figure 3.19 gives an example. The data at a given depth as noted on the laboratory sheets was entered into the appropriate row as well. If a depth range was provided for a certain data point, rather than an exact depth, the data was entered at the middle of the range. For instance, if N_{60} values were given for a 12 inch section, say from 5.5 to 6.5 ft, this data would be entered at a depth of 6.0 ft. The corresponding gradation characteristics and Atterberg limits for that sample would be entered at the same depth. Shelby tube data was entered at the depth corresponding to the midpoint of the tube.

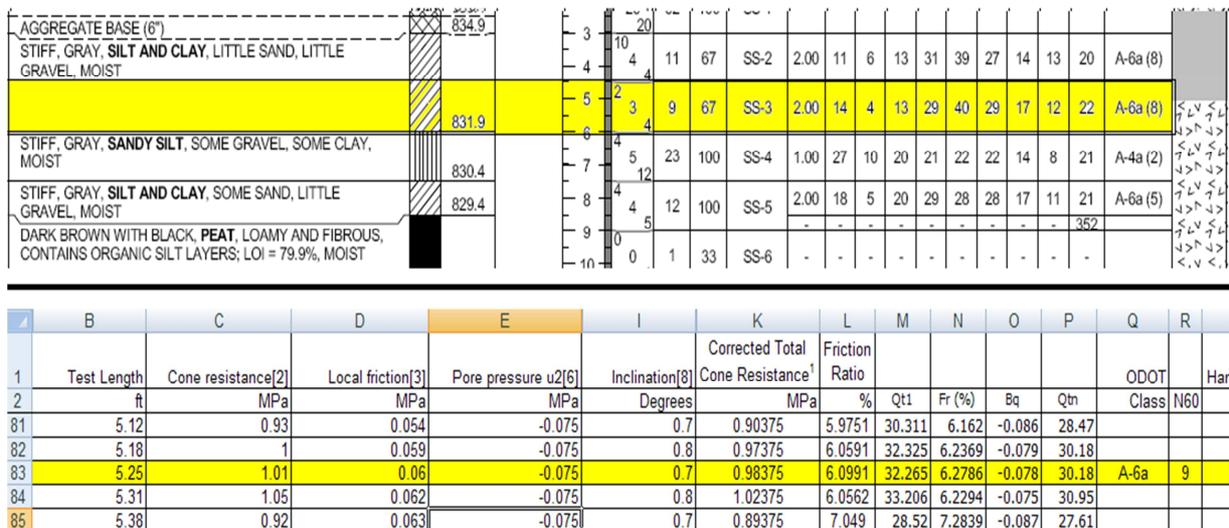


Figure 3.19. Boring log data and corresponding spreadsheet row.

3.4.4 MASTER WORKBOOK FOR 17 SOIL TYPES

Once the laboratory and boring log data were entered into the CPT spreadsheets, a master workbook was created with a worksheet for each of the 17 modified AASHTO soil types. To fill this master workbook, all values of corresponding CPT and conventional data from each CPT file were examined to determine validity. If a given set of corresponding data was determined to be valid, it was included in the master workbook database, which was then used to generate correlations.

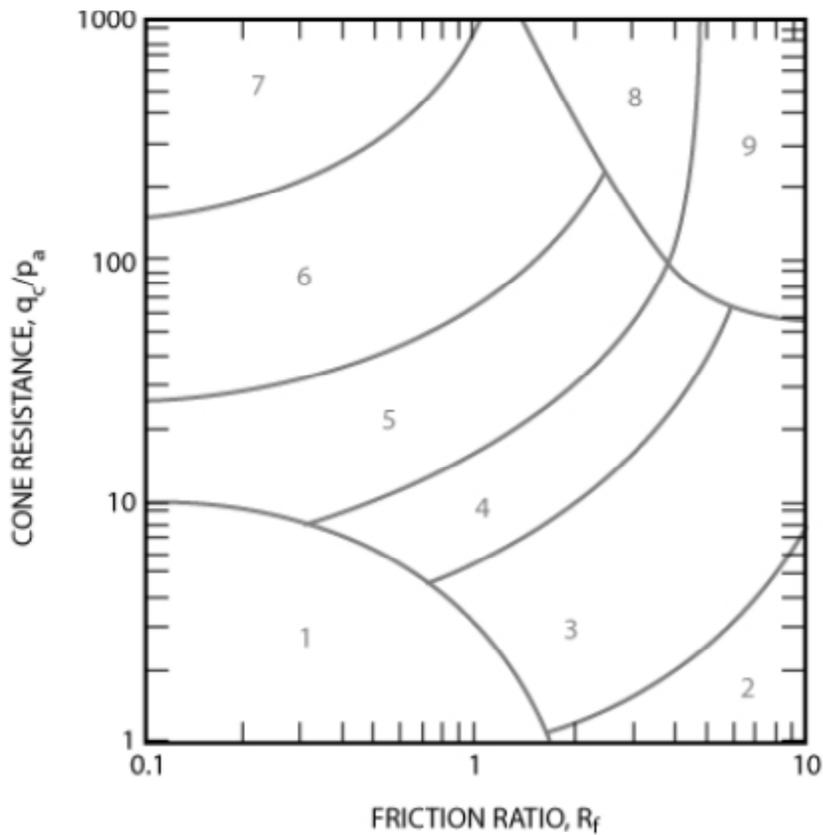
Several criteria were used to assess data validity. First, the date of the original boring was checked to verify whether or not the site had undergone any subsequent changes that would affect soil conditions for the CPT sounding (e.g., construction of an embankment). In such cases, the area of influence of the change was determined and any CPT data taken in this area was not used. For older borings (> 10 years), data in the top 5 ft was not used to avoid property changes due to freeze-thaw or desiccation. Data was also not included if a soil layer was less than 1.5 ft thick because the accuracy of the GPS surface elevations was not precisely known and cone tip resistance may not reach its full value for thin layers (Lunne et. al 1997). If the zero readings taken before and after a CPT were not within the acceptable range, the data was not used for correlation purposes.

Data was also eliminated from the correlations if it appeared to be unreasonable. The maximum allowable distance between a conventional boring and a corresponding CPT sounding was 15 ft and the minimum distance was $10 \times$ auger diameter. Even with this precaution, unexpected lateral soil variability sometimes occurred between the CPT and SPT holes. For instance, if a boring log indicates soft clay and $N_{60} = 3$ at a depth of 12.7 m and the CPT log shows a corresponding tip resistance of 25 MPa, this would be unreasonable. A possible explanation might be that a cobble or sand lens was encountered for the CPT but for the boring. If many such instances of unreasonable data correlation occurred for a given CPT sounding, the GPS surface elevations may have been incorrect and no data was used for the entire sounding.

Heaving sands (A-3 and A-3a) were encountered in many locations and the data was included in the correlations. However, this data may not be representative of true soil properties. The N_{60} values for these sands may not be accurate and the conventional samples may not correspond to the indicated depths. This data was included because without it, the database for A-3 would be scarce and because the OGE uses SPT values for heaving sands in design.

3.4.5 CORRELATION AND INTERPRETATION PROCEDURES

This section describes procedures that were followed to develop correlations between CPT and conventional borehole data. The first step was to reproduce the soil classification charts shown in Figure 3.20. The research data was plotted on the same axes to assess validity of these charts for the ODOT soil classification system and Ohio soils. These plots are important because prediction of soil type (e.g., sand vs. clay) is a key requirement for routine CPT usage. The plots mainly follow the Unified Soil Classification System (UCSC) and yield accurate representation of soil behavior (Lunne et. al 1997, Robertson 2009, Mayne 2007). However, these plots do not necessarily correlate with soil texture (i.e., grain size information), but are more indicative of general soil behavior.

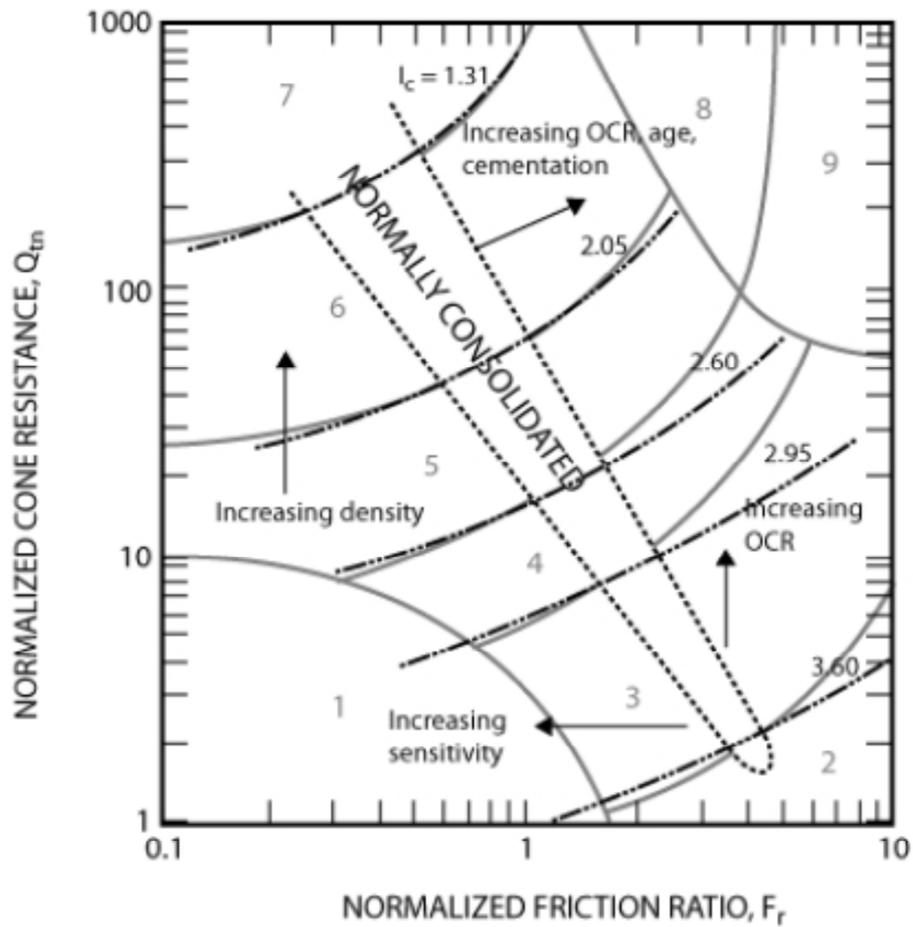


<i>Zone</i>	<i>Soil Behavior Type</i>
1	<i>Sensitive, fine grained</i>
2	<i>Organic soils - clay</i>
3	<i>Clay - silty clay to clay</i>
4	<i>Silt mixtures - clayey silt to silty clay</i>
5	<i>Sand mixtures - silty sand to sandy silt</i>
6	<i>Sands - clean sand to silty sand</i>
7	<i>Gravelly sand to dense sand</i>
8	<i>Very stiff sand to clayey sand*</i>
9	<i>Very stiff fine grained*</i>

** Heavily overconsolidated or cemented*

$P_a = \text{atmospheric pressure} = 100 \text{ kPa} = 1 \text{ tsf}$

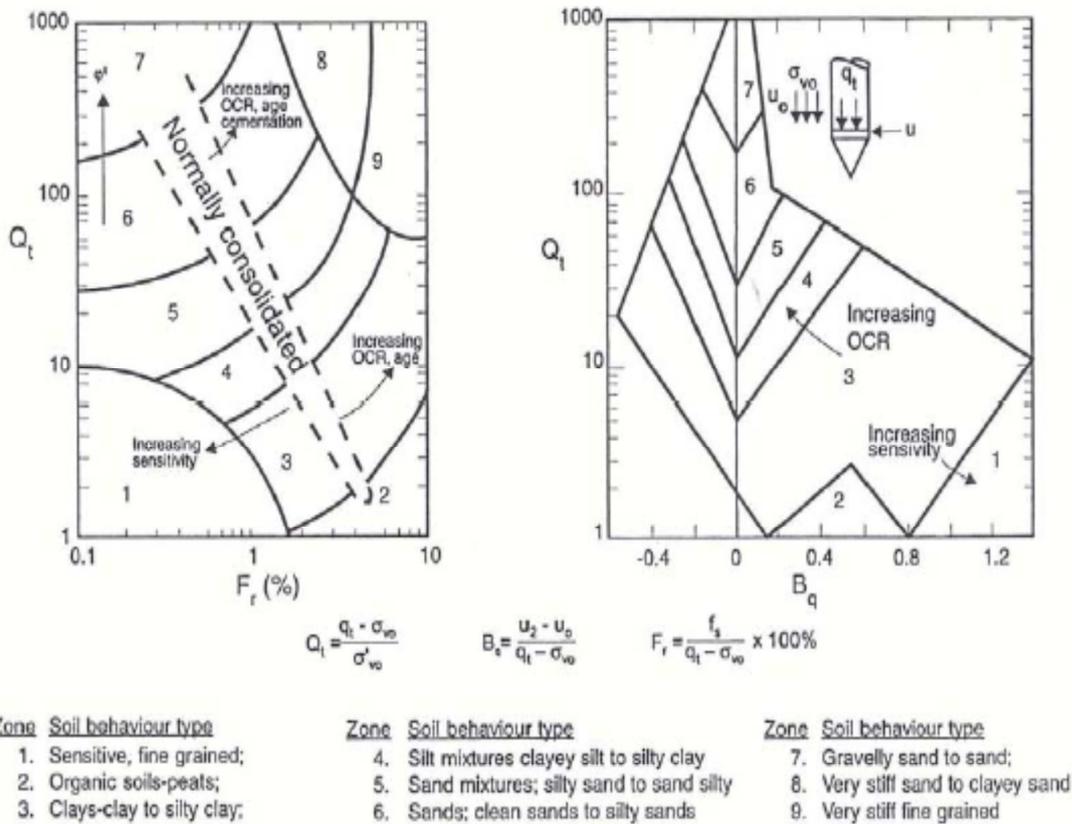
(a)



<i>Zone</i>	<i>Soil Behavior Type</i>	<i>I_c</i>
1	<i>Sensitive, fine grained</i>	N/A
2	<i>Organic soils – clay</i>	> 3.6
3	<i>Clays – silty clay to clay</i>	2.95 – 3.6
4	<i>Silt mixtures – clayey silt to silty clay</i>	2.60 – 2.95
5	<i>Sand mixtures – silty sand to sandy silt</i>	2.05 – 2.6
6	<i>Sands – clean sand to silty sand</i>	1.31 – 2.05
7	<i>Gravelly sand to dense sand</i>	< 1.31
8	<i>Very stiff sand to clayey sand*</i>	N/A
9	<i>Very stiff, fine grained*</i>	N/A

** Heavily overconsolidated or cemented*

(b)



(c)

Figure 3.20. Soil behavior type plots: (a) Uncorrected cone resistance/atmospheric pressure vs. friction ratio, (b) Normalized cone resistance (Q_{tn}) vs normalized friction ratio (R_f), and (c) Normalized cone resistance (Q_t) vs normalized friction ratio (F_r) and pore pressure ratio (B_q) (Robertson and Cabal 2010).

The following plots are included in the current report:

- Fines content vs. friction ratio R_f
- Liquid limit vs. corrected tip resistance, q_t
- Plastic limit vs. corrected tip resistance, q_t
- Dry unit weight vs. corrected tip resistance, q_t
- Friction ratio, R_f vs. corrected tip resistance, q_t
- Normalized friction ratio, F_r vs. normalized cone resistance, Q_{T1}
- SPT N_{60} vs. corrected tip resistance, q_t
- SPT N_{60} vs. soil behavior index, I_c
- Undrained shear strength vs. corrected tip resistance, q_t

A minimum of 10 data points were used to generate each correlation plot. As such, there was some quality laboratory data that could not be correlated with CPT due to a lack of data sufficiency. In these instances, previously developed correlations are presented.

3.5 DATA REDUCTION AND PROCESSING

3.5.1 INTRODUCTION

This section describes methods of data reduction, processing, and presentation. The program that is currently used to generate CPT reports is CPeT-IT. This section will describe CPeT-IT and its use for data analysis, and will also explain how to use and interpret the generated CPT reports.

3.5.2 CPET-IT USERS GUIDE

The CPeT-IT software program was developed by Geologismiki (Serres, Greece) in conjunction with Gregg Drilling, Inc. (California, USA). The main function of CPeT-IT is to process field CPT data to yield useful soil properties. CPeT-IT produces a report that contains raw data plots as well as corrected plots along with estimated soil properties.

3.5.2.1 GETTING STARTED WITH CPET-IT

This section outlines the CPeT-IT program and describes the most commonly completed tasks. Other functions and capabilities of CPeT-IT are described in the official user's guide at:

<http://www.geologismiki.gr/Documents/CPeT-IT/HTML/index.html>

Raw CPT data is saved as a gorilla file (.gru). CPeT-IT cannot directly import .gru files, thus the .gru files need to be converted to text (.txt) files. A special add-on (converter.exe) is used for the conversion process. Figure 3.21 shows the opening screen. To convert the .gru files to .txt, first open the folder that contains the needed files and the files will appear in the right hand box. Select the files for conversion (multiple files can be selected at once), specify the location to save the .txt files using "browse directory", then click "convert". The default units are correct and do not need to be adjusted. Although the .gru file contains all the data from a given test (depth, tip resistance, sleeve friction, pore pressure, inclination in x, inclination in y, total inclination, speed, and time), the only columns that are exported to the .txt file are depth (m), cone resistance (MPa), sleeve friction (kPa), and pore pressure(kPa). The rest of the data is ignored. To convert the .gru file to an Excel (.xls) file to see all the data columns, please refer to technical note "Converting Gorilla files to Excel Files" located in Appendix C (Brylawski 2009).

Once the desired files have been converted to .txt, they can then be imported to CPeT-IT by clicking the  button in the upper left hand corner of the screen. A window will ask for the file type. Choose the correct import file option (i.e., .txt file), and click "ok". The next box that will open is shown in Figure 3.22. Select the current directory where the file is located. Once the directory is open, all .txt files in the directory will be displayed in the right hand box. Select the tests that need to be imported by clicking on each (hold the "ctrl" button to select multiple tests). If using the converter.exe add-on as described previously, no other parameters on this window need to be changed, the user can click "import file", and the file(s) will then be visible on the CPeT-IT homepage. If a test is imported from a separate format, the user needs to make sure the units are consistent with the default units for the program (m, MPa, kPa). Once the data has been imported, a conversion to English units (ft, tsf, psi) can be made. After a test has been chosen from the file selection window, a preview of data and input

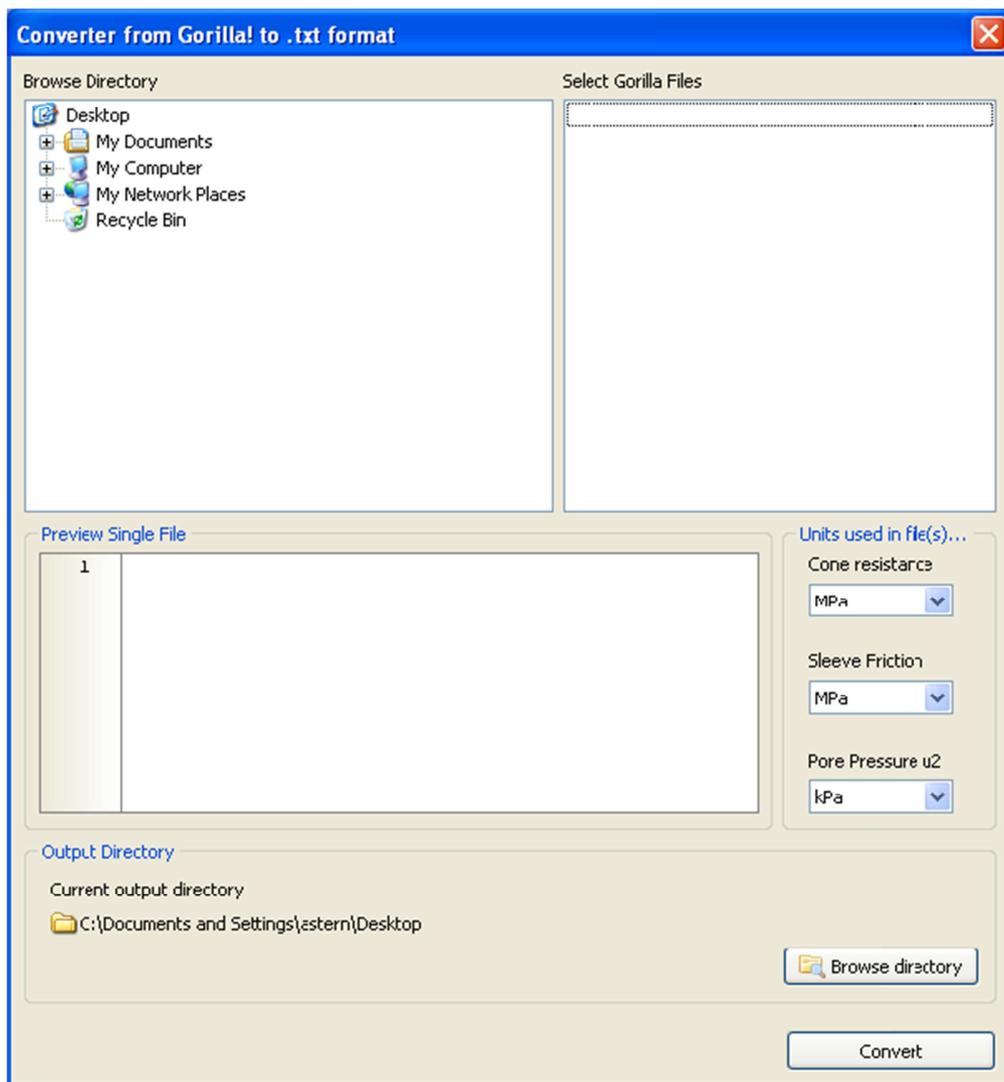


Figure 3.21. Text converter add-on for CPeT-IT.

parameters will be shown. This box will allow the user to change any necessary parameters such as “data begin from line:” option. If these options are not correct, the test will not be imported as desired.

The screen in Figure 3.23 will appear once the file is imported. Initially, each file has a generic name. To change the file name, double click on the name and a box will open. Also in this box are options to enter the depth to the ground water level (GWL), the number of intervals that should be averaged (default = 1), and whether the soil unit weight should be auto-calculated or entered by the user. Test data that is imported into CPeT-IT should be from the same project. To enter the project information, click on the “Project” drop down menu and choose “Project Parameters.” From this box, the units can be changed as well as company/project information.

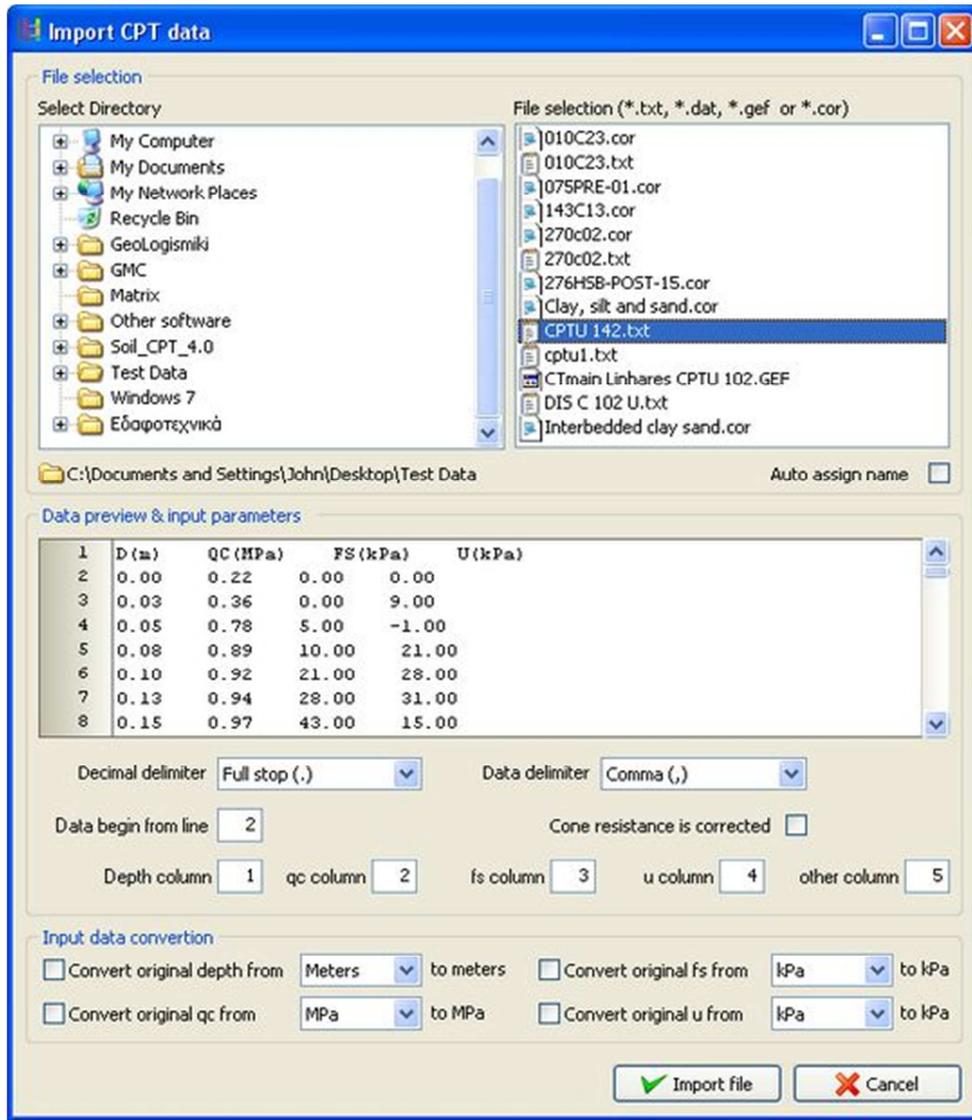


Figure 3.22. Screen for importing CPT data to CPeT-IT.

3.5.2.2 USER INPUT DATA

Some parameters are automatically calculated by the CPeT-It program. The following values are needed from the user:

- Units for display (English or metric)
- Atmospheric pressure, p_a (1.06 tsf or 0.1 MPa)
- Elevation of ground surface (ft or m)
- Depth to groundwater table, z_w (ft or m) - pore pressures below are assumed to be hydrostatic
- Net area ratio for cone, a (default to 0.65)
- Relative density constant, C_{DR} (default to 350)
- Undrained shear strength cone factor for clays, N_{kt} (default to 14)

- Overconsolidation number, k_{OCR} (default to 0.33)
- Unit weight of water (default to 62.4 pcf or 9.81 kN/m³)
- Probe radius (default to 0.14337 ft or 0.0437 m)
- Auto transition layer detection: When checked, the software will try to detect data that are in transition from either clay to sand or vice-versa. Data belonging to transition zones will not be shown in the estimations plots.

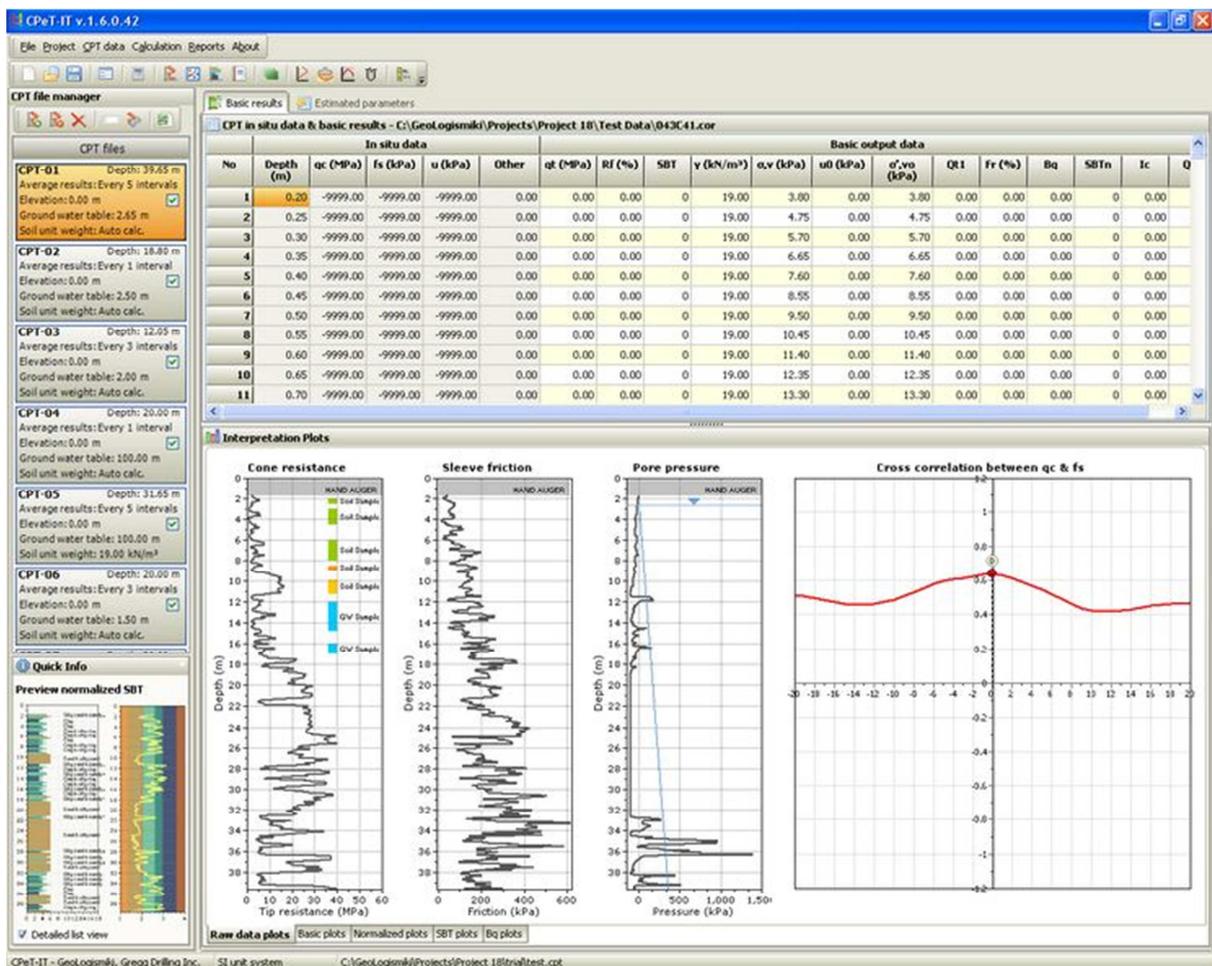


Figure 3.23. Screen after loading test data into CPeT-IT.

The above data can be entered by clicking the  icon located in the CPT File Manager toolbar. The method to adjust the constants is described below. One of the more important values is the groundwater table elevation. Figure 3.24 shows a pore pressure plot without and with a GWL added. The blue line represents the equilibrium pore pressure, u_0 .

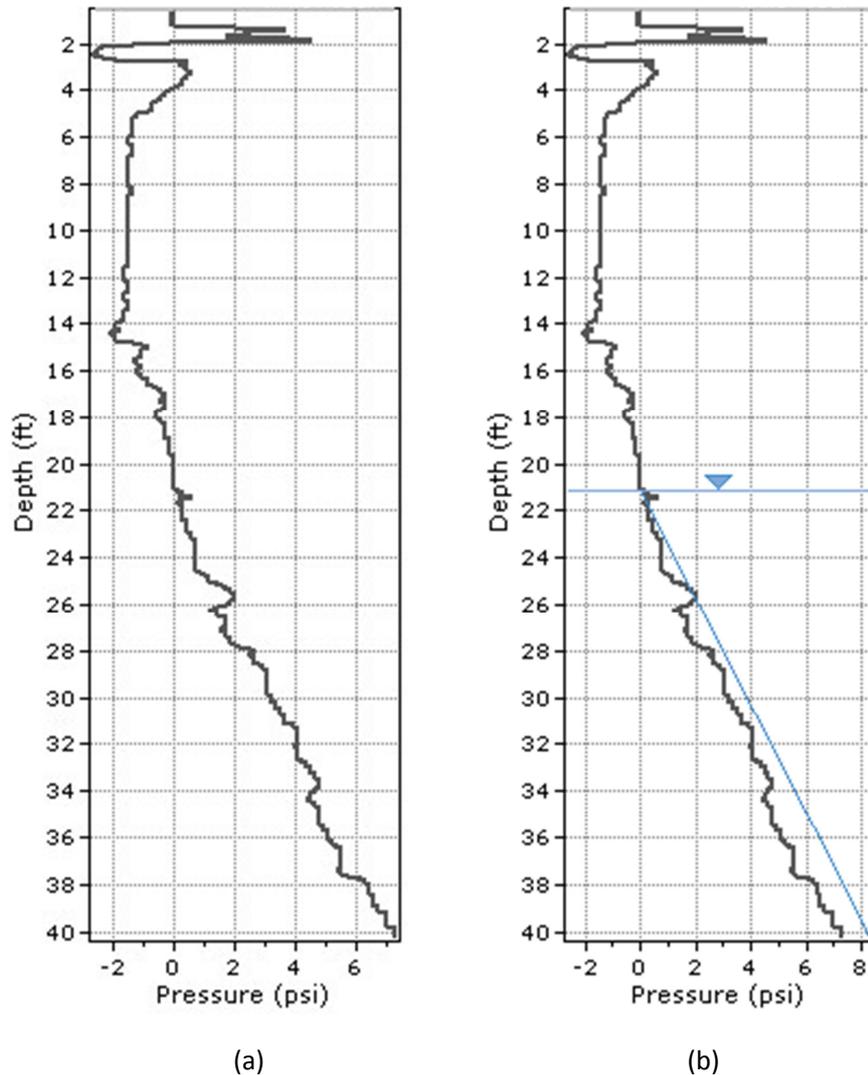


Figure 3.24. Pore pressure profiles: (a) without GWL identified, (b) with GWL identified.

If not known from a piezometer or adjacent boring, the GWL must be estimated from the CPT sounding pore pressure plot or a from a dissipation test. In Figure 3.24, positive pore pressures were measured at the beginning of the sounding, but then negative values were recorded for the next 20 ft. At 21.1 ft, the pore pressure again reads positive and continues to increase at a constant rate. This sounding clearly indicates the location of the GWL, but for many tests this determination will not be straightforward. Figure 3.25 shows an example of such a case. Records such as this can be caused by perched groundwater and undrained soils. Undrained soils can produce transient positive or negative pore pressures, depending on the tendency of the soil to contract or dilate during cone penetration. For cases such as Figure 3.25, conventional methods (e.g., piezometers) will be needed to locate the GWL.

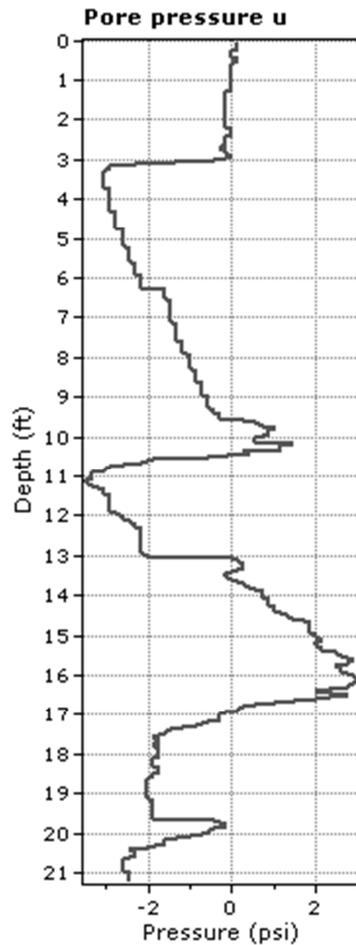


Figure 3.25. Pore pressure plot in which the GWL is unclear.

Tests are imported in metric units. To change to English units, click the project dropdown menu and select project parameters. The elevation of the ground surface can be obtained from GPS coordinates taken at the site. For a 15 cm² cone, the probe radius and cone area ratio will not need to be changed.

3.5.2.3 GENERATION OF REPORTS

Once the required information has been entered into CPeT-IT and any manipulations of the estimated parameters (described below) have been completed, a project report can be created. To generate a report, click on the Reports dropdown menu located on the top toolbar of the program. The options on this menu include:

- Report Page Settings
- Selected CPT Report
- Overall CPT Report
- Create Overlay Report

Figure 3.26 is displayed if the “Report Page Settings” option is selected. Each check box option is a page in the report. While pages can be added or removed from the report, the individual page contents cannot be edited. The contents of the available pages are:

- Page 1: Raw Data Plots
 - Cone resistance, q_c
 - Sleeve friction, f_s
 - Pore pressure, u_2
 - Cross correlation between q_c and f_s
- Page 2: Soil Behavior Type Page (SBT) Plots
 - SBT plot (q_t/p_a vs. R_f)
 - B_q plot (B_q vs. Q_t)
- Page 3: Normalized Soil Behavior Type Page (SBT_n) Plots
 - SBT_n plot (Q_{tn} vs. F_R)
 - Normalized B_q plot (Q_{tn} vs. B_q)
- Page 4: Basic Interpretation Plots
 - Cone resistance, q_t
 - Friction ratio, R_f
 - Pore pressure, u_2
 - SBT index, I_c
 - Soil behavior type
- Page 5: Basic Interpretation Plots (Normalized)
 - Normalized cone resistance, Q_{t1n}
 - Normalized friction ratio, F_R
 - Normalized pore pressure ratio, B_q
 - SBT_n index, I_c
 - Normalized soil behavior type
- Pages 6 and 7: Estimations Plots
 - Permeability, K_{SBT}
 - SPT N_{60}
 - Young’s modulus, E_s
 - Relative density, D_r
 - Friction angle, ϕ'
 - Constrained modulus, M
 - Shear modulus, G_o
 - Shear strength, s_u
 - Undrained strength ratio, s_u/σ'_v
 - Overconsolidation ratio

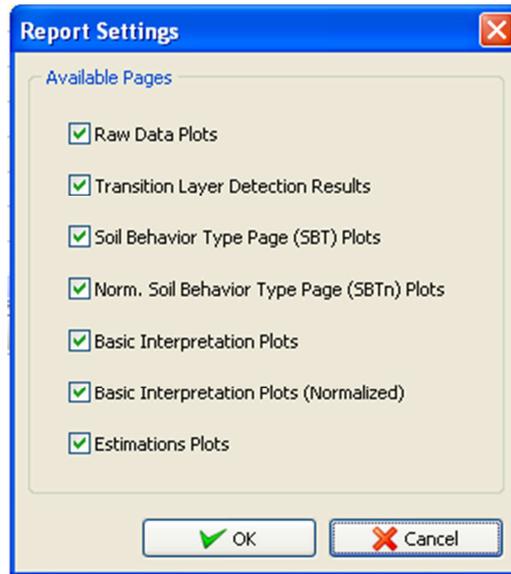


Figure 3.26. Report page settings.

To create a report for a single test, highlight the desired sounding and select “Selected CPT Report.” To generate a report for the entire project, select “Overall Report.” CPeT-IT can also compare adjacent soundings or conditions across a site by selecting the “Create Overlay Report” option. Every test in the project will be initially plotted. To remove unwanted tests, unselect the test from the top of the overlay report settings page. Once all desired tests are selected, click “Preview Report” and the test data will be plotted together. This option is particularly useful to check the consistency of two soundings in close proximity.

The following disclaimer should be included on the cover page of all CPT reports:

“These Cone Penetration Test (CPT) Soundings follow ASTM D 5778 and were made by ordinary and conventional methods and with care deemed adequate for the Department’s design purposes. Since subsurface conditions outside each CPT sounding are unknown, and soil, rock, and water conditions cannot be relied upon to be consistent or uniform, no warrant is made that conditions adjacent to this sounding will necessarily be the same as or similar to those shown on these logs. Furthermore, the Department will not be responsible for interpretations, assumptions, projections, or interpolations made by the contractor, or other users of this report. While the Department believes that the information as to the condition and materials reported is accurate, it does not warrant that the information is necessarily complete. Pore pressure measurements and subsequent interpreted groundwater levels should be used with discretion since they represent dynamic conditions. Dynamic pore pressure measurements may deviate substantially from hydrostatic conditions, especially in cohesive soils.”

3.5.2.4 CPET-IT EQUATIONS AND PLOTS

This section presents equations that are used for the calculation of estimated parameters in CPeT-IT. These equations can also be used outside of CPeT-IT to estimate soil parameters. Section 4.4 presents additional equations that may be used to estimate parameters from CPT data logs.

3.5.2.4.1 SOIL BEHAVIOR TYPE PLOT

The soil behavior type (SBT) plots, both normalized and non-normalized, are shown in Figure 3.20. These plots were initially developed by Lunne et al. (1997) and have been updated and improved by Robertson (2009). One of the major applications of CPT is the determination of soil stratigraphy and identification of soil type. Figure 3.20 shows the most recently updated and most widely used charts for this purpose. Robertson et al. (1986) and Robertson (1990) have emphasized that SBT charts are useful because the cone responds to the in-situ mechanical behavior of the soil and not directly to soil classification criteria such as grain-size distribution and soil plasticity in the Unified Soil Classification System (USCS). Although Molle (2005) states that soil classification criteria relate reasonably well to *in situ* soil behavior, there are instances where the SBT will differ from the actual soil type. For example, a soil with 60% sand and 40% fines may be classified as “silty sand” or “clayey sand” based on the USCS. If the soil contains non plastic fines, the soil behavior will be controlled more by the sand and the SBT would predict a more sandy material, like “sand mixtures”. If the fines have higher clay content and are thus more plastic, the SBT will indicate a “silt mixture” (Robertson 2009). Robertson (2009) provided the following summaries that should be considered when using a SBT chart:

- Very stiff, heavily overconsolidated fine-grained soils tend to behave more like a coarse-grained soil in that they tend to dilate under shear and can have high undrained shear strength compared with their drained strength and can have a CPT-based SPT in either zone 4 or 5.
- Soft, saturated low-plasticity silts tend to behave more like clays because they have low undrained shear strength and can have a CPT-based SBT in zone 3 (clay to silty clay).

3.5.2.4.2 SOIL UNIT WEIGHT

Soil unit weight is an important parameter because overburden stress is used in many of the CPeT-IT analysis equations. Unit weight can be estimated using two methods. The first method is through SBT as shown previously in Table 3.9. Based on discussions with an ODOT engineer (C. Pridemore 2010), these unit weights are reasonably accurate for materials commonly encountered in Ohio. The second method to estimate unit weight is using the following equation:

$$\frac{\gamma}{\gamma_w} = 0.27 \log(R_f) + 0.36 \log\left(\frac{q_t}{\sigma_{atm}}\right) + 1.236 \quad (3.10)$$

where γ_w is the unit weight of water. The option tab allows the user to choose if the soil unit weight is auto-calculated. If so, the unit weight will be calculated using one of these two methods. If this box is unchecked, the unit weight will default to 19 kN/m³ (120.9 pcf). If the actual unit weight for a particular soil layer is known, this value should be manually entered into CPeT-IT. Mayne et al. (2010) provides further discussion on the estimation of soil unit weight from CPT.

3.5.2.4.3 EQUIVALENT SPT N_{60}

The following equation is used to estimate SPT N_{60} :

$$\frac{q_t/\sigma_{atm}}{N_{60}} = 8.5 \left(1 - \frac{I_c}{4.6}\right) \quad (3.11)$$

Jeffries and Davies (1993) suggested that Eq. 3.11 provides a better estimate of N_{60} than actual measured values due to the low reliability of the SPT.

3.5.2.4.4 RELATIVE DENSITY

Soil relative density can be estimated as (Lunne et al. 1997):

$$D_r = \sqrt{Q_{tn}/C_{Dr}} \quad (3.12)$$

where C_{Dr} is the relative density constant and is usually taken as approximately 350. Soil relative density is only calculated for SBT_n zones 5, 6, 7, and 8. The value $C_{Dr} = 350$ is considered most appropriate for unaged quartz sands that are younger than 1,000 years (Robertson and Cabal 2010). The constant is closer to 300 for fine sands and 400 for coarse sands. C_{Dr} increases significantly when the age of the soil exceeds 10,000 years.

3.5.2.4.5 OVERCONSOLIDATION RATIO

The overconsolidation ratio (OCR) can be estimated as (Kulhawy and Mayne 1990):

$$OCR = k_{OCR}(q_t - \sigma_{vo}) \quad (3.13)$$

where the default value for k_{OCR} is 0.33 and the expected range is 0.2 to 0.5. If the soil type is known to be aged or heavily overconsolidated, then higher values of k_{OCR} should be specified. The user must manually enter k_{OCR} in such cases. OCR is calculated only for soils in SBT_n zones 1, 2, 3, 4, and 9.

3.5.2.4.6 UNDRAINED SHEAR STRENGTH

Undrained shear strength, s_u , can be difficult to assess because of the different types of tests that are used to determine s_u (e.g., triaxial shear, simple shear, vane shear). The value of undrained shear strength estimated by CPeT-IT corresponds to the simple shear test. This value often represents an average strength (Robertson and Cabal 2010) and is calculated as:

$$s_u = \frac{q_t - \sigma_v}{N_{kt}} \quad (3.14)$$

where N_{kt} is the undrained shear strength constant. Typical values of N_{kt} range from 10 to 18 with 14 being the default value in CPeT-IT. N_{kt} tends to increase with increasing soil plasticity and decrease with increasing soil sensitivity. Higher values of N_{kt} yield more conservative estimates of s_u . The range of N_{kt} reported at the CPT '10 conference was 8 to 27. Variations in N_{kt} are associated with (1) stress path (e.g., $s_{u,DSS}$, $s_{u,CIUC}$, $s_{u,UU}$, $s_{u,VST}$, $s_{u,PMT}$), (2) soil rigidity (G/s_u), (3) strain rate effects, (4) partial consolidation during penetration, testing, or between penetration and testing, (5) sample disturbance, (6) spatial variability between CPT and conventional samples, (7) CPTU area ratio correction factors, (8) drift in CPT zero load readings, and (9) soil structure and fabric effects, such as fissuring and sensitivity (Schneider 2010).

To change the value of N_{kt} in CPeT-IT, click the  icon and modify the “undrained strength factor”. Using known values of s_u , back-calculated values of N_{kt} ranged from 9 to 18 in the current research. Thus, the default value of 14 in CPeT-IT appears to be reasonable for ODOT purposes.

3.5.2.4.7 EFFECTIVE FRICTION ANGLE

The effective stress friction angle, ϕ' , can be estimated by using following equation (Kulhawy and Mayne 1990):

$$\phi'(deg) = 17.60 + 11 \log Q_t \quad (3.15)$$

which is applicable for SBT_n zones 5, 6, 7 and 8.

3.5.2.4.8 YOUNG'S MODULUS

Young's Modulus, E_s , can be estimated using the following equation (Robertson and Cabal 2010):

$$E_s = \alpha_E (q_t - \sigma_{vo}) \quad (3.16)$$

where:

$$\alpha_E = 0.015 \times 10^{0.55 I_c + 1.68} \quad (3.17)$$

This relationship is valid for $I_c < 2.60$.

3.5.2.4.9 CONSTRAINED MODULUS

The constrained modulus M can be estimated using the following equation (Robertson and Cabal 2010):

$$M = \alpha_M (q_t - \sigma_{vo}) \quad (3.18)$$

$$\text{for } I_c > 2.2: \quad \alpha_M = Q_t \quad (\text{if } Q_t < 14, \text{ use } \alpha_M = 14) \quad (3.19)$$

$$\text{for } I_c < 2.2: \quad \alpha_M = 0.0188 \times 10^{0.55 I_c + 1.68} \quad (3.20)$$

The constrained modulus is used to estimate permeability from pore pressure dissipation data (Section 3.5.2.5). If laboratory testing was performed to obtain M at the appropriate depth, this value should be entered manually.

3.5.2.4.10 SMALL STRAIN SHEAR MODULUS

The small strain shear modulus, G_o , can be estimated using the following equation (Robertson and Cabal 2010):

$$G_o = \alpha_M (q_t - \sigma_{vo}) \quad (3.21)$$

where α_M is defined by Eq. 3.20.

3.5.2.4.11 PERMEABILITY

The following table can be used to estimate soil permeability in the absence of dissipation tests

Table 3.10. Estimates of soil permeability based on SBT_n (Robertson and Cabal 2010).

Soil Permeability		
SBT _n	Permeability (ft/sec)	(m/sec)
1	3×10^{-8}	1×10^{-8}
2	3×10^{-7}	1×10^{-7}
3	1×10^{-9}	3×10^{-10}
4	3×10^{-8}	1×10^{-8}
5	3×10^{-6}	1×10^{-6}
6	3×10^{-4}	1×10^{-4}
7	3×10^{-2}	1×10^{-2}
8	3×10^{-6}	1×10^{-6}
9	1×10^{-8}	3×10^{-9}

Estimates of soil permeability as given by Table 3.10 must be considered very approximate.

3.5.2.5 DISSIPATION TEST ANALYSIS

Pore pressure dissipation test data is also analyzed by CPeT-IT. If a .gru file contains dissipation data, there will be two .txt files created during conversion – one for cone advancement and one for pore pressure dissipation. To import a dissipation .txt file into CPeT-IT, select the appropriate sounding, click the  button on the main toolbar, and the window shown in Figure 3.27 will appear.

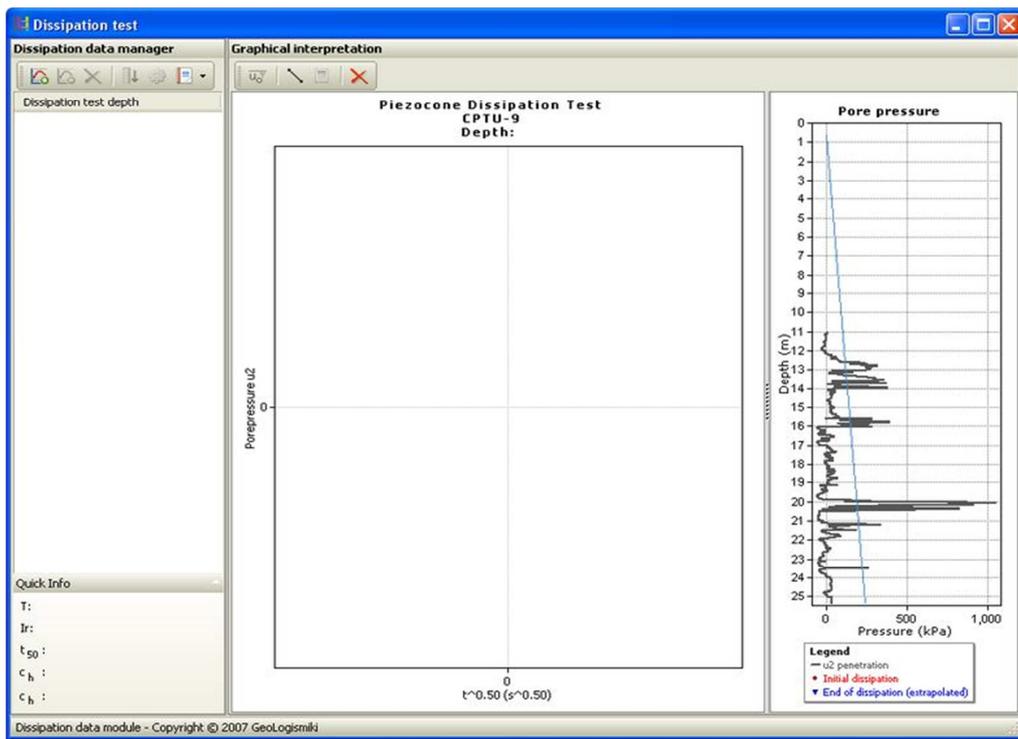


Figure 3.27. Dissipation test home screen.

To import a test, click the  button and choose the option to download a .txt file. Once the dissipation data is imported into CPeT-IT, the screen will appear as Figure 3.28. The user then clicks the  button and traces a line over the linear portion of the data. This line will be extrapolated to show the estimated initial pore pressure. The  button should be pressed once this line is drawn.

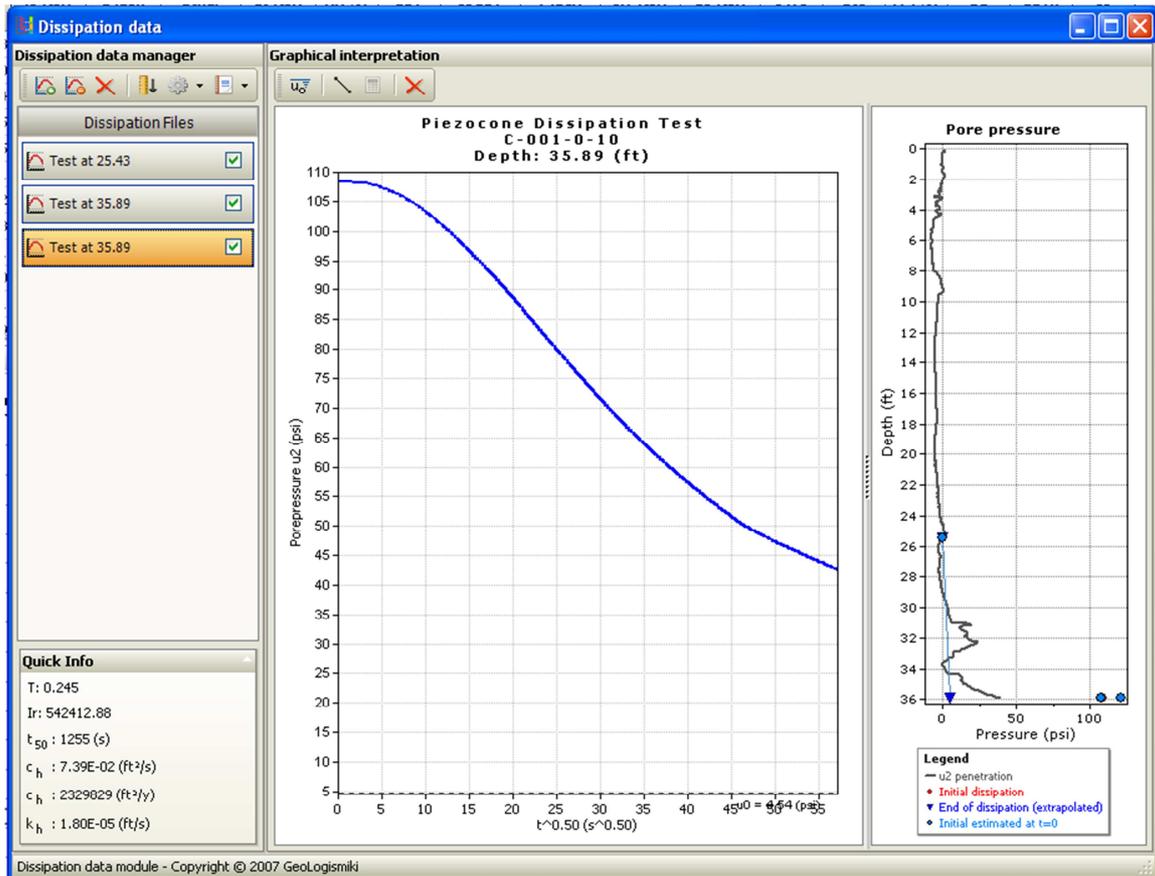


Figure 3.28. Dissipation test data imported into CPeT-IT.

The Quick Info box in Figure 3.29 shows the results of such a calculation. The red dashed line indicates the square root time, $\sqrt{t_{50}}$, corresponding to 50% dissipation. The equation used to calculate the coefficient of consolidation in the horizontal direction is (Houlsby and Teh 1988):

$$c_h = \frac{T^* \times r^2 \times I_r^{0.5}}{t_{50}} \quad (3.22)$$

where: T^* = time factor given in Figure 3.30
 r = piezocone radius
 I_r = Stiffness Index = G/s_u (estimated by CPeT-IT)

If 50% dissipation is specified, which is usually the case, $U_2^* = 0.5$ and $T^* = 0.245$ in Figure 3.30.

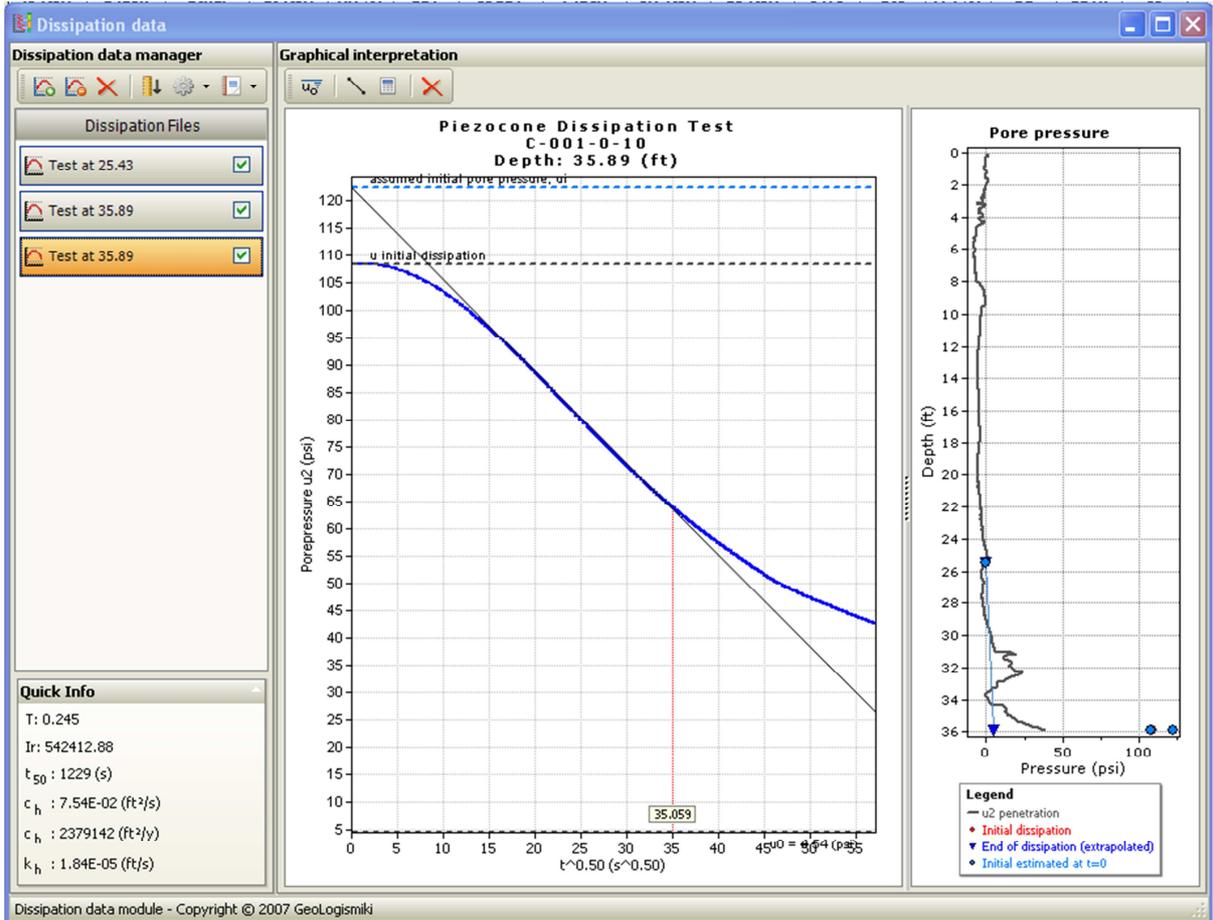


Figure 3.29. Dissipation test data after analysis.

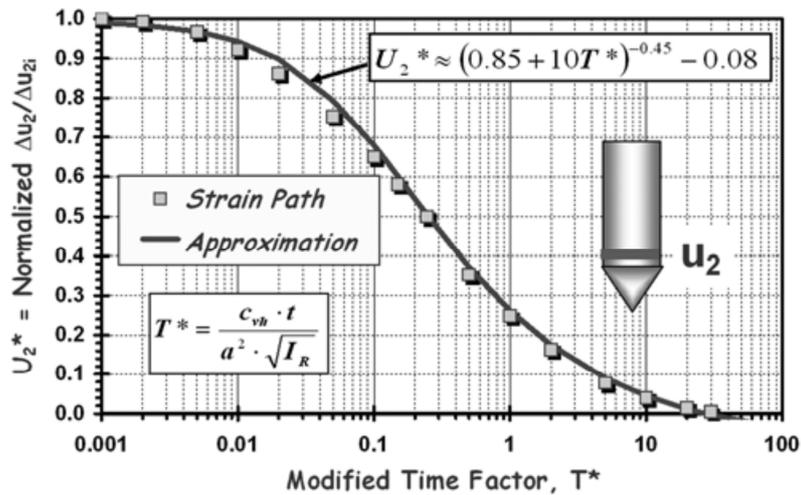


Figure 3.30. Chart used to find modified time factor (Houlsby and Teh 1988).

The GWL is taken from the original CPeT-IT page for the test. If a different value is used for the dissipation analysis, it can be manually entered using the u_o button. Parameters for Equation 3.22 are normally taken from the CPeT-IT file, but can also be manually entered by pressing the  button, which brings up Figure 3.31. These values are used in the calculation unless there is a known discrepancy in the CPTU file.

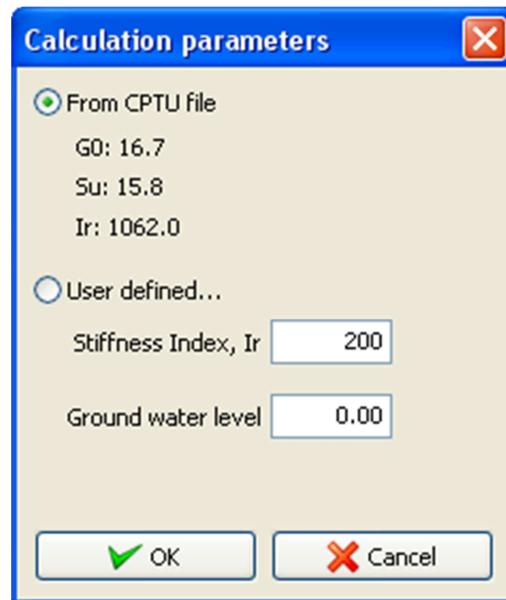


Figure 3.31. Calculation parameters for dissipation test.

Once c_h is known, horizontal soil permeability can be estimated using the following equation:

$$k_h = c_h \frac{\gamma_w}{M} \quad (3.23)$$

where M is given by Eq. 3.18. A dissipation test analysis can also be performed without CPeT-IT using the raw data plot given from GOnsite! and using the raw data files. ASTM D6067 provides useful information on standard procedures for analysis of pore pressure dissipation tests.

3.5.2.4 CPET-IT ADDITIONAL INFORMATION

The equations in CPeT-IT are widely used for CPT analysis. Key features of CPeT-IT and similar programs are:

- Accurate specification of the GWL is important
- Default parameters (e.g., C_{Dr} , k_{OCR}) are included
- Manual manipulation of the raw data and estimated data is sometimes needed, and important in some cases.

In addition to the methods described above, CPTeT-IT can also provide estimates of:

- Settlement
- Single pile capacity
- Geotechnical cross section

3.5.3 SEISMIC TEST ANALYSIS

Seismic testing should be completed every 0.5-1.5 m (2-5 ft) to obtain a shear wave velocity profile for the soil. The test procedure is described in ASTM D740 and in Section 3.3.6. Equations 3.24 and 3.25 are used in the analysis and Figure 3.32 provides a description of the variables. The length, L , of signal travel and the shear wave velocity, V_s , are calculated as:

$$L = [(E_s - E_G + D_G)^2 + X^2]^{0.5} \quad (3.24)$$

$$V_s = \frac{L_{R2} - L_{R1}}{\Delta T_{R2-R1}} \quad (3.25)$$

where: E_s = ground surface elevation at the signal source
 E_G = ground surface elevation at the top of the sounding
 D_G = depth to geophone receiver
 X = horizontal distance between signal source and CPT sounding
 L_1 = signal travel length for receiver at depth D_1
 L_2 = signal travel length for receiver at depth D_2
 ΔT_{R2-R1} = difference in signal travel times for depths D_2 and D_1

The resulting plot of V_s vs. depth gives the shear wave velocity profile for the CPT sounding.

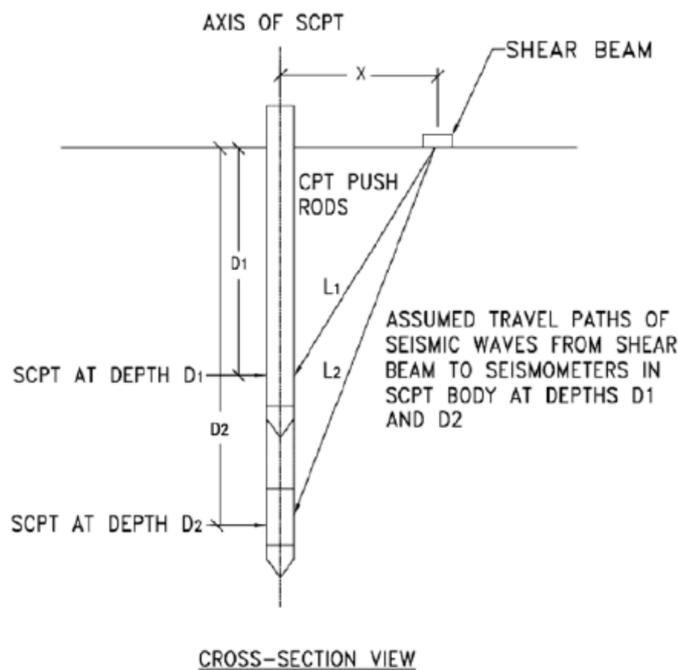


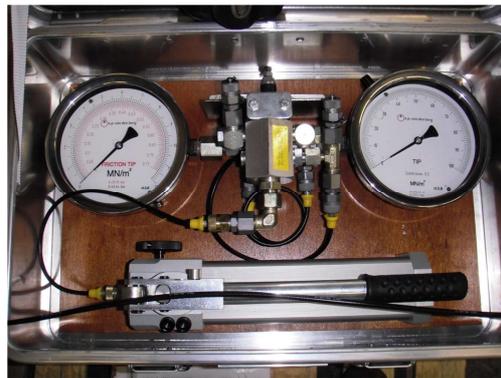
Figure 3.32. Shear wave velocity tests at two depths (ASTM 2008).

3.6 CONE CALIBRATION

Electric cones need to be calibrated every three months (more often during heavy use) to ensure quality CPT data. To do this, the measured tip resistance, sleeve friction, and pore pressure are verified directly using independent load cells and pressure gages. Figure 3.33 shows the cone calibration equipment. A manual is included with this equipment that describes the complete procedure.

Currently, all calibration work is conducted inside the cabin of the CPT machine. To prepare for a calibration test, the data acquisition system is set up in the same manner as for a CPT sounding. The equipment in Figures 3.33b and 3.33c are removed from their storage containers and placed on the work bench, and the container holding the dial gauges (Figure 3.33a) is also placed on the bench. The data acquisition system is set up on the work bench to view readings from the cone.

The calibration equipment manual clearly explains the process from set-up to interpretation of the results. The pressure on the dial should be 33% greater than the pressure indicated in GOnsite! for tip and friction sleeve resistance. This occurs because the calibration equipment is designed for a 10 cm² cone, which is 33% smaller than the 15 cm² used by ODOT. For instance, if the dial reads 20 MPa for tip resistance, GOnsite should indicate 13.33 MPa.



(a)



(b)



(c)

Figure 3.33. Cone calibration equipment: (a) pump and gauges, (b) tip and friction sleeve device, and (c) pore pressure device.

CHAPTER 4. DATA CORRELATIONS AND INTERPRETATIONS

This chapter summarizes the CPT data that was collected for research and the correlations and interpretations that were developed based on this data. Published correlations are also presented for some parameters where the current database was insufficient for generation of new correlations.

4.1 CPT DATABASE

The CPT research program consisted of 106 soundings taken at 20 project sites across Ohio. Figure 4.1 shows the locations of these sites and Table 4.1 provides a list along with the number of soundings for each site. The combined (i.e., cumulative) depth of CPT work completed for all 20 projects was 1291 m. From these soundings, 383 rows of data were extracted and imported into the master spreadsheet. Thus, the resulting database consisted of 383 points in which the soil type was identified. Not every parameter correlation has 383 data points, however, because conventional (laboratory or field) data was not available for comparison in most cases. For example, only two comparisons were available for soil preconsolidation pressure. Table 4.1 lists all soundings performed, including those that did not contribute any data points to the correlations.

Table 4.1. Summary of CPT field research sites.

PROJECT SITES		
Location	Number of Soundings	Total Depth (m)
ADA-52-4.70	2	25.2
ATB-531	3	43.2
Central Viaduct	4	83.5
DEF-49	19	160.8
ERI-Milan Gar.	4	61.0
HAM-75-5.58	7	68.0
HAR-250-23.29	3	16.0
HEN-24@ Bad Creek	3	41.0
HEN-24@ CR4A	2	17.6
HEN-24@ N Turkeyfoot	5	62.8
HEN-24@ SR 109 Bridge	4	51.8
HUR-224-7.60	3	60.3
LIC-161/37- Chimney Creek	5	102.0
LIC-Thornwood Dr	7	59.6
MED-71/76 ES Ramp	9	134.4
POR-303	4	47.0
TUS-250-18.99	3	16.0
TUS-77-25.00	8	65.0
WAY-53-16.87	8	118.0
WIL-49-2.72	3	58.0
Total	106	1291.2

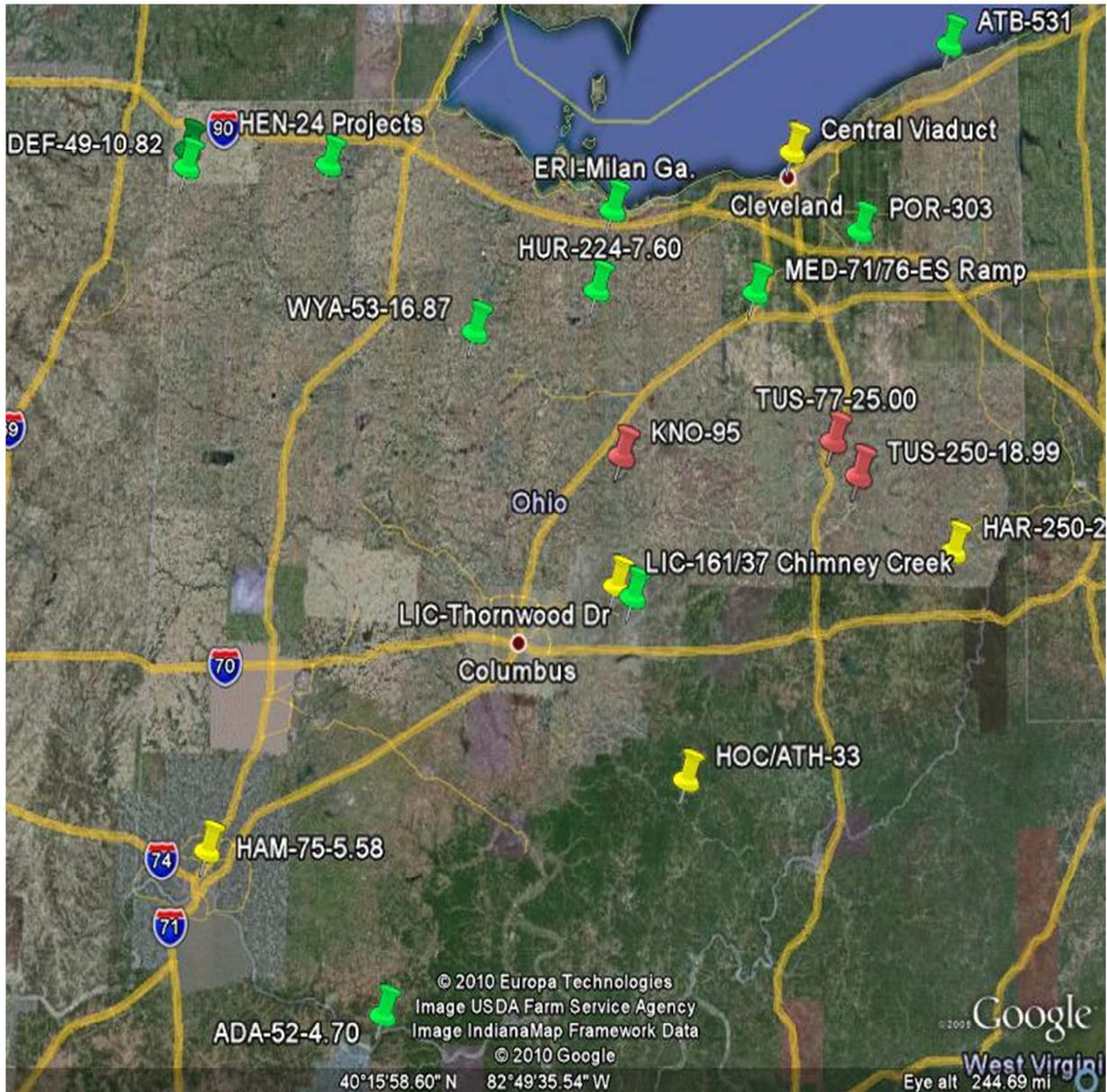


Figure 4.1. Locations of CPT field research sites in Ohio. Red tacks indicate locations where testing could not be completed, green tacks indicate locations where no problems were encountered, and the yellow tacks indicate locations where testing was completed, but problems were encountered.

Table 4.2 presents the number of data points for each soil type and the percentage of data points for each soil type in the total database. This table also provides corresponding values for the 2009 ODOT conventional drilling program.

Table 4.2. Frequency of soil types encountered for research program.

Soil	Conventional Drilling		CPT	
	Number of Points	Percentage	Number of Points	Percentage
A-1-a	28	1.5	5	1.3
A-1-b	119	6.5	26	6.8
A-3	10	0.6	28	7.3
A-3a	52	2.9	29	7.6
A-2-4	140	7.7	16	4.2
A-2-5	0	0	0	0
A-2-6	35	1.9	3	0.8
A-2-7	1	0.1	0	0
A-4a	731	40.2	75	19.5
A-4b	90	5.0	37	9.7
A-5	0	0	1	0.3
A-6a	479	26.4	87	22.6
A-6b	87	4.7	24	6.3
A-7-5	4	0.2	26	6.8
A-7-6	38	2.1	19	5.0
A-8a	0	0	4	1.0
A-8b	3	0.2	3	0.8

4.2 CORRELATIONS FOR STRATIGRAPHY

This section presents two examples of correlations for site stratigraphy based on CPT measurements. This application is one of the main advantages of CPT because data is collected continuously with depth. Figure 4.2 shows a comparison of stratigraphy for Defiance County project DEF-49-10.47, Boring C-006-0-09. In this plot, raw CPT data profiles are presented for cone resistance, sleeve friction and friction ratio. Soil behavior type is then presented based on the method of Robertson et al. (1986). With depth, the SBT profile consists of interbedded sands and clays followed by interbedded clays and organic soils and finally clay soils in the lower 3 ft. The ODOT soil bar profile for this site, as obtained from conventional drilling and testing, is shown on the right-hand side of the figure. Comparison of the soil bar with the SBT profile indicates very good correlation of major soil types over the entire sounding depth.

Figure 4.3 shows a comparison of stratigraphy for Erie County project ERI-Milan Garage, Boring C-001-07. In this case, the SBT profile consists of interbedded sands, silts and clays with coarser layers located at depths of 10-14 ft. and 22-26 ft. The ODOT soil bar indicates generally consistent soil types but a stratigraphy with some differences. In particular, the soil bar does not contain some of the coarser layers and clay layers indicated in the SBT profile. Both Figures 4.2 and 4.3 show considerably more detail for the SBT profiles than the ODOT soil bars. This is expected based on the continuous logging of the CPT measurements.

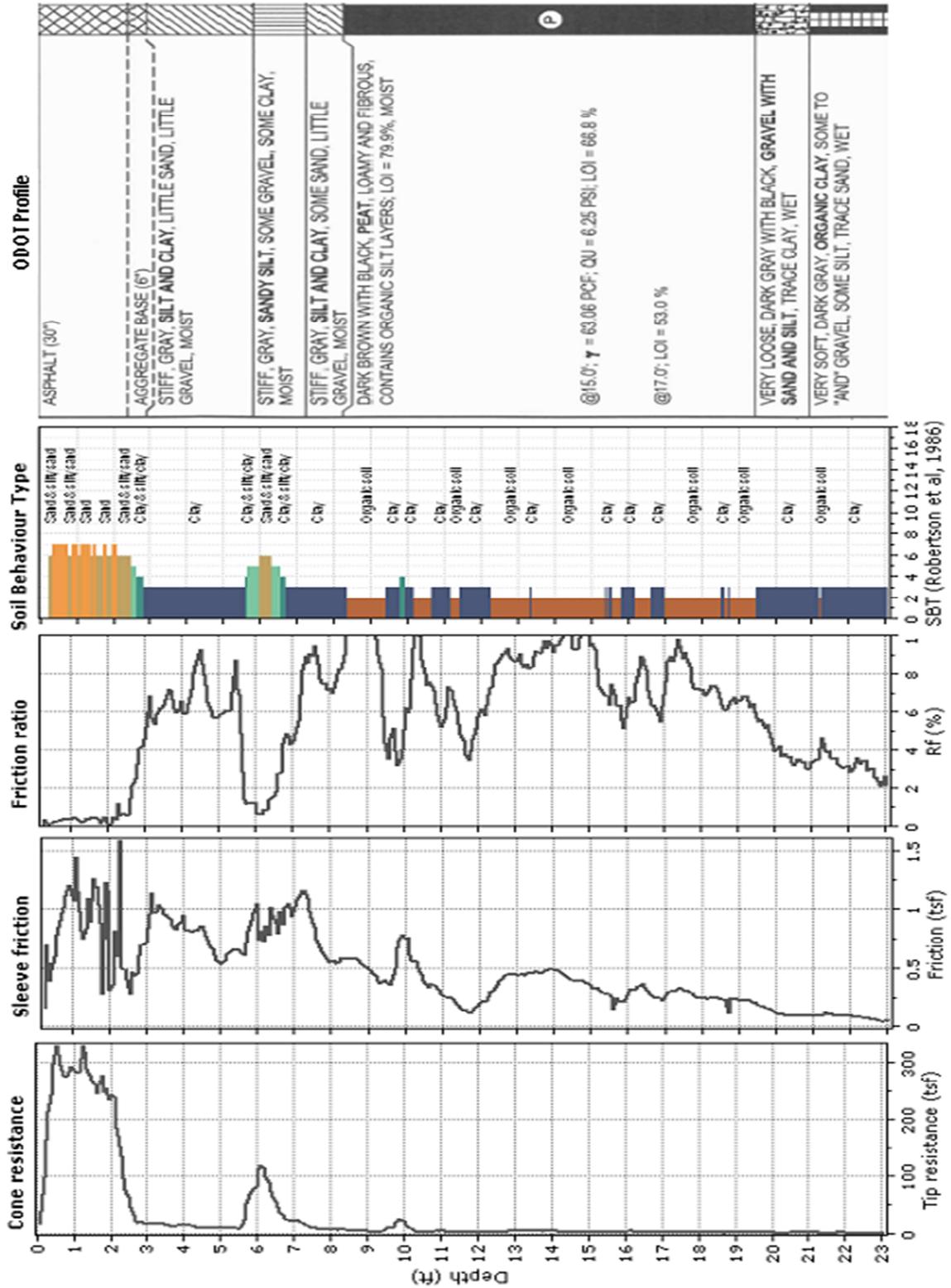


Figure 4.2. Example of stratigraphy correlation for DEF-49-10.47.

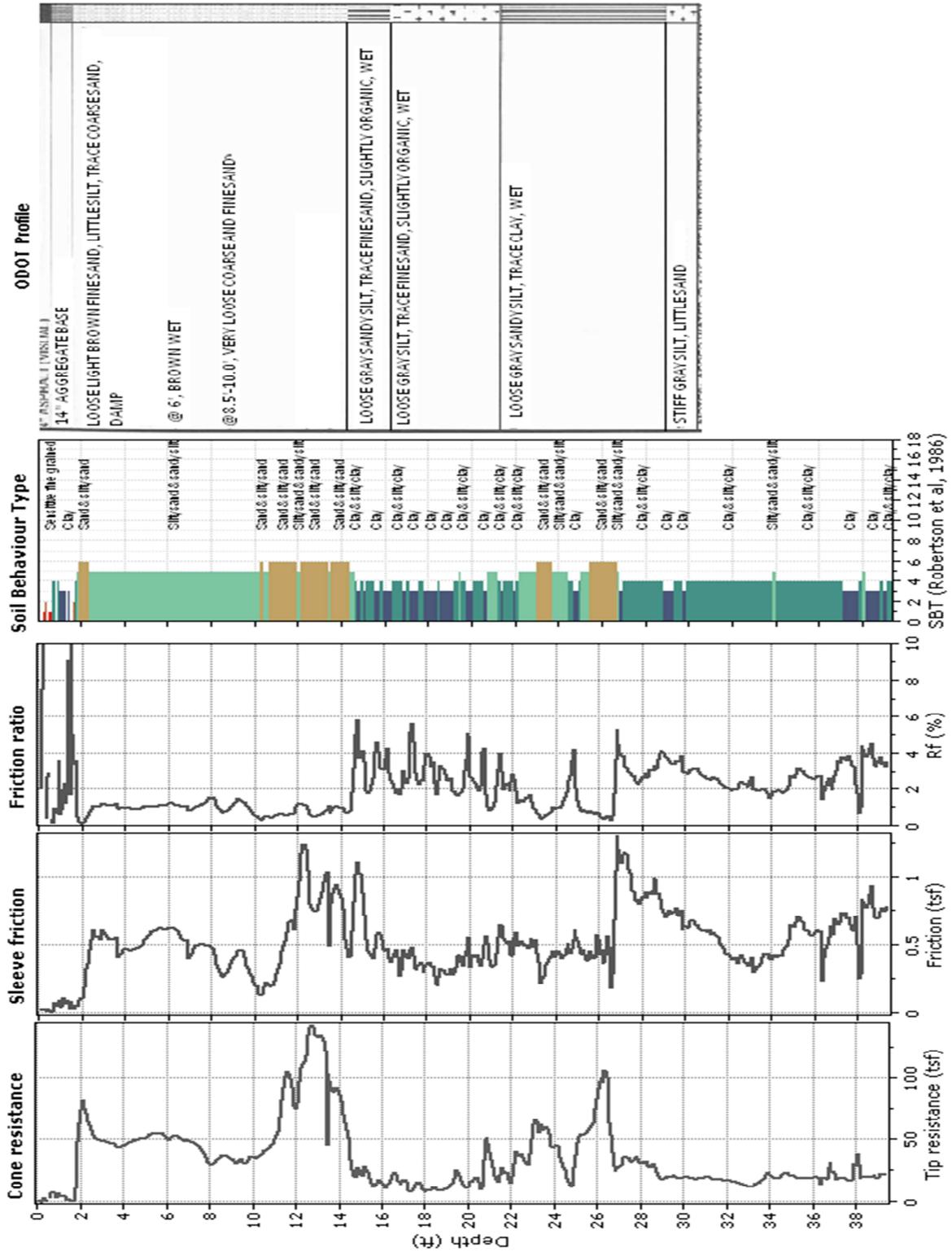


Figure 4.3. Example of stratigraphy correlation for ERI-Milan Garage.

4.3 CORRELATIONS FOR SOIL PROPERTIES

This section presents correlations between CPT measurements and soil properties based on conventional measurements as obtained from the research program. As per the original project scope, the correlations were developed in terms of the Ohio soil classification system that is widely used by ODOT. This section will also present some additional correlations that have been previously developed by others and discuss their applicability for Ohio soils.

4.3.1 SOIL TEXTURE AND PLASTICITY

The first types of correlations are those associated with soil texture and plasticity. Figure 4.4 shows a plot of soil fines content vs. friction ratio for all CPT data points. Coarse soils (A-1, A-2, A-3) are located on the left-hand side, whereas fine soils (A-4, A-5, A-6, A-7, A-8) are located on the right-hand side. Although some very limited grouping of individual soil types is observed (e.g., A-3a), Figure 4.4 indicates that friction ratio did not correlate closely with soil fines content. A similar plot (not shown) also indicates that corrected tip resistance does not correlate closely with fines content.

Atterberg limits provide a measure of soil plasticity. Figure 4.5 shows plots of liquid limit and plastic limit vs. corrected tip resistance. For both plots, the data show a general trend of increasing Atterberg limits with increasing fines content (as indicated by soil classification) and decreasing tip resistance. These trends are consistent with expectations. However, the data show significant scatter and, as a result, corrected tip resistance can only be used to provide a crude estimate of either the liquid limit or plastic limit of a given soil. As such, Figure 4.5 indicates that corrected tip resistance does not correlate closely with Atterberg limits for the soils investigated.

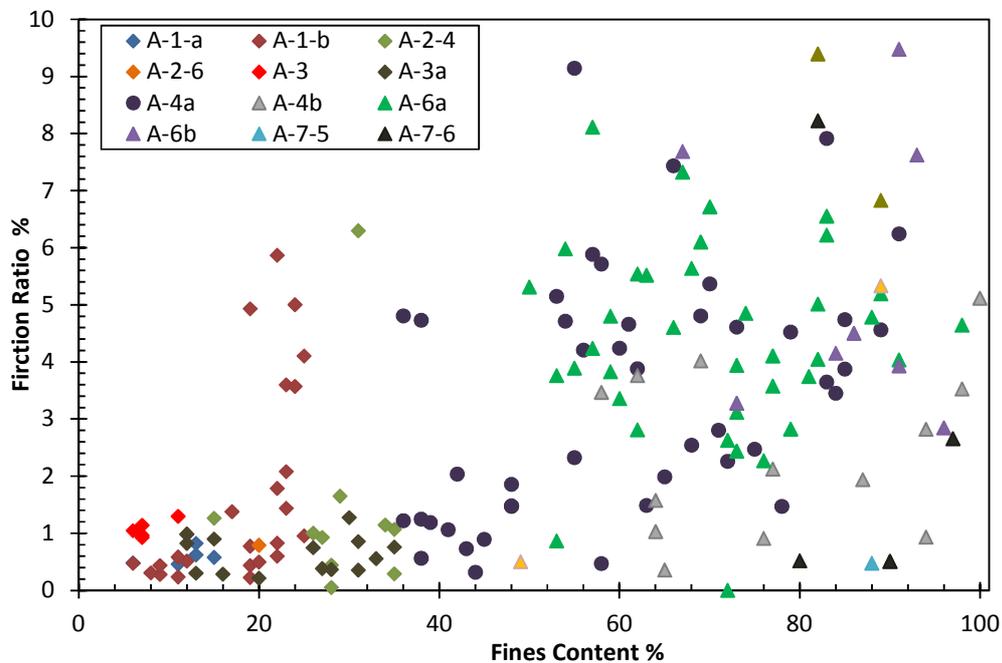
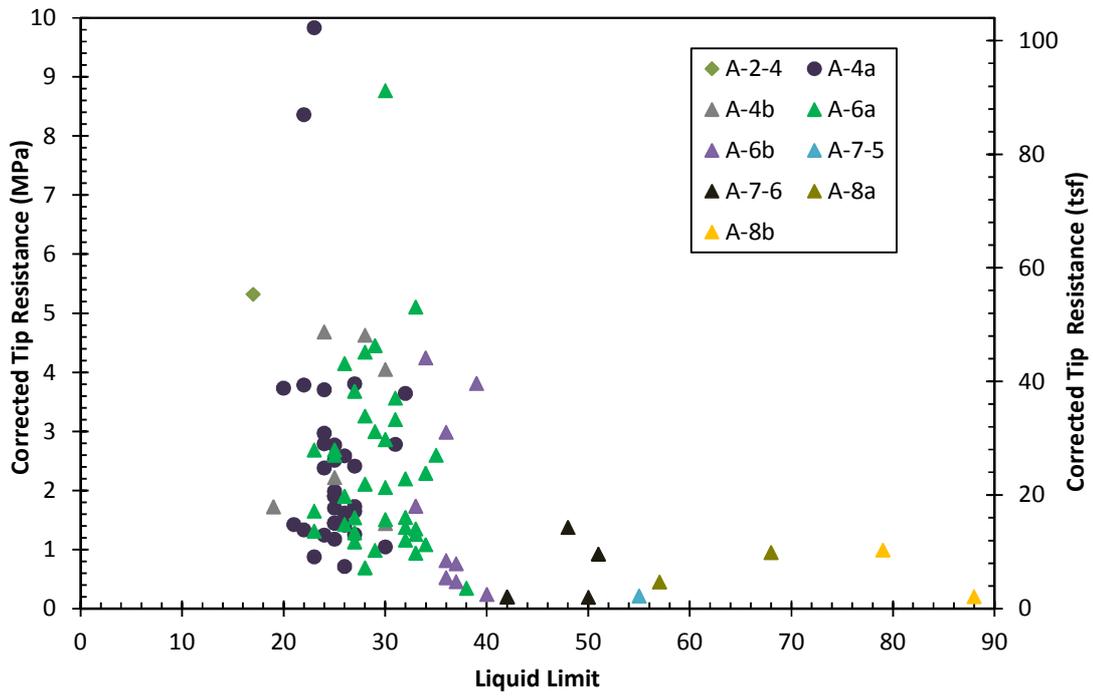
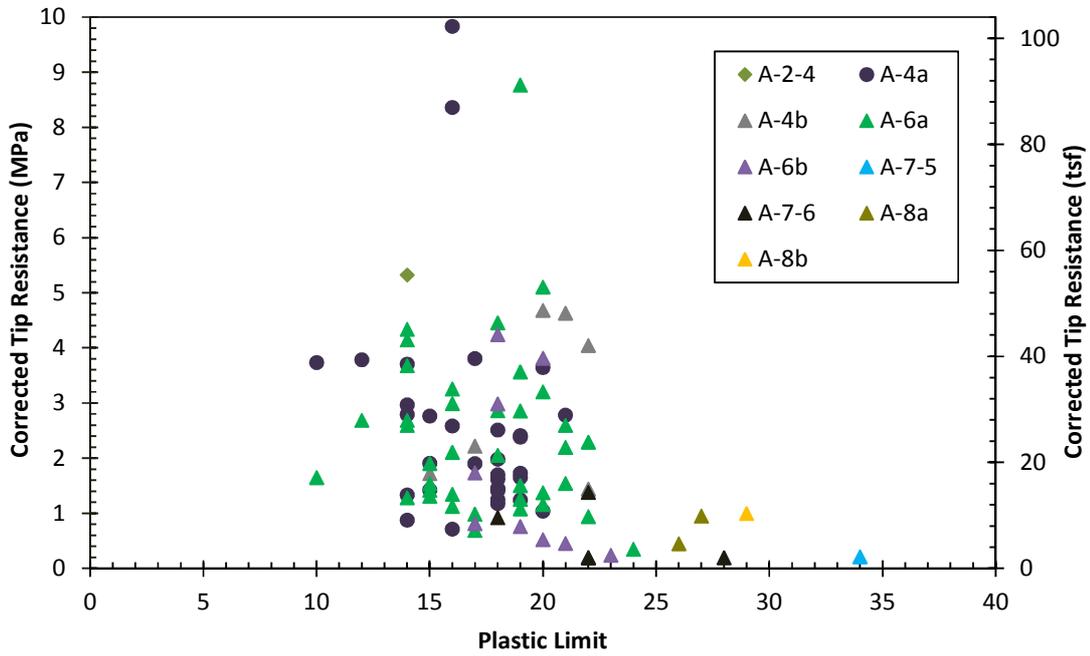


Figure 4.4. Fines content vs. friction ratio for Ohio CPT sites.



(a)



(b)

Figure 4.5. Atterberg limits for Ohio CPT sites: (a) Liquid limit vs. corrected tip resistance, and (b) Plastic limit vs. corrected tip resistance.

4.3.2 DRY UNIT WEIGHT

Soil unit weight is an important parameter that controls calculated values of total and effective overburden stress. A reliable correlation for the unit weight of cohesionless soils would be particularly useful as these values are difficult to measure. Figure 4.6 shows corrected tip resistance vs. dry unit weight for fine grained and organic soils. Measured unit weights are not available for cohesionless soils in the current ODOT database. In general, a higher tip resistance indicates higher unit weight; however, the plot shows no clear trend in the area of primary interest (100 – 140 pcf). Figure 4.6 indicates that dry unit weight does not correlate closely with corrected tip resistance and, as such, CPT will be of limited use for estimating soil unit weight at this time.

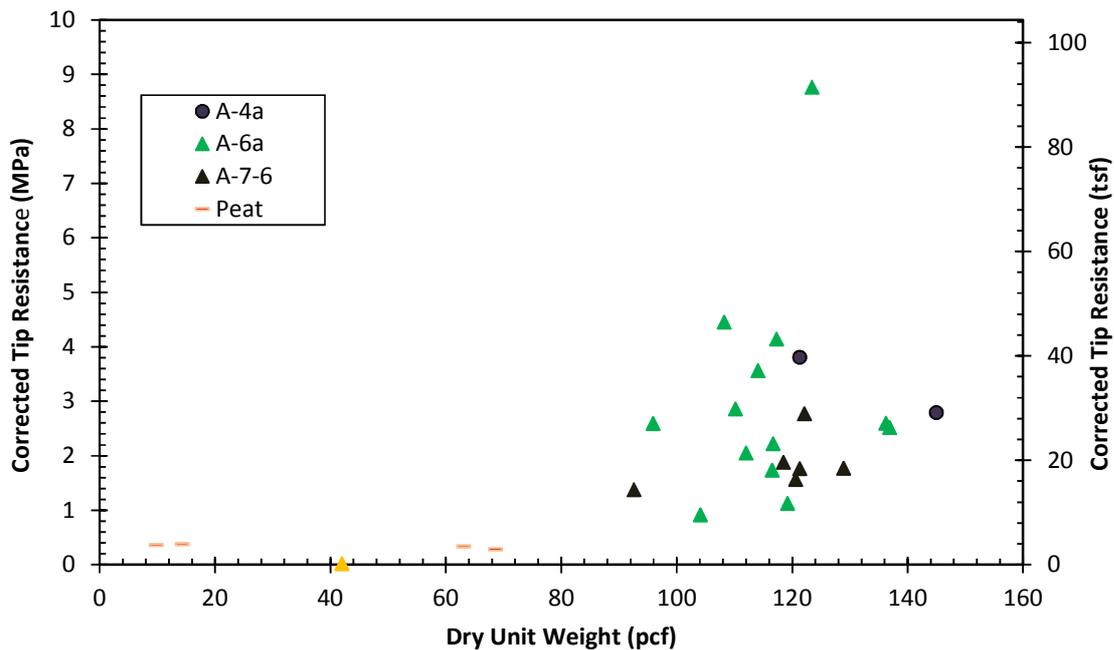
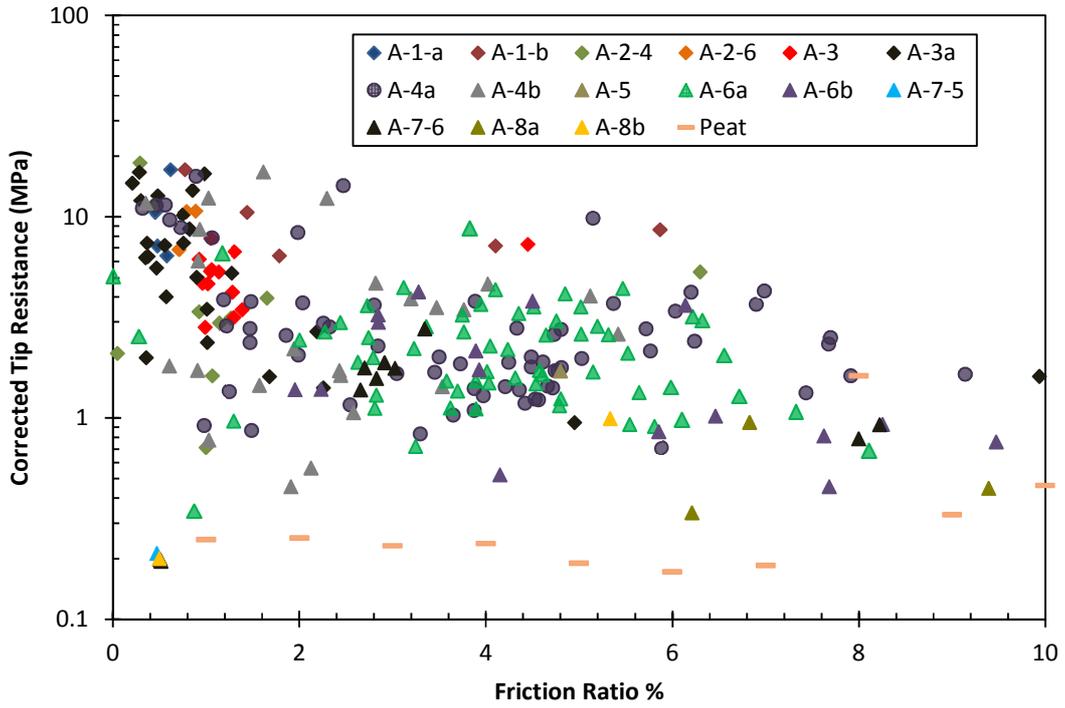


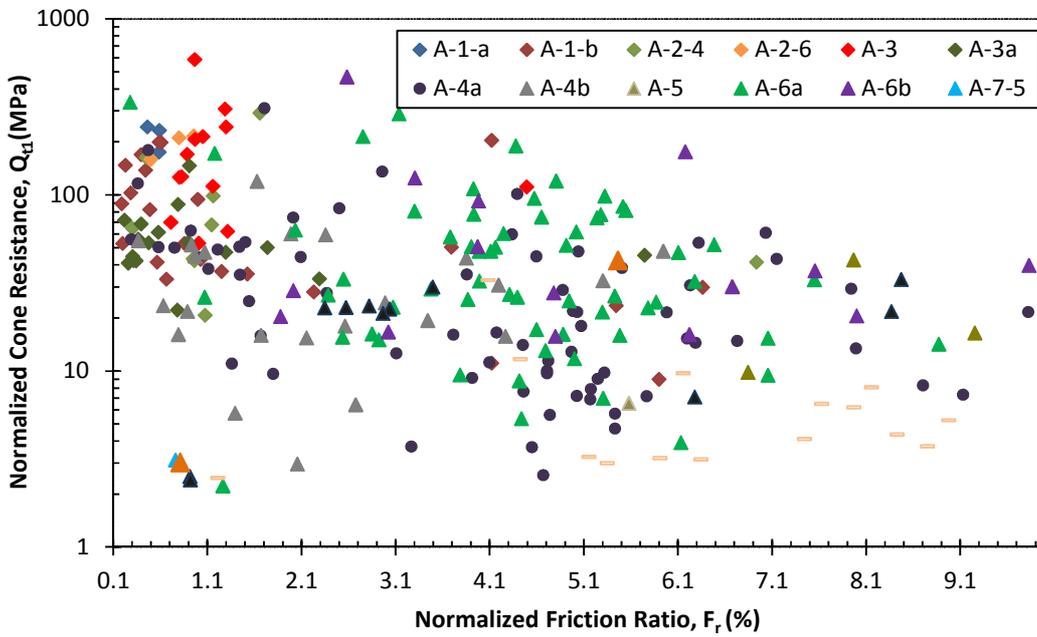
Figure 4.6. Corrected tip resistance vs. dry unit weight for Ohio CPT sites.

4.3.3 SOIL CLASSIFICATION

Correlations for soil classification are important because no soil samples are obtained with CPT. Figure 4.7 shows plots of corrected tip resistance vs. friction ratio and normalized cone resistance vs. friction ratio for all CPT data points combined. These plots indicate that the different soil types do not form close clusters. The diamonds on the plots represent coarse grained materials, squares correspond to fine grained soils, and the circles are A-4 materials which can be either coarse or fine grained depending on the percentage of sand and silt. In Figure 4.7, coarse grained soils tend to have a higher tip resistance and lower friction ratio than fine grained soils. Although this is consistent with previously published reports, the research data for this project does not form close clusters for each soil type. Sandy Silt (A-4a) and Silt and Clay (A6-a) show the most scatter. Organic soils (A-8 and Peat) generally have a very low tip resistance and are found at the bottom of the plot.



(a)



(b)

Figure 4.7. Results for Ohio CPT sites: (a) Corrected tip resistance vs. friction ratio, (b) Normalized cone resistance vs. normalized friction ratio.

The new CPT data was compared with the SBT chart from Robertson (2010) and the resulting combination overlay plot is shown in Figure 4.8. The CPT data is grouped into coarse soils, fine soils and peats. In general, these groupings are consistent with the broad categories of the SBT chart (i.e., between zones 6 and 7). Although these charts are able to identify fine grained soils, the above plots show that it may not accurately differentiate between A-4a and A-6a, for example. The A-4a soils are not shown on Figure 4.8 because these soils are spread widely across the chart.

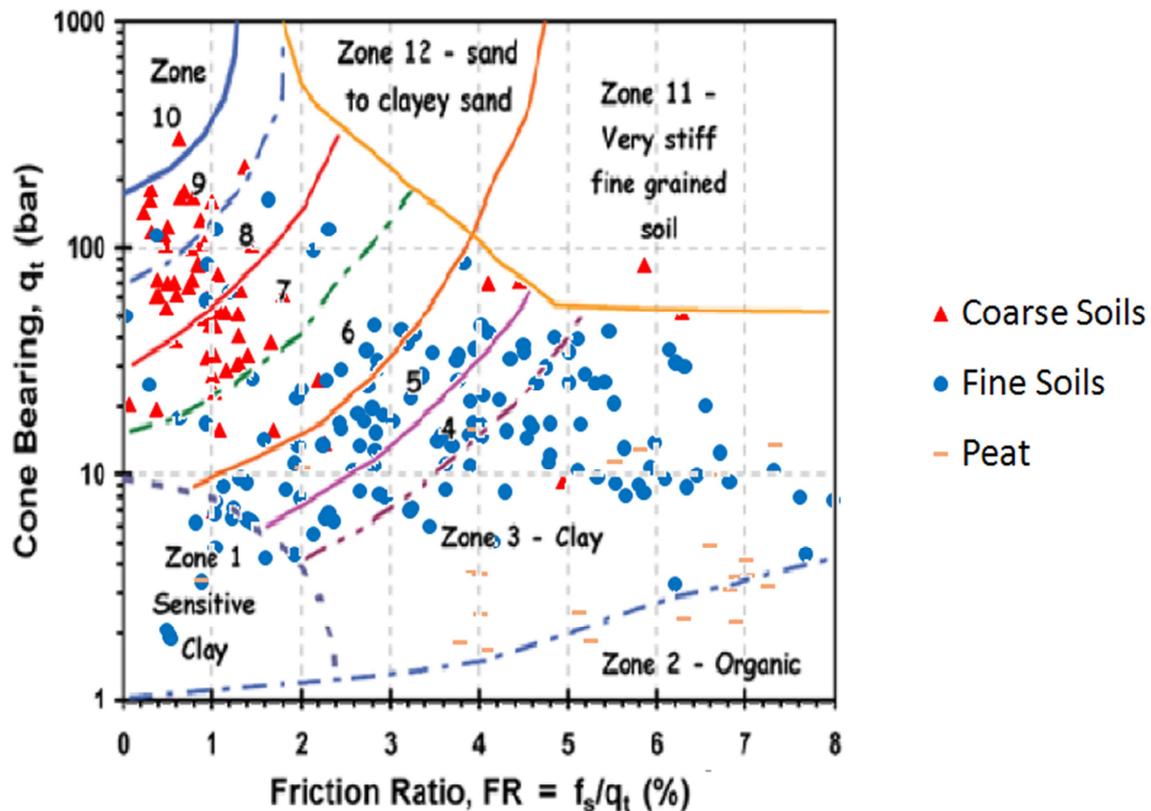


Figure 4.8. Overlay plot of SBT classification chart and new CPT data for Ohio CPT sites.

4.3.4 SPT N_{60}

Currently, ODOT relies almost entirely on SPT for subsurface exploration. Figure 4.9 shows a plot of SPT N_{60} vs. corrected tip resistance for all CPT data points. Although N_{60} appears to very generally increase with increasing tip resistance, a clear correlation is not observed. The scatter of points in Figure 4.9 will not change if a different system, such as USCS, is used to classify the soil types. Past research (Daniels and Jacob 1993, Lunne et al. 1997) has suggested that N_{60} is better estimated from CPT soundings than from direct measurements (i.e., SPT) due to the better repeatability of CPT.

The trend line shown in Figure 4.9 is based on the following relationship from Lunne et al. (1997):

$$\frac{q_t/p_a}{N_{60}} = 8.5 \left(1 - \frac{I_c}{4.6} \right) \quad (4.1)$$

Using Eq. 4.1, a value of N_{60} was calculated for each data point (not shown) and the curve shown in Figure 4.9 was fitted to these calculated values. It can be seen that Eq. 4.1 tends to overestimate N_{60} for non-cohesive soils and under estimates N_{60} for cohesive and A-4 soils.

Figure 4.10 shows a plot of SPT N_{60} vs. soil behavior type index I_c . Although these plots indicate a general increasing trend of N_{60} with decreasing I_c , no clear correlation is observed.

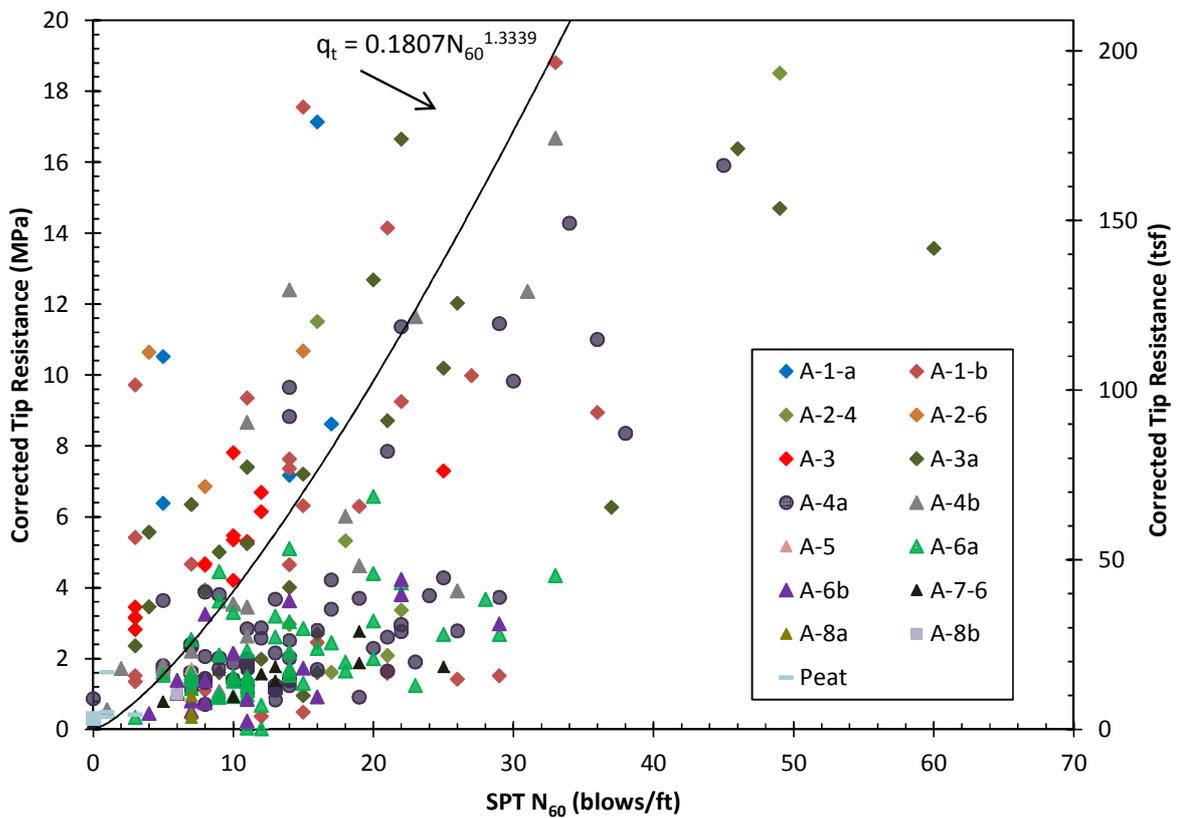


Figure 4.9. Corrected tip resistance vs. SPT N_{60} for Ohio CPT sites.

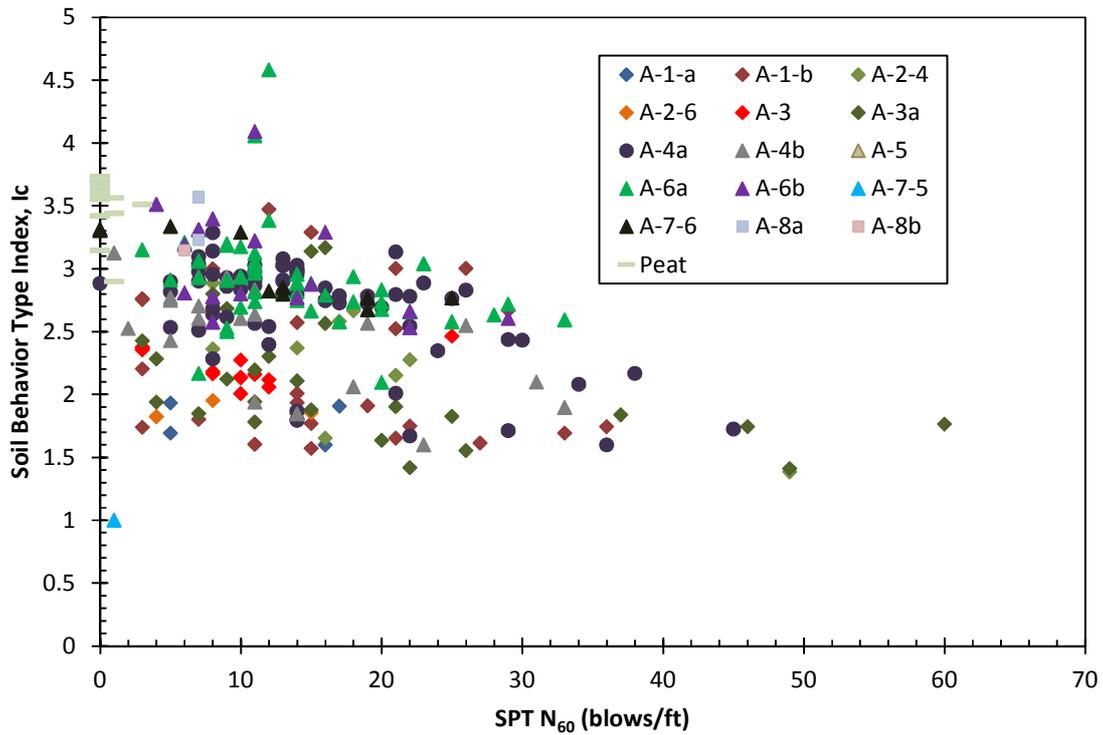


Figure 4.10. Soil behavior type index vs. SPT N_{60} for Ohio CPT sites.

4.3.5 UNDRAINED SHEAR STRENGTH

Figure 4.11 shows a plot of undrained shear strength as obtained from laboratory shear testing vs. corrected tip resistance. This plot indicates that, similar to published correlations, s_u increases with increasing tip resistance. The linear regression equation is:

$$q_t \text{ (MPa)} = 0.28 s_u \text{ (psf)} - 4.9 \quad (4.2)$$

The R^2 value is 0.2712, which indicates that this relationship is very approximate. Equation 4.2 can also be written as:

$$s_u \text{ (psf)} = 3.6 (q_t \text{ (MPa)} + 4.9) \quad (4.3)$$

4.4 PUBLISHED CORRELATIONS

The above plots developed from the research program are not very useful due to the scatter of data and lack of sufficient conventional soil property measurements in some cases. Additional data should be added to the CPT research database on an ongoing basis to improve the correlations for Ohio soils. This section describes two additional correlations that are available in the literature for shear wave velocity and preconsolidation stress.

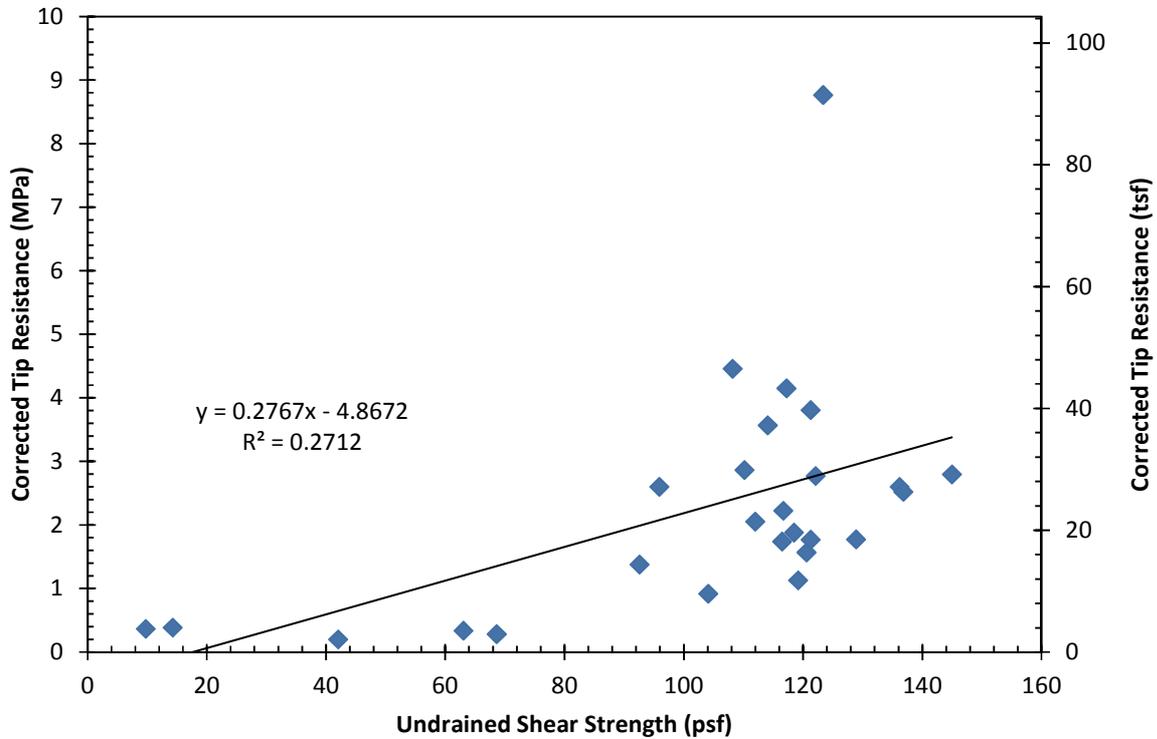


Figure 4.11. Undrained shear strength vs. corrected tip resistance for Ohio CPT sites.

4.4.1 SHEAR WAVE VELOCITY

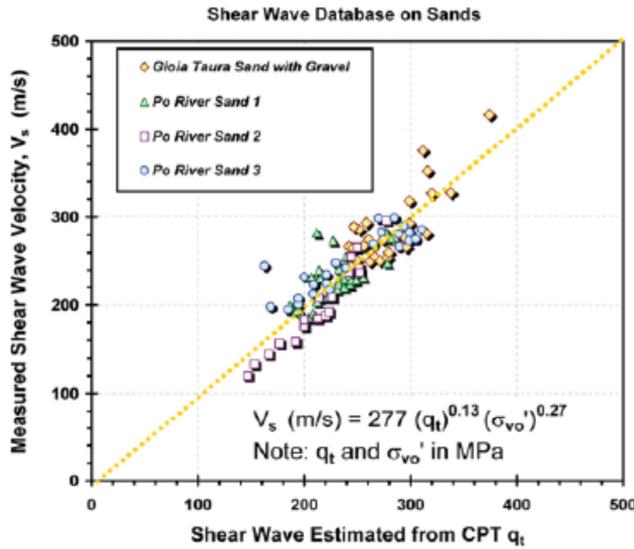
Shear wave velocity, V_s , is a fundamental measurement that is directly related to soil stiffness. Although the ODOT CPT machine is capable of shear wave (i.e., seismic) testing, problems with the equipment prevented such testing during the current research program. As an alternative, Baldi et al. (1989) showed that V_s may be estimated for uncemented quartz sands using the following relationship:

$$V_s(m/s) = 277(q_t)^{0.13}(\sigma'_{vo})^{0.27} \quad (4.3)$$

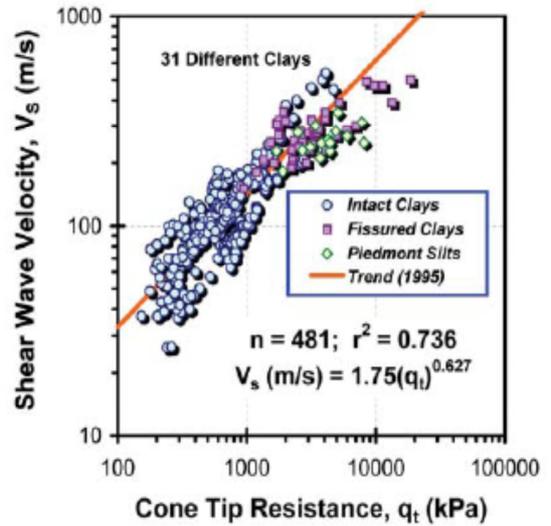
where q_t is the corrected cone tip resistance (MPa) and σ'_{vo} is the effective overburden stress (MPa). Mayne and Rix (1995) developed the following relationship for soft to stiff intact clays and fissured clays:

$$V_s(m/s) = 1.75(q_t)^{0.627} \quad (4.4)$$

where q_t is in kPa. Figure 4.12 shows both of these relationships along with the data on which they are based.



(a)



(b)

Figure 4.12. Charts for estimation of shear wave velocity for: (a) clean sands and (b) clay soils (Mayne and Rix 1995).

A more general equation was proposed for all soils by Mayne (2007):

$$V_s (m/s) = [10.1 \log q_t - 11.4]^{1.67} [f_s/q_t * 100]^{0.3} \quad (4.5)$$

Eq. 4.5 was obtained from testing in sands, silts, and clays as well as mixed soils. Mayne (2007) also proposed the following relationship between V_s and sleeve friction f_s (kPa):

$$V_s (m/s) = 118.8 \log f_s + 18.5 \quad (4.6)$$

4.4.2 PRECONSOLIDATION STRESS

Preconsolidation stress, σ'_p , is a fundamental parameter for soils of all types and is particularly important for fine-grained soils. A known value of σ'_p allows for the calculation of OCR with a known value of effective overburden stress. Figure 4.13 presents σ'_p vs. net cone resistance as published by Mayne (1995). Data from a wide variety of sites are represented and display a clear trend that is defined by the following equation:

$$\sigma'_p = 0.33 (q_t - \sigma_{vo}) \quad (4.7)$$

The overburden pressure can be estimated from CPeT-IT or a similar CPT data analysis program. If the GWL is known, the preconsolidation stress can also be estimated by (Mayne 1995):

$$\sigma'_p = 0.53 (u_2 - u_o) \quad (4.8)$$

Figure 4.13 also shows two data points from the current ODOT CPT database. These points follow the same general trend but are shifted downward from the rest of the data. Thus, the ODOT

points are not consistent with Figure 4.13. Note that the vertical axis is logarithmic and, as such, the ODOT points are lower than Eq. 4.7 by approximately a factor of 2.

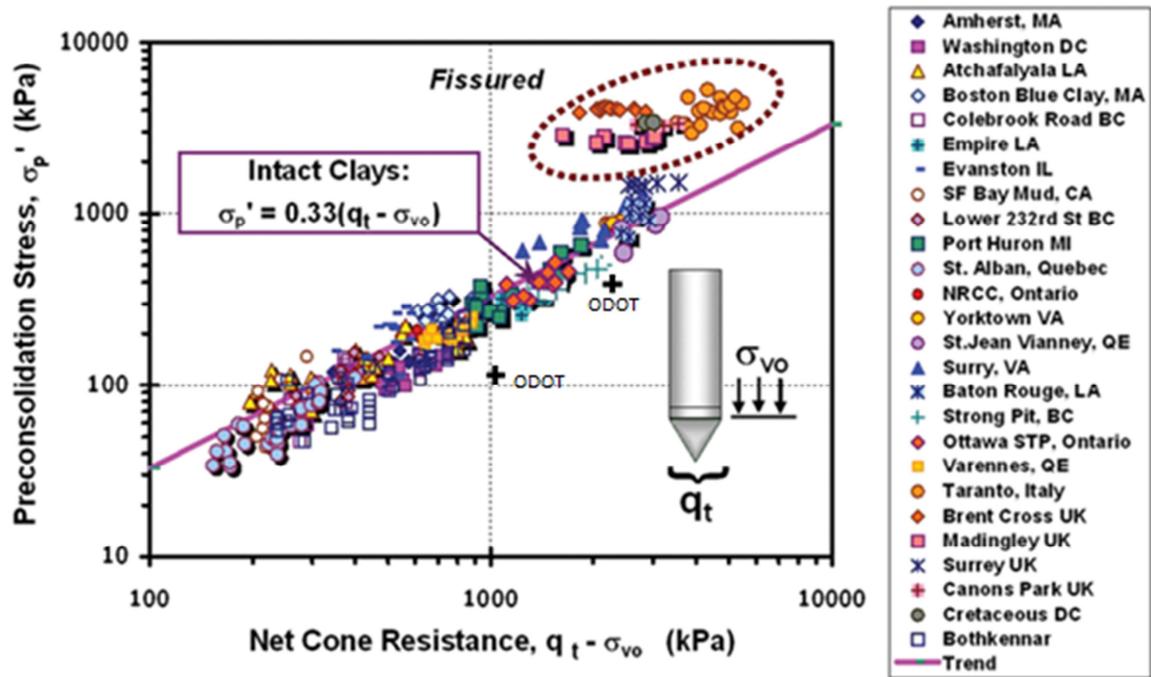


Figure 4.13. Preconsolidation stress vs. net cone resistance (Mayne 1995) with two additional points based on current ODOT research.

CHAPTER 5. CPT USAGE FOR ODOT

5.1 INTRODUCTION

This chapter describes potential usage of the CPT machine for ODOT projects. Previous sections discussed methods to interpret data obtained from a project, but the first step is to decide when and how to use CPT for subsurface exploration. Limitations of CPT with regard to Ohio geology will also be discussed. This chapter concludes with a presentation of quality assurance/ quality control (QA/QC) protocols.

ODOT currently uses conventional drilling for their subsurface exploration program. With the incorporation of CPT, the OGE will greatly expand the available capabilities for subsurface exploration. This section describes the following potential uses of CPT for ODOT:

- Before conventional drilling
- After conventional drilling
- Alongside conventional drilling
- Instead of conventional drilling

5.2 CPT USE BEFORE CONVENTIONAL DRILLING

CPT can be used before conventional drilling as a rapid method to determine general subsurface conditions and to guide future drilling operations. There are several advantages to using CPT as a first exploration method when little is known about a project location. Since CPT can be completed more quickly and at lower cost than conventional drilling, starting a subsurface exploration program with CPT will produce rapid data that can be used to guide future investigations. Problem soils can be quickly identified during a CPT sounding and will generally plot in the range for organic soils or soft fine grained soils (e.g., low tip resistance, high friction ratio) on the SBT charts. If additional testing is required, conventional drilling can then be conducted at these locations. Using CPT first can also result in more efficient use of soil sampling and laboratory testing time. For example, if CPT indicates an area where soft soils are overlain by competent soils, soil sampling and laboratory testing can be minimized in the upper section, leaving more field and laboratory testing resources available for the soft soils underneath.

Another example where CPT might be used prior to conventional drilling is when the exact location of a structure or roadway is not known a priori. CPT can be used to identify the preferred location by rapidly assessing the entire site. Once this area is identified, conventional drilling and testing can then be conducted as needed. This may result in significant cost savings for a project.

5.3 CPT USE AFTER CONVENTIONAL DRILLING

CPT can be used after conventional drilling and testing to provide additional information. If SPT provides questionable data at certain depths, CPT can be used to verify or discount this data. In areas of soft soils with low N_{60} values, CPT can more accurately determine the stratigraphy of these layers and obtain additional information needed for design. Sands can also pose problems. Conventional drilling is difficult for running sand conditions and retrieving high quality sand samples is not possible using conventional means. CPT can be used to avoid these problems and provide quality data for design in such cases.

5.4 CPT USE ALONGSIDE CONVENTIONAL DRILLING

CPT can also be used alongside conventional drilling. A good example would be a site with hard soils at the surface. In such cases, an auger will be needed to bore through the hard soils so that a CPT sounding can be performed underneath. Section 5.6 describes soils that can be evaluated using CPT and soils that may damage CPT equipment. When testing a site with gravelly soils, conventional drilling may be needed at times to allow the CPT to reach the desired sounding depth.

In order to compare results, a SPT boring should be completed within 10 ft of a CPT sounding. Direct comparisons can be used to generate correlations for a specific site and should be prepared whenever possible. Such information can greatly enhance the use of CPT for a particular project. Not only will this assist in project design, but it will also continue to build the CPT research database for ODOT.

5.5 CPT USE INSTEAD OF CONVENTIONAL DRILLING

CPT may be the only subsurface exploration method that is needed for areas where subsurface conditions are fairly well known. For example, if conventional drilling was previously conducted on a site, CPT can be used to verify the subsurface conditions and soil properties.

CPT can also be used to verify if a particular stratum exists within a soil profile. If a previous boring identified a soft organic layer at a certain depth, CPT can be used to locate this layer and determine its depth and thickness at various locations. This will save time and money as compared to conventional investigation methods. CPT can also be used to find the depth to bedrock on a site. To do this, the cone should be advanced until reaching a tip resistance greater than 45 MPa (470 tsf). Cone inclination should not jump significantly when bedrock is encountered. If the inclination does jump significantly, there is a good chance that bedrock was not encountered and the cone came into contact with a large cobble or boulder.

Although not emphasized in this report, CPT is useful for pile design. In one report, LADOT (2007) saved \$11,000 by using CPT for design of a 200 ft pile. Pile design was one of the earliest uses for CPT (Robertson et al. 1997) and there are methods to determine ultimate pile capacity directly from CPT tip resistance and sleeve friction. Geotechnical textbooks also include CPT equations for calculation of pile capacity and ultimate settlement (e.g., Das 2009).

5.6 LIMITATIONS OF CPT WITHIN OHIO GEOLOGIC SETTING

Although CPT has many advantages for subsurface exploration, CPT is not the best method for subsurface testing in all instances. Table 5.1 outlines the usefulness and suitability of CPT for Ohio soil classification types as determined through experience gained on the current project.

Table 5.1. General suitability of CPT for Ohio soils.

Soil Type	CPT Suitability	Comments
A-1-a	Poor	Can push occasionally, but not every time
A-1-b	Poor	Can push occasionally, but not every time
A-2-4	Poor	Can push occasionally, but not every time
A-2-5	Poor	Not encountered during research program
A-2-6	Poor	Can push occasionally, but not every time
A-2-7	Poor	Not encountered during research program
A-3	Excellent	
A-3a	Good	Very dense sand can cause large q_c
A-4a	Excellent	
A-4b	Excellent	
A-5	Excellent	
A-6a	Excellent	
A-6b	Excellent	
A-7-5	Excellent	
A-7-6	Excellent	
A-8a	Excellent	
A-8b	Excellent	
Peat	Good	Very soft layers may cause inclination problem

A-1 and A-2 soils often contain cobbles or boulders that prevent cone advancement. While testing at a project in Licking County, over 100 ft was pushed in mostly A-1-b material. However, when the CPT machine was moved to a new location 10 ft away, the cone could be pushed only 4 ft before encountering an obstruction. A cone can be damaged in such materials and caution should be used at all times. Thus, it is often a good idea to pre-auger a hole through hard soils before pushing the cone.

Geologic conditions make CPT work difficult in many places throughout Ohio. In locations where bedrock is very shallow (< 10 ft), CPT should generally be avoided because it is not economical and conventional drilling and coring will likely be needed anyway. There are instances, however, where shallow bedrock areas are well suited for CPT. If many (7+) shallow soundings (5-15 ft) are needed, such as for a highway subgrade investigation, then CPT would be well suited for such cases due to the cost savings over conventional drilling and testing. Hard soil conditions may also limit CPT usage as previously discussed.

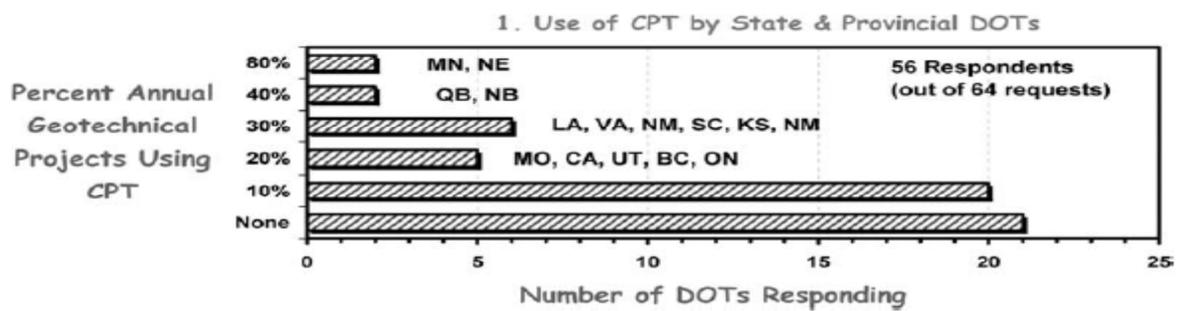
Although the ODOT CPT machine is on tracks, there are limitations regarding the maximum slope that the machine can climb or descend. The steepest slope that has been climbed was a 2:1 embankment. The CPT engine slowed down considerably going uphill such the operator had to move slowly using short bursts from the remote control. Thus, the steepest slope that the ODOT CPT machine can traverse is 2:1. If the CPT must be moved to a location where steeper slopes are present, earthwork will be needed to reduce the slopes. The steepest slope on which CPT can be conducted is 8° (roughly

7:1). If the slope is steeper, a bench will need to be cut on the slope prior to testing. The CPT machine is easier to level on flatter ground, so this should be kept in mind when choosing sounding locations.

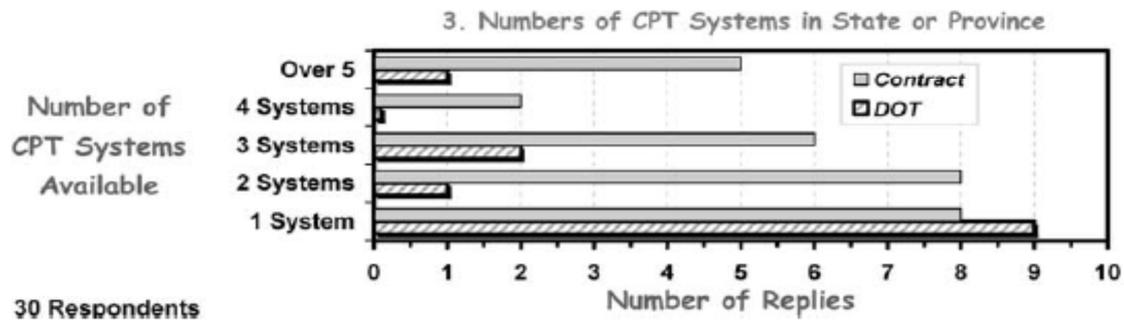
5.7 CPT USAGE FOR U.S. DOTs.

The National Cooperative Highway Research Program (2007) conducted a study of state DOTs in the United States and Canada on their usage of CPT. Responses to several questions are presented below and provide indication of the importance and various uses of CPT around the U.S.

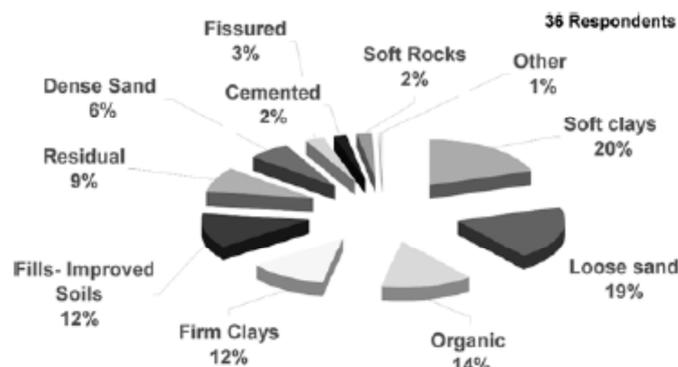
Question: On an annual basis in your state or province, what approximate percentage of geotechnical projects utilize cone penetration testing?



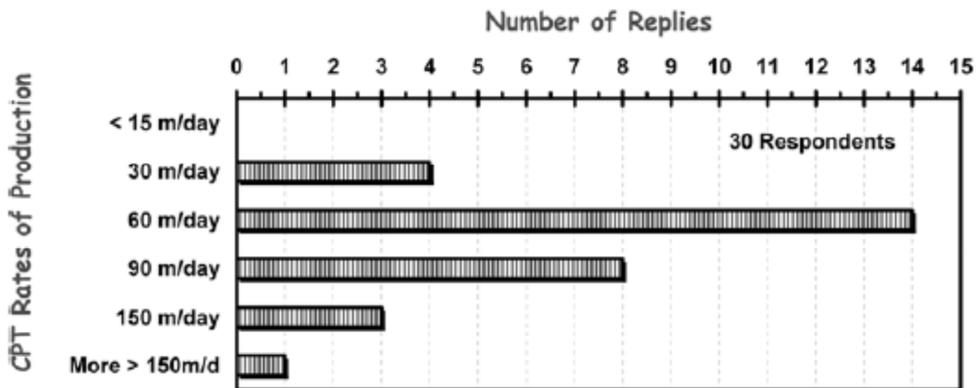
Question: How many CPT systems are available and who runs them in-state?



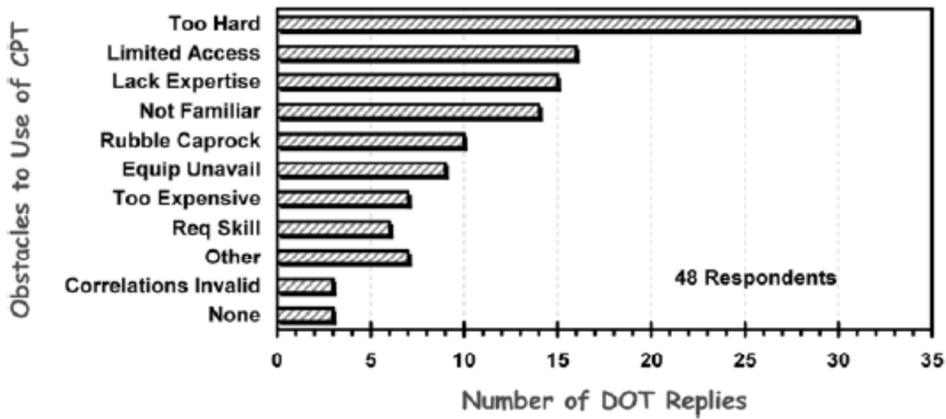
Question: What soil types do you investigate by CPT?



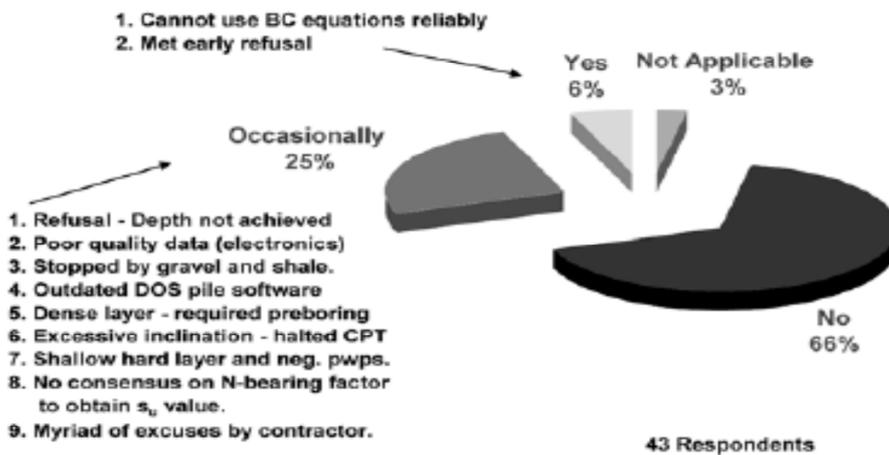
Question: What average daily footage (metric rate) of CPT is accomplished on your projects?



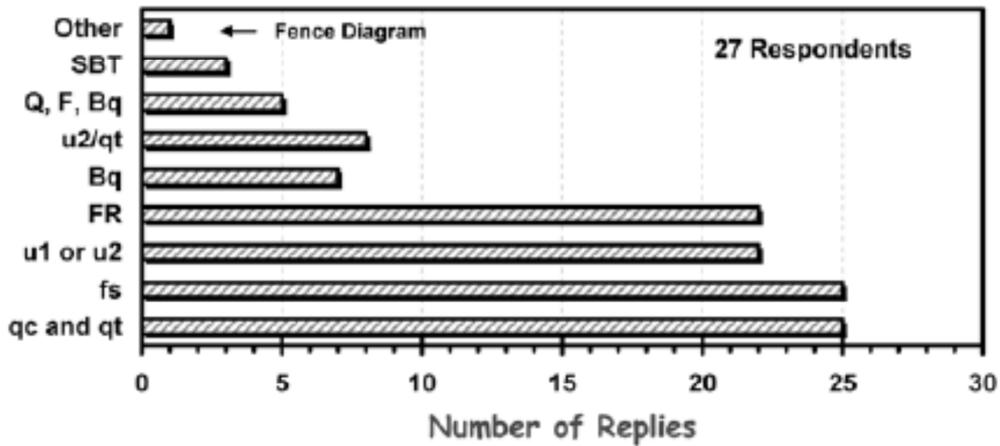
Question: What circumstances prevent the use of CPT?



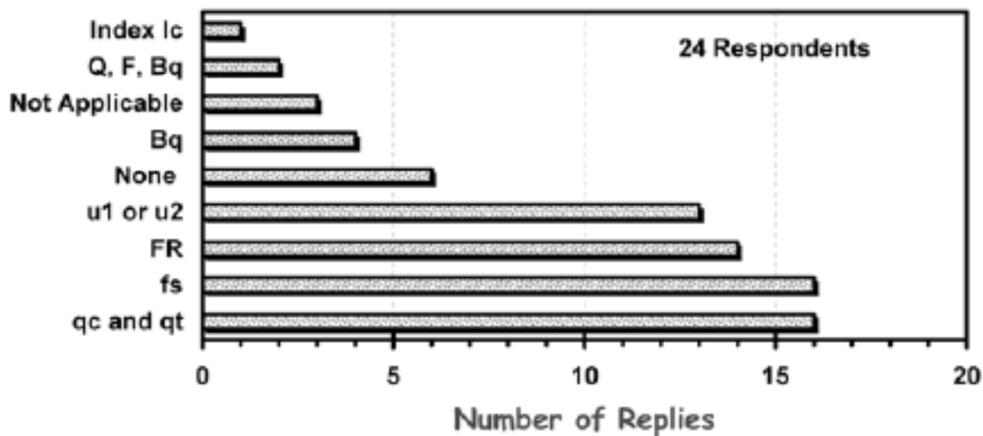
Question: Have you had any unfavorable experiences with CPT on your projects?



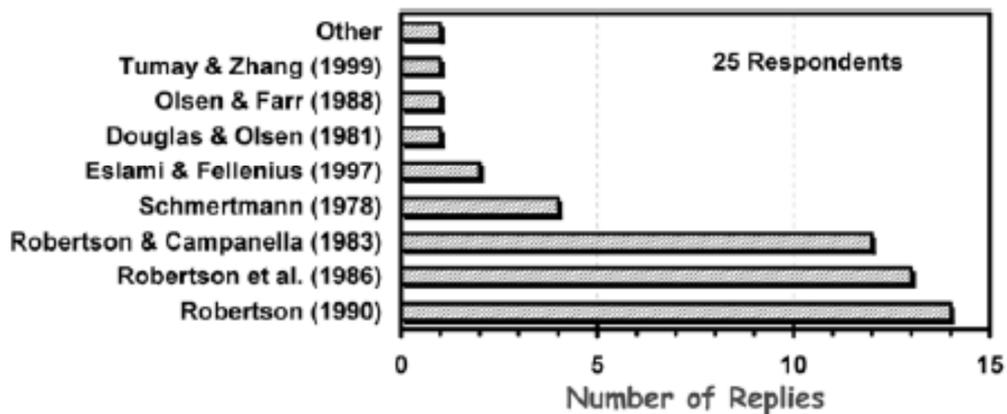
Question: In presenting CPT results for in-house use, we use:



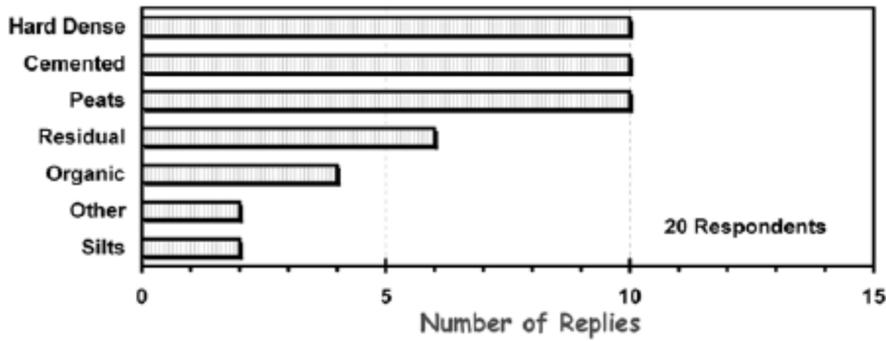
Question: In presenting CPTs for bid documents, our department provides:



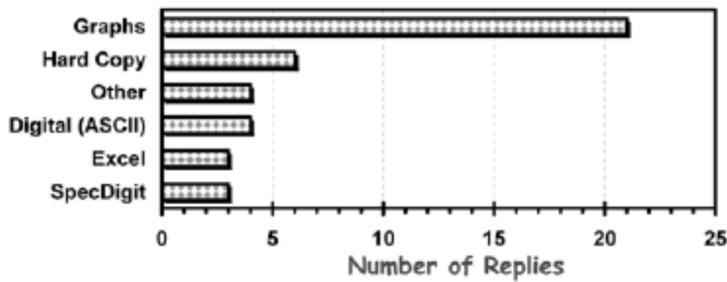
Question: Our state uses the following CPT soil behavioral classification type:



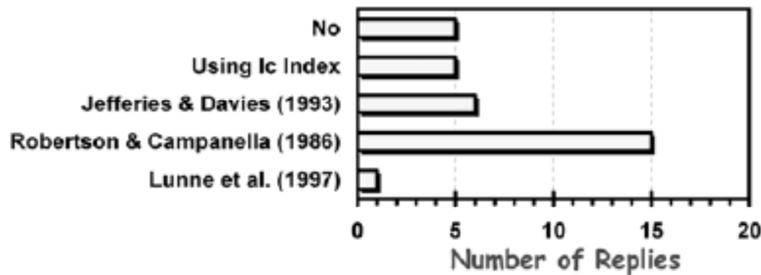
Question: What soil types are not well reflected by the CPT classification methods?



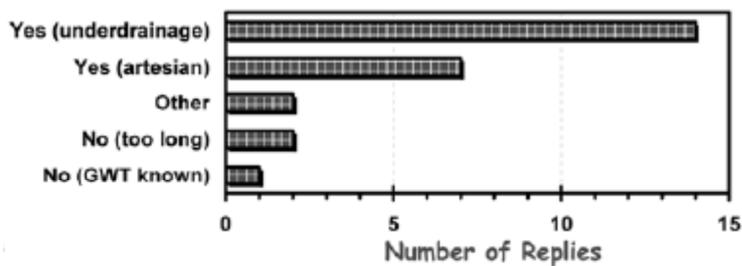
Question: The selected CPT results that are presented as part of the plans package include:



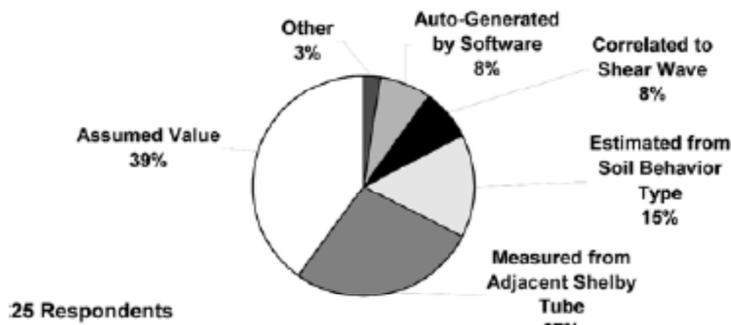
Question: Are CPT results used to estimate equivalent SPT N-values?



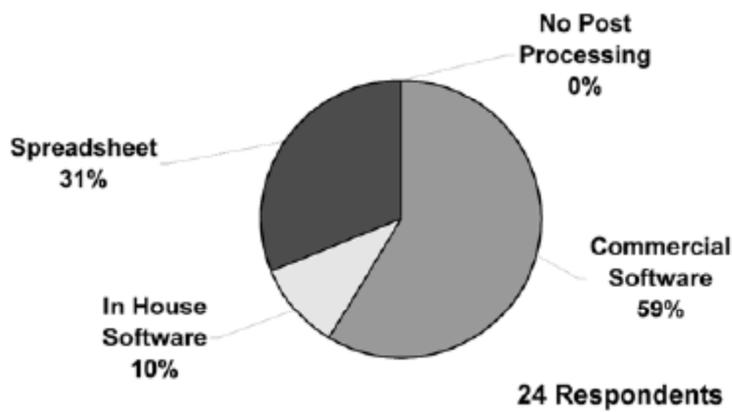
Question: Have you used piezo-dissipation tests to determine hydrostatic pore water pressures?



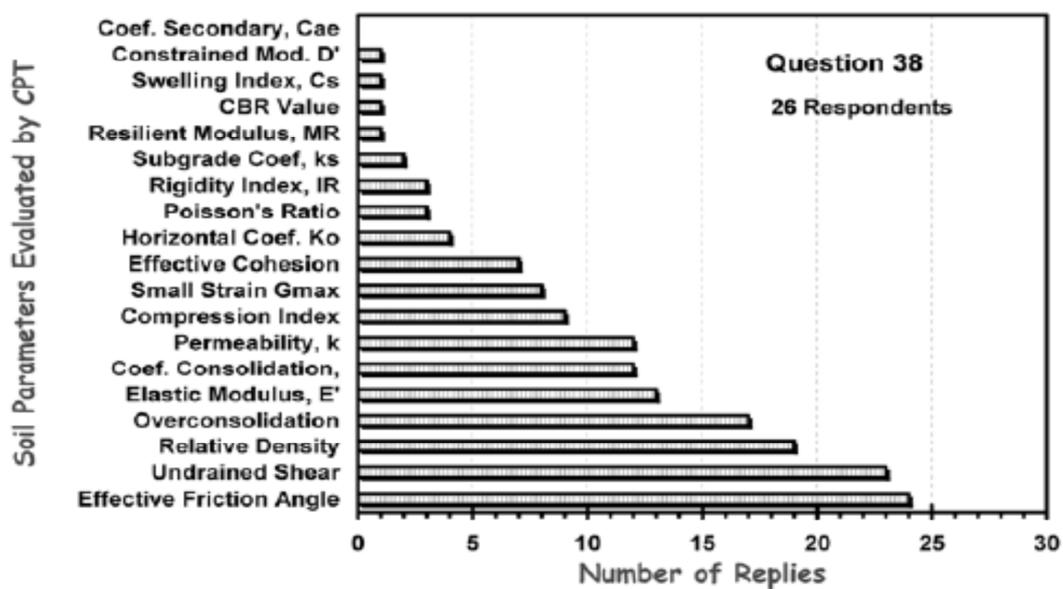
Question: The total soil unit weight for calculating overburden stress is evaluated by:



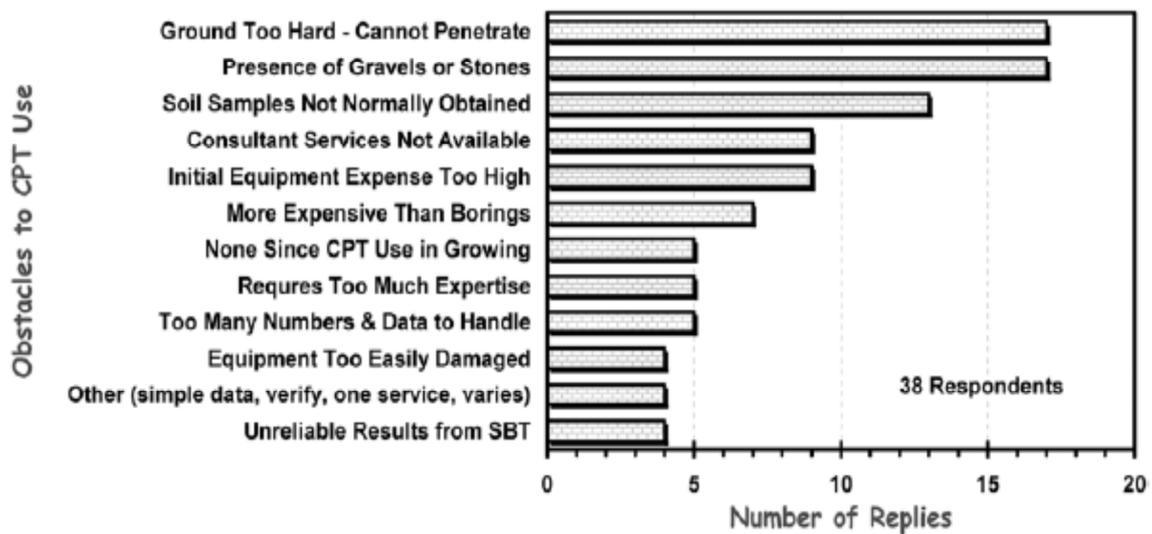
Question: In the post-processing of CPT data, our group uses:



Question: What soil parameters are evaluated from the CPT results?



Question: What is the biggest obstacle to increase use of CPT in your area?



5.8 QUALITY ASSURANCE/QUALITY CONTROL

Many protocols must be followed to obtain accurate data with CPT. ASTM D-5778 provides a complete set of instructions for CPT, including testing and data reduction methods. Some of the most important guidelines from this standard are:

- Rate of penetration must be 20 mm/s (+/- 5 mm/s)
- A cone sounding must not be performed closer than 10 borehole diameters from an existing unbackfilled or uncased bore hole
- The cone and data acquisition system should be powered up at least 15 minutes prior to use
- The cone must be unloaded before the test begins, and unloaded values after testing should be recorded
- The porous filter and pore pressure housing need to be completely de-aired before testing
- Push rods must be straight
- Cones should be calibrated every three months.

Equipment wear should be noted as a regular maintenance check. Figure 5.1 gives acceptable tolerances for a 15 cm² cone. From experience, the cone tip is usually the first component that needs to be replaced. It is good practice to replace the tip and friction sleeve at the same time. In general, the tip and friction sleeve need to be replaced about every 6 months, depending on usage and predominant soil types (Robertson and Cabal 2010).

CONE BASE AREA	NOMINAL			TOLERANCE MANUFACTURED (OPERATIONS)		
	BASE DIAMETER	CONE HEIGHT	EXTENSION	dc mm	hc mm	he mm
	cm ²	dc mm	hc mm			
15	43.7	37.8	5.0 - 6.0	+0.3 - 0.0 (≥42.7)	+0.3 - 0.0 (≥29.0)	+0.0 - 0.5 (≥2.0)

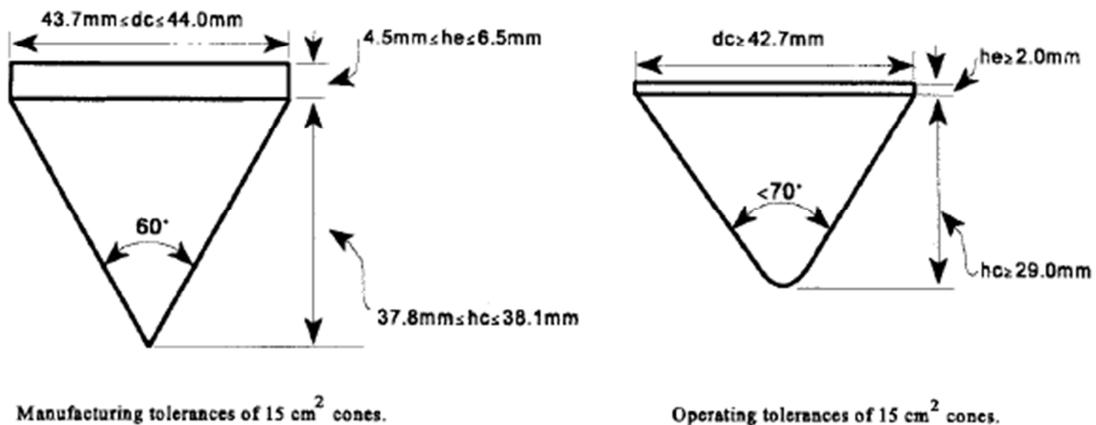


Figure 5.1. Manufacturing and operating tolerances for 15 cm² cone (ASTM D-5778).

5.9 CPT REPORTS

The following list describes information that should be included in a CPT report (ASTM 2008):

General — each sounding log should provide as a minimum:

- Operator name
- Project information
- Water surface elevation (if applicable)
- Sounding location
- Sounding number
- Sounding date
- Reports should contain information concerning:
 - Equipment data, including sensors
 - Graphical data
 - Procedures
 - Equipment calibration information
- Each sounding should be documented with:
 - Sounding plot
 - Accompanying tabular output—optional due to its bulk. Computer data files should be preserved and archived for later use.
 - Computer data files—preferably in ASCII format.
 - must contain header with sounding log information. Some programs require data in a particular format.

- Comments should contain notes on equipment and procedures, particular to the individual sounding.

Equipment—report should include notes concerning:

- Penetrometer manufacturer
- Penetrometer tips used in the investigation
- Penetrometer details such as friction sleeve end areas, location and types of sensors, location and type of friction reducers
- Offset between tip and sleeve resistance as used for friction ratio determination
- Serial numbers of penetrometer tips
- Type of thrust machine
- Method used to provide reaction force—with notes as to possible surface deformations
- Method of recording data
- Condition of push rods and penetrometer tip after withdrawal
- Special difficulties or other observations concerning performance of the equipment
- Details on piezocone design, filter elements, and fluid conditioning procedures
- Information on other sensing devices used during the sounding

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 CONCLUSIONS

The CPT machine will be a very useful tool for ODOT subsurface exploration work and is expected to provide considerable cost savings over the long term. As with any new technology, time is needed to develop the skills necessary to efficiently perform CPT investigations and utilize the results to maximum advantage. It is expected that once ODOT engineers and geologists become familiar with its capabilities, CPT will become an important tool for investigation and design.

In general, research data show good correlations with site stratigraphy but do not provide good correlations with soil properties. Possible reasons for this lack of success are:

- Complex stratigraphy, such as in parts of Ohio, produce high lateral and vertical variability of soil deposits. Such lateral variation can invalidate correlations between side-by-side conventional boreholes and CPT soundings. Vertical variations can alter CPT measurements due to the influence of soil layer boundaries.
- Many published correlations, which show substantially less variability, were developed based on research with laboratory calibration chambers and hence reflect closely controlled soil conditions. Therefore, more variability is expected for *in situ* field data.
- Thin layers of material that appear in a CPT sounding profile may have been missed during conventional drilling and sampling.
- A larger data set is needed for many parameters and soil types for the associated correlations to be statistically significant.
- Many variables that affect conventional soil sampling and testing can introduce additional variability into the correlations.
- Elevations of soundings were determined from a handheld GPS unit with an accuracy of +/- 0.5 ft. Therefore, some depths may include small errors which would shift the data vertically and reduce the accuracy of the correlations.

Efforts to continue the CPT research program as outlined in Section 6.2 will augment the current database and bring clarity to these issues. CPT is best used in sands, silts and clays. Gravels present problems and risk to the equipment and should be avoided if possible. Close adherence to ASTM D5778 is needed to ensure proper test methods and data reduction.

6.2 RECOMMENDATIONS FOR FUTURE WORK

Future research work is needed to identify best uses of CPT data for Ohio transportation projects. In order to build the database, conventional drilling and laboratory testing should continue alongside CPT whenever possible. Additional testing and correlation work is needed for every soil type. In particular, more laboratory test results are needed for the following parameters:

- Unit weight
- Overconsolidation ratio and preconsolidation stress
- Coefficient of consolidation
- Permeability
- Effective stress shear strength parameters

- Undrained shear strength

Consolidation and permeability tests should be conducted on soil samples taken depths corresponding to CPT dissipation tests. Offset boreholes for comparison and correlation should be located within 5-10 ft of a CPT sounding. The methods described in Chapter 3 should then be followed to match CPT, SPT and laboratory data. Additional good quality data should improve CPT correlations for Ohio soils.

One possible explanation for the lack of success reflected in the current soil property correlations is that they were prepared using the Ohio soil classification system as a basis, which was developed for pavement subgrade applications. It is recommended that ODOT OGE consider using the Unified Soil Classification System (USCS) as a basis for future CPT correlation studies. This is consistent with many previous similar studies that have produced better soil property correlations using the USCS.

IMPLEMENTATION PLAN

Cone penetration testing is expected to become a valuable resource for the ODOT Office of Geotechnical Engineering. CPT will improve response time for projects because data can be quickly analyzed and processed to generate reports. Continuous profiling gives a clearer picture of the subsurface, which is expected to yield higher confidence in design parameters and lower project costs. With the ability to clearly determine the extent of problematic soil layers, conventional investigations can be more focused. This saves drilling time in the field and makes laboratory testing time more efficient. Thus, the motivation to bring CPT into routine use for ODOT is compelling. This section discusses the implementation of CPT into the OGE subsurface investigation program.

The most important consideration to ensure successful CPT implementation is the establishment of a primary CPT operator. The CPT machine is a sophisticated piece of equipment that requires considerable skill and training to operate properly such that consistent high quality data is obtained. As of this writing, a primary and secondary operator have been identified and successfully trained. Clear specification of responsibilities and individual job duties should be provided to these operators. Unnecessary rotation of these positions to less skilled persons may result costly time delays as well as damage to the CPT cones and machine.

Modification of the ODOT drilling request system is needed to facilitate the routine use of CPT. A reconnaissance form has been developed to assist in this process. Also, once the capabilities of CPT are better understood, the Specifications for Geotechnical Engineering (SGE) need to be updated to include CPT. This update is several years away. Specific correlations and interpretations for CPT will need to be included in the new SGE.

Research to develop Ohio-based CPT correlations should continue as outlined in this report. Conventional drilling should be completed alongside CPT whenever possible. Likewise, additional laboratory testing is needed to determine soil properties for CPT correlations. Data compilation is expected to continue for the next several years to build the CPT database, at which time improved correlations can be developed. A specific staff member of the OGE should be identified to complete this work and it would be beneficial to have involvement from the primary CPT operator as well.

The OGE should establish the primary applications for CPT in Ohio. These applications might include identifying the boundaries of problematic soils (e.g., heaving sands) and testing their properties, bridge pile design, preliminary site investigations, and geotechnical explorations. Most applications will involve conventional drilling with SPT but in different sequences. A plan will be needed to identify the optimal sequence for use of CPT for typical projects. CPT can be used in combination with or instead of conventional drilling as discussed in this report. Development of specific guidelines to assist ODOT engineers and geologists in these decisions will help to optimize the use of CPT time in the field.

Although the CPT program will be operated out of the central office, district offices will also benefit from its use. One or more experts on CPT should be identified to provide technical support to central and district office staff. This staff member(s) will also be able to provide ongoing training to engineers for design applications. Along with providing training, the expert(s) should also establish a QA/QC program for CPT using this report and ASTM D5778 as a starting point.

The use of CPT for ODOT projects also has risks. The primary risk is CPT equipment damage and failures. There are not many CPT machine experts in Ohio or the Midwest. As such, when equipment problems arise, the factory in Holland almost always needs to be contacted. The weight and height of the machine can present a problem for transportation. The rig must be transported on a low boy trailer

which is not always available when needed. A staff member needs to be identified as the full time CPT operator. If this operator also has a commercial driver license, which is recommended, then only one person is needed for CPT operation. The primary CPT operator should not have significant other duties outside of CPT. Another important obstacle is the lack of good CPT correlations for soil properties in Ohio, which reduces confidence in design parameters.

Steps can be taken to overcome the above risks. A good maintenance schedule for the CPT equipment will significantly reduce equipment failures; such schedules are included in Appendix A. Well trained operators and drivers will reduce accidents and equipment damage. A new technical staff position created specifically for CPT is needed to develop in-house expertise for training and data usage for design. Lastly, the research program should continue for the next several years to build the CPT database and develop improved soil property correlations.

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APPENDICES

APPENDIX A

MAINTENANCE SCHEDULES

NOTE: The service intervals below are for standard industrial engines.				
Item	Daily	500 hr/ 12 month	2000 hr/ 24 month	As Required
Check engine oil and coolant level	•			
Check fuel filter/water bowl	•			
Check air cleaner dust unloader valve & restriction indicator gauge. ¹	•			
Visual walk around inspection	•			
Service fire extinguisher		•		
Check engine mounts		•		
Service Battery		•		
Change engine oil and replace oil filter ^{2,3}		•		
Check crankcase vent system		•		
Check air intake hoses, connections and system		•		
Replace fuel filter elements		•		
Check automatic belt tensioner and belt wear		•		
Check engine electrical ground connection		•		
Check cooling system		•		
Coolant solution analysis-add SCAs as required		•		
Pressure test cooling system		•		
Check engine speeds		•		
Check crankshaft vibration damper (6.8 L Engines) ⁴			•	
Flush and refill cooling system ⁵			•	
Test thermostats			•	
Check and adjust engine valve clearance			•	
Add coolant				•
Replace air cleaner elements				•
Replace fan and alternator belts				•
Check fuses				•
¹ Replace primary air cleaner element when restriction indicator shows a vacuum of 625 mm (25 in.) H2O.				
² During engine break in, change the oil and filter for the first time after 100 hrs.				
³ Service intervals depend on the sulfur content of the diesel fuel, oil pan capacity, and the oil and filter used, which means that intervals may be reduced.				
⁴ Replace crankshaft damper every 4500 hours or 60 months, whichever comes first				
⁵ If John Deere Cool-Gard is used, the flushing interval may be extended to 3000 hours or 36 months.				

CPT Service Schedule		Operational Hours			
O = Check and/or adjust X = Replace					
All service work to be performed at operating temperature		10 hour	50 hour	250 hour	1 year or 1500 hour
1	Fuel Level	O			
2	Clean or replace engine air filter		O	X	X
3	Check and or adjust engine idle			O	
4	Check for exhaust leaks			O	
5	Check battery terminals and acid level		O		
6	Check for leaks on pipes, tubes, hydro pumps, etc.	O	O		
7	Check hydraulic oil and replace if sample test indicates replacement	O		O	X
8	Check and or replace hydraulic oil filters			X	
9	Replace hydraulic oil filters when indicators show				X
10	Pressure check hydraulic controls			O	
11	Check and or adjust control components	O		O	
12	Electrical and warning lights on operating panel	O		O	
13	Grease nipples			O	
14	All oil levels, oil change planetary gear boxes		O	X	X
15	Chain tension of tracks		O		
16	Oil level idlers of tracks, check for leaks			O	O
17	Mountings of drive sprockets of tracks			O	
18	Mountings of planetary gear boxes			O	
19	Overall check for damage, cracks, tears, leaks	O			
20	Test run			O	
21	Check bellow for damage or leaks				
22	Warning labels and operating instruction labels check/replace		O		
23	Clean CPT rods			O	
24	Rotate CPT rods			O	
25	Clean cone assemblies			O	
26	Clean and check upper clamp		O	O	
27	Clean and check inner casing		O	O	
28	Test cone assemblies and measuring instruments			O	
29	Check wear pads in tracks			O	
30	Grease locks and hinge with Teflon spray		O		

APPENDIX B
RECONNAISSANCE FORM


State of Ohio Department of Transportation
Office of Geotechnical Engineering

Field Sounding Reconnaissance Report
 Project: _____
 PID: _____

Project Type: Structure Soil Profile Subgrade Landslide Rockfall Mine Other:

Location: Quad: _____ Twp: _____ Dist: _____ City Limits: Y / N City: _____
 Closest Intersection: _____ Direction: N E S W N Dist Off Pavement: _____

CPT: # On-Road Soundings: _____ # Off-Road Soundings: _____ MOT: Y / N MOT Type: Shoulder Drive Lane Passing Lane
 ROE: Y / N Soundings #s requiring ROE: _____ Site Access: Open Requires Some Work Requires Significant Work
 Site Prep: Tree Removal Access Road Bench Work Pad Equipment: Dozer Water Truck Truck Rig Track Rig
 Fill Elect. Shielding Pave. Core Other: _____
 Field Marking: Painted Lathe w/ Ribbon Off-set Lathe Loading Zone: _____ MOT
Utilities: Overhead Underground Type: Phone Elect. Cable Gas Oil Water/Sanitary Other: _____
 Company _____ Phone _____

Land Usage: Wooded Agriculture Abandoned Residential Commercial Waste Other:
 Roadway: Y / N Type: Asphalt Concrete Gravel Condition: Poor Moderate Good Patching: Y / N
 Springs/Wells: Y / N Type: Contact Depression Joint Fracture Flow Rate: _____ Drilled Wells Dug Wells
 Bedrock: Y / N Type: SS SH SiSt ClSt Coal LS Dol Rock Exposure/Joints
 Depth-Road to Water: _____ Maxi. Depth-Road to Stream Bottom: _____ Steam Bottom: Cl/Si Gr/Cobble Bedrock
 Stream Conditions: Bank Erosion Scour Debris Piles Headwall Erosion Other:
 New Replace Culvert D-Culvert 3-Sided Box Conc. Arch Pre-stress Steel Wall Other:
 Length: _____ Width: _____ Deck Thick: _____ # of Spans: _____ Condition: Poor Fair Good

Soil Profile Existing Embankment Height: _____ Slope (%): _____ # Benches: _____ Notes: _____
 Ponds Wet Areas Low Lying Areas Peat Other:
 Uncontrolled Fill Waste Material Other:

Geohazard Depression in ROW Depression in Roadway Other:
 Mine Opening AMD Mine Spoil Drainage Capture Tension Cracks Slide Scarp Toe Bulge
 Hummocky Ground Other:

Field Reconnaissance Notes: _____

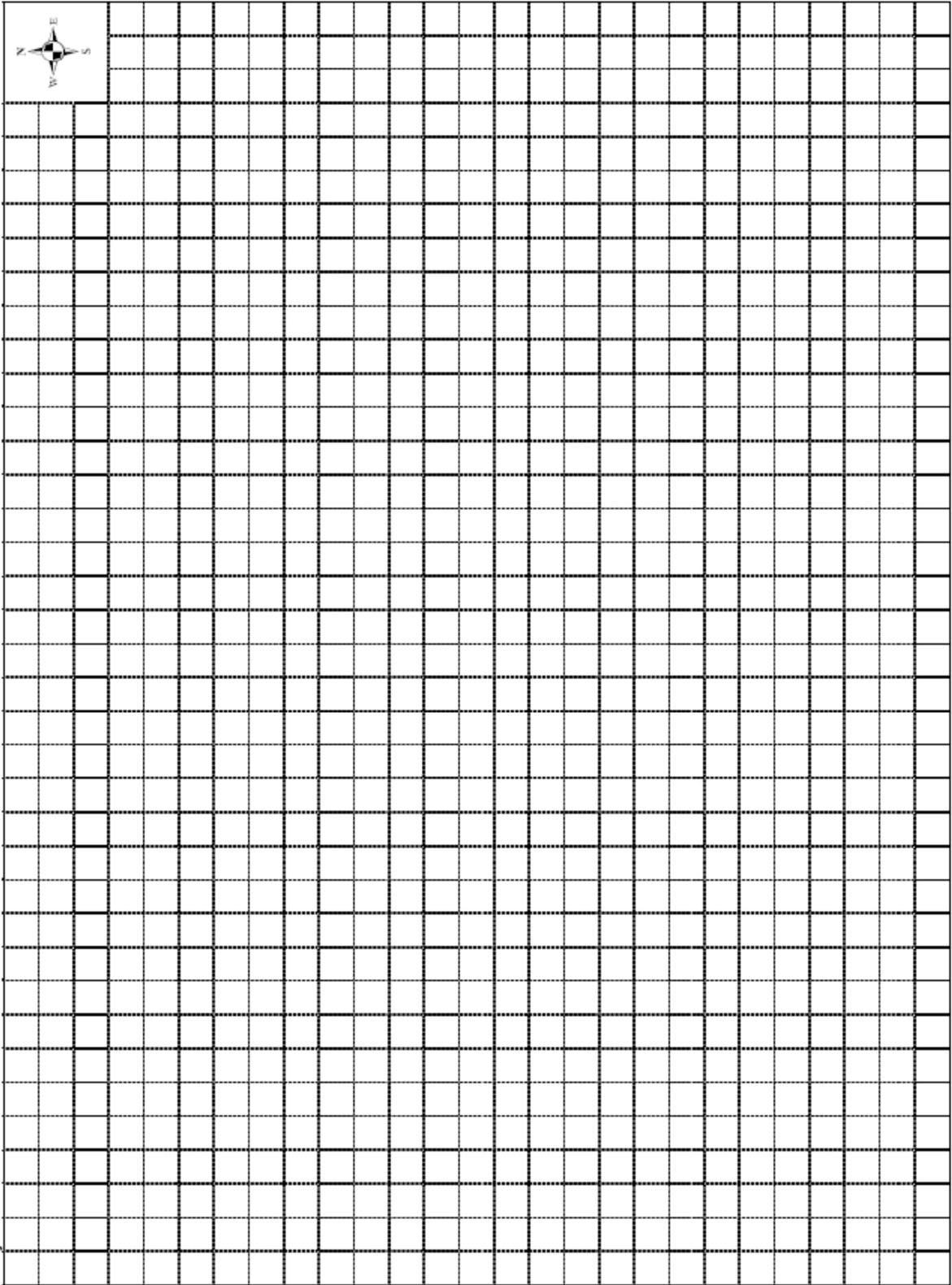
Photos Taken: Y / N GPS Files: Y / N Signature: _____ Date: _____
 File Name: _____


Provide Site Sketch on Back of Sheet with all Feature Locations

Revised 6/07/10

SITE SKETCH

Project:



Date:

Scale:

APPENDIX C
TECHNICAL NOTE

TECHNICAL NOTE

Date: 10-SEP-2009

By: Ed Brylawski, P.E.
A. P. Van den Berg, Inc.

SUBJECT: IMPORTING CPT DATA FROM GOnsite! TO EXCEL

A.P. Van den Berg's GOnsite! software stores CPT files in ASCII text format. The files have a [.gru extension](#).

I use the following steps to import the files to Excel and Separate the data into columns.

NOTE: I use an attached 35-m deep CPT data file in this example.

1. Open the *.gru file in Excel. In the example file:
 - rows 1 to 85 in the EXCEL worksheet contain the CPT parameters
 - rows 87 to 1837 contain the CPT data for the 35-m deep CPT.
2. I want to replace the colons (:) in the data with a pound symbol (#) to simplify the separation of the data into columns.
 - Click **[EDIT] [REPLACE]**
 - The REPLACE window opens
 - In the "Find What:" box type : (colon)
 - In the "Replace With:" box type # (pound symbol)
 - Click **[REPLACE ALL]**
3. Excel replaces the colons (:) in the CPT data with pound symbol (#)
4. Next, I want to remove the final exclamation points (!) at the end of each depth's data set
 - Click **[EDIT] [REPLACE]**
 - The REPLACE window opens.
 - In the "Find What:" box type !
 - Leave the "Replace With:" box blank
 - Click **[REPLACE ALL]**
5. Excel removes the final exclamation point (!) in the CPT data
6. Now I export the text file to columns in Excel
 - I highlight the data in the field (A88..A1837)
 - Click **[DATA][TEXT TO COLUMNS]**
 - The TEXT TO COLUMNS WIZARD STEP 1 OF 3 window opens
 - Select the DELIMITED radio button and click **[NEXT]**
 - The TEXT TO COLUMNS WIZARD STEP 2 OF 3 window opens
 - Uncheck the TAB delimiter box, and check the OTHER delimiter box
 - In the next box to the right type type # (pound symbol) and click **[NEXT]**
 - The TEXT TO COLUMNS WIZARD STEP 3 OF 3 window opens
 - in the DESTINATION box type **\$H\$88**
 - Click **[FINISH]**
 - This separates your columns in the field (H88..Y1837)

7. Refer to the Table in Appendix A that shows the standard channel number A. P. Van den Berg uses for the various CPT parameters. After separating the data into columns I place the channel number symbol and unit at the head of each parameter column. Then I delete the channel number columns.
8. The data is now ready to graph, export to other databases or to add new columns with U.S. customary units.

The Excel spreadsheet has several example graphs of the CPT data.

Tip resistance vs. depth

Local friction vs. depth

Friction ratio vs. depth

Pore-water pressure vs. depth

Inclination vs. depth

Ed Brylawski, P.E.

A.P. Van den Berg, Inc.

Tel: 570-296-8224

Table

A. P. Van den Berg Channel Number Assignment for CPT Parameters

Channel	Symbol	Unit	Measurement parameter	Symbol Units
D	z	m	Depth	meter
0	t	s	Time	second
1	q _c	MPa	Cone tip stress, cone tip resistance	MegaPascal
2	f	MPa	Local friction stress, local friction resistance	MegaPascal
3	u ₁	kPa	Pore-water pressure on cone tip	kiloPascal
4	u ₂	kPa	Pore-water pressure at base of cone	kiloPascal
5	u ₃	kPa	Pore-water pressure above friction sleeve	kiloPascal
6	l	°	Inclination, vector resultant of l _x & l _y	degrees
7	F	kN	Total friction force	kiloNewton
8	Q	kN	Total force	kiloNewton
9	v	cm/s	Speed of penetration	centimeters/second
10	G	mS	Electrical conductance of soil	milliSiemen
11	pH		pH of soil	
12	E ⁰ _r	mV	Redox potential of soil	milliVolt
13	T	°C	Temperature	degrees C
14			unassigned	
15			unassigned	
16			unassigned	
17	V _{sL}	V	Seismic shear wave left	Volt
18	V _{sR}	V	Seismic shear wave right	Volt
19	V _{pL}	V	Seismic compression wave	Volt
20	rf	%	Friction ratio = f/qc	
21	σ	mS/m	Electrical conductivity of soil	MilliSiemen/meter
22			unassigned	
23			unassigned	
24			unassigned	
25			unassigned	
26			unassigned	
27			unassigned	
28			unassigned	
29			unassigned	
30	l _x	°	Inclination in the x-z plane	degrees C
31	l _y	°	Inclination in the y-z plane	degrees C