Use and Application of Piezocone Penetration Testing in Presumpscot Formation

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ABSTRACT: This paper examines the advantages and limitations of CPTu and SCPTu as an exploration method for geotechnical engineering of Presumpscot Formation. Discussion will include typical results of CPTu and SCPTu data for Presumpscot Formation, application and use for settlement prediction, bearing capacity analysis, slope stability evaluation, and seismic design considerations. The intent is to provide an overview of the Use and Application of Piezocone Penetration Testing for the Presumpscot Formation in geotechnical engineering.

1 INTRODUCTION

Presumpscot Formation is commonly described as marine sediment consisting of lean clay with a mixture of silt and minor sand. Geotechnical properties for the Presumpscot Formation typically include low shear strength, higher sensitivity, and moderate to high compressibility. Challenges for geotechnical design include reduced bearing capacity, excessive settlements, slope instability, and lower seismic profile classification.

Geotechnical investigations are required to obtain necessary information for engineering design of the Presumpscot Formation which typically includes site reconnaissance, subsurface explorations, and soil laboratory testing. Results of the investigations are interpreted by the geotechnical engineer for application to the project design. As one might say, a carpenter is limited to the tools available in the toolbox. The same is true when it is applied to geotechnical investigations.

Piezocone Penetration Testing (CPTu) and CPTu with seismic measurements (SCPTu) are useful methods of field exploration available to geotechnical consultants for exploring the presence and properties of Presumpscot Formation. Like most tools there are advantages and limitations. This paper discusses the advantages and limitations of CPTu and SCPTu as exploration methods for geotechnical engineering of Presumpscot Formation. It additionally presents the use and application of CPTu and SCPTu for geotechnical design with case histories for Presumpscot Formation as follows:

- Subsurface Investigation
  Peninsula Drive Kennebunk
- Shallow Foundation Design
  Auto Dealership Westbrook
- Deep Foundation Design
  Commercial Complex Portland
- Slope Stability
  Bunganuc Bluff Brunswick
- Seismic Design
  Fire Station Norridgewock

2 SUBSURFACE INVESTIGATION

Piezocone Penetration Testing (CPTu) is performed by a cone on the end of a series of rods pushed into the ground at a constant rate (2 cm/s) to obtain continuous measurements of the resistance to penetration of the cone. Parameters obtain include cone resistance (q_c), sleeve friction (f_s), and piezocone pore pressure (u_2). Results of the CPTu penetration tests are interpreted to obtain soil type and soil parameters for engineering design. Shear wave velocity tests can be performed at select intervals, typically 1 meter (3-feet), during CPTu testing referred to as SCPTu. CPTu is performed in accordance with ASTM D5778. Shear wave velocity testing is performed in accordance with ASTM D7400.

Equipment used to perform CPTu includes large push platforms or multipurpose drill rigs. Push platforms consist of a heavy truck or tracked machine capable of applying enough push/pull force necessary for cone penetration and retrieval. On multipurpose machines soil anchors are used to achieve down force. Devoted CPTu rigs typically have enclosed cabins for storage of electronics providing minimal setup. Multipurpose rigs provide the versatility of performing test borings along with CPTu however require additional setup for performing each task.

Figure 2-1 Multipurpose Rig (AMS PowerProbe©)

Figure 2-2 Devoted Rig (USGS Mack Truck 6x6)

In local practice rotary wash test borings are widely used to explore Presumpscot Formation. Test borings is performed with standard penetration test, vane shear test, and collection of undisturbed Shelby tubes. The advantage to test borings are the collection of samples available for visual inspection and laboratory testing. Vane shear tests also provide in-situ testing for undrained shear strength (S_u). The disadvantage is that test boring data are limited to where samples are collected, commonly performed at discrete intervals of 5 feet for deep explorations.

Test borings become increasingly slower in production with depth. Typical production for rotary wash test borings with standard 5-foot sampling may range from 100 to 150 feet per day. Where Shelby tube sampling and vane shear tests are performed production can be reduced. CPTu typically obtains production of 150 to 300 feet per day using multipurpose rigs. Production of 300 to 500 feet per day can even be obtained using larger devoted CPTu push machines.

Presumpscot Formation commonly ranges in thickness from 25 to 125 feet with possible thicknesses in excess of 150 feet. From a production standpoint, CPTu can provide greater efficiency than test borings where explorations deeper than 25 to 50 feet are required. Exploration costs for CPTu are approximately 25 percent greater than conventional test borings in locations where both services are offered. Projects requiring numerous deep explorations within Presumpscot Formation, however, can offset the cost for CPTu through increased efficiency when compared to test borings.

CPTu and SCPTu data can be empirically correlated to predict a range of geotechnical design parameters. Parameters of interest for geotechnical investigations in Presumpscot Formation include over consolidation ratio (OCR) and undrained shear strength (S_u).

The most common correlation used for over consolidation ratio (OCR) is presented as:

$$OCR = k*Q_t \quad (1)$$
$$Q_t = (q_t - \sigma_{vo})/ \sigma_{vo'} \quad (2)$$

where Q_t is normalized cone resistance, q_t is corrected cone resistance, σ_{vo} is vertical total stress, $\sigma_{vo'}$ is vertical effective stress, and k is the empirical cone factor.

Calibration of the k factor is recommended for local deposits such as the Presumpscot Formation using results from laboratory one dimensional consolidation testing. Typically the k factor ranges from 0.2 to 0.5 with an average of 0.33 (Robertson et al., 2010). A conservative estimate of OCR will be obtained using a lower k value.

The most commonly used method for undrained shear strength (S_u) is presented as:

$$S_u = (q_t - \sigma_{vo})/N_{kt} \quad (3)$$

where q_t is corrected cone resistance, σ_{vo} is vertical total stress, and N_{kt} is undrained shear strength cone factor.

Calibration of the N_{kt} factor is recommended for local deposits such as the Presumpscot Formation using results from in situ vane shear tests and laboratory testing for estimating undrained shear strength (S_u). Typically the N_{kt} factor ranges from 10 to 18 with an average of 14 (Robertson et al., 2010). A conservative estimate will be obtained using a higher N_{kt} value.

One should consider, when calibrating CPTu data, the quality and accuracy of the measured reference data as well as the mode of shear anticipated in the analysis. Sensitivity analyses are recommended to evaluate the probable values within a reasonable k and N_{kt} range.

Findings from local projects performed by Summit Geoengineering Services, Inc. have resulted in good correlation to the k and N_{kt} values published by (Robertson et al., 2010).

A variety of soil behavior type (SBT) classification interpretive charts have been published. However the most commonly used were developed by Robertson and Campanella (1983) for the friction cone, by Robertson et al., (1986) for piezocone with normalized pore pressure and by Robertson et al., (1990) using normalized piezocone parameters.

The method developed by Robertson et al., (1986) includes non-normalized parameters for cone resistance (q_t) and friction ratio (R_f) along with normalized pore pressure (B_q). The soil behavior type classification is separated into 12 zones. The method developed by Robertson et al., (1990) includes the normalized parameters of normalized cone resistance (Q_t), normalized friction ratio (F_r), and normalized pore pressure (B_q). The soil behavior type classification is separated into 9 zones.

The soil behavior type may conflict when comparison is made between other methods such as the Unified Soil Classification System (USCS). Use of soil behavior type for subsurface profiling should only be used for generalization of soil type and confirmed with results of test borings where available. A simplistic approach for interpreting soil types within Presumpscot Formation can be made by observation of the cone resistance and piezocone pore pressure. Layers of sand or silt typically generate a higher cone resistance with lower piezocone pore pressure whereas clay will generate a higher piezocone pore pressure with lower cone resistance. Observing the fluctuation between cone resistance and piezocone pore pressure can give approximate subsurface profiling when indentifying layers of sand (drained) and clay (undrained).

2.1 *Peninsula Drive Kennebunk, Maine*

Summit Geoengineering Services (SGS) was asked to conduct a geotechnical investigation for a proposed 3 story residence along Peninsula Drive in Kennebunk, Maine. The subsurface conditions at the site consisted of organic peat 10

feet in thickness overlying glacial marine deposits (Presumpscot Formation) overlying bedrock encountered at a depth of 69 to 72 feet. Inter-bedded sand seams were present within the predominant clay deposit. The subsurface conditions were explored by 2 test borings and 1 piezecone penetration test with shear wave velocity (SCPTu). Test borings were performed to a depth of 30 feet with rod probe to refusal depths ranging from 69 to 72 feet. Fieldwork was completed in 1 day of exploration utilizing a multipurpose drill rig. Below are interpretive results from the SCPTu exploration performed:

Figure 2-3 Interpretive SCPTu Plot

On the left are corrected cone resistance (q_t) and piezocone pore pressure (u_2). Sand layers within the clay deposit were indentified between depths of 37 and 43 feet and again at 51 feet. Correlated SPT-N values are plotted next showing a comparison of cone resistance to standard penetration test (SPT-N_{60}) resistance. To the right is the shear wave velocity. On the far right is the observed soil profile interpreted from test borings and CPTu soil behavior type.

An interesting discovery with this particular deposit is the noticeable increase in piezocone pore pressure between the upper and lower clay units between the sand layers encountered at 37 to 43 feet. Increase in corrected cone resistance (q_t) and shear wave velocity suggest the lower clay unit to be of higher shear strength. However, due to the increase in effective stress with depth the OCR ratio indicates the clay to be over consolidated from a depth of 10 to 37 feet and normally consolidated from 43 to 70 feet. The upper clay approaches normally consolidated conditions near the drainage path at 37 feet. The findings suggest the upper and lower portions of the clay were created under different conditions (time of formation) as evident by the sand seams splitting the upper and lower clay units. This information gives the engineer a greater understanding of the stress history and drainage paths of this particular deposit.

This project is an example of utilizing multiple exploration methods to better obtain a complete picture of the subsurface conditions. Performance of the test borings provide visual inspection of the soil conditions and sample collection for corresponding laboratory index and compressive testing. Use of SCPTu provided the following additional subsurface information:

- Identification of sand layers for evaluation of drainage paths during consolidation
- Identification of upper/lower clay subunits
- Generation of an interpretive over-consolidation ratio (OCR) profile
- Shear wave velocity for seismic design

3 SHALLOW FOUNDATION DESIGN

Cone penetration testing CPTu can be useful in evaluating bearing capacity and settlement for shallow foundations bearing upon Presumpscot Formation. Allowable bearing pressure can be reduced due to settlement. Settlement can become problematic where fill loads, typically 5 feet or greater, are introduced as part of development. Loading imposed by foundations and/or fill result in consolidation settlement over time. Predicting the magnitude and rate of consolidation settlement is critical in determining bearing pressure and fill limitations for foundation design.

3.1 *Auto Dealership Westbrook, Maine*

Summit Geoengineering Services (SGS) was asked to conduct a geotechnical investigation for a proposed Auto Dealership in Westbrook, Maine. Previously a preload fill, without wick drains, was installed by others in late fall of 1997 approximately 16.5 years prior to our investigation. The subsurface conditions were explored with the performance of 7 test borings and 3 piezecone penetration tests CPTu. Test borings were performed to a depth of 10 to 20 feet except one test boring performed to a depth of 50 feet with Shelby tube sampling. Work was performed within 3 days of exploration utilizing a multipurpose drill rig. Interpretive subsurface cross section beneath the building footprint from test borings and CPTu:

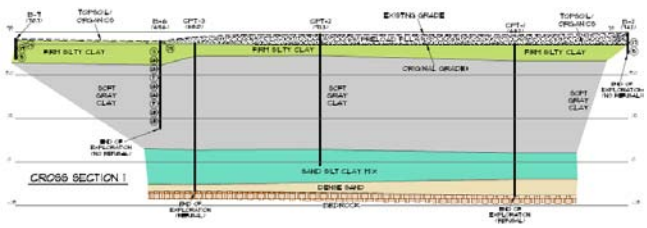

Figure 3-1 Interpretive Subsurface Profile

Moisture content for the marine clay ranged from 23.3% (firm clay) to 52.7% (soft clay). Field vane shear tests performed in 1989 during a previous investigation by others indicate undrained shear strength (S_u) ranged from 350 to 650 psf for the lower soft clay. One dimensional consolidation testing was performed on an undisturbed Shelby tube sample obtained at a depth of 20 feet. From results of the consolidation test an over consolidation ratio (OCR) of 1.3 was estimated at a depth of 20 feet. Shear strength (S_u) and over consolidation ratio (OCR) for the underlying soft clay were estimated from the CPTu explorations graphed as follows:

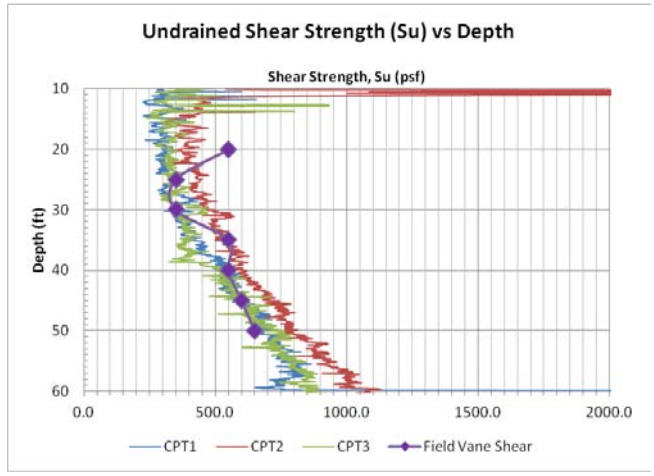

Figure 3-2 Factor N_{kt} for (S_u) = 15

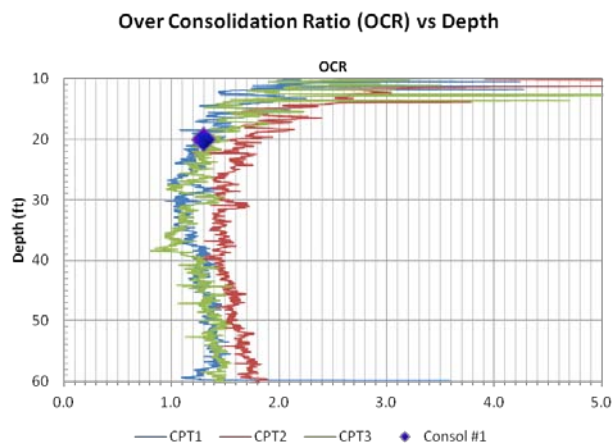

Figure 3-3 Factor k for (OCR) = 0.45

CPTu-1 was performed near the edge of the preload, CPTu-2 was performed beneath the center of the preload, and CPTu-3 was performed outside the preload area. Observation of the undrained shear strength (S_u) and over consolidation ratio OCR suggests CPTu-2 has achieved an increase in strength compared to the results for CPTu-1 and CPTu-3 performed at the edge or outside the preload footprint. This would appear consistent with fundamental soil mechanics that suggest strength increase over time during preload (consolidation).

Estimate for potential settlement was performed based on findings from the subsurface investigation, results of the laboratory testing, and review of settlement data provided for the existing preload. Settlement observed for the preload was compared to the estimates obtained from the laboratory consolidation test and the OCR determined by the CPTu explorations.

The completed preload was monitored from November 3, 1997 to January 19, 1999 for a total period of 1.2 years. The preload was approximately 5 feet in height, 250 feet in length, and 100 feet in width. Total settlement observed during the preload monitoring was 0.37 inches. Time rate for consolidation obtained from the consolidation test estimated the preload settlement was between 30 and 40 percent completion when at 0.37 inches for a period of 1.2 years. The calculated estimate for primary consolidation (100 percent) was 1.2 inches in 12 years. The predicted settlement at 30 to 40 percent completion is 0.36 to 0.48 inches showing reasonable agreement between predicted and measured settlement values.

Review of the preload settlement and comparison with the geotechnical findings enabled better prediction of future settlements for the proposed development. Results of the preload with comparison to the findings suggested consolidation at the site would be slow (over years) at a gradually decreasing rate. Minimizing site fill to less than 5 feet and utilization of foundation loads less than 80 kips were recommended to reduce total settlement of the underlying soft clay. Due to the low consolidation rate, preload was not recommended unless wick drains or similar were to be installed to reduce preload time. If heavy foundation loads were to be required, a mat foundation and/or pile supported foundation may have been appropriate for development at the site. However, in working with the developer the single story 25,000 ft^2 building was able to be supported using conventional spread footings with a net allowable bearing pressure of 3,000 psf. Use of CPTu provided the following additional information:

- Subsurface profiles from 3 CPTu explorations (248 total feet) within 1 day of exploration
- Generation of an interpretive undrained shear strength (S_u) profile
- Generation of an interpretive over-consolidation ratio (OCR) profile
- The lack of drainage paths (sand layers) for soft clay 55 feet in thickness
- The discovery of S_u and OCR increase for marine clay beneath center of the preload

4 DEEP FOUNDATION DESIGN

Cone penetration testing CPTu can be useful in evaluating pile design for deep foundations within Presumpscot Formation. The total pile axial bearing capacity consists of end bearing resistance and side friction resistance. For sand deposits end bearing tends to be more dominant however for soft clays the side friction tends to play a bigger role. Pile length and end bearing material also greatly affect pile capacity. Where short piles within soft clay are end bearing on bedrock the end bearing capacity will control the design. However, deep soils with end bearing piles warrant consideration of the side friction.

Since CPTu is a close model to the pile installation process it serves as a useful tool in predicting pile capacity using static methods. SCPTu is also useful for further evaluation of appropriate seismic site design. Since piles are typically used for soft or loose soil conditions such as Presumpscot Formation, determining the appropriate seismic site classification can be critical to the project. Other design considerations for pile design in Presumpscot Formation include down drag effects from fill or surface loading resulting in consolidation settlements and corresponding down drag along both friction and end bearing piles. Buckling has to be considered where confinement soils are very soft and end bearing is rigid such as bedrock, particularly during pile installation. Piles end bearing in soil have to be considered for settlement. Lateral capacity may also be required for design.

The use of CPTu provides an excellent method for estimating continuous profiles of undrained shear strength (S_u) and over consolidation ratio (OCR). For obtaining an estimate of ultimate pile capacity, a static method of analysis is available as follows:

$$Q_{ult} = f_p A_s + q_p A_p \qquad (4)$$

Where f_p is unit side friction, A_s is outer pile shaft area, q_p is unit end bearing, and A_p is pile end area (Robertson et al., 2010). For cohesive soils the unit side friction (f_p) and unit end bearing (q_p) are obtained from the undrained shear strength (S_u) multiplied by coefficients α for side friction and N_t for end bearing. The coefficients α range

from 0.5 to 1 depending on OCR and N_t range from 6 to 9 depending on pile size and depth of embedment. Continuous profiles of undrained shear strength and OCR plot can be estimated from results of CPTu data giving a better and more detailed pile design using static coefficients.

Other methods of analysis available using empirical approaches from CPTu data, including a method outlined by Bustamante and Gianeselli 1982 – LCPC Method (Robertson et al., 2010). The LCPC method estimates pile capacity as unit end bearing as:

$$q_p = k_c q_{ca} \quad (5)$$

where k_c is end bearing coefficient and q_{ca} is average cone resistance. The unit side friction is

$$fp = q_c/\alpha \quad (6)$$

where q_c is cone resistance and α is friction coefficient for LCPC.

Using both the static method and empirical method gives independent analyses for comparison requiring minimal input to quickly and efficiently estimate ultimate pile capacity.

4.1 *Commercial Complex Portland, Maine*

Summit Geoengineering Services (SGS) was asked to conduct a geotechnical investigation for a proposed 4 story commercial complex in Portland, Maine. The subsurface conditions were explored with the performance of 4 test borings, 8 ledge probes, and 1 piezecone penetration test with shear wave velocity (SCPTu). Test borings were performed to depths of 10 to 20 feet. Ledge probes were performed to a depth range of 45 to 75 feet. Work was performed within 1.5 days of exploration utilizing a multipurpose drill rig. Below are interpretive results from the SCPTu exploration performed:

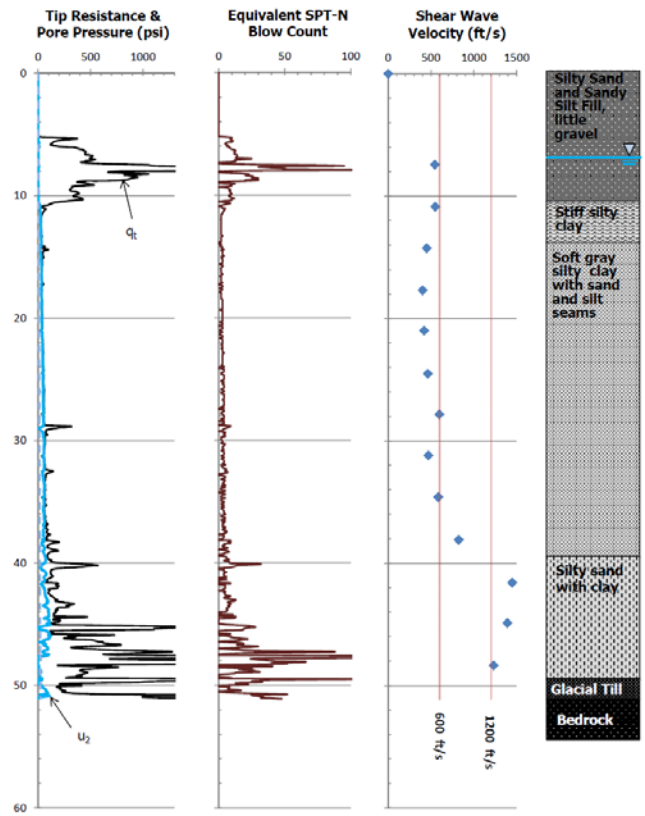

Figure 4-1 Interpretive SCPTu Plot

The presence of soft clay, large column loads, and estimates for excessive settlement resulted in a deep foundation system to support the 4 story commercial building complex. Preliminary pile design was performed using static and empirical methods of analysis. Bedrock was found to range from a depth of 45 to 75 feet below ground surface. Based on the foundation loads and subsurface profile interpreted from the SCPTu, HP12x53 H-piles end bearing on bedrock were selected. Wave equation analysis using GRLWEAP™ was performed using interpretive soil behavior type and soil strength/density estimated from the SCPTu to model the soil profile as shown below:

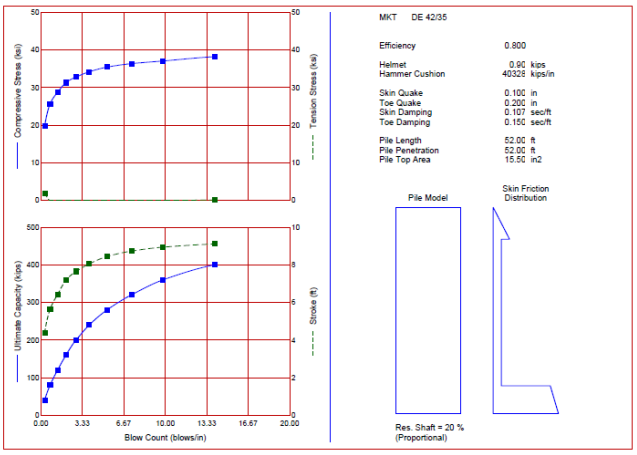

Figure 4-2 GRLWEAP™ for HP12x53 Steel H-piles

To determine the appropriate International Building Code (IBC) seismic site classification, results from the SCPTu shear wave velocity tests were used. The shear wave velocity V_s obtained for the soil profile explored to a depth of 52 feet ranged from 400 to 1450 ft/s and averaged 720 ft/s resulting in a site classification of D. Plasticity index for the soft clay ranged from 12 to 20 excluding the site from a site classification of E, which is required where a soil profile of greater than 10 feet has undrained shear strength (S_u) of less than 500 psf and moisture content of greater than 40 percent. Below is the waterfall graph for the shear wave velocity V_s obtained during the SCPTu:

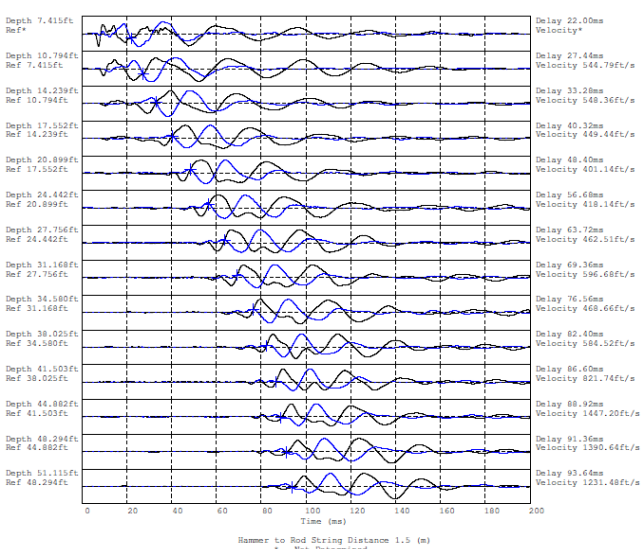

Figure 4-3 Seismic Shear Wave Velocity Waterfall Plot

The use of SCPTu provided the following information used for pile design:

- Continuous interpretive subsurface profile to a depth of 52 feet
- Generation of an interpretive undrained shear strength (S_u) profile
- Generation of an interpretive over-consolidation ratio (OCR) profile
- Ability to use both static and empirical methods of analysis for preliminary pile design
- Continuous subsurface profile for modeling soil in GRLWEAP™ wave equation analysis
- In situ shear wave velocity V_s for improved IBC seismic site classification

5 SLOPE STABILITY

Cone penetration testing CPTu can be useful in evaluating slope stability of Presumpscot Formation. CPTu provides near continuous soil profiling giving the engineer better confidence that potential drainage layers or soft layers are not missed. Visual inspection of the piezocone pore pressure along with cone resistance provides detailed information for silt or sand lenses or seams within clay deposits. This data helps identify drainage layers for possible development of slip planes between dissimilar materials and locations of concentrated groundwater. The near continuous data can also be interpreted for a continuous plot of undrained shear strength (S_u). With this information the engineer can adjust the stability analysis for fluctuation in shear strength and account for identified drainage paths.

5.1 *Bunganuc Bluff Brunswick, Maine*

Summit Geoengineering Services (SGS) was asked to conduct a geotechnical investigation for recent landslide activity at a residence along Bunganuc Bluff in Brunswick, Maine. The slope was approximately 300 feet in length with a height of approximately 40 feet above tidal flats extending towards Maquoit Bay.

Figure 5-1 Photograph of Existing Slope

Figure 5-2 Photograph of Existing Slope

The subsurface conditions were explored with the performance of 2 test borings and 3 piezecone penetration tests, one with shear wave velocity (SCPTu). Test borings were performed to a depth of 40 to 50 feet with SPT split spoon sampling, shelby tube sampling, and vane shear testing. Groundwater observation wells were installed at the test borings. Work was performed within 2 days of exploration utilizing a multipurpose drill rig. Below is the SCPTu-3 data log from SCPTu-3 performed at the top of the slope and used for stability analysis:

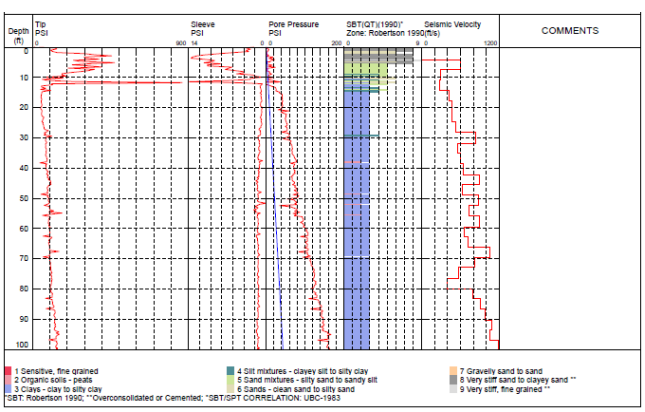

Figure 5-3 SCPTu Log

The subsurface conditions at the site consisted of thin topsoil overlying glacial marine deposits (Presumpscot Formation) explored to a depth of 100 feet. The upper 12 feet of glacial marine deposits consisted of firm clay-silt with fine sand seams. The lower glacial marine deposit consisted of soft gray silty clay with trace fine sand. The liquid limit ranged from 32 to 36, plasticity index ranged from 12 to 14, and moisture content ranged from 32.3 to 38.3 percent. Drained strength parameters obtained from laboratory direct shear testing indicated a peak friction angle (ϕ') of 32.9° at a cohesive intercept (c') of 288 psf. Groundwater depth ranged from 10 to 12 feet at top of embankment. Tidal ebb and flow was present at the toe of slope.

Geotechnical properties of the lower glacial marine deposits for undrained shear strength (S_u) were estimated from field vane shear tests conducted in test borings and from interpretation of cone resistance using a correction factor N_{kt} of 16. Estimation of the over consolidation ratio (OCR) was determined from results of laboratory one dimensional consolidation tests and from interpretation of the cone resistance using a correction factor k of 0.30. Graphic representation of the undrained shear strength (Su) and over consolidation ratio (OCR) are presented below:

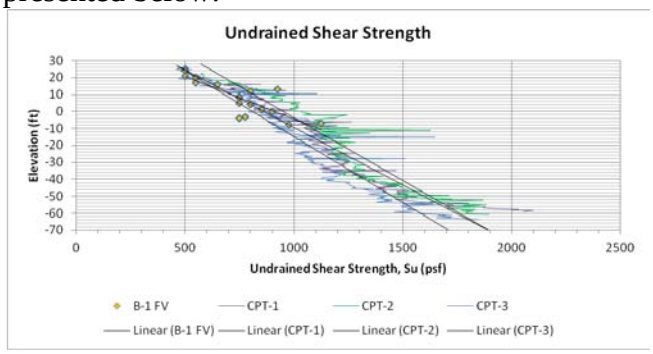

Figure 5-4 Undrained Shear Strength (S_u)

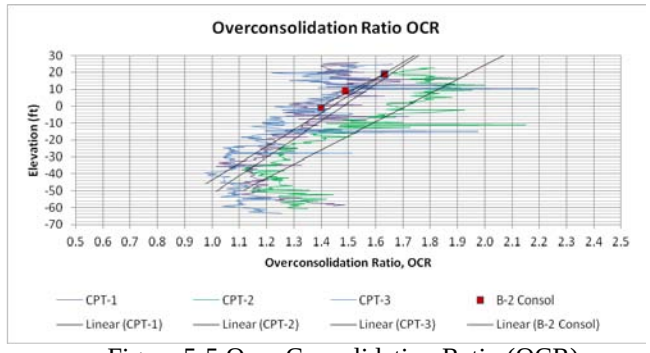

Figure 5-5 Over Consolidation Ratio (OCR)

The normalized undrained shear strength referred to as:

$$(S_u/\sigma'_v) = (0.23 +/- 0.04)*OCR^{0.8} \qquad (7)$$

where the ratio of undrained shear strength (S_u) to vertical effective stress (σ'_v) is approximated by the over consolidation ratio (OCR) (Jamiolkowski et al., 1985). The average ratio determined from the above results is 0.24 +/- 0.03 thus showing good agreement between the estimated undrained shear strength (S_u) and over consolidation ratio (OCR) estimated from the CPTu tests, field vane shear tests, and laboratory one dimensional consolidation tests.

Stability analysis was performed for the existing slope at an inclination of 33° (1.5 horizontal to 1 vertical). The factor of safety was estimated at 1.15 to 1.30 using Bishop and Janbu methods for rotational failure under steady state conditions for the embankment bluff. Result of stability analysis where based on using Janbu Corrected for existing conditions with hydraulic fluctuation:

Material Name	Color	Unit Weight (lbs/ft3)	Sat. Unit Weight (lbs/ft3)	Strength Type	Cohesion (psf)	Cohesion Type	Cohesion Change (psf/ft)	Water Surface	Ru
Upper Clay-Silt		120		Undrained	1000	Constant		None	0
Marine Clay		120	120	Undrained	500	FDepth	14	None	0

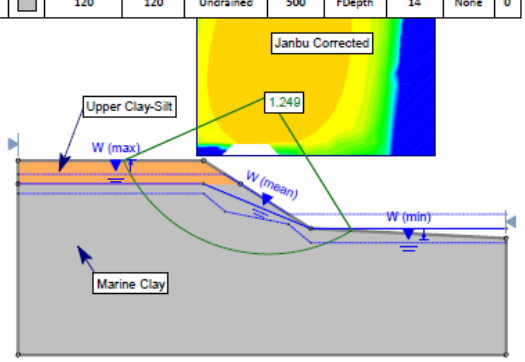

Figure 5-6 Slope Stability Analysis SLIDE 6.0 Software

Sensitivity analyses indicate the stability was greatly affected by the cohesion intercept (c') for effective stress analysis and the undrained shear strength (S_u) for total stress analysis where the slope approaches an inclination of 33° or greater. Small fluctuation of cohesion (drained) or shear strength (undrained) indicate a quick drop in factor of safety to near 1.0 representing slope failure. Observation of the slumped areas along the bluff provides evidence of slope failure occurring at or near predicted conditions. Back calculation using sensitivity analyses determined a factor of safety of 1.0 occurred where the undrained shear strength (S_u) approaches 375 to 400 psf for total stress analysis or where the cohesive intercept (c') approaches 0 psf. Conditions identified in potentially reducing strength include:

- The presence of surface tension cracks
- Soil creep over time due to slope steepening at the toe
- Localized softening where soil was exposed by previous slumping and erosion
- Excess pore pressure buildup during tidal fluctuation (ebb and flow)

The results of the slope stability analysis showed good agreement among three independent methods of analyses. This includes back calculation for observed slumped locations of slope failure using sensitivity analysis, stability modeling analysis using effective stress parameters (drained friction angle ϕ' with cohesive intercept c'), and stability modeling analysis using total stress parameters (undrained shear strength S_u). Agreement among the independent methods gives the engineer better confidence in the geotechnical parameters to use for design of slope stabilization. Use of cone penetration testing CPTu provided the following information:

- Subsurface profiles from 3 CPTu explorations (300 total feet)
- Generation of an interpretive undrained shear strength (S_u) profile
- The discovery of minimal drainage paths (sand layers) for profile to 100 feet

6 SEISMIC DESIGN

Seismic cone penetration testing SCPTu can be useful in evaluating appropriate seismic site classification of Presumpscot Formation. SCPTu provides near continuous soil profiling for depths up to 100 feet as required by the International Building Code (IBC). This gives the engineer better confidence that variation of soil layers are not missed. Observation of the piezocone pore pressure along with cone resistance provides information for soil behavior type (sand/silt/clay).

The in situ shear wave velocity profile V_s can be obtained from shear wave testing performed during SCPTu. Shear wave data is typically collected at each rod break interval of 1 meter (3-feet). Correlation for standard penetration resistance N_{60} and undrained shear strength S_u can be obtained independently from the same SCPTu test from cone penetration resistance for further evaluation of appropriate IBC site classification. When in comparison, it is suggested that the in situ shear wave velocity profile V_s is of greater accuracy and less conservatism than procedures utilizing correlated N_{60} or undrained shear strength S_u. The ability to match 3 independent methods of analysis utilizing one exploration provides the engineer with greater accuracy and less conservatism. Liquefaction analysis can also be performed using cone penetration resistance for sand layers below groundwater with low density.

6.1 *Fire Station Norridgewock, Maine*

Summit Geoengineering Services (SGS) was asked to conduct a geotechnical investigation for a proposed fire station in Norridgewock, Maine. The subsurface conditions at the site consist of thin topsoil overlying glacial marine deposits (Presumpscot Formation, Qps) consisting of sand underlain by silt-clay overlying bedrock encountered at a depth of 101 feet. The subsurface conditions were explored with the performance of 3 test borings and 1 piezecone penetration test with shear wave velocity (SCPTu). Test borings were performed to depths of 10 to 20 feet. Work was performed within 1 day of exploration utilizing a multipurpose drill rig.

Figure 6-1 Photograph of SCPTu performed with AMS PowerProbe© and Vertek VTK cone system

Figure 6-2 Photograph of AMS dual anchor with pre-drilled pilot hole augured through frost

In summary the subsurface profile at the site consist of sand grading to silty sand to a depth of 46 feet overlying silty clay to refusal at a depth of 101 feet. Groundwater was encountered at a depth of 18 feet. Undrained shear strength (S_u) for the silty clay averaged 2,200 psf based on cone resistance using an estimated N_{kt} factor of 15. The over consolidation ratio (OCR) averaged 2.1 using an estimated k factor of 0.35. Below is the SCPTu:

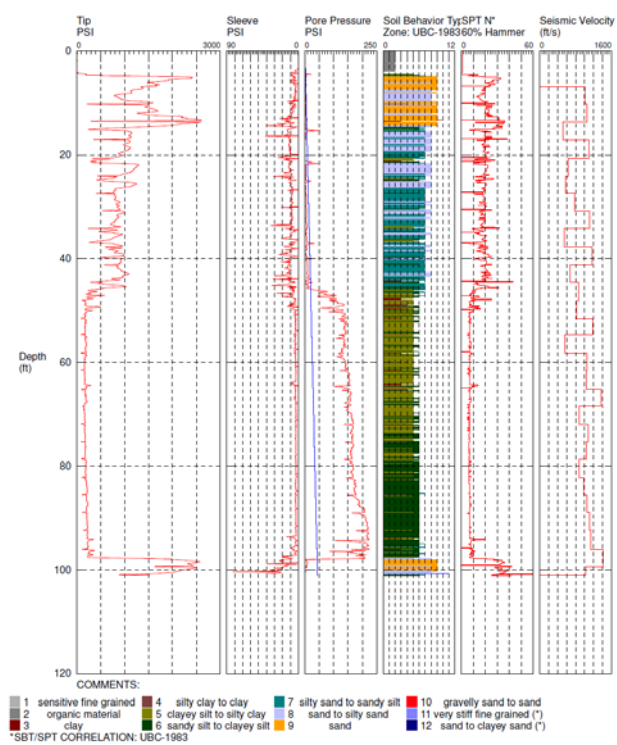

Figure 6-3 SCPTu log

The soils at the site were categorized as site class D in accordance with the International Building Code (IBC) based on an average shear wave velocity V_s of 950 ft/sec. Correlated N_{60} values

from the SCPTu test for the soil profile averaged 13 resulting in site class E. Undrained shear strength (S_u) for the silty clay encountered from a depth of 46 to 98 feet averaged 2,200 psf using a N_{kt} factor of 15 resulting in site class C. This case presents a unique situation in that 3 different methods of analyses recommended by the IBC resulted in 3 different site classifications all while using shared results from a single SCPTu test.

Where discrepancy is encountered, it is suggested that shear wave velocity V_s shall be considered the most accurate classification because the site class is based on field measured shear wave velocity for existing site conditions. It is worth noting that in using the N method, results are obtained from correlated N_{60} values along with conservatism built into the IBC N charting criteria. The average N profile of 13 is also relatively close to the value of 15 required for a site class D suggesting that conservatism may exists when using the N method.

The average undrained shear strength (S_u) of 2,200 psf was estimated using an N_{kt} factor of 15. Since field vane shear testing or laboratory shear strength testing were not performed calibration of the N_{kt} factor was not available. Based on this it is quite possible that an N_{kt} factor might be slightly higher of say 17 which would have resulted in lowering the average shear strength to 1,900 psf which would reduce the site class to D where below an average of 2,000 psf.

In the end, this example shows the value of using SCPTu as a method for evaluating the IBC site classification for soil profiles. Typically the independent methods of shear wave velocity Vs, standard penetration test N_{60}, and undrained shear strength S_u would result in similar findings. However, where discrepancy is encountered engineering judgment should be used to determine the suitable site class for design. The use of SCPTu provides the ability for comparison of the results so that engineering judgment can be made.

The marine sand encountered from a depth of 18 to 46 feet was evaluated for liquefaction during seismic events based on penetration resistance obtained from SCPTu-1. The peak horizontal acceleration with 2 percent probability in 50 years for the site was mapped as 0.12g by the United States Geological Survey (USGS). The mean factor of safety to resist significant liquefaction by earthquake was estimated at 1.6 for earthquake magnitude 6.5 and 1.1 for earthquake magnitude 7.5. Localized layers approach liquefaction potential for earthquake magnitude 7.5. From this analysis the sand marine deposit is considered resistant to widespread liquefaction where earthquake magnitude is below 7.5.

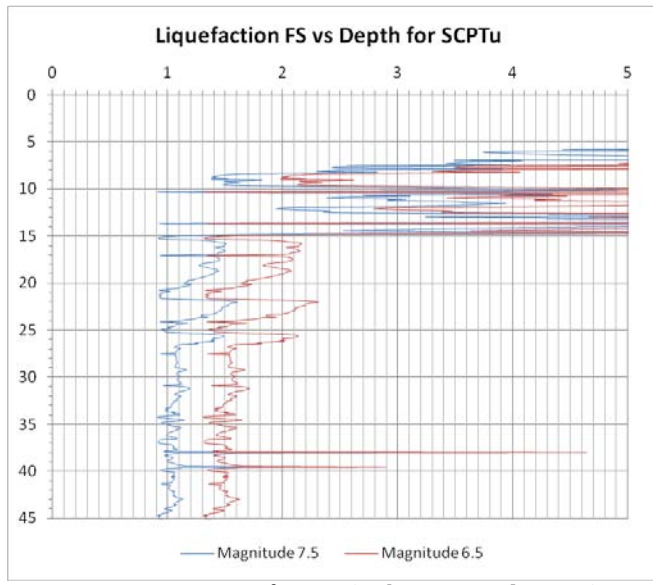

Figure 6-4 Liquefaction (Robertson et al., 2010)

Due to the amount of variation and detail outlining the procedure (Robertson et al., 2010), it is recommended that a spread sheet be generated using the equations and methods recommended by Robertson & Wride, 1998; Zhang el al., 2002 and 2004; Robertson, 2009.

The use of SCPTu provided the following information used for seismic design:

- Continuous interpretive subsurface profile to a depth of 101 feet
- Generation of an interpretive undrained shear strength S_u profile
- Generation of an interpretive N_{60} standard penetration profile
- In situ shear wave velocity V_s for improved IBC seismic site classification
- Ability to use SCPTu data for evaluation of liquefaction potential of the upper sand layer

7 CONCLUSIONS

This paper discusses the advantages and limitations of CPTu and SCPTu as an exploration method for geotechnical engineering of Presumpscot Formation. Case histories for 5 example projects are provided to show practical use of CPTu and SCPTu explorations for; Subsurface Investigation, Shallow Foundation Design, Deep Foundation Design, Slope Stability, and Seismic Design. These examples demonstrate real projects where utilization of CPTu or SCPTu improved geotechnical engineering design.

It should be mentioned that CPTu and SCPTu explorations can also be utilized for geological and geoenvironmental investigations within Presumpscot Formation, particularly where deep stratigraphy profiling is required, identification of drainage layers for possible contaminant flow, and the ability to add electric conductivity, fuel florescent detection, and other sensors to CPTu systems. Dissipation tests are also available by pausing CPTu advancement and recording piezocone pore pressure over time. This can be useful in estimating in situ permeability and horizontal coefficient of consolidation.

The ability of CPTu and SCPTu to be useful as exploration tools in Presumpscot Formation is only limited to creativity of the engineer and the advances in electronics and equipment available. The key to success for a geotechnical design relies on the information obtained from a proper and successful investigation. For this reason CPTu and SCPTu should be considered to improve overall performance of geotechnical investigations and subsequent design when working with Presumpscot Formation.

8 REFERENCES

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