Correlations of SPT, CPT and PMT Tests along Lakeshore and Don River Corridors in Toronto, Canada

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ABSTRACT
Several Standard Penetration Tests (SPT), Cone Penetration Tests (CPT) and Pressuremeter Tests (PMT) were recently carried out along the Lakeshore and Don River corridors in the Greater Toronto Area, Canada. These tests were carried out in pairs at a general spacing guideline of 3 to 5 m to ensure that the same stratum was tested while avoiding interference between each test. This paper presents the correlations between the measured SPT, CPT and PMT test results for different types of soil with same gradation and plasticity. The results have been used to evaluate the effect of mean grain size, fines content and plasticity which are known to affect the relations of the SPT, CPT and PMT values. The test data have been compared to the available correlations in literatures, including CPT to SPT ratio versus mean particle size plot presented in the Canadian Foundation Engineering Manual. Finally, the applications of the existing correlations in literatures and their limitations to the test data have been discussed.

RÉSUMÉ
Plusieurs essais de pénétration standard (SPT), essais de pénétration au cône (CPT) et essais au pressiomètre (PMT) ont été récemment effectués au long du Lakeshore et du corridor Don River dans la région du Grand Toronto, au Canada. Ces essais ont été effectués par paires selon une règle générale d'espacement de 3 à 5 m pour s'assurer que la même couche a été examinée tout en évitant des interférences entre chaque essai. Cet article présentes les corrélations entre les résultats des essais SPT, CPT et PMT évalués pour différents types de sols ayant le même tamisage et plasticité. Les résultats ont été utilisés pour évaluer l'effet de la taille moyenne des grains, de la teneur en fines et de la plasticité qui sont connus pour affecter les liens ou rapports des valeurs SPT, CPT et PMT. Les données des essais ont été comparées aux liens disponibles dans les littératures, comprenant la proportion SPT a CPT contre la tracée granulométrique présenté dans le Manuel Canadien d'Ingénierie de Fondations. Enfin, les rapports des applications existantes dans les littératures et leurs limites aux données d'essais ont été débattues.

1 INTRODUCTION

A typical practice of geotechnical site investigation involves Standard Penetration Test (SPT) along with borehole drilling. The simplicity, low cost and ability to retrieve samples have made SPT a common choice for field testing in all sizes of projects. However, SPT also has drawbacks of repeatability and reliability as the field test procedure is influenced by several factors including energy delivered, overburden stress, borehole size and drill rod length. Several corrections are proposed to adjust and standardize the field SPT blow count (N) values.

Depending on the project type or anticipated subsoil condition, advanced geotechnical field tests are considered to supplement SPT and obtain reliable soil design properties. Cone Penetration Test (CPT) and Pressuremeter Test (PMT) are among the advanced field tests. CPT allows continuous assessment of subsoil profile with higher repeatability and reliability of test data. It measures the continuous profiles of cone tip resistance (q_c) and sleeve friction resistance (f_s). PMT provides a direct measurement of horizontal Elastic Modulus of subsoil. This modulus is referred in this paper as E_{PMT}.

Due to higher costs associated with advanced geotechnical field tests, they are not feasible to consider in every project. Thus, the use of SPT correlations with advanced field tests is a practice in low risk projects with familiar similar subsoil conditions.

2 REVIEW OF EXISTING CORRELATIONS

2.1 SPT - CPT Correlations

The pioneering work of Robertson et al. (1983) reveals the dependency and correlation of q_c/N_{55} ratio with mean particle size (D_{50}) of soil; where N_{55} is the corrected field SPT blow count to transferred hammer energy ratio of 55%. This correlation has been adopted in Figure 4.2 of the fourth edition of Canadian Foundation Engineering Manual (CGS 2006).

Based on the above relation, the CPT tip resistance is directly proportional to the SPT blow count for a given soil type with similar mean grain size. The proportionality constant a varies as a function of mean particle size. The general form of this relation is presented in Eq. 1.

$$q_c = a\ N \qquad [1]$$

Robertson et al. (1983) showed the need of N value corrected to a referenced or standardized energy ratio in order to obtain a reliable correlation with q_c. Values of the constant a have been reported in literatures for different types of soil. Jarushi et al. (2015) and Shahri et al. (2014) summarized the constant a values per soil type from various sources.

Other linear forms and power forms of correlations have also been presented in literatures as shown in Eq. 2 and Eq. 3, respectively.

$$q_c = b\ N + c \qquad [2]$$

$$q_c = d\ N^e \qquad [3]$$

The parameters b, c, d and e are constants. Linear and power forms of correlation equations were presented by Jarushi et al. (2015) for different types of sandy soil in Florida (unified classification of SP, SM and SC), and by Shahri et al. (2014) for different types of soil in Southwest of Sweden. Shahri et al. (2014) presented the correlations for both field data and normalized data (of q_c and N) for overburden pressure.

Both Eq. 2 and Eq. 3 are straight line plots on a linear and logarithmic scale, respectively. However, the q_c and N data are generally more scattered in linear scale plots than logarithmic scale plots (Jarushi et al. 2015). The constants e and log(d) are the slope and y-intercept of the straight line plot in logarithmic scale, and Eq. 3 will reduce to Eq. 1 when the straight line has a unit slope. Correlations given in the form of Eq. 2 or Eq. 3 (with e not equal to 1) will deviate from the fact that q_c/N ratio is a function of soil gradation alone as implied from the correlation presented in Eq. 1.

Correlations of q_c/N have also been provided with fines content instead of mean soil particle size (Kulhawy and Mayne 1990; Chin et al. 1988). The fines content (F) was defined as percent passing No. 200 Sieve (or particle size of 0.075 mm). Other correlations of q_c/N have been provided with Behavior Index (Ic) which is a dimensionless number as function of normalized CPT tip and skin resistances (Lunne et al. 1997).

2.2 PMT - CPT & SPT Correlations

Numerous correlations have been proposed to relate soil modulus (E) with CPT tip resistance (q_c) in a general form as shown in Eq. 4 (Mitchell and Gardner 1975; Kulhawy and Mayne 1990; Mayne and Liao 2004; Robertson 2009).

$$E = \alpha\ q_c \qquad [4]$$

Robertson (2009) summarized published data of flat-plate Dilatometer Test (DMT) and CPT for various soils, and plotted the normalized data of Dilatometer Modulus (E_D) versus q_c on log scale. The slope of the log scale data plot was found to be 1 which confirmed the linear relationship of the soil modulus with cone tip resistance. However, the value of α ranged from 2 to 10 with a value of 5 for an average fit line to the data. Robertson (2009) discussed that the value of α may vary relative to the density, age, and stress history of the soil. The constrained tangent modulus versus q_c plot (in linear scale) presented in Robertson and Campanella (1983) also showed the variation of α with density and overburden pressure.

Mitchell and Gardner (1975) made a comprehensive review of the existing linear correlations between drained constrained modulus and q_c for various types of soil. For cohesive soils, the value of α ranged from 1 to 8 depending on the cohesive soil types and the cone resistance values (Guen 2014). For sand soils, the factor α is generally recommended in the range of 1.5 to 4 (Robertson and Campanella 1983).

Several other correlations are also available to show a nonlinear relationship of soil modulus with q_c in a general form expressed in Eq. 5.

$$E = \alpha\ (q_c)^{\beta} \qquad [5]$$

Robertson and Campanella (1983) replotted in linear scale the soil modulus versus q_c data obtained from the Calibration Chamber tests conducted by Baldi et al. (1981). The soil modulus data was determined from triaxial laboratory testing. The plots were hyperbolic confirming the non-linear relationship of the general form shown in Eq. 5 with $\beta < 1$. The curves varied with effective overburden pressure and soil density.

Another form of presenting the nonlinear E-q_c relation has been done in terms of E/q_c ratio versus normalized q_c, such as $(q_c - \sigma_v)/\sigma'_v$ where σ_v' is effective overburden pressure. Baldi et al. (1989) presented plots of G/q_c and E/q_c versus normalized q_c, where G is the shear modulus. This was based on large number of in situ tests performed in a calibration chamber and in the field and secant Young modulus from triaxial lab tests. The modulus to q_c ratios decreased with an increase of normalized q_c, and the curves varied with age and overconsolidation ratio. Robertson and Cabal (2015) presented the data plot of E/q_c versus normalized q_c in log scales and found a linear curve with negative slope.

Correlations were also proposed between soil modulus (E) and SPT N value. A linear correlation in the form of Eq. 1 (with q_c replaced by E_{PMT}) was proposed by Briaud et al (1985), Kenmogne et al. (2011) and Balachandran et al. (2015). Another form of linear correlation (similar to Eq. 2 with q_c replaced by E_{PMT}) was proposed by Yagiz et al. (2008) and Zaki et al. (2019).

Several nonlinear correlations taking a power form similar to Eq. 3 (with q_c replaced by E_{PMT}) are also available in literatures (Ohya et al. 1982; Bozbey and Togrol 2010; Anwar 2016). The nonlinear correlation equations had exponent (e) values generally less than 1.

The published data in the correlation of E_{PMT} to N were generally scattered. Zaki et al. (2019) compared several correlation equations obtained from literature including their proposed equation by plotting the equations in a single E_{PMT} - N graph. The comparison showed a wide range of predictions by the correlation equations which suggested a careful choice of correlations in actual practice.

Finally, a ratio of constrained modulus to SPT N was correlated to Plasticity Index (PI) by Stroud (1974). The constrained modulus to N ratio decreased with increase of PI and became flatter for PI values greater than about 40. The above observed variation was similar to the well-known correlation of friction angle with PI.

3 STUDY AREA AND FIELD TESTS

3.1 Study Area

Several Standard Penetration Tests (SPT), Cone Penetration Tests (CPT) and Pressuremeter Tests (PMT) were recently carried out within the Greater Toronto Area, Canada, mainly along the Lakeshore corridor and Don River corridor. These tests were carried out in sets or pairs at a general spacing guideline of 3 to 5 m to ensure that the same stratum was tested while avoiding interference between each test.

The locations of field tests are shown in Figure 1 below.

Figure 1. Locations of CPT and PMT Tests. SPT tests were carried out adjacent to all CPT and PMT locations.

A total of 58 SPT boreholes accompanied by either CPT or PMT tests or both were available within the study area. 28 SPT boreholes were accompanied by adjacent CPT tests, 24 SPT boreholes were accompanied by adjacent PMT tests and 6 boreholes were accompanied by both CPT and PMT tests.

3.2 Field Tests

The SPT blow counts were generally taken every 0.75 m for shallow depths up to about 5 m, and every 1.5 m after for deeper depths. Different SPT intervals were also followed in some boreholes depending on the subsurface soil conditions and project requirements. Each SPT test was conducted for a total penetration of 610 mm (24 inches) and blow counts were recorded every 152.4 mm (6 inches). The SPT N number was reported as the sum of blow counts in the 2^{nd} and 3^{rd} penetrations of 152.4 mm.

The CPT tests involved continuous measurements of cone tip resistance (q_c) and sleeve friction resistance (f_s). The data was then tabulated every 25 mm and output was available for review in MS Excel sheets. In this paper, q_c and f_s values corresponding to the SPT N numbers were generally determined by taking the average of their measurements over a length of 304.8 mm (12 inches) at corresponding SPT N elevation. Even though the pairs of SPT and CPT tests were conducted at adjacent locations with similar surface elevations, the N and q_c profiles at some depths were offset by a few centimeters, particularly where a sudden change of profile occurred. In such cases, the q_c and f_s values at the appropriate elevation were considered to match with the corresponding SPT N. Only a appropriate portion of the q_c and f_s values within the 304.8 mm length were also averaged at some depths. At other depths where a sharp increase of q_c was encountered, the SPT blow counts at the 3^{rd} and 4^{th} penetrations of 152.4 mm were added to get SPT N number reasonably matching q_c value.

The PMT tests were carried out at pre-selected depths within the PMT boreholes. A Pressuremeter Modulus (E_{PMT}) was determined from a linear portion of initial loading curve in accordance to ASTM D4719. In this paper, the SPT N number corresponding to E_{PMT} value was generally determined from the corresponding elevation in the SPT borehole. Where the SPT number was not available at a corresponding elevation to E_{PMT}, a SPT N number above or below the corresponding elevation or their average was taken as appropriate. At some depths, the SPT blow counts at the 3^{rd} and 4^{th} penetrations of 152.4 mm were added to get an SPT N number that was reasonably matching E_{PMT} value.

Soil index testing of grain size analyses and Atterberg Limits tests were conducted for selected samples from the SPT boreholes. In this paper, mean particle sizes (D_{50}), fines content (F) and Plasticity Indices (PI) were generally determined from the index test results at corresponding elevations to q_c and E_{PMT} values. Where no index test was available at the corresponding elevation, the index tests above or below the corresponding elevation within same soil layer (type) were considered. In cases of no available index test data for a similar soil type in a corresponding borehole, index test data from other nearby boreholes were considered. About 50% of the D_{50}, F and PI data were determined from corresponding borehole index tests at corresponding elevations to q_c and E_{PMT} values.

Based on the data analyses described above, a total of 193 SPT and CPT test results and 123 SPT and PMT test results were obtained from all the SPT, CPT and PMT field tests presented in Section 2.1.

4 DATA ANALYSES AND DISCUSSIONS

In the subsequent presentations of analyzed data, all the N, q_c and E_{PMT} data were not normalized to overburden pressure. Robertson (2009) discussed that if consistent normalization methods are applied to each in situ test, the correlations may not change significantly. Thus, the correlations between N, q_c and E_{PMT} data may not be affected whether a similar normalization factor is used for all data or unfactored data is used.

The field boreholes were drilled by different subcontractors out of Greater Toronto Area, Canada. The SPT hammer energies were not measured during the field SPT testing. However, similar hammer efficiency is assumed considering the similarity of drilling rigs and SPT hammers used by the different subcontractors. Thus, the SPT N data values presented below were not corrected for energy.

4.1 CPT - SPT Data Analyses and Discussions

The corresponding N and q_c data are presented in Figure 2 in terms of q_c/N ratio versus mean particle size similar to Figure 4.2 of the fourth edition of Canadian Foundation Engineering Manual (CFEM). The upper and lower ranges and the average correlation line in Figure 4.2 of CFEM are also replotted here in Figure 2 for comparison. The data points are colour coded based on the soil type. Table 1 presents the abbreviations of the soil type names.

Table 1. Abbreviations to name soil types in all Figures.

Abbreviations	Descriptions
CSi	Clayey Silt
CSiwsa	Clayey Silt with sand
GSa	Gravelly Sand
SaCSi	Sandy Clayey Silt
SaCSiT	Sandy Clayey Silt Till
SaSi	Sandy Silt
SaSiCT	Sandy Silty Clay Till
SaSiT	Sandy Silt Till
Sawsi	Sand with silt
SiC	Silty Clay
SiCT	Silty Clay Till
SiSa	Silty Sand
SiSaT	Silty Sand Till
Siwc	Silt with clay
Siwsa	Silt with sand
Sa	Sand

The presented data in Figure 2 generally falls within the lower and upper ranges except for some of the data points plotted outside the ranges. The lower and upper ranges in CFEM (CGS 2006) were determined based on the work of Burland and Burbidge (1985). The majority of data that falls within the range may suggest that the SPT hammers used in the current field tests would have similar energy transfer ratio (efficiency) with the historical SPT hammers used to determine the upper and lower ranges. It is discussed in CFEM that the energy efficiency of most of the SPT equipment currently in use in Canadian practice is very similar to that used when the various N-value empirical relationships were developed, so the energy correction may be small.

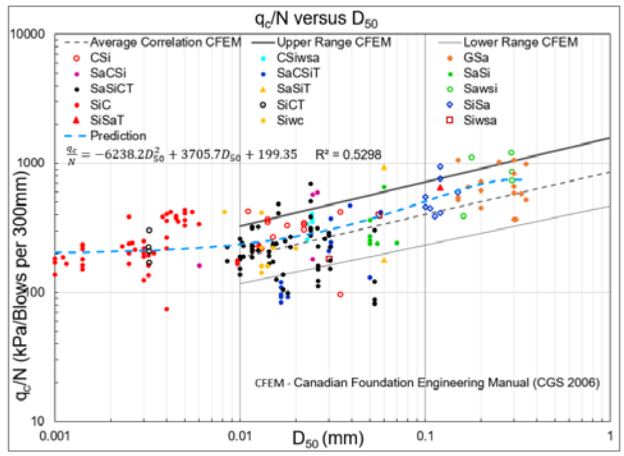

Figure 2. q_c/N ratio versus mean particle size (D_{50})

The upper and lower ranges and the average correlation line in CFEM were plotted for mean particle size of greater than 0.01 mm. Extrapolation of these lines to mean particle sizes below 0.01 mm will plot them below the silty clay data points. The best fit line to the data points, shown in Figure 2 as Prediction line, was obtained using a polynomial equation. The use of power equation resulted in the best fit line plotted below the silty clay data points similar to the extension of the average correlation line from CFEM.

Fine grained soils are classified and characterized based on plasticity instead of particle size. The q_c/N data for fine grained soils in Figure 2 are replotted in Figure 3 versus Plasticity Index (PI). Even though the q_c/N to PI correlation is very weak, due to wide scatter of data, it shows a general trend similar to the well-known correlation of friction angle with PI for cohesive soils.

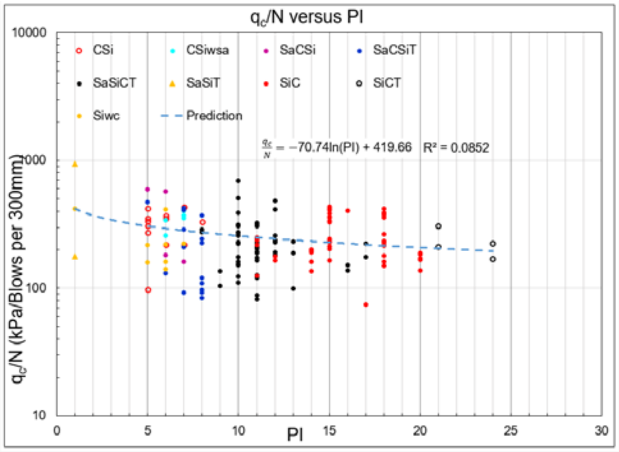

Figure 3. q_c/N ratio versus Plasticity Index (PI)

The same q_c/N data in Figure 2 are also plotted versus the fine content (F) in Figure 4. The fines content was determined as percent passing No. 200 Sieve or particle size of 0.075 mm (Kulhawy and Mayne 1990). A best fit line based on a polynomial equation is also obtained for fines content with similar correlation coefficient as for D_{50} in Figure 2. Comparison of the above figures suggests that the fines content and D_{50} may have similar correlation with q_c/N ratio and can be used interchangeably, except for fine grain soils (of sizes less than about 0.01 mm) where the fines content will be more than 90% and the data points will concentrate to one location.

The use of fines content for correlation may be advantageous over D_{50} as hydrometer laboratory testing is required to determine D_{50} for fine grained soils. A hydrometer lab test is more time consuming and expensive than a quick sieve analysis test which is sufficient to determine the fines content for all soil types.

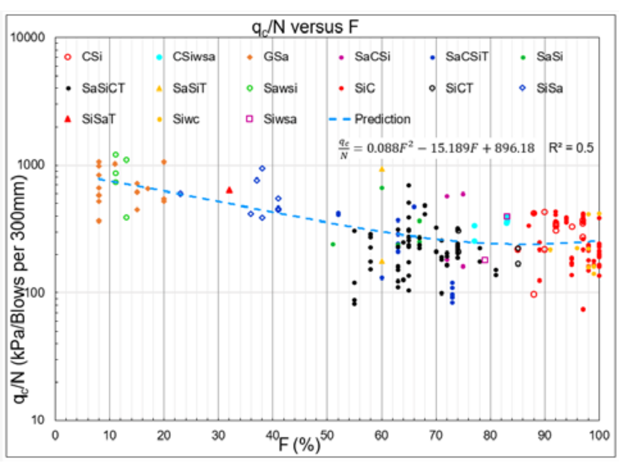

Figure 4. q_c/N ratio versus Fines Content (F)

As discussed in Section 2.1, power forms of correlation equations (similar to Eq. 3) are presented in literature (Jarushi et al. 2015; Shahri et al. 2014). If the exponent of a power form correlation is not equal to one, it implies that the q_c/N ratio will also depend on SPT N value, and hence on soil density, stress history and age that influence the SPT N value. This will deviate from the fact that the q_c/N ratio will depend on soil gradation alone as implied from the correlation of q_c/N with D_{50} presented in literature (Robertson et al. 1983; CGS 2006).

In order to investigate the relationship of q_c and N in the presented data in this paper, q_c values were plotted versus the corresponding N values in log scales and the slope of average fit line for each soil type was examined. For demonstration purposes, the data plots and average fit lines for gravelly sand and silty clay soil types are presented in Figure 5. The slopes of visually-drawn average fit lines appear to be fairly one. The q_c intercepts shown in Figure 5 are actually the values of constant d in Eq. 3 or the values of q_c/N ratio (constant a in Eq. 1). These q_c intercepts are consistent with the q_c/N ratio determined from Figure 2. For example, the q_c intercept of 225 kPa for silty clay soil is the q_c/N ratio determined from Figure 2 for the same soil type.

Thus, the relationship of q_c and N data presented in this paper is fairly linear and can be represented by Eq. 1.

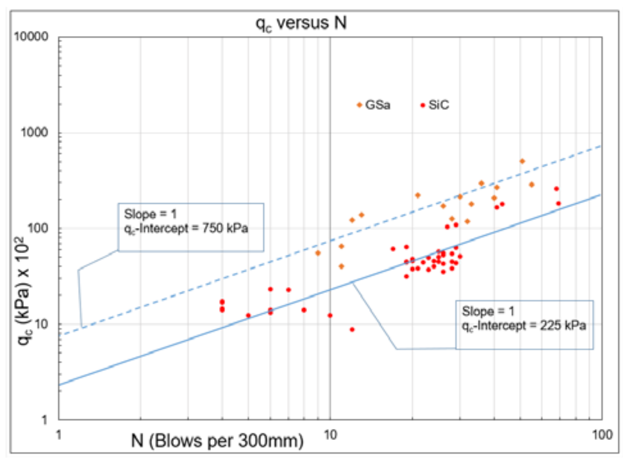

Figure 5. q_c versus N

4.2 E_{PMT} - CPT & SPT Data Analyses and Discussions

A correlation of E_{PMT}/q_c or E_{PMT}/N ratio with soil gradation (D_{50} or F) is not presented in literature similar to the q_c/N ratio. Instead, the common correlation in literature is the linear relationship of E_{PMT} and q_c in the form of Eq. 4. Part of the reason for this may be the coefficient α in Eq. 4 that depends on several other factors including soil density, stress history and age in addition to soil gradation or type. As discussed previously in Section 2.2, the value of α has wide range. Thus, the ratio of E_{PMT}/q_c cannot be attributed only to a single factor such as D_{50}.

This paper presents the data of only six (6) locations where adjacent PMT and CPT field tests that were carried out. The available corresponding E_{PMT} and q_c data are plotted on log scales in Figure 6.

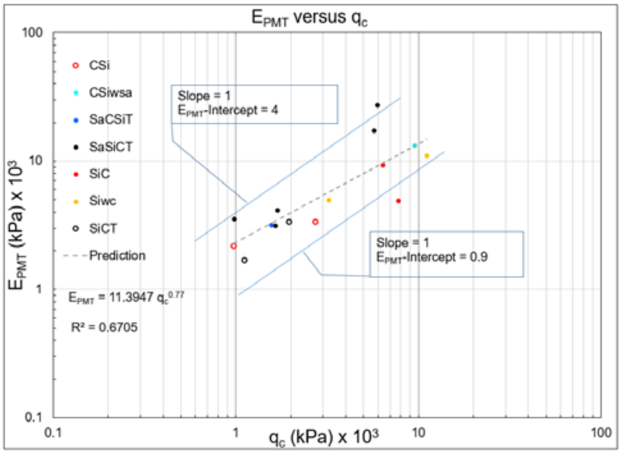

Figure 6. E_{PMT} versus q_c

The data in Figure 6 are not sufficient to analyze the E_{PMT}-q_c correlation. However, based on the presented data in the figure, an average fit line of having unit slope can be drawn visually across the data. The visually drawn upper and lower ranges of this average fit line are shown in Figure 6. Based on the E_{PMT} intercepts of these lines, the value of α in Eq. 4 ranges from 0.9 to 4.

On the other hand, a best fit line was obtained using a power form correlation equation. The slope of the best fit line in log scales is 0.77, and the value of α (in Eq. 5) for the best fit line is 11.39 or 2.33 when both E_{PMT} and q_c are in kPa or in MPa, respectively.

Since the nonlinear relationship of E_{PMT} and q_c is emphasized in literatures, the E_{PMT}/q_c ratio of the data presented in Figure 6 are replotted with the normalized q_c in Figure 7.

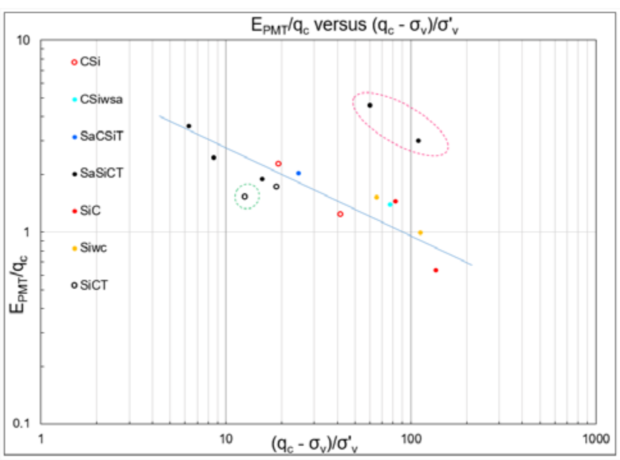

Figure 7. E_{PMT}/q_c versus normalized q_c with overburden

A linear correlation of E_{PMT}/q_c ratio to normalized q_c was obtained in log scales in Figure 7 similar to the finding of Robertson and Cabal (2015). The two data points highlighted within a pink circle in Figure 7 are from overconsolidated very stiff sandy silty clay till soils (SPT of about 24) at shallow depths of less than 5 m. The single datum highlighted within the green circle was from a normally consolidated soft silty clay till soil (SPT of 3 to 5) at depth of 6.5 m. As discussed in Robertson and Cabal (2015), the range of the linear correlation line varies with stress history or overconsolidation ratio, age and cementation or bonding. The line moves away from the origin with increase of the above factors. The data presented in Figure 7 also demonstrates the effect of overconsolidation.

Many of the correlations between E_{PMT} and N presented in literature are provided for individual soil types. However, the E_{PMT} and N data for different soil types in this paper are presented together in Figure 8 to investigate a general correlation similar to the E_{PMT} - q_c correlation in the form of Eq. 4.

Like Figure 6 for E_{PMT} - q_c, a linear correlation of E_{PMT} and N in log scales is observed in Figure 8. A best fit line to the presented data was obtained with a use of power function which resulted in an exponent value of close to 1. Based on the E_{PMT} intercepts of the upper and lower ranges of correlation line, the value of α (in Eq. 4 with q_c replaced by N) ranges from 190 to 1,900 in units of kPa with average value of 547 as noted from the correlation equation. Similar factors affecting the E_{PMT} - q_c relations are also expected to affect the E_{PMT} - N relations.

A reasonable value of α should be selected based on soil density, stress history, age and cementation for use of correlations in actual practice. For cohesive soils, the drained/undrained condition will also affect the value of α. Ohya et al. (1982) presented nonlinear correlation equations of E_{PMT} and N for clay and sand soils. The equations provide an E_{PMT} of clay that was almost twice the E_{PMT} of sand. The E_{PMT} correlation data for clay by Ohya et al. (1982) was reported as the undrained modulus in Kulhawy, F. H., and P. H. Mayne (1990).

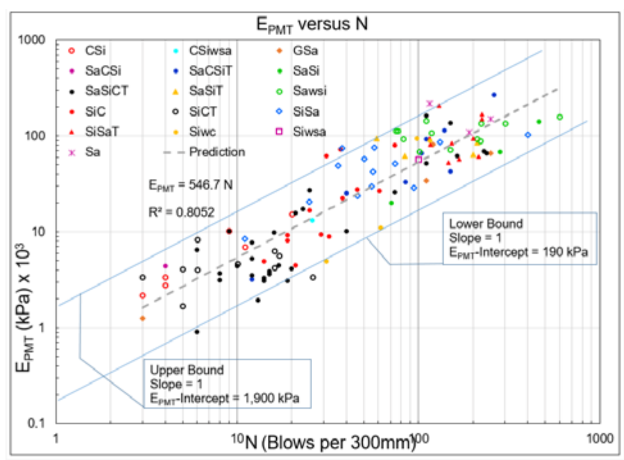

Figure 8. E_{PMT} versus N

Following the presentation of the data correlation between constrained modulus to SPT N ratio and Plasticity Index (PI) by Stroud (1974), the E_{PMT}/N and PI data in this paper are presented in Figure 9. No best fit line correlation was obtained due to the wide scatter of the data. However, the E_{PMT}/N ratio was generally found to be nearly horizontal and independent of PI as shown in Figure 9.

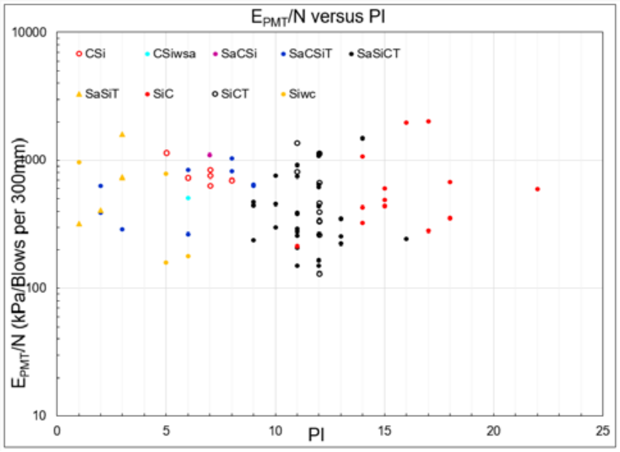

Figure 9. E_{PMT}/N versus Plasticity Index (PI)

5 CONCLUSIONS AND RECOMMENDATIONS

The correlation adopted in Figure 4.2 of the fourth edition of Canadian Foundation Engineering Manual (CFEM) can be used within the study area for overburden soil types of sand and silt with clay and gravel contents.

The correlation in Figure 4.2 of CFEM is adopted for soils with mean particle size of equal to or greater than 0.01 mm. Based on the presented data in this paper, extrapolation of the adopted correlation for soils with mean particle sizes of less than 0.01 mm may not be appropriate. However, additional study is required to confirm the validity of the adopted correlation in CFEM for soils with $D_{50} < 0.01$ mm. The polynomial best fit correlation in Figure 2 of this paper can be considered for soils with $D_{50} < 0.01$ mm until further study finds a better correlation equation.

Fines content can be considered as an alternative parameter to D_{50} for correlation with q_c/N ratio. A laboratory sieve analysis is sufficient to determine fines content. However, a laboratory hydrometer analysis will be required to determine D_{50} for fine grained soils. A hydrometer test is more time consuming and expensive than a quick sieve analysis test.

The correlation of q_c/N and E/N ratios with Plasticity Index should also be investigated further for cohesive soils as the cohesive soils are characterized by plasticity instead of gradation.

The value of α in a linear (Eq. 4) or nonlinear (Eq. 5) correlation of soil modulus (E) with q_c or N depends on several factors including soil density, stress history, age and cementation. There are a wide range of correlation equations available in literatures. A reasonable value of α should be selected based on soil condition for use correlations in actual practice.

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