Relationship between the pressuremeter test results, the SPT-N values and other in-situ tests for deposits in the Saint-Charles River area, Quebec City, Canada

Relation entre les résultats d'essais pressiométriques, les valeurs N-SPT et d'autres essais in-situ pour les dépôts du secteur de la rivière Saint-Charles, Québec, Canada

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ABSTRACT

This paper presents the relationship between the pressuremeter modulus (E_{pmt}) measured using the Texam pressuremeter and the N-SPT value of the standard penetration test for deposits in the Saint-Charles River area, the longest watercourse crossing Quebec City, Canada. This study is based on various geotechnical investigations carried out over the years in this urbanized sector of Quebec City, where these large deposits can reach a thickness of over 50 metres. The objective of this contribution is first to propose correlations between the N-SPT value and the pressuremeter modulus, to compare with the correlations from CPTu tests carried out in this deposit and to compare the results with some correlations from the literature.

RESUME

Cet article présente la relation entre le module pressiométrique (E_{pmt}) mesuré à l'aide du pressiomètre Texam et la valeur N-SPT de l'essai de pénétration standard pour les dépôts du secteur de la rivière Saint-Charles, le plus long cours d'eau traversant la Ville de Québec, Canada. Cette étude repose sur des investigations géotechniques diverses réalisées à travers les années dans ce secteur très urbanisé de la Ville de Québec, où ces importants dépôts peuvent atteindre plus de 50 mètres d'épaisseur. L'objectif de cette contribution est tout d'abord de proposer des corrélations entre la valeur N-SPT et les modules pressiométriques, de comparer avec les corrélations tirées des essais CPTu réalisés dans ce dépôt et de mettre en parallèle les résultats avec certaines corrélations tirées de la littérature.

Keywords: Pressuremeter test; standard penetration test; sand deposit.

1. Introduction

In sandy deposits, the geotechnical response to serviceability limit states (SLS) mainly dictates the design of shallow foundations and of large dimensional raft foundations. For engineers, obtaining precise geotechnical soil parameters to predict settlements is crucial to make appropriate recommendations. In the province of Quebec, the main approach used for calculating settlement in cohesionless (granular) soil layers is based on a pseudo-elastic model. This method is strongly influenced by the determination of the elastic modulus applied to the soil at different intervals. Laboratory tests can be used for this purpose, but several correlations from in-situ tests are also available. Using different methods and comparing their results is a good practice.

The objective of this paper is to propose a correlation between the N value obtained from the SPT test and the pressuremeter modulus (E_{pmt}) for St-Charles River area sand deposit in Quebec City, and to compare the resulting empirical relationship to empirical relationships from the literature. Wagh & Bambole (2024) summarize the correlations in the literature. However, the results of the correlations are varied, which may lead to errors in settlement prediction. In addition, these correlations are performed on different soil types not specifically located in the Quaternary region of Quebec City. Local or developed correlations for a specific deposit are significantly more accurate than general correlations derived from literature. Finally, pressuremeter data will be compared with piezocone test results gathered in the sand deposit located in the study area.

2. Site description and deposit characteristics

In this study, 8 geotechnical investigation sites located in Quebec City (Eastern Canada), were analyzed. The data came from a sand layer ranging from compact to dense, which is frequent in the Saint-Charles River area. Laboratory test results on samples collected from this deposit show a fine to medium-grained sand with proportions of fine particles (less than 0.08 mm) ranging from 4 to 15%.

This deposit is found 3 to 34 m below the surface at the sites shown and is sometimes underlain by a thin (0.30 to 0.60 m) but very dense gravel layer overlying a stiff to hard clay deposit of variable thickness. In certain places, the clay deposit overlies a till, followed by the underlying bedrock. Based on the investigations carried out, sand properties barely change with depth. In fact, the grain size distribution is constant throughout the deposit.

The approximate locations of the sites are shown in Figure 1 (modified from Lamarche, L., Parent, M., Bolduc, A. et Paradis, S.J. 2010). According to information derived from maps of unconsolidated deposits in the region (Lamarche 2010), the sand deposit originates mainly from ancient estuarine sediments and alluvium from fluvial terraces. Located at the eastern end of the St. Lawrence Lowlands, these deposits were formed by the Champlain Sea, which covered the area at the end of the last ice age.

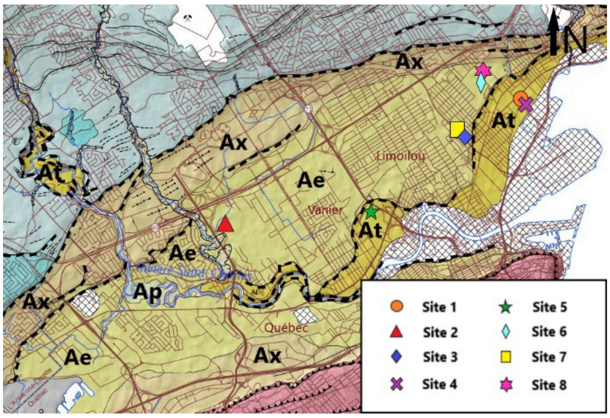

Figure 1. Location of study sites (modified from Lamarche 2010). At: Alluvial deposits of river terraces: sand, sandy silt, gravelly sand and gravel, Ae: Ancient estuarine sediment: silt, sandy silt, sand, Ax: Ancient alluvial deposits of river terraces: sand, sandy silt and gravel, Ap: Present day alluvial deposit: sand, sandy silt, gravely to sand and gravel.

3. In-situ testing

3.1. Standard Penetration Test (SPT)

The Standard Penetration Test is an in-situ dynamic penetration test used to take a remolded sample and determine the nature and state of compaction of soils. Used extensively throughout the world, ASTM D 1586 and CAN/BNQ 2501-140 standards provide the test method in North America. The standardized test involves driving a 51 mm O.D. split barrel sampler, using a 63.5 kg hammer falling free from a height of 760 mm. The number of blows required to drive the sampler for a 300 mm increment after the initial 150 mm penetration is the SPT-N. As this test is carried out at different levels in the soil through a casing or an auger, particular care must be taken to avoid any disturbance of the soil by the drilling operations.

In some empirical correlations, this data is often used without corrections but can also be calculated according to a corrected value normalized to an energy level of 60%. The result of the calculation is a normalized N_{60} value. Energy correction, in accordance with ASTM D 4633, is especially used for studies with presence of liquefaction risks. It is indeed useful to specify the driving energy for each SPT-N value in order to obtain optimized liquefaction potential assessment results for sand deposits. Several other correction factors can be applied to the number of blows, such as: correction factor for earth pressure, correction for rod length, correction for borehole diameter, correction for the addition of an inner liner tube. The data presented in this study are the uncorrected N index and the normalized N_{60} index for driving energy.

The results presented come from tests carried out in accordance with ASTM D1586. In addition, the energy transferred by hydraulics hammers used was measured by a SPT analyzer from Pile Dynamics, Inc. The recommended drilling methods were casing rotation with bentonite mud injection.

3.2. Pressuremeter

The pressuremeter test (PMT) is an in-situ loading test used to determine the lateral deformation of a soil at a certain depth. The results presented in this article come from pre-bored tests carried out with a TEXAM pressuremeter developed by Texam A&M university and Roctest Ltd. This equipment, widely used in North America, uses a single-cell hydraulic probe inflated by a mechanical actuator. The preparation of the test zones, an essential element in the consistency of pressuremeter test results, was carried out using rotary drilling with bentonite mud circulation. The consistency of the method seems to ensure a certain uniformity in the results. This test procedure is governed by ASTM D4719 "Standard Test Methods for Prebored Pressuremeter Testing in Soils", procedure B - Equal Volume Increments.

The three main soil properties derived from the analysis of pressure-volume curves are:

- The PMT first load modulus E_{pmt} or E_0, obtained by multiplying the slope of the linear portion of the pressure vs. radial deformation curve by (1+Poisson ratio) and defines pseudo-elastic behavior.
- Limit pressure p_L, defined as the pressure required to double the volume of the test cavity, characterizes the soil failure. The net limit pressure p_L* is equal to the limit pressure minus the horizontal earth pressure (p_{0H}).
- Yield pressure, which marks the transition between pseudo-elastic behavior and the plastic state in which the soil undergoes permanent deformation.

3.3. Piezocone

Piezocone tests (CPTu) were also carried out as part of the studies presented. These tests were carried out in accordance with ASTM D5778. The probe, consisting of an instrumented penetrometer point, is pushed into the ground at a constant rate (20 mm/s) by means of drill rods. During penetration, the main parameters that were discontinuously measured (every 1 cm of penetration) are: cone resistance (q_c), pore pressure (u_2) and lateral friction on the sleeve (f_s). Among the many types of in-situ geotechnical equipment available, the piezocone offers several advantages, such as versatility (several modules available), reproducibility, speed of execution, and continuous data acquisition. Empirical equations based on CPTu test results can also be used to determine several mechanical parameters of the soil (undrained shear strength, preconsolidation pressure, oedometer modulus, soil stratigraphy, etc.).

4. Preliminary data analysis

For each site, the data were sorted to select SPT, PMT and CPT test data from boreholes close from each other (7 meters maximum) and at similar depths. The results were then validated and compared.

SPT-N_{60} and SPT-N results were compared, and Figure 2 shows the distribution of the data collected. A total of 87 SPT-N data sets were used. The average C_e value (corrected for driving energy) is 1.27 for the 8 sites in this article. In the absence of driving energy measurements, this average value was considered. The average C_e value calculated for each site ranges from 1.12 to 1.43.

The distribution of uncorrected N values shown in Figure 2 ranges from 9 to 39, with a mean value of 22, while N_{60} values varies from 11 to 47, with a mean of 27. The distribution of N values when corrected for energy is upwardly arranged following the application of the correction. N values above 50 were not included in this study, in order to compare data mainly in the loose to dense deposit.

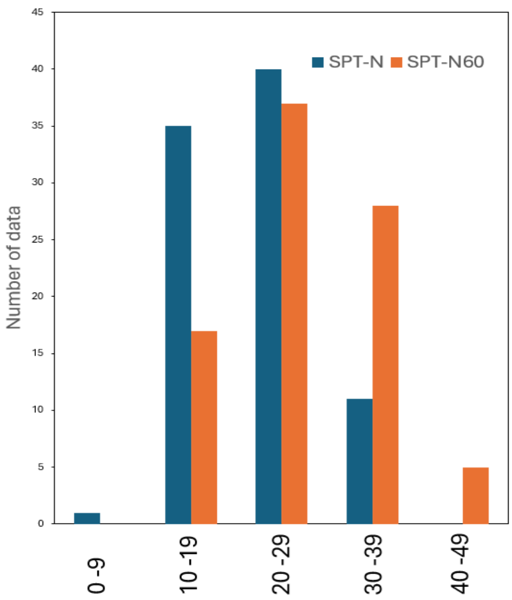

Figure 2. Histogram of SPT-N and SPT-N_{60} data

Figure 3 shows the distribution of pressuremeter data obtained from tests carried out in the region's sandy soils and at similar depths to the SPT-N data. Pressuremeter modulus values obtained in Figure 3a), from the 87 measurements collected, range from 8 to 29.3 MPa. The E_{pmt} range of values is close to the expected range for compact to dense sand according to Briaud (1992), i.e.:

$$3.5\text{MPa} < E_{pmt} < 22.5\text{MPa}$$

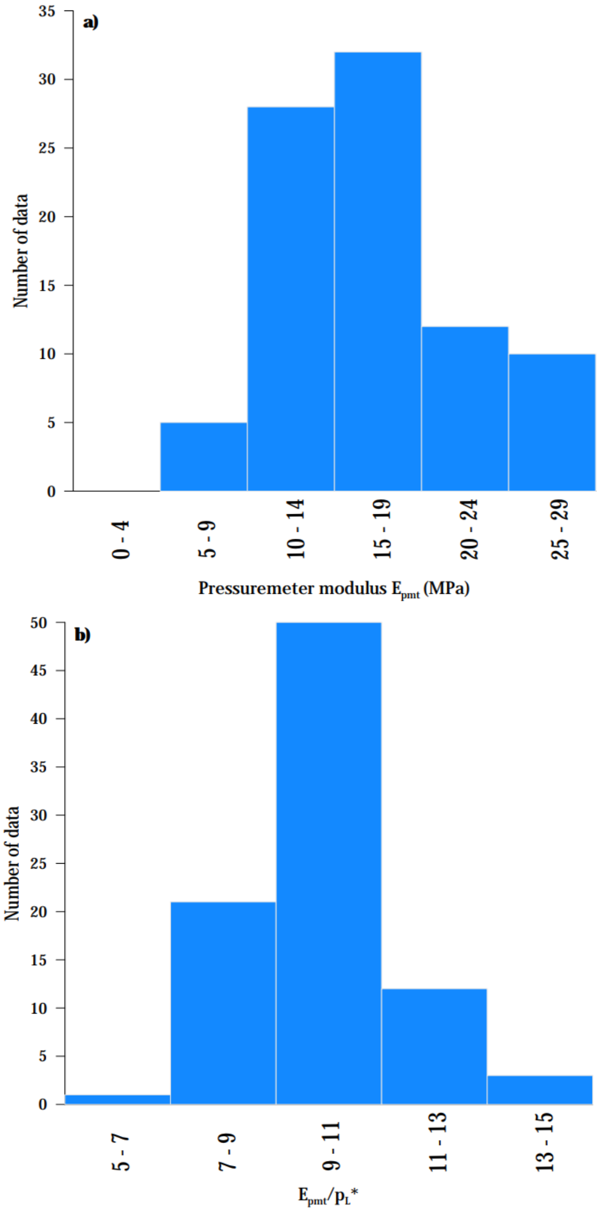

Figure 3. Histogram of the variation in a) pressuremeter modulus and b) E_{pmt}/p_L* ratio data.

The histogram of the E_{pmt}/p_L* ratio, presented in Figure 3b), is also based on these 87 data. In addition to analyzing the shape of the pressure-volume curves, this ratio allows to estimate the level of soil disturbance and assess the validity of a test. The values of this ratio range from 6.63 to 13.36.

These results correspond to the ratio expected for compact to dense sand according to Briaud (1992), i.e.:

$$7 < E_{pmt}/p_L* < 12$$

The data selected for this study are those showing a typical sand curve and no evidence of hole disturbance, in order to compare data of good quality.

5. Results and discussion

5.1. Relationship between SPT-N and SPT-N_{60} with the pressuremeter modulus (E_{pmt})

Figure 4 presents the pressuremeter modulus and the SPT-N relationship obtained for the 8 sites considered. The trend line equation (Eq. 1) gives a coefficient of determination of 0.69, indicating a clear correlation between the two parameters.

According to the 87 data, the linear relation is as follows:

$$E_{pmt} = 699N + 2185 \quad (1)$$

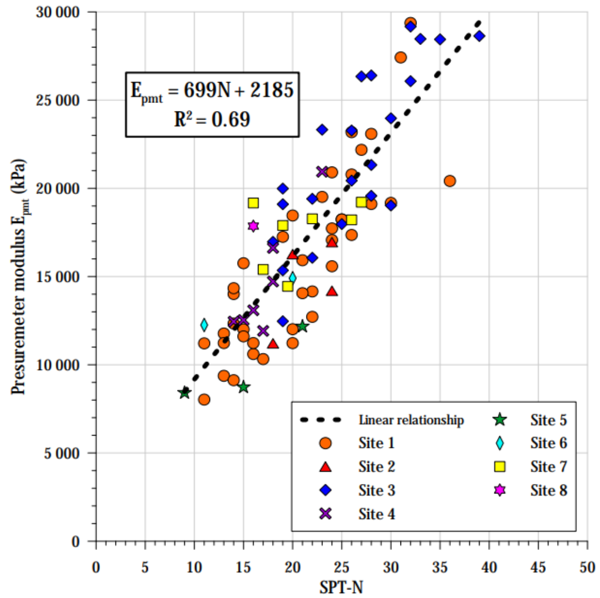

Figure 4. Relationship between SPT-N and the pressuremeter modulus E_{pmt}

Correcting the SPT-N for energy transferred by SPT hammers is a good practice for normalizing the data. Figure 5 shows the plotted values of pressuremeter modulus as a function of their respective SPT-N_{60} values.

Corrected SPT-N were also studied, as there are several correlations based on them in the literature, as shown in Table 1.

Table 1. Correlation between pressuremeter modulus and SPT-N_{60}

Source	Soil type	Equation (kPa)
Bozbet & Togrol (2010)	Sandy soil	E_{pmt}=1000(1.33$N_{60}^{0.77}$)
Yildiz (2021)	Sandy Soil	E_{pmt}=1000(0.5187N_{60}+3.3673)
Cheshomi & Ghodrati (2014)	Silty sand	E_{pmt}=1000(0.98N_{60}-9.43)

The equation obtained (Eq. 2) for Saint-Charles River sand fits well with the relationship proposed by Bozbey and Togrol (2010), and Yildiz (2021), suggesting that these models are appropriate for the soil studied. The linear relation is as follows:

$$E_{pmt} = 577N_{60} + 1533 \quad (2)$$

However, the relationship proposed by Cheshomi and Ghodrati (2014) does not seem to agree with the results obtained or with the other relationships proposed. This could be explained by the higher proportion of dense soil (N > 30) or the higher proportion of fine particles of the sand studied by these authors. Furthermore, the correction of the SPT data does not affect the significantly quality of the relationship between the parameters, which is observed when comparing the R^2 obtained for the two correlations presented in Figures 4 and 5.

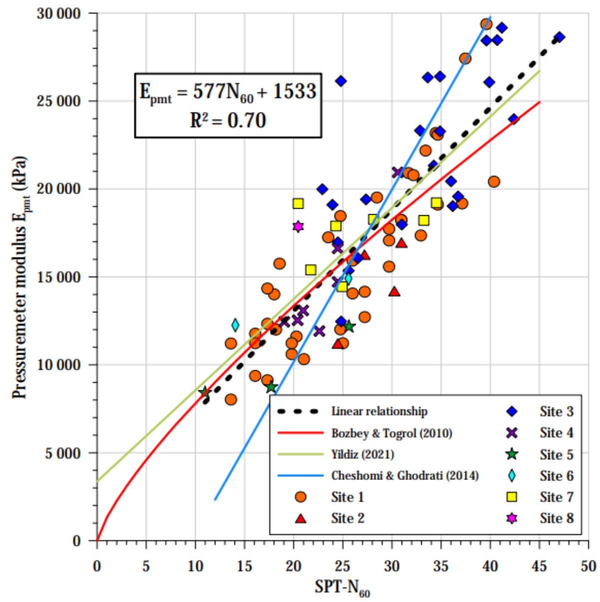

Figure 5. Relationship between SPT-N60 and the pressuremeter modulus E_{pmt} compared with literature

5.2. Relationship between SPT-N and the elastic modulus estimated from PMT test

The E_{pmt} pressuremeter modulus can be used to estimate the elastic modulus (Young's modulus) by using the rheological coefficient α, called Menard's factor as discussed in "The Pressuremeter" (Briaud, 1992). It has been suggested that E_{pmt}/α ratio is equivalent to Young's modulus for the soil as mentioned by Leblanc (1982). In this study, the elastic modulus E was estimated, as in the Eq. (3):

$$\frac{E_{pmt}}{E} = \alpha \quad (3)$$

The α values were selected according to the typical criteria proposed by Menard (Briaud 1992) considering the type of soil (sandy) and the $E_{pmt}/p_L{}^*$ ratio. Values of 1/3, and occasionnaly 1/2, were selected.

Table 2 compares the relationship in Saint-Charles River sand deposit with various correlations in sandy soils taken from the literature.

Table 2. Relationship between SPT-N and soil elastic modulus E

Source	Soil type	Equation (kPa)
Schmertmann & al. (1978)	Gravelly sand	$E=1500 \leq N \leq 2500$
Wagh & Bambole (2024)	Granular soil	$E=1705N+7705$
Kishida & Nakai (1977)	Sand	$E=1600N$
Onya & col. (1982)	Sand	$E=400N$
Mentioned in Bowles (1988)	Sand	$E=500(15+N)$

Figure 6 shows the estimated elastic modulus from PMT test as function to uncorrected SPT-N values from St-Charles River sand deposit compared to some literature relationships.

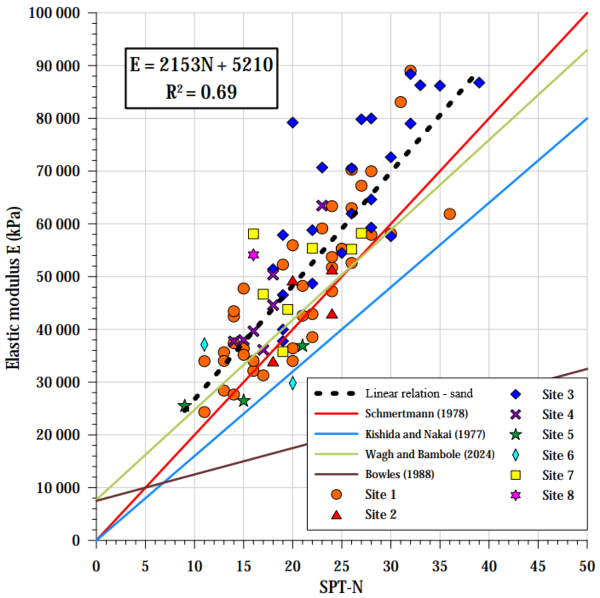

Figure 6. Relationship between elastic modulus and SPT-N compared with literature

The linear relation (Eq. 3) shows a coefficient of determination of 0.69.

$$E = 2153N + 5210 \quad (3)$$

The differences observed between the correlations, could be explained by the local nature of relationships, or in the presented case, to the imprecision obtained when using the alpha parameter. In addition, the use of hydraulic hammers differs from most previous studies, thus affecting the uncorrected N values collected. Schmertmann relationship, currently used in practice in Quebec City, is nevertheless relatively good compared to the data collected for the deposit, despite the fact that it tends to underestimate elastic modulus values, which is therefore conservative.

6. Case study (Site 1)

6.1. Comparison of E_{pmt} modulus estimated using different methods

Soil parameters estimated from PMT tests can also be compared with other types of tests, such as the piezocone penetration test (CPTu). Several authors proposed relationships between the cone tip resistance (q_c), and the pressuremeter modulus (E_{pmt}) or limite pressure (p_L). Vaillant and Aubrion (2014) studied and summarized the values proposed by different authors for the ratios E_{pmt}/q_c and E_{pmt}/p_L for different types of soil. Their conclusion suggests sand E_{pmt}/q_c values varying between 0.3 and 2 with a mean value of 1.1 and a standard deviation of 0.3, and q_c/p_L values varying between 5 and 12 with a mean value of 9 and a standard deviation of 1.1.

Figures 7 and 8 show and compare the results of 45 pressuremeter tests performed in 4 boreholes and 4 piezocone tests performed in parallel with these boreholes on site 1. Mean cone tip resistance (q_c) presented was determined using an average value of (q_c) obtained from 45-centimeter penetration length corresponding to the same depth as the closest PMT test was performed. The relationship shown in Figure 7 was determined by fitting the regression line so that it passes through the origin. The result is very similar to E_{pmt}/q_c = 1.15 proposed by Briaud's (1992). The linear relation (Eq. 4) shows a coefficient of determination of 0.94.

$$E_{pmt} = 1.18q_c \quad (4)$$

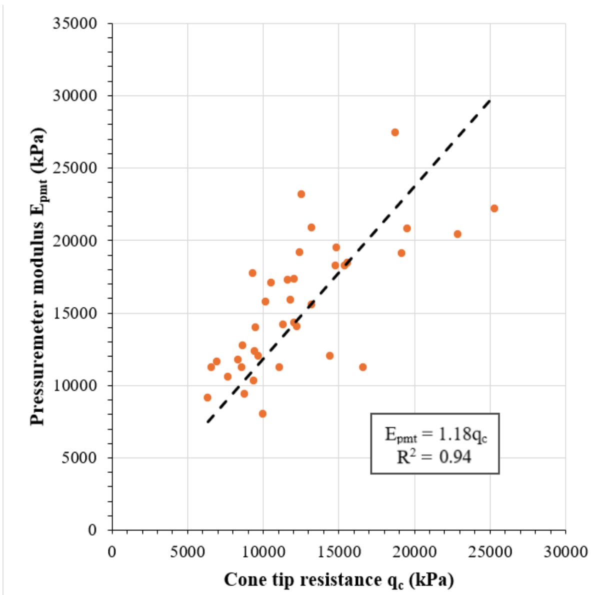

Figure 7. Relationship between cone tip resistance (q_c) and pressuremeter modulus E_{pmt} for all data from site 1 and compared with literature relationship

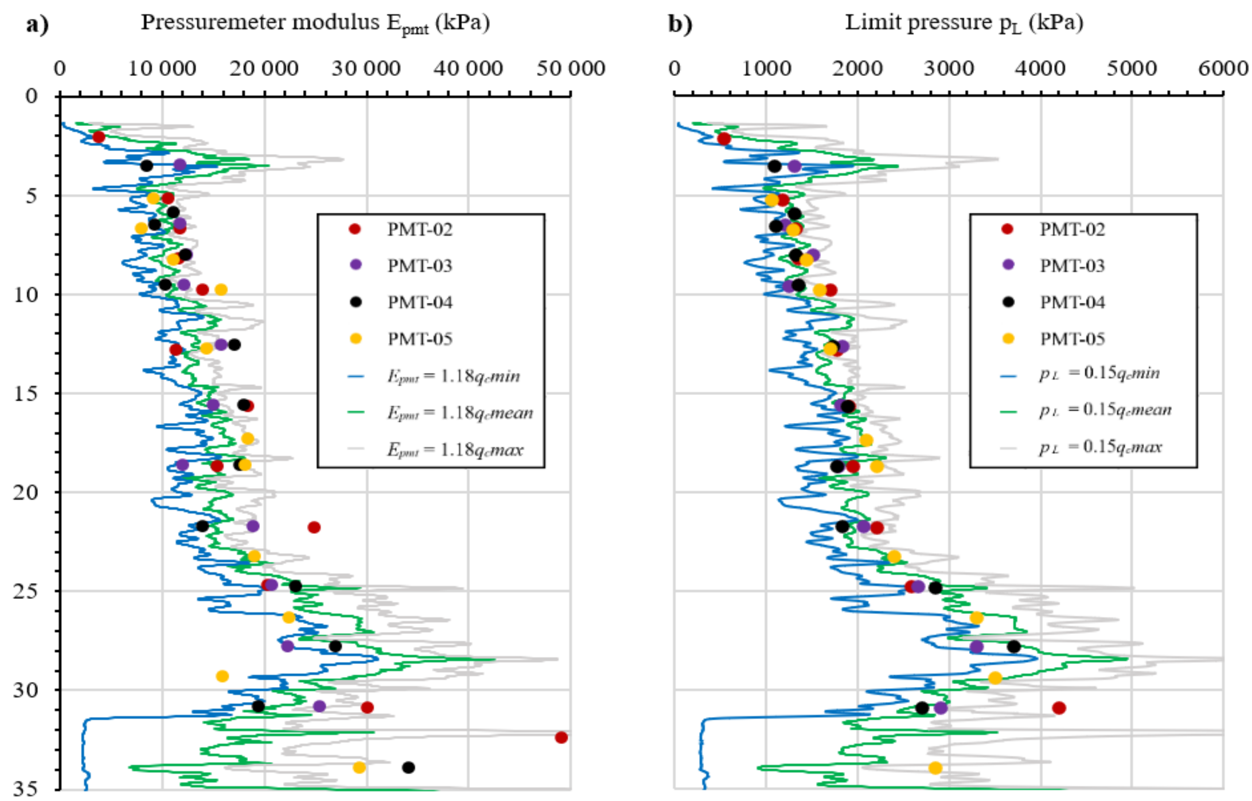

Figure 8. Comparison between measured pressuremeter tests data and CPT cone tip pressure a) modulus (E_{pmt}) and pressuremeter modulus estimated using 1.18q_c b) limit pressure (p_L) and limit pressure estimated using 0.15q_c as a function of depth for site 1.

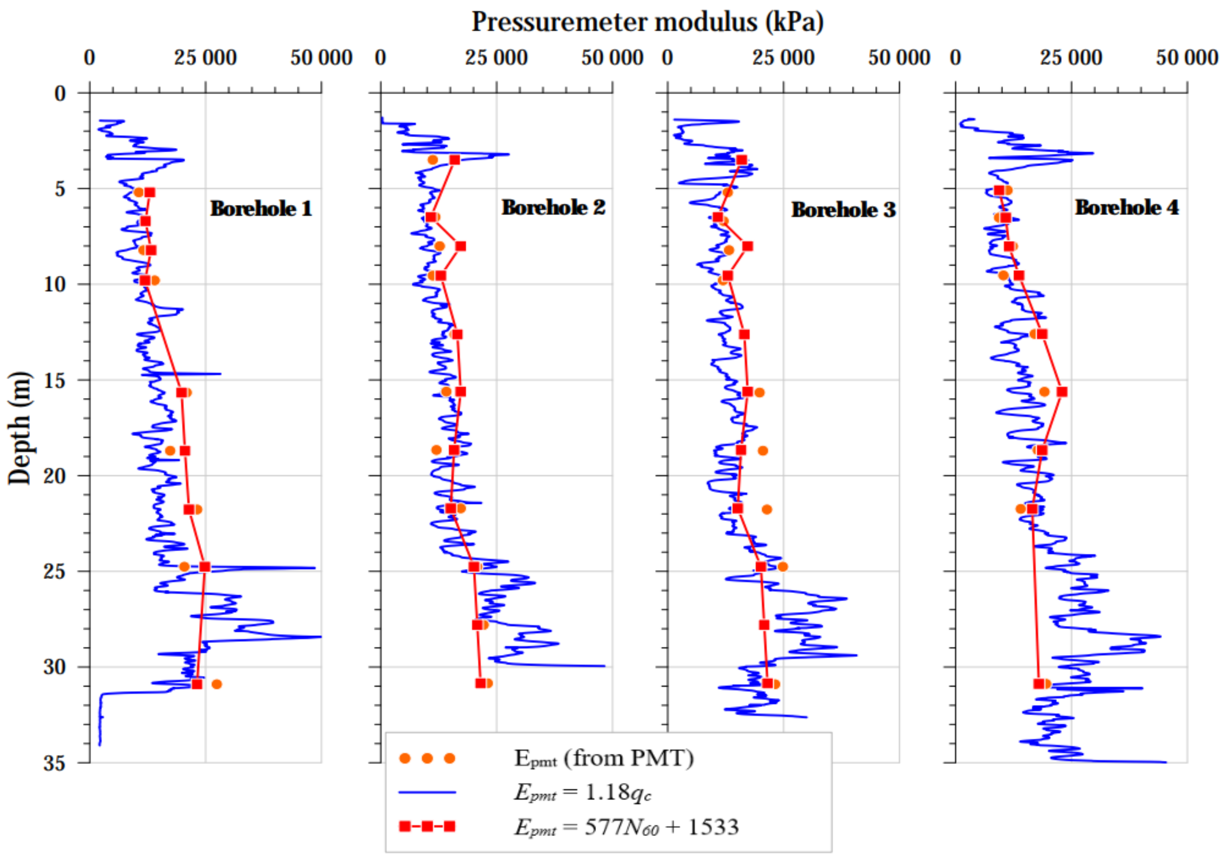

Figure 9. Comparison between the pressuremeter modulus (E_{pmt}) from PMT tests, from CPT i.e. 1.18q_c and from the SPT-N_{60} present relationships studied, for the boreholes at site 1.

Figure 8a) and b) show the comparison between measured pressuremeter moduli and E_{pmt} estimated using CPTu tip resistance (q_c) and limit pressure (p_L) from CPTu test correlation established for Saint-Charles River sand deposit as a function of depth for data from Site 1. The linear relation (Eq. 5) obtained for limit pressure and q_c for the studied site is:

$$p_L = 0.15 q_c \quad (5)$$

The limit pressure (p_L) correlation is equal to $0.15q_c$, which is close to $0.11q_c$ in Briaud (1992).

Figure 9 shows the comparison between the E_{pmt} test results, the E_{pmt} profile obtained from $1.18q_c$, and the E_{pmt} profile obtained from the SPT-N_{60} test previously presented for the Quebec sites, for 4 boreholes at site 1.

7. Conclusions

This article compares the results of pressuremeter (E_{pmt}) and Standard Penetration Tests (SPT-N) performed in compact to dense sand on 8 sites near the Saint-Charles river in Quebec City. The results show a good correlation. This article also presents the relationship between the E_{pmt} and the CPTu tip resistance (q_c) values obtained on one of these sites. This relationship is very similar to the one proposed by Briaud (1992) for this type of soil. It could be used to provide continous estimates of pressuremeter moduli.

In a subsequent step, it will be interesting to study the soil modulus values for settlement estimation established from the various correlations obtained for the Saint-Charles River deposits to determine the method that produces the results most closely matching the observed settlements on these sites.

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