# 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 a 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 are over 50 metres thick. 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 une 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 atteignent 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 estimate anticipated settlements is crucial to making 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. One good practice is to use different methods and to compare their results, or to develop site-specific correlations.

The objective of this paper is to propose a correlation between the N value obtained from the SPT test and the pressuremeter modulus ($E_{pmt}$) in the sand deposit from the St-Charles River area 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. 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 location of the sites is shown in Figure 1 (modified from Lamarche 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.

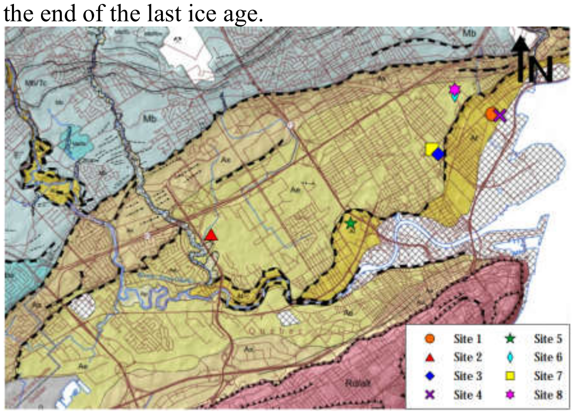


**Figure 1.** Location of study sites (modified from Lamarche 2010). At: Alluvial deposits of river terraces: sand, sandy silt, gravelly sand and gravel, Ae: Ancient estuarine sediment: silt, sandy silt, sand, Ax: Ancient alluvial deposits of river terraces: sand, sandy silt and gravel.

## 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 should be noted that in the region under study, the sand deposit is constantly under scrutiny for this problem, which requires frequent calibration of the driving energy to optimize the results of the liquefaction potential of the deposit. 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 drills used a hydraulic hammer, and the SPT energy measurement was collected using a Pile Dynamics, Inc. analyzer. 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 tests carried out with a TEXAM pressuremeter developed by 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 the rotation method with bentonite slurry injection. 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 pressuremeter 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 fracture resistance.
- 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 push 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, which make it particularly interesting from a financial standpoint. Using empirical equations, the CPTu test can also be used to determine several mechanical parameters of the soil (undrained shear strength, preconsolidation pressure, oedometer modulus, soil stratigraphy, etc.).

## 4. 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 (corrected and uncorrected) 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 the distribution of $N_{60}$ values varies from 11 to 47, with a mean of 27. N values above 50 were not included in this study.

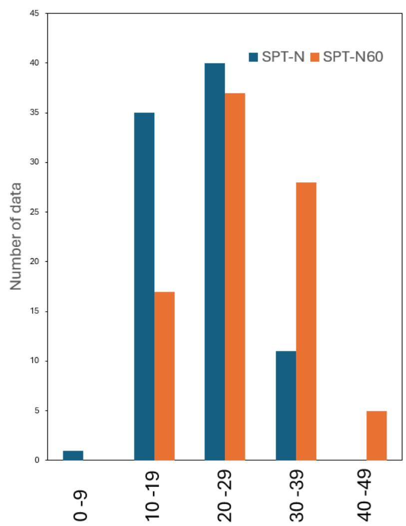


**Figure 2.** Histogram of SPT-N and SPT-$N_{60}$ data

Figure 3 shows the distribution of pressuremeter data obtained from tests carried out in the region's sandy soils and at similar depths from the SPT-N data collected. Pressuremeter modulus values obtained in Figure 3a), from the 87 measurements collected, range from 8 to 29.3 MPa.

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 is an important tool for judging 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):

$$7 < \frac{E_{pmt}}{p*_L} < 12$$

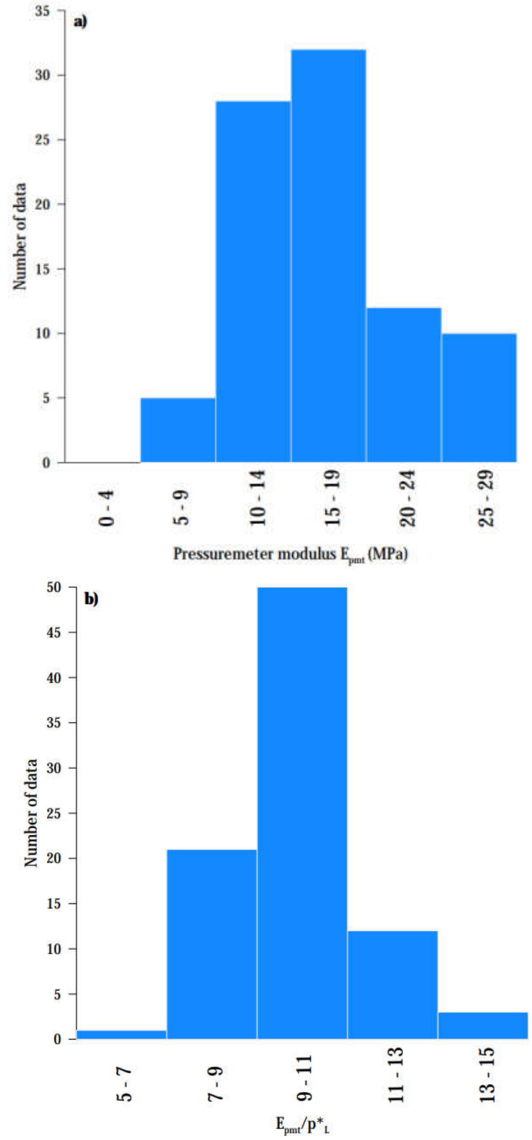


**Figure 3.** Histogram of the variation in a) pressuremeter modulus and b) $E_{pmt}/p*_L$ ratio data.

## 5. Discussion

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

Figure 4 shows the pressuremeter modulus of the 8 sites as a function of their respective SPT-N values. The trend line equation gives a coefficient of determination of 0.69, indicating a good level of correlation between the two parameters. The linear equation, according to the 87 data, as in Eq. (1):

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

The data generally follow the trend, except for one test at site 3.

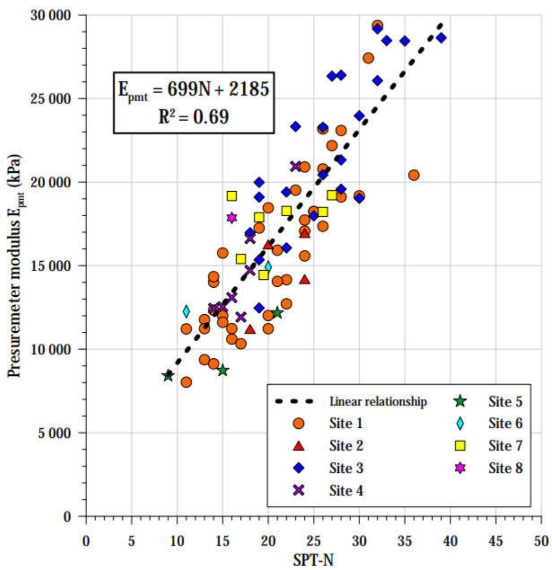


**Figure 4.** Relationship between SPT-$N_{60}$ and the pressuremeter modulus $E_{pmt}$ for Saint-Charles River sand

Correcting the energy lost when collecting SPT-N is a good practice for normalizing the data. Figure 5 shows the relationship between SPT-$N_{60}$ and pressuremeter modulus. Corrected SPT-N were also studied, as there are several correlations based on them in the literature, as shown in Table 1. The $R^2$ is 0.70, which is similar to the uncorrected SPT data. The relationship between SPT-$N_{60}$ and pressuremeter modulus is shown directly in Figure 5, along with the correlations in Table 1.

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

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

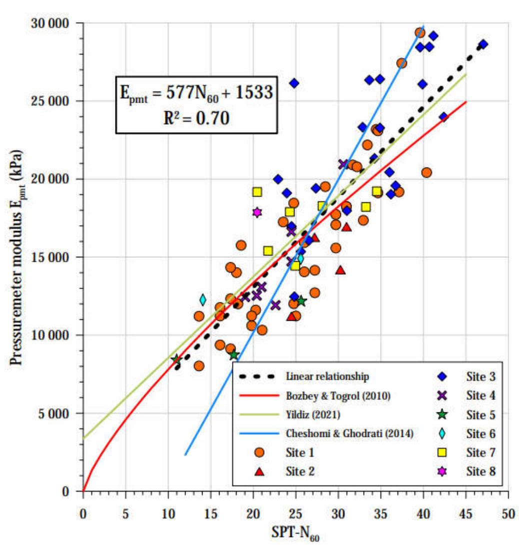


**Figure 5.** Relation between pressuremeter modulus and SPT-$N_{60}$

The equation obtained for Saint-Charles River sand fits well with the data of Bozbey and Trogol (2010) and Yildiz (2021), suggesting that these models are appropriate for the soil studied. In his case, the relationship of Cheshomi and Ghodrati (2014) tends to overestimate pressuremeter modulus calculated from $N_{60}$ values greater than 25. This could be explained by the higher proportion of dense soil ($N > 30$) in the Cheshomi and Ghodrati (2014) study. Furthermore, the correction of the SPT data does not affect the 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.

## 5.2. Relationship between SPT-N and the elastic modulus of deformation

The $E_{pmt}$ pressuremeter modulus can be used to determine the elastic modulus of deformation according to a rheological coefficient α. In this study, this parameter is taken from The Pressuremeter (Briaud 1992). The parameter E was estimated, as in the Eq. (2):

$$\frac{E_m}{E} = \alpha \qquad (2)$$

where $\alpha$ is the typical Menard factors from (Briaud, 1992). $\alpha$ is generally 1/3 to 1/2 for sand deposit normally consolidated or overconsolidated.

To apply this relationship, it was assumed that the test performed with a Texam pressuremeter would provide similar data to the Menard pressuremeter. Figure 6 shows the relationship between elastic modulus and uncorrected SPT-N. The relationship in Saint-Charles River sand is compared with various correlations in sandy soils taken from the literature and presented in Table 2:

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

| Source | Soil type | *Equation (kPa)* |
|---|---|---|
| Schmertmann & al. (1978) | Gravelly sand | *E=(1500 to 2500)N* |
| 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)* |

The coefficient of determination is 0.69 between the two (2) parameters according, as in Eq. (3):

$$E = 2032N + 7384 \qquad (3)$$

Despite a good correlation between the parameters, the relationship for the site under study does not agree with those in the literature. This could be explained by the local nature of relationships, or by the estimation of the alpha parameter. In addition, the use of a hydraulic hammer in this study differs from most previous studies, thus affecting the uncorrected N values collected. The Schmertmann relationship, currently used in practice in

Quebec City, is nevertheless relatively good when compared with the data collected for the deposit.

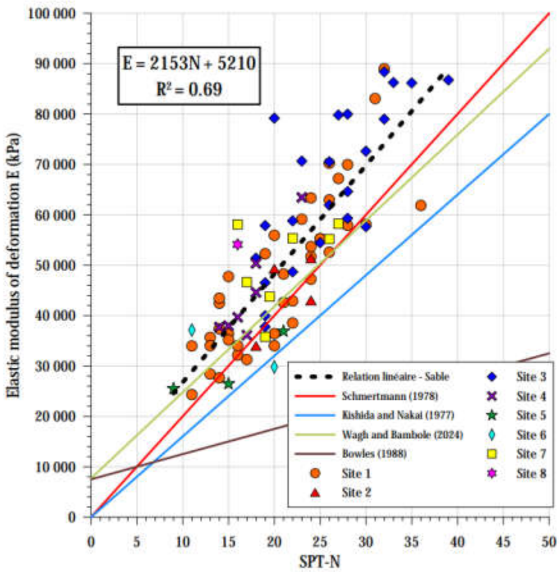


**Figure 6.** Relationship between elastic modulus of deformation and SPT-N

## 6. Case study (Site 1)

### 6.1. Comparison of $E_{pmt}$ modulus calculate using different methods

In order to compare our pressuremeter data with an in-situ test method other than SPT-N, we also used cone resistance ($q_c$) profiles obtained with a piezocone.

Figure 7 shows the comparison between the raw $E_{pmt}$ results, the $E_{pmt}$ profile obtained from the Briaud (1992) relationship, i.e. $E_{pmt}$ equal to $1.15q_c$, and the $E_{pmt}$ profile obtained from the SPT-$N_{60}$ test previously presented for the Quebec sites, for 4 boreholes at site 1.

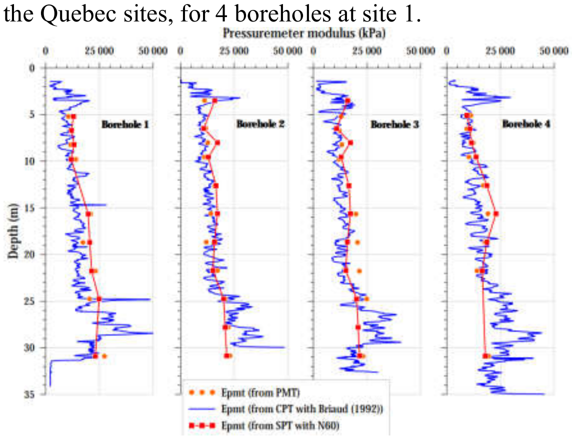


**Figure 7.** Comparison between the raw $E_{pmt}$ results, the $E_{pmt}$ profile obtained from the Briaud (1992) relationship and the $E_{pmt}$ profile obtained from the SPT test for the 4 boreholes at site 1.

The relationships between $q_c$ and pressuremeter modulus have also been studied by several authors and are presented in Table 3, including that of Briaud (1992) discussed above.

**Table 3.** Relationship between piezocone peak resistance and pressuremeter modulus

| **Source** | **Soil type** | ***Equation (kPa)*** |
|---|---|---|
| Briaud (1992) | Sand | $E_{pmt}=1.15q_c$ |
| Mezouar & al. (2017) | Sand | $E_{pmt}=0.37q_c+6.5$ |
| Costet & Sanglerat (1981) | Sand | $E_{pmt}=(0.5 \text{ to } 1.0)q_c$ |

By comparing with some available relationships, Briaud (1992), Mezouar et al. (2017), Costet and Sanglerat (1981), the correlation obtained for the Quebec sand deposit site is very similar to that of Briaud (1992). The relationship shown in Figure 8 was determined by fitting the regression line so that it passes through the origin.

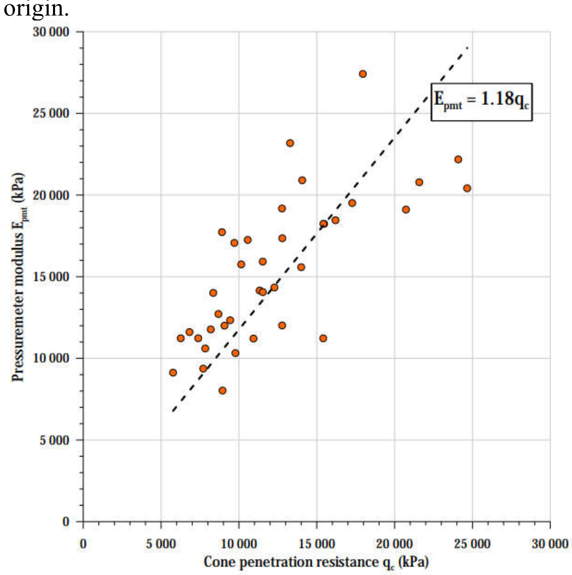


**Figure 8.** Relationship between cone resistance $q_c$ and pressuremeter modulus $E_{pmt}$

Figure 9a) and b) show the comparison between measured pressuremeter modulus and $E_{pmt}$ estimated using $q_c$ and $p^*_L$ as a function of depth for data from Site 1.

It is interesting to note that the $E_{pmt}$ correlation equal to 1.18 $q_c$ is good when mean, minimum and maximum qc profiles are used for the given site. Figure 9b) relates the qc to the pressure limit ($p^*_L$) obtained from the pressuremeter, which seems to give an even lower variance of values. The $p^*_L$ correlation equals $0.135q_c$. According to the literature, it was demonstrated that these parameters compare even better.

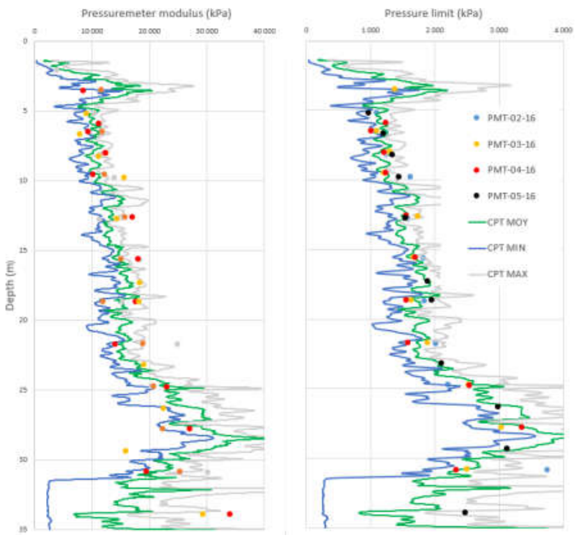


**Figure 9.** a) Comparison between measured $E_{pmt}$ pressuremeter modulus and pressuremeter modulus estimated using $q_c$ and b) $p^*_L$ as a function of depth for site 1 data.

## 7. Conclusions

This article presents a different correlation based on the results of $E_{pmt}$ and SPT pressuremeter tests for compact to dense sand near the Saint-Charles River in Quebec City. The correlation obtained is good. In the case of the relationship obtained with the CPTu tip resistance ($q_c$) and the $E_{pmt}$ profile, this relationship demonstrated that the Briaud (1992) relationship is very similar to that obtained at the site under study. This correlation could provide a continuous modulus estimate. 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 St-Charles River repository, and to evaluate the method that makes it possible to obtain an estimate very close to the settlements measured on the sites studied.

## Acknowledgements

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