Reliability of self-boring pressuremeter in sand

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Abstract: The cone penetration test (CPT) is viewed by a majority in the geotechnical engineering profession as a preferred in situ testing tool, while the self-boring pressuremeter test (SBPMT) is sometimes viewed to be of questionable reliability. A comparative statistical study of SBPMT data and CPT cone tip resistance is undertaken in this research to examine whether the test data do actually support the perceived notion. Data from seven sand and silt sites in western Canada and one location in the United States have been examined. The sensitivity of the SBPMT to the variability in the state of packing is quantified and compared with the corresponding values for the cone tip resistance. The results indicate that the sensitivity of cone tip resistance and the SBPMT data to the variability in the in situ state of packing is comparable. Comparison of estimates of procedural uncertainties in the SBPMT and the CPT also leads to a similar conclusion. These observations do not support the notion of a general lack of reliability of the self-boring pressuremeter at sand–silt sites.

Key words: reliability, sand, self-boring pressuremeter, piezocone, inherent variability, procedural uncertainty.

Résumé : L'essai de pénétration au cône (CPT) est regardé par une majorité dans la profession d'ingénieur géotechnicien comme étant l'outil préféré de sondage in situ, alors que l'essai au pressiomètre autoforeur (SBPMT) est parfois considéré comme étant d'une fiabilité douteuse. Une étude comparaison statistique des données du SBPMT et de la résistance à la pénétration en pointe du CPT est entreprise dans cette recherche pour examiner si de fait les données des essais soutiennent cette perception. Des données de sept sites de sable et de limon dans l'ouest du Canada et d'un site localisé aux États-Unis ont été examinées. La sensibilité du SBPMT à la variabilité dans l'état de compacité est quantifiée et comparée avec les valeurs correspondantes pour la résistance en pointe du cône. Les résultats indiquent que les sensibilités de la résistance en pointe du cône et des données du SBPMT à la variabilité dans l'état de compacité in situ sont comparables. La comparaison des estimations des incertitudes dans les procédures du SBPMT et du CPT conduisent également à la même conclusion. Ces observations n'appuient pas la notion d'un manque généralisé de fiabilité du pressiomètre autoforeur dans des sites sable–limon.

Mots clés : fiabilité, sable, pressiomètre autoforeur, piézocône, variabilité inhérente, incertitude dans les procédures.

[Traduit par la Rédaction]

Introduction

Characterization of deposits of sand with the self-boring pressuremeter test (SBPMT) has three distinct advantages: (*i*) the test can be performed in soil without causing appreciable disturbance, (*ii*) measurements cover a wide range of deformation, and (*iii*) the data can be analyzed following the principles of mechanics. Several attempts have been reported in the literature involving the use of self-boring pressuremeters in sand sites, some of which provided useful information. Fahey and Randolph (1984), Lacasse et al. (1990), and Fahey et al. (1993), for instance, were able to derive reasonable values of strength and deformation parameters of sand (e.g., shear modulus and the effective stress friction angle, ϕ') and the effective horizontal geostatic stress, σ_h', from field SBPMTs. Bruzzi et al. (1986) and Robertson (1982), on the other hand, failed to obtain reliable results from SBPMTs. Partial success with the use of the tool in sand sites has thus lead to a debate as to whether it is at all practicable to develop an appropriate test procedure in sand for the self-boring pressuremeter (Clarke and Gambin 1995; Bruzzi et al. 1986; Robertson 1982). Some investigators are of the opinion that the virgin cavity expansion in an SBPMT is of less practical value due to its apparent sensitivity to factors that are difficult to control such as installation-related disturbance (Clarke and Gambin 1995).

Although an objective assessment of sensitivity of SBPMT data to inherent soil variability and the extent of procedural uncertainty in the test is essential for establishing the relevance (or lack thereof) of the test at sand sites, such investigations are extremely rare in the literature. However, qualitative agreement between the SBPMT and other in situ tests from adjacent locations has occasionally been reported in the literature (e.g., Pass 1994; Mori 1981). In situ test data obtained by the authors from several sand sites are also in agreement with these observations. For instance, in deposits that are characterized by a uniform cone tip resistance, the measured pressure–expansion response in SBPMT vary over a very narrow band (e.g., LL Dam data, Fig. 1). In contrast, at sites with highly variable cone tip resistance (e.g., Highmont Dam, Fig. 1), a higher variability is ob-

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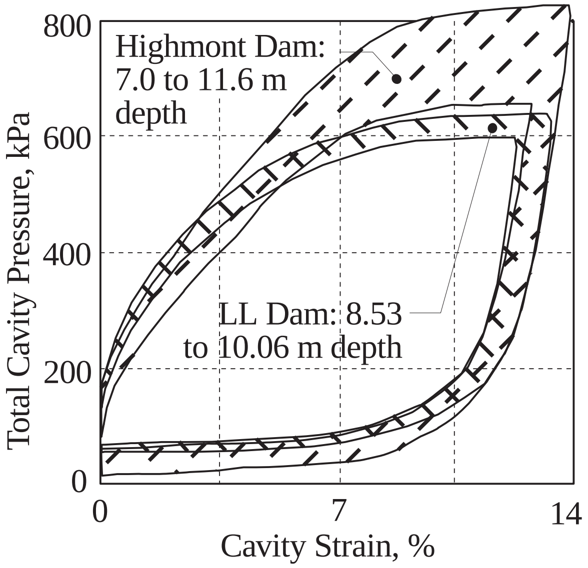
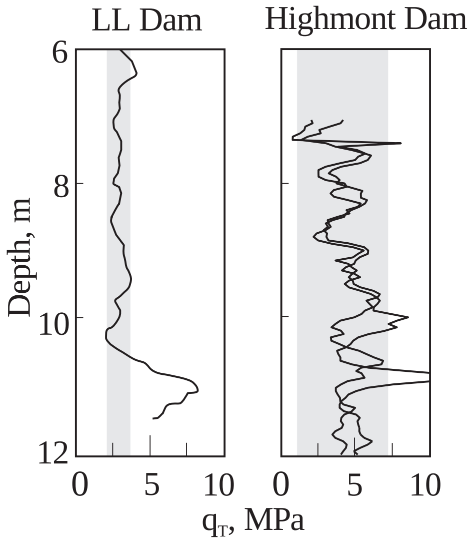
Fig. 1. Qualitative comparison of CPT and SBPMT data.



(a) Self-boring pressuremeter test data



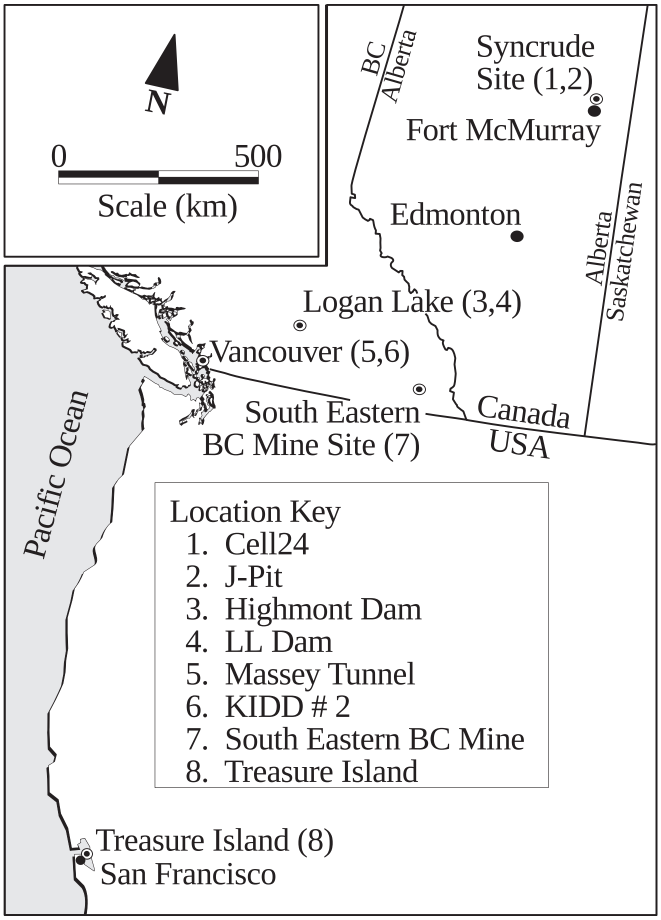
(b) CPT data

served in the SBPMT data. It is therefore logical to hypothesize that if cone penetration test (CPT) data from sand sites are of acceptable reliability, SBPMT data are reliable as well.

Reliability of several in situ testing procedures other than the self-boring pressuremeter has been assessed by Orchant et al. (1988), Phoon and Kulhawy (1996), and Kulhawy and Trautmann (1996). The estimates of reliability of SBPMT reported in these studies were deduced from prebored pressuremeter test (PMT) data based on qualitative reasoning. Actual SBPMT data were not examined by the authors to verify their conclusions.

The statistical approach of this paper is similar in essence to that adopted by Orchant et al. (1988), Phoon and Kulhawy (1996), and Kulhawy and Trautmann (1996). As in those studies, data measured in the SBPMT and CPT are treated here as normally distributed random variables characterized by sample mean and sample standard deviation. However, unlike the earlier research, the reliability of the SBPMT is estimated directly from actual measurements using data from several sites. These estimates are then compared with the corresponding values pertaining to the CPT at the same sites to examine the consistency of the SBPMT and CPT. The procedural uncertainty in SBPMT due to installation-related disturbance, which is a major contributor to the procedural uncertainty in an SBPMT, is also compared with the procedural uncertainty in the CPT.

Fig. 2. Site location.



The data examined in this paper originate from several sand sites in western Canada and one location in Treasure Island near San Francisco (Fig. 2). Relevant particulars of the deposits examined in this study are summarized in Table 1. All the tests at a given site were conducted within a horizontal distance of 10 m. Several piezocone penetration and self-boring pressuremeter tests were carried out within the test area at each site (see Pass 1994; and Roy 1997 for more details).

Test procedures and random variables

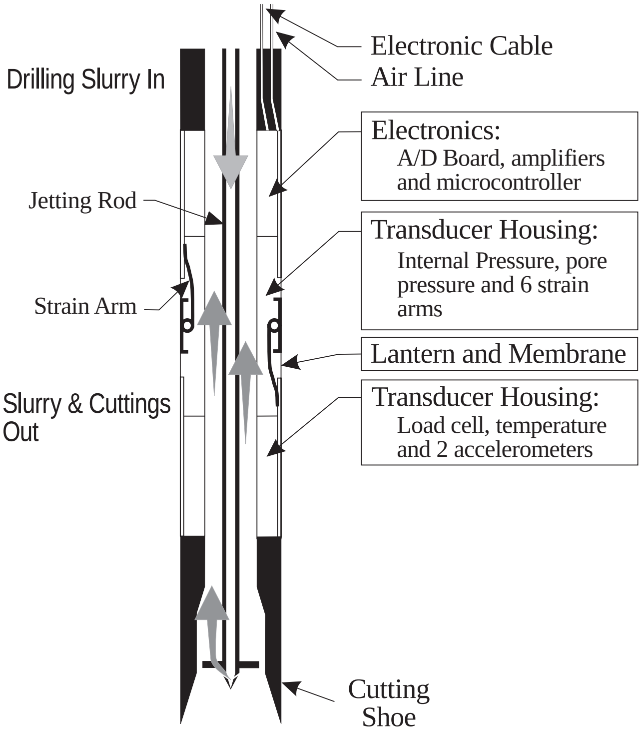
In the CPT, an instrumented, close-ended cylindrical probe with a cross-sectional area of 10 or 15 cm^2 and a conical tip with 60° apex angle is pushed into the ground at a

Table 1. Site particulars.

Site	Target zone (m)	FC	D_{50} (mm)	D_R (%)	ϕ_{cv} (°)	Reference
Cell 24	31–38	7–12	0.20	60–75	29	Campanella et al. 1995
J-Pit	3–9	7–12	0.20	20–50	29	Iravani et al. 1995
Highmont Dam	7–12	18	0.12	30–60	34	Bigger and Robertson 1996
KIDD # 2	15–17.5	7	0.14	50–70	31	In-situ Testing Group 1995*b*
LL Dam	5–10	7–9	0.14	35–45	34	Bigger and Robertson 1996
Massey Tunnel	8–16	2	0.14	30–50	31	In-situ Testing Group 1995*a*
Southeastern British Columbia mine site	0–10	50	0.074	1–10	33	Roy 1997
Treasure Island	9.5–11	12	0.25	30–50	32	Pass 1994

Note: D_R, relative density; FC, percent passing the No. 200 sieve; ϕ_{cv}, constant-volume friction angle.

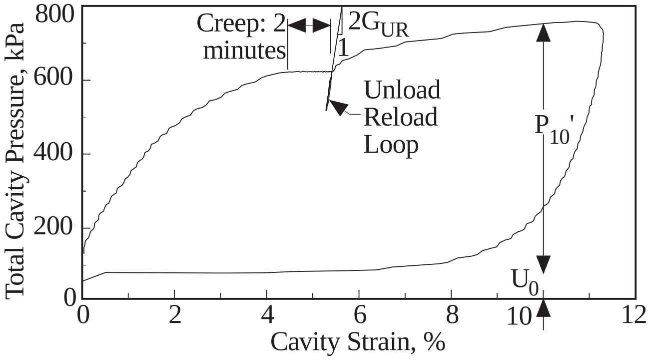
Fig. 3. Schematic details of the self-boring pressuremeter.



steady rate of penetration of about 20 mm/s. The resistance against penetration near the conical tip, q_T, is measured at a vertical interval between 25 and 50 mm. During the penetration of the conical probe, other measurements are also made, e.g., frictional resistance against penetration immediately behind the tip. These measurements are not as repeatable as q_T and are affected by extraneous factors like the surface roughness of the probe and probe geometry. The effect of state of the soil (e.g., the relative density, D_R) and the environmental variables (e.g., the state of effective geostatic stress) on these measurements is also not as well understood as that pertaining to q_T. As a result, q_T is chosen in this study as the random variable of interest for quantifying the reliability of the CPT.

In an SBPMT, an instrumented cylindrical inflatable probe is installed in the soil layer of interest. The probe is installed in the ground by jetting (as in the tests reported in this study), drilling, or cutting. Care is taken during installation to minimize the disturbance in the surrounding soil and to avoid stress relief. Once at the desired depth, the probe is inflated by gas pressure. The self-boring pressuremeters used in this study are of the monocell design, i.e., the instrument consists of a single inflatable “cell.” The expandable section has a diameter of 74 mm, except for the probe used at Treasure Island, and a length to diameter ratio of about 6. The diameter of the expandable section of the self-boring pressuremeter used at Treasure Island is 82 mm. The history of radial deformation of the cavity was monitored at its central height except at Treasure Island, where three sets of strain arms were used, one at the central height, one 120 mm above the central height, and one 120 mm below the central height. The gas pressure within the deforming cavity (also called the total cavity pressure) is measured continually during the deformation process. Schematic details of a typical self-boring pressuremeter with one set of strain arms are shown in Fig. 3. For additional particulars on the geometry of the self-boring pressuremeter probes refer to Campanella et al. (1990) and Pass (1994). More details on the actual test procedure at the sites examined here can be found in Pass (1994) and Roy (1997).

Fig. 4. Typical SBPMT pressure–expansion curve (Test no. MSPM 245: 11.205 m depth at Massey Tunnel).



A typical SBPMT pressure–expansion curve within a sand deposit is shown in Fig. 4. The random variables of interest are the unload–reload modulus G_{UR} and the effective cavity pressure (equal to the total cavity pressure minus the ambient pore-water pressure) at $\varepsilon_\theta = 10\%$, P'_{10}. The symbol ε_θ denotes cavity strain, i.e., radial deflection of the cavity wall divided by the original cavity radius. As opposed to the CPT, SBPMT measurements pertain to a wide range of deformations. It is therefore necessary to estimate the effect of inherent soil variability on the SBPMT data over the entire range of deformation. In this study, G_{UR} and P'_{10} are chosen as the random variables to represent small and large deformations, respectively. The connotation "large deformation" is used in this paper loosely and should not be construed to signify the presence of geometric nonlinearity. The choice of ε_θ = 10% is rather arbitrary and is motivated by the fact that SBPMT cavity expansions are often terminated at cavity strains of about 10%.

Like the SBPMT effective cavity pressure at a given deformation, the cone tip resistance, q_T, increases with σ_h' and ϕ'. However, σ_h' affects SBPMT measurements at small values of cavity strain, whereas ϕ' has a more pronounced effect upon the data at larger deformations. In contrast, different combinations of ϕ' and σ_h' may lead to the same q_T. Also, the soil around the piezocone penetrometer is greatly disturbed during the CPT. Thus, the CPT is in essence an index test that is only amenable to empirical interpretation. Nevertheless, the piezocone has emerged as a popular site-characterization tool. A reason for its popularity is its excellent spatial resolution: layers as thin as 50 mm can be distinguished. The tool is robust and the test procedure is relatively inexpensive. Also, existence of a large database makes the user confident about data interpretation despite the empiricism, especially where the database has been established. These were the motivations for using the CPT as the benchmark to assess the reliability of the SBPMT.

Major causes of variability in the CPT and SBPMT data

Laboratory chamber test results suggest that both CPT and SBPMT data are affected by the soil state (i.e., relative density, D_R), grain characteristics (e.g., grain shape and mineralogy), and environmental factors (e.g., the state of effective stress and soil fabric). This study is aimed at estimation and comparison of the effect of inherent soil variability upon the CPT and SBPMT. Since the data examined in this research originate from young, normally consolidated uncemented hydraulic deposits of sand and silt, soil fabric at these sites is similar. The data are preprocessed to approximately eliminate the effects of grain characteristics and the environmental factors. The estimates of the effect of inherent soil variability on the CPT and SBPMT reported in the following are thus ascribable essentially to the state of packing. Other causes of variability in the CPT and SBPMT measurements are as follows.

CPT data

Procedural uncertainty in the CPT data may arise from the difference in the installation procedure and probe geometry. The uncertainty due to a difference in probe geometry is only examined in this article. According to the American Society for Testing and Materials (ASTM 1995), a conical probe with 10 or 15 cm^2 cross-sectional area can be used in the CPT. Given the fact that soil layers over a deeper segment are sampled in the data obtained using a penetrometer with a larger cross-sectional area (Robertson and Campanella 1986), the smoothing effect due to spatial averaging is expected to be larger in the case of a 15 cm^2 cone. As shown later, CPT data obtained in this research using a 15 cm^2 probe support this argument.

SBPMT data

As in case of the CPT, the procedural uncertainty in the SBPMT mainly arises from installation procedure and differences in probe geometry (Phoon and Kulhawy 1996). SBPMT data examined in this research were largely obtained using self-boring pressuremeters with similar geometry and design. As a result, direct assessment of procedural uncertainty related to dissimilar probe geometry is not possible from the available database. The procedural uncertainty due to installation-related disturbance is estimated for data from Massey Tunnel using SBPMT data affected by installation-related disturbance together with those without appreciable disturbance.

Preprocessing of raw data

As mentioned earlier, raw data from in situ tests were preprocessed to eliminate the effects of environmental variables, e.g., the state of effective stress. Correction was also applied to account for systematic differences in grain characteristics at individual sites. Essential details of corrections for the level of effective stress and grain compressibility are as follows.

Stress normalization

Among all the state variables, relative density has the most significant effect on the mechanical response of young uncemented sand–silt. It may thus be argued that inherent soil variability in such a deposit primarily arises from a variation in the relative density of the deposit. Although the mechanical behavior of granular deposits is also affected to a significant extent by the state of effective stress, this study is not aimed at examining the effects of environmental factors on CPT and SBPMT measurements. Since the influences of the state of effective stress on q_T, G_{UR}, and P_{10}' are not identical, these variables need to be normalized for the state of effective stress before quantifying their sensitivity to inherent soil variability and procedural uncertainty. The exercise is analogous to spatial detrending, a procedure routinely undertaken in the presence of a physically significant trend in a spatial data set before undertaking a statistical analysis. The following relationships are used to normalize the random variables of interest:

$$[1] \qquad (q_T)_1 = q_T\left(\frac{\sigma_h'}{P_a}\right)^{-0.6}$$

$$[2] \qquad (P_{10}')_1 = P_{10}'\left(\frac{\sigma_h'}{P_a}\right)^{-0.8}$$

and

$$[3] \qquad (G_{UR}^c)_1 = G_{UR}\left(\frac{\sigma_{UR}'}{P_a}\right)^{-0.43}$$

where σ_{UR}' is the average effective horizontal stress for an unload–reload loop. Symbols with the subscript 1 represent normalized random variables used to assess the effect of inherent soil variability and procedural uncertainty in CPT and SBPMT, with the subscript signifying normalization to σ_h' =

Table 2. Bases for stress normalization.

Equation	Reference	Particulars
[1]	Houlsby and Hitchman 1988	Empirically found from calibration chamber tests on CPT
[2]	This study	Identified from a series of numerically simulated cylindrical cavity expansion tests following Carter et al. (1986) using typical model parameters for medium-dense sand, viz., $\phi' = 38°$, $\phi_{cv} = 31°$, shear modulus = 27 MPa, and Poisson's ratio = 0.25
[3]	Bellotti et al. 1989	Identified semiempirically for elastic – perfectly plastic materials validated by ideal SBPMTs in a calibration chamber on a medium-compressibility sand

P_a, where P_a is atmospheric pressure (≈ 100 kPa). Superscript "c" is used to denote the fact that G^c_{UR} is corrected for the stress level representative of the unload-reload loop. For loose to medium dense, normally consolidated deposits of young uncemented sand and silt such as those found at sites studied in this research, $\sigma_h' \approx 0.5\sigma_v'$, where σ_v' is the effective vertical geostatic stress. For an elastic perfectly plastic Mohr-Coulomb frictional material, σ'_{UR} can be calculated following Bellotti et al. (1989) from

$$[4] \qquad \sigma'_{UR} = \frac{\left(\dfrac{1}{2\sin\phi'} - \dfrac{\sigma_h'}{\sigma_c'}\dfrac{1+\sin\phi'}{2\sin\phi'}\right)\sigma_c'}{\ln\left[\left\{\dfrac{\sigma_c'}{\sigma_h'(1+\sin\phi')}\right\}^{(1+\sin\phi')/2\sin\phi'}\right]}$$

where σ_c' is the effective cavity pressure at the beginning of the unload–reload loop. The effective stress friction angle is estimated here from the cone tip resistance from a CPT adjacent to the SBPMT using the correlation proposed by Robertson and Campanella (1986). The quantity $(q_T')_1$ is obtained by subtracting the ambient pore-water pressure, U_0, from $(q_T)_1$. Experimental or analytical bases of the relationships in eqs. [1], [2], and [3] are summarized in Table 2.

Correction for grain compressibility

Data summarized in Robertson and Campanella (1986) indicate that q_T for angular sands is about 0.85 times that for those comprising subround to subangular grains. To account for dissimilar grain compressibility, q_T measured at LL Dam, Highmont Dam, and southeastern British Columbia mine site, where angular sands and silts are found, is divided by 0.85 to obtain the equivalent q_T for medium-compressibility sand.

Recent analytical work on the effect of grain compressibility on SBPMT pressure–expansion curves indicates that P'_{10} for a high-compressibility sand is about 0.92 times that for a medium-compressibility sand (Roy 1997). Therefore, to correct for systematic differences in grain compressibility, P'_{10} values measured at LL Dam are divided by 0.92. Since the average stress pertaining to a typical unload–reload loop, σ'_{UR}, is a small fraction of those imposed during the measurements of q_T and P'_{10}, the effect of grain compressibility on G_{UR} is expected to be negligible. No correction is therefore applied to G_{UR} to account for the systematic differences in grain compressibility.

Effect of inherent variability of deposits on SBPMT and CPT

Following Orchant et al. (1988), Kulhawy and Trautmann (1996), and Phoon and Kulhawy (1996), the normalized variables $(G^c_{UR})_1$, $(P'_{10})_1$, and $(q_T')_1$ are modeled as normally distributed random variables. The influence of inherent soil variability on SBPMT and CPT can thus be quantified using the best estimate of the coefficient of variation (COV) $\hat{C}$, where $\hat{C}$ is equal to the sample standard deviation of the random variable divided by the sample mean . The "hat" is used to indicate the best estimates of the statistics and not in symbols representing their true values.

The COVs for inherent soil variability and procedural factors are denoted here by $\hat{C}_s$ and $\hat{C}_P$, respectively. The symbol without a subscript, $\hat{C}$, denotes total variability. Assuming independence between the uncertainty in the value of the random variable of interest ascribable to inherent soil variability and that due to procedural factors, the following relationship between $\hat{C}$, $\hat{C}_S$, and $\hat{C}_P$ is obtained:

$$[5] \qquad \hat{C}^2 = \hat{C}_P^2 + \hat{C}_S^2$$

The above relationship will be used later to estimate the procedural uncertainty from total uncertainty and that arising from inherent soil variability.

To calculate $\hat{C}_S$ for the CPT measurements, the normalized cone tip resistance from 10 cm^2 penetrometers are used. The preference for the 10 cm^2 piezocone over the 15 cm^2 piezocone does not have any motive other than the fact that a considerably larger database of measurements using 10 cm^2 piezocones is available. To calculate $\hat{C}_S$ for the random variables representing the SBPMT, data from those tests with minimal installation-related disturbance were used. Composition of the database from which the estimates of $\hat{C}_S$ were obtained for random variables $(q_T')_1$, $(P'_{10})_1$, and $(G^c_{UR})_1$ are summarized in Table 3 and the results are listed in Table 4.

From the fact that $\hat{C}_S$ values for $(P'_{10})_1$ and $(G^c_{UR})_1$ are less than the values pertaining to $(q_T')_1$ it can be concluded that the SBPMT is less sensitive to natural soil variability than the CPT. Because of a larger probe diameter and larger vertical interval between consecutive pressure expansion tests (–0.5 to 1 m in this study as opposed to 0.025–0.05 m in a typical CPT), SBPMT data reflect average soil properties over a larger volume of soil than the piezocone. As a result, SBPMT is less sensitive to inherent soil variability than the CPT. The results of Table 4 are plotted in Figs. 5 and 6, whence the existence of monotonic relationships between $\hat{\mu}$ and $\hat{C}_S$ for SBPMT and $(q_T')_1$ are apparent. The implications

Table 3. Database details.

	No. of soundings		Sample size			
			$(P'_{10})_1$		$(G^c_{UR})_1$	
Site	CPT	SBPMT	Disturbed	Undisturbed	Disturbed	Undisturbed
Cell 24	4 3^b	1^a				
J-Pit	4	2^b		11		11
Highmont Dam	2 2^d	2^{bc}				
KIDD #2	3	1^a				
LL Dam	5 1^d	2^b	7	10	3	13
Massey Tunnel	7	2	10	11	6	
Southeastern British Columbia mine site	1	1		10		
Treasure Island	1^b	1^b		6		

[a] Insufficient data for estimating univariate statistics.

[b] Installed using a drill rig. Unless indicated otherwise, probes were installed using in situ testing vehicles.

[c] No undisturbed data. Consequently, data were not included in statistical analyses.

[d] Cross-sectional area of the piezocone is 15 cm^2. Unless indicated otherwise, piezocones have a cross-sectional area of 10 cm^2.

Table 4. Influence of inherent soil variability on CPT and SBPMT.

		$(q_T')_1$		$(P'_{10})_1$		$(G^c_{UR})_1$	
Site	Database composition	$\hat{C}_S$	$\hat{\mu}$ (MPa)	$\hat{C}_S$	$\hat{\mu}$ (MPa)	$\hat{C}_S$	$\hat{\mu}$ (MPa)
Cell 24	CPT adjacent to SBPMT (between 35 and 36.6 m)	0.17	9.18				
	All SBPMTs						
J-Pit	Entire database	0.50	4.27	0.37	0.658	0.33	18.51
KIDD #2	Entire database	0.20	9.83				
LL Dam	10 cm^2 cone	0.24	7.52				
	Undisturbed SBPMT			0.16	0.885	0.20	23.39
Massey Tunnel	10 cm^2 cone	0.22	7.24				
	Undisturbed SBPMT			0.14	1.028		
Southeastern British Columbia mine site	Entire database	0.84	3.61	0.54	0.631		
Treasure Island	Entire database	0.18	6.80	0.04	0.910		

of these relationships are as follows: (*i*) the measurements from a carefully conducted SBPMT correlate well with the CPT cone tip resistance from the same site; and (*ii*) inherent soil variability affects the SBPMT and CPT measurements in a similar fashion, i.e., for a highly interlayered deposit $\hat{C}_S$ for both CPT and SBPMT measurements is higher than the corresponding values for a more uniform deposit.

Vertical sampling density and confidence intervals

Although the inferences of the preceding section are based on the best-estimate statistics, it should be recognized that the vertical sampling density for $(q_T')_1$ (one measurement every 25–50 mm) is considerably larger than that in a typical SBPMT sounding (one measurement every 0.5–1.0 m). This makes it necessary to examine the effect of such a difference upon the confidence intervals of the statistical estimators. The confidence intervals for the mean of a normally distributed random variable can be calculated from the expression (see, e.g., Kreyzig 1983):

$$[6] \quad \hat{\mu} - t_{0.975,(n-1)} \frac{\hat{\sigma}}{\sqrt{n}} < \mu < \hat{\mu} + t_{0.975,(n-1)} \frac{\hat{\sigma}}{\sqrt{n}}$$

and the corresponding inequality for sample variance (sample variance is equal to the square of sample standard deviation) is

$$[7] \quad \frac{(n-1)\hat{\sigma}^2}{\chi^2_{0.025,(n-1)}} < \sigma^2 < \frac{(n-1)\hat{\sigma}^2}{\chi^2_{0.975,(n-1)}}$$

where t is Student's t; χ^2 is the chi-squared value; μ and σ are the true values of mean and standard deviation, respectively; and n is the sample size. The calculated confidence intervals for the results of Table 4 are summarized in Table 5.

The results presented in Table 5 indicate that the confidence intervals for the estimates of sample mean are small

Fig. 5. Relationship between sample means.

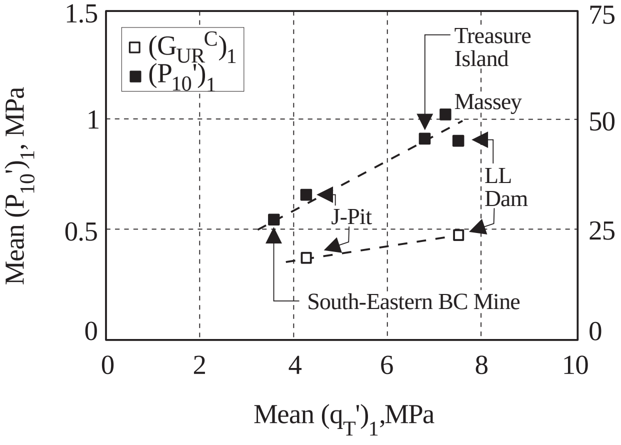
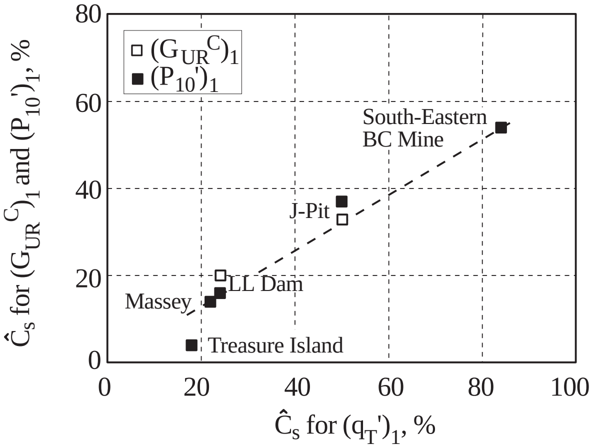


Fig. 6. Relationship between coefficients of variation.



fractions of the best estimates of the statistic for both CPT (4% of the best estimate: average for all sites) and SBPMT (17% of the best estimate: average for all sites). The confidence intervals for the estimates of standard deviation are considerably larger, with 90% of the best estimates (average for all sites) for the normalized random variables representing the SBPMT and 11% of the best estimates (average for all sites) for the normalized variables representing the cone tip resistance. Also, the confidence intervals for the statistics pertaining to $(q_T')_1$ are smaller than those for $(P_{10}')_1$ and $(G_{UR}^c)_1$, especially for the coefficients of variation for inherent soil variability. As a result, the relationships of Fig. 5 are more precise than that of Fig. 6.

Procedural uncertainty in SBPMT

Procedural uncertainty in an SBPMT due to operational factors, i.e., installation procedure, is examined herein. Adoption of an inappropriate installation procedure in SBPMT leads to either a "pushed-in" type of disturbance or "wash boring." A drilling process incapable of removing the amount of soil that is necessary to advance the probe without imparting an appreciable outward radial displacement in the soil leads to a pushed-in type of disturbance. On the other hand, if more soil is removed than is necessary to avoid stress relief, an oversized cavity is created. A tell-tale sign of this type of disturbance, often called wash boring, is an unusually low lift-off pressure and can be remediated by simply reducing the mudflow. Unlike wash boring, the pushed-in type of disturbance is more difficult to detect and control. The procedural uncertainty due to the pushed-in type of disturbance is quantified in what follows.

Trial SBPMTs at the beginning of the in situ testing program at Massey Tunnel were carried out to identify an optimum installation procedure. The probe was withdrawn from the borehole at regular intervals to inspect for the occurrence of shoe-plugging. Excessive shoe-plugging, where more than one half of the cross-sectional area of the cutting shoe is plugged, is assumed to indicate that the pressure–expansion test prior to the withdrawal of the probe from the borehole was affected by a pushed-in type of disturbance. The cutoff of one half of the cross-sectional area of the cutting shoe was arrived at from an observation that interpretation of SBPMT data from tests with a greater amount of shoe-plugging usually leads to anomalous results (da Cunha 1994). The data from the tests affected by a pushed-in type of disturbance are used to quantify the uncertainty due to the installation procedure as detailed below. SBPMT data from LL Dam by a pushed-in type of disturbance are also used in the following exercise.

The coefficient of variation of a mixed database of pressure–expansion tests with and without installation-related disturbance, $\hat{C}$, is first estimated. $\hat{C}_P$ is then calculated from eq. [5] using the estimate of $\hat{C}_S$ reported earlier. The results of this exercise are summarized in Table 6. As seen from the results, $\hat{C}_P$ for $(P_{10}')_1$ is about 0.1 at LL Dam and Massey Tunnel. A dearth of data did not allow estimation of $\hat{C}_P$ at other sites.

Compared with the coefficients of variation for procedural uncertainty at sand sites inferred by Orchant et al. (1988) and Phoon and Kulhawy (1996) from prebored pressuremeter tests, $\hat{C}_P$ for $(P_{10}')_1$ at Massey Tunnel and LL Dam are lower. As pointed out earlier, the estimates of Orchant et al. and Phoon and Kulhawy are based on the qualitative experience of the investigators and not on actual measurements. Nevertheless, the estimates of SBPMT procedural uncertainty listed in Table 6 do not include the uncertainty due to dissimilar probe designs. All self-boring pressuremeters, measurements from which have been examined in this study, are of the Cambridge design and are installed by a central jetting system with a length to diameter ratio of about 6.

It may be mentioned here that the procedural uncertainty in the SBPMT due to operational factors can be minimized by the adoption of an appropriate procedure for the installation of the self-boring probe. A summary of such procedures for self-boring probes of several types can be found elsewhere (see, e.g., da Cunha 1994; Roy 1997).

Procedural uncertainty in CPT

For the SBPMT, the repeatability is understood to be most significantly affected by operational aspects, i.e., installation procedure. The operational procedure for the CPT, on the other hand, has been standardized. As a consequence, CPT data are not affected to a considerable extent by the operational factors. However, ASTM (1995) allows both 10 and 15 cm^2 cone penetrometers in the CPT. It is of interest to ex-

Table 5. Confidence intervals.

		$(q_T')_1$ (MPa)		$(P'_{10})_1$ (MPa)		$(G^c_{UR})_1$ (MPa)	
Site	Database composition	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\mu}$	$\hat{\sigma}$
Cell 24	CPT next to SBPMT (35–36.6 m)	±0.08	–0.13, 0.15				
J-Pit	Entire database	±0.17	–0.13, 0.14	±0.16	–0.07, 0.19	±4.11	–1.85, 4.60
KIDD #2	Entire database	±0.22	–0.15, 0.17				
LL Dam	10 cm^2 cone	±0.11	–0.08, 0.09				
	Undisturbed SBPMT			±0.09	–0.04, 0.10	±2.69	–1.24, 2.83
Massey Tunnel	10 cm^2 cone	±0.07	–0.04, 0.05				
	Undisturbed SBPMT			±0.01	–0.04, 0.11		
Southeastern British Columbia mine site	Entire database	±0.24	–0.14, 0.17	±0.24	–0.11, 0.28		
Treasure Island	Entire database	±0.44	–0.24, 0.43	±0.04	–0.02, 0.05		

Table 6. Procedural uncertainty in CPT and SBPMT.

Site	Variable	$\hat{C}$	$\hat{C}_S$	$\hat{C}_P$
Highmont Dam	$(q'_T)_1$	0.34	0.32	0.11
LL Dam	$(q'_T)_1$[a]	0.14	0.11	0.09
	$(P'_{10})_1$	0.18	0.16	0.09
Massey Tunnel	$(P'_{10})_1$	0.18	0.14	0.13

[a] Based on CPT data within the target zone from two adjacent soundings, one using a 10 cm^2 cone and the other using a 15 cm^2 cone.

amine how such a difference in probe geometry affects the measurement.

As in case of the SBPMT, the total uncertainty, $\hat{C}$, in the cone tip resistance is quantified in the following using a mixed database of CPTs at LL Dam and Highmont Dam using 10 and 15 cm^2 penetrometers. Due to the prevalence of the 10 cm^2 piezocones in the industry, normalized effective cone tip resistance $(q_T')_1$ from 10 cm^2 probes is treated as the reference for computing the procedural uncertainty in the cone tip resistance. In other words, $\hat{C}_S$ for the cone tip resistance is calculated solely from 10 cm^2 cone tip resistance. Using these estimates of $\hat{C}$ and $\hat{C}_S$ in eq. [5], the procedural uncertainty due to the difference in the probe geometry, $\hat{C}_P$, is calculated.

The estimates of $\hat{C}_P$ arising out of the difference in the diameter of the piezocone at LL Dam and Highmont Dam are presented in Table 6. These values are in agreement with the value suggested in ASTM (1995) and are somewhat higher than the corresponding value of 5% reported by Orchant et al. (1988) and Phoon and Kulhawy (1996). Prevalence of the 10 cm^2 piezocone penetrometers appears to be the primary reason behind the perception that the CPT data are significantly more repeatable than the SBPMT data.

Conclusions

A comparative study of the piezocone, which is among the most preferred tools for site characterization, and the SBPMT was undertaken to ascertain the reliability of the self-boring pressuremeter in granular deposits. SBPMT and CPT data from several sand and silt sites in western Canada and one site in the United States have been examined.

A relationship of approximately monotonic nature is apparent between the coefficients of variation ascribable to natural soil variability for $(q_T')_1$ and the corresponding values for $(P'_{10})_1$ and $(G^c_{UR})_1$. The sample means of $(P'_{10})_1$ and $(G^c_{UR})_1$ also relate to that of $(q_T')_1$ in a similar manner at the sites examined in this research. These observations can be interpreted as follows: (*i*) inherent variability of a deposit of granular soils has a similar effect on carefully conducted self-boring pressuremeter tests and piezocone penetration tests, and (*ii*) carefully conducted self-boring pressuremeter test data correlate reasonably with CPT cone tip resistance at sand and silt sites.

Since $(P'_{10})_1$ and $(G^c_{UR})_1$ represent large- and small-strain measurements in an SBPMT, respectively, the inferences listed above are valid for well-conducted SBPMTs irrespective of strain level in the test.

Procedural uncertainty in the CPT due to dissimilar probe geometry and that in the SBPMT due to imperfect installation have also been examined, since these factors are understood to have the most significant influence on these tests. Examination of test data indicates that these factors have a similar influence on CPT and SBPMT data.

It is therefore apparent that SBPMT is as reliable a tool as the piezocone at a sand site, provided that a proper procedure is followed during the installation of the probe. The lack of reliability of some interpretation procedures for the SBPMT which has occasionally been reported in the literature does not provide evidence of a general drawback of the tool itself, and should be viewed as a limitation of the interpretation procedure.

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