Interpretation of in situ test results from the CANLEX sites

C.E. (Fear) Wride, P.K. Robertson, K.W. Biggar, R.G. Campanella, B.A. Hofmann, J.M.O. Hughes, A. Küpper, and D.J. Woeller

Abstract: One of the primary objectives of the Canadian Liquefaction Experiment (CANLEX) project was to evaluate in situ testing techniques and existing interpretation methods as part of the overall goal to focus and coordinate Canadian geotechnical expertise on the topic of soil liquefaction. Six sites were selected by the CANLEX project in an attempt to characterize various deposits of loose sandy soil. The sites consisted of a variety of soil deposits, including hydraulically placed sand deposits associated with the oil sands industry, natural sand deposits in the Fraser River Delta, and hydraulically placed sand deposits associated with the hard-rock mining industry. At each site, a target zone was selected and various in situ tests were performed. These included standard penetration tests, cone penetration tests, seismic downhole cone penetration tests (giving shear wave velocity measurements), geophysical (gamma–gamma) logging, and pressuremeter testing. This paper describes the techniques used in the in situ testing program at each site and presents a summary and interpretation of the results.

Key words: CANLEX, in situ testing, shear wave velocity, geophysical logging, pressuremeter.

Résumé : Un des principaux objectifs du projet CANLEX était d'évaluer les techniques d'essais in situ et les méthodes d'interprétation existantes faisant partie de l'objectif global de focaliser et de coordonner l'expertise géotechnique canadienne sur le sujet de la liquéfaction des sols. Six sites ont été sélectionnés par le projet CANLEX dans le but de tenter de caractériser divers dépôts de sols sableux meubles. Les sites consistaient en une variété de dépôts de sols, incluant des dépôts de sable mis en place par méthode hydraulique et reliés à l'industrie des sables bitumineux, des dépôts de sable naturel dans le delta du fleuve Fraser, et des dépôts de sables mis en place par méthode hydraulique et reliés à l'industrie minière de roches fragiles. Sur chaque site, une zone cible a été sélectionnée et divers essais in situ ont été réalisés. Ceux-ci incluaient des essais de pénétration standard (SPT), des essais de pénétration au cône (CPT), des essais séismiques en bout de forage (donnant des mesures de la vitesse de l'onde de cisaillement), des essais de profilage géophysique (gamma–gamma) et de pressiomètre. Cet article décrit les techniques utilisées dans le programme d'essai in situ sur chacun des sites et présente un résumé et l'interprétation des résultats.

Mots clés : CANLEX, essais in situ, vitesse de l'onde de cisaillement, profilage géophysique, pressiomètre.

[Traduit par la Rédaction]

Introduction

The Canadian Liquefaction Experiment (CANLEX) project has involved detailed investigation of six sites in Western Canada, all of which contain relatively loose sand deposits. The phase I and phase III sites (Mildred Lake Settling Basin and J-pit, respectively) consisted of hydraulically placed sand deposits associated with the oil sands industry at the Syncrude Canada Ltd. mine in Alberta. The phase II sites (Massey and Kidd) were natural sand deposits in the Fraser River Delta of British Columbia. The phase IV sites (LL Dam and Highmont Dam) consisted of hydraulically placed sand deposits associated with the hard-rock mining industry at the Highland Valley Copper Mine in British Columbia. This paper describes the in situ testing carried out and presents a summary of the interpretation.

At each site, a target zone was selected based on initial site screening using the cone penetration test (CPT) in an effort to characterize a loose, uniformly graded, relatively clean, sandy deposit at each site. Various in situ tests were performed through the individual target zone. These included standard penetration tests (SPTs), cone penetration tests (CPTs), seismic CPTs (giving shear wave velocity measurements), geophysical (gamma–gamma) logging, and pressuremeter testing.

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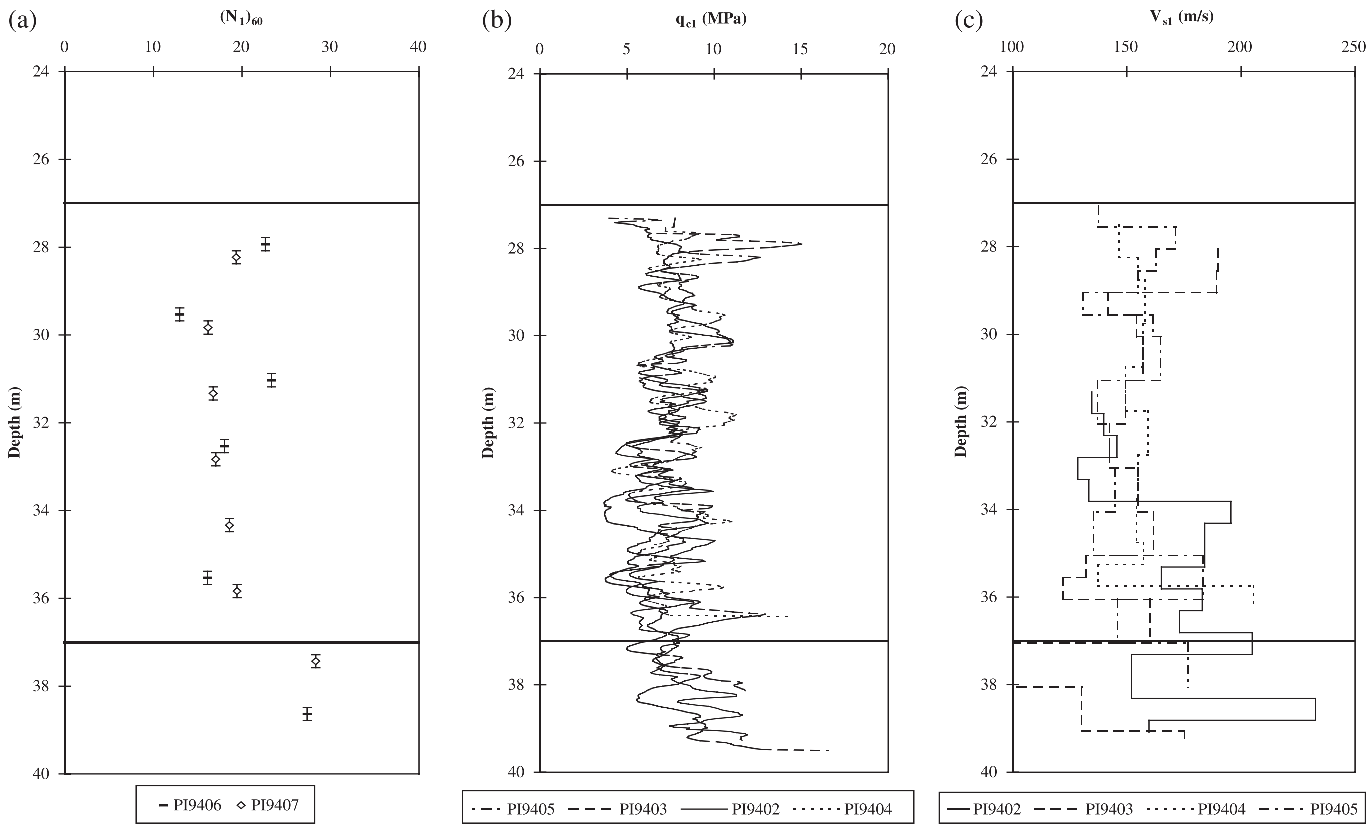
Test sites

The location, geology, and target zones for each of the six sites are described by Robertson et al. (2000*a*). The typical layout of the detailed site characterization at each of the six CANLEX sites is also described by Robertson et al. In the centre of each test site, in situ ground freezing was performed to obtain undisturbed samples of sand (Wride et al. 2000). Along a typically 5 m radius circle around the central

Fig. 1. Corrected (*a*) SPT, (*b*) CPT, and (*c*) V_{s1} profiles at the phase I (Mildred Lake) site.



ground-freezing location, the in situ testing through the target zone at each site consisted of the following: CPTs, SPTs, shear wave velocity (V_s) measurements (seismic CPTs), geophysical logging, and pressuremeter testing. The ground-freezing samples were tested in the laboratory and the results were compared with the in situ data (Robertson et al. 2000*b*).

An additional site that can be incorporated into this study is Duncan Dam, a zoned earthfill hydroelectric dam located on the Duncan River, about 8 km upstream from Kootenay Lake in southeastern British Columbia. Prior to the start of the CANLEX project, a similar type of detailed field and laboratory investigation was carried out at Duncan Dam to characterize the sandy soil beneath the dam as part of a dam safety review by B.C. Hydro (Little et al. 1994). Several of the CANLEX participants were involved in various aspects of this study. In situ testing and sampling (Sego et al. 1994; Plewes et al. 1994), laboratory testing of undisturbed frozen samples (Pillai and Stewart 1994), and subsequent analysis (Pillai and Salgado 1994; Byrne et al. 1994) indicated that the soil unit of greatest concern was unit 3-c, which is located under the downstream side of the right half of Duncan Dam. Unit 3-c consists of uniform, angular to subangular, fine sand with approximately 5% fines (i.e., essentially a clean sand). The age of the unit 3-c sand is just over 10 000 years (approx. 10 400 years; Little et al. 1994).

The ground freezing and sampling of unit 3-c sand was performed at the downstream toe of the dam, within a target zone from 12 to 17 m (Sego et al. 1994). In the immediate vicinity of the ground-freezing and sampling location, the following in situ testing was performed (B.C. Hydro 1993; Plewes et al. 1994): one seismic CPT, one drillhole with SPT testing, one borehole for sampling with a Christensen core barrel, and one borehole for sampling with a fixed piston sampler. These tests, combined with the ground freezing and sampling, have been incorporated into this study.

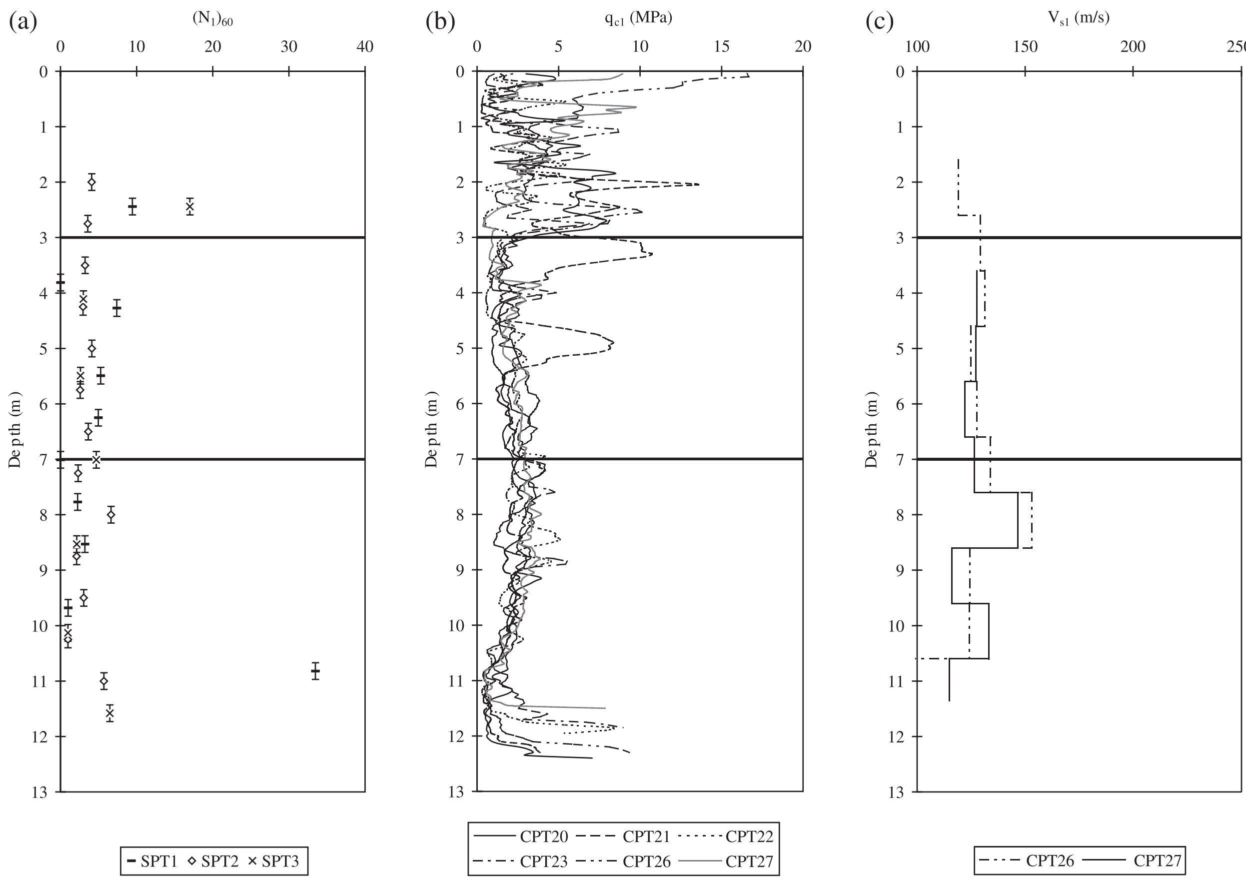
Based on the results of this study, the sands at the CANLEX sites are of Holocene age (i.e., less than 10 000 years old), are essentially normally consolidated and uncemented, and are composed primarily of quartz minerals. These sands are uniformly graded with a mean grain size (D_{50}) of 0.16–0.25 mm and a fines content of generally less than 12%, with some less than 5%.

In situ test procedures

Energy measurements were made for and appropriate corrections were applied to almost all of the individual SPT blow counts. The exception was at phase III. Overall average measured energy ratios (ER) at the six sites ranged from about 50% (at the phase III site) to about 80% (at both phase II sites). This range in measured ER indicates that energy corrections for the SPT are important, in order to calculate values of $(N_1)_{60}$ and compare data within a given site or from a variety of sites.

Initial CPT screening was performed at each site to select the specific area in which to conduct the detailed site characterization. Many of the CPTs also incorporated downhole V_s measurements. The advantage of the seismic CPTs was that both the conventional CPT measurements and the V_s

Fig. 2. Corrected (*a*) SPT, (*b*) CPT, and (*c*) V_{s1} profiles at the phase III (J-pit) site.



measurements were made in the same sounding and allow for two independent in situ assessments of a given soil deposit at the same depth and spatial location.

Geophysical logging was carried out at each site in uncased, mud-supported boreholes. Each geophysical log typically consisted of several runs down the same borehole which were averaged to give one overall profile per borehole. The results were also typically subjected to a five-point data smoothing filter. Details of corrections made to geophysical logs to obtain in situ void ratios are given by Plewes et al. (1988).

Self-boring pressuremeter tests were conducted at each of the CANLEX sites. In addition, some prebored pressuremeter tests were conducted at the phase I site. At the two phase IV sites (LL Dam and Highmont Dam), difficulties were encountered with installing the self-boring pressuremeter. As a result, different types of jetting systems were tried. The most successful tests at the phase IV sites used a central jetting system with jetting ports at the cutting face.

Results and interpretations of in situ tests

SPT, CPT, and V_s results

The SPT, CPT, and V_s results for each of the six CANLEX sites were corrected for effective overburden stress (and energy effects, in the case of the SPT profiles) using the following equations:

$$[1] \qquad (N_1)_{60} = N\left(\frac{P_a}{\sigma'_v}\right)^{0.5}\left(\frac{\mathrm{ER}}{60}\right)$$

where $(N_1)_{60}$ is the SPT blow count corrected for stress level and energy, N is the measured SPT blow count, P_a is a reference pressure of 100 kPa, σ'_v is the vertical effective stress (in kPa), and ER is the measured energy ratio (in percent);

$$[2] \qquad q_{c1} = q_c\left(\frac{P_a}{\sigma'_v}\right)^{0.5}$$

where q_{c1} is the CPT tip resistance corrected for stress level, and q_c is the measured CPT tip resistance;

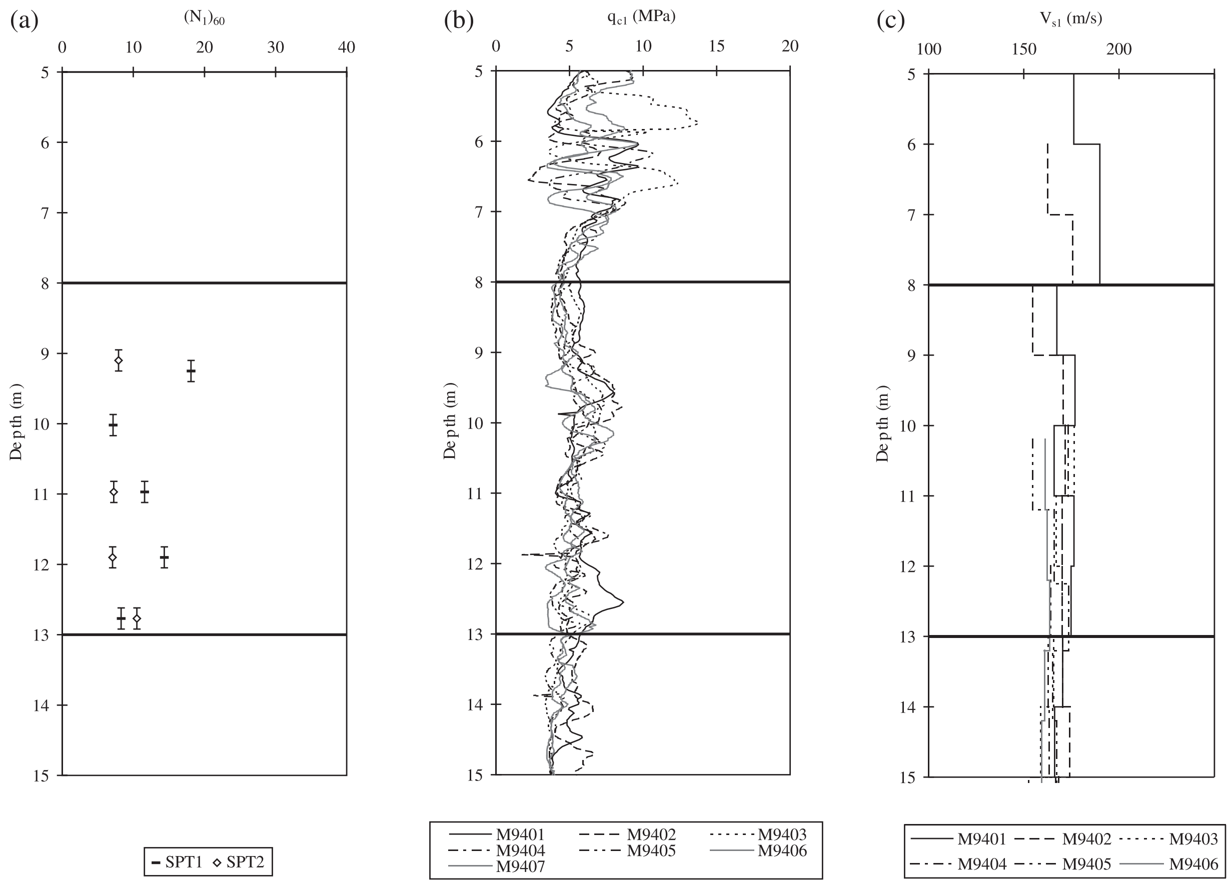
$$[3] \qquad F = \frac{f_s}{q_c - \sigma_v} \times 100\%$$

where F is the normalized friction ratio, f_s is the measured sleeve friction, and σ_v is the vertical stress (Robertson 1990); and

$$[4] \qquad V_{s1} = V_s\left(\frac{P_a}{\sigma'_v}\right)^{0.25}$$

where V_{s1} is the shear wave velocity corrected for stress level, and V_s is the measured shear wave velocity.

Fig. 3. Corrected (*a*) SPT, (*b*) CPT, and (*c*) V_{s1} profiles at the Massey site (phase II).



Since most sites had essentially clean sand, measured pore pressures during the CPT were close to equilibrium pore pressures. Conceptually, all CPT tip resistance values should be expressed as q_t (corrected for pore-pressure effects due to unequal areas; Robertson 1990). However, since all the data are for clean sands where the measured tip resistance is high and penetration pore pressures are low, the measured tip resistance, q_c, is essentially always the same as q_t. Hence, in this paper all CPT tip resistance values are shown as q_c.

All profiles of the raw in situ test data are available in the CANLEX summary data reports.[2]

Figures 1–6 present the corrected in situ test signatures for the SPT, CPT, and shear wave velocity logs at the six CANLEX sites. The SPT profiles are shown as discrete points with attached bars, corresponding to the midpoint and range, respectively, of the 30 cm over which the value of *N* was measured. The CPT profiles are shown as continuous profiles, since measurements were taken every few centimetres (typically 5 cm). The shear wave velocity profiles are shown as step functions, indicating that the shear wave velocity was measured (using a method of differences) as an average value over a given interval (typically about 1 m). The thick horizontal lines in each figure indicate the extent of the target zone at each site. The scales have been selected to provide a similar range of values based on average correlations.

Table 1 summarizes the overall average and standard deviation (SD) values of SPT $(N_1)_{60}$, CPT q_{c1}, and V_{s1} measured in the target zone at each of the six CANLEX sites. Also in Table 1 are the overall average and standard deviation values of CPT normalized friction ratio *F*. In general, the SPT shows larger variability than either the CPT or V_s.

CPT-based soil classification

Figure 7 presents the normalized CPT soil behaviour type classification chart proposed by Robertson (1990). If the in situ effective stresses are close to 100 kPa, the CPT data can be plotted directly on the soil classification chart by Robertson (1990) in terms of the linear normalization of the measured cone tip resistance, Q (= $(q_c - \sigma_v)/\sigma'_v$), and F (= $f_s/(q_c - \sigma_v)$, in percent). However, if the in situ effective stresses are significantly smaller or larger than 100 kPa, the normalization used to calculate the normalized cone tip resistance becomes very important. Olsen and Malone (1988) correctly proposed that the exponent used to normalize cone tip resistance should be a function of the soil behaviour type; however, this method requires a complex iterative approach to plotting CPT data on a soil classification

[2] Complete summary reports on the project are available from BiTech Publishers Ltd., 173 – 11860 Hammersmith Way, Richmond, BC V7A 5G1, Canada.

Fig. 4. Corrected (*a*) SPT, (*b*) CPT, and (*c*) V_{s1} profiles at the Kidd site (phase II).

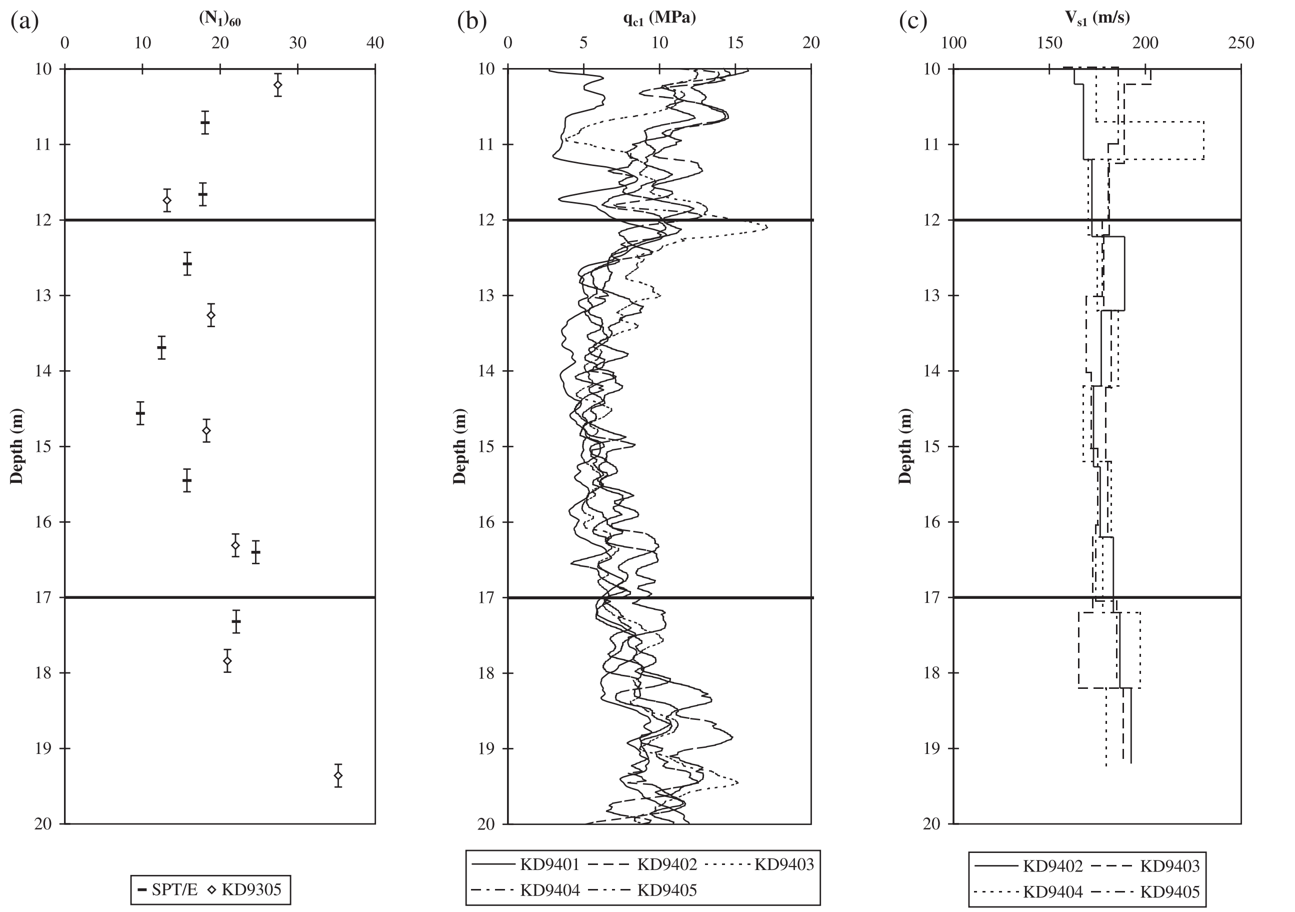


Table 1. Summary of SPT, CPT, and shear wave velocity results from the six CANLEX sites.

Site data			Field data			
Phase	Location	Site	SPT $(N_1)_{60}$	CPT q_{c1} (MPa)	CPT F (%)	Shear wave velocity V_{s1} (m/s)
I	Syncrude	Mildred Lake	18.2 (3.0)	7.38 (1.67)	0.727 (0.150)	156.4 (20.1)
II	Fraser River Delta	Massey	10.3 (3.8)	5.34 (1.00)	0.398 (0.089)	168.2 (6.4)
		Kidd	13.4 (2.9)	6.83 (1.77)	0.369 (0.048)	177.4 (5.4)
III	Syncrude	J-pit	3.4 (2.0)	2.04 (0.79)	0.872 (0.331)	127.1 (3.0)
IV	HVC Mine	LL Dam	5.4 (1.6)	3.94 (0.78)	0.409 (0.096)	153.1 (15.3)
		Highmont Dam	4.9 (2.6)	4.39 (1.26)	0.384 (0.127)	141.3 (11.7)

Note: The numbers given in the table are overall average values in the target zone, with standard deviations in parentheses. F, CPT friction ratio = $f_s/(q_c - \sigma_v) \times 100\%$; $(N_1)_{60}$, SPT N value corrected for overburden stress and to an energy ratio of 60% (see eq. [1]); q_{c1}, CPT penetration resistance corrected for overburden stress (see eq. [2]); V_{s1}, measured shear wave velocity corrected for overburden stress (see eq. [4]).

chart. As a simplified iterative approach, Robertson and Wride (1998) suggested the application of a soil behaviour type index, I_c, defined as $I_c = [(3.47 - \log Q)^2 + (\log F + 1.22)^2]^{0.5}$. Robertson and Wride suggested that if CPT data fall in zones 2, 3, or 4 (i.e., soil behaviour type index $I_c > 2.6$, clayey soils; see Fig. 7) when plotted in terms of Q and F, the linear normalization of cone tip resistance (Q) should continue to be used. However, if CPT data fall in zones 5, 6, or 7 (i.e., $I_c < 2.6$, sandy soils) when plotted in terms of Q and F, the normalization using an exponent of 0.5 (i.e., $q_{c1N} = q_{c1}/P_a$; see Fig. 8) should be used to replot the data in the soil classification chart. If, when replotted, any of these data then plot with $I_c > 2.6$, a normalization similar to the definition of q_{c1N}, but using an exponent of 0.75, should be used to replot such data in the soil classification chart.

Figures 8–10 plot the CPT data in the target zone from each of the CANLEX sites in the soil behaviour type classification chart following the modified method described above. The majority of the phase I data fall into zone 6 and would be classified as a sand, ranging from a clean sand to a silty sand. The majority of the phase III data fall into zone 5

Fig. 5. Corrected (*a*) SPT, (*b*) CPT, and (*c*) V_{s1} profiles at the LL Dam site (phase IV).

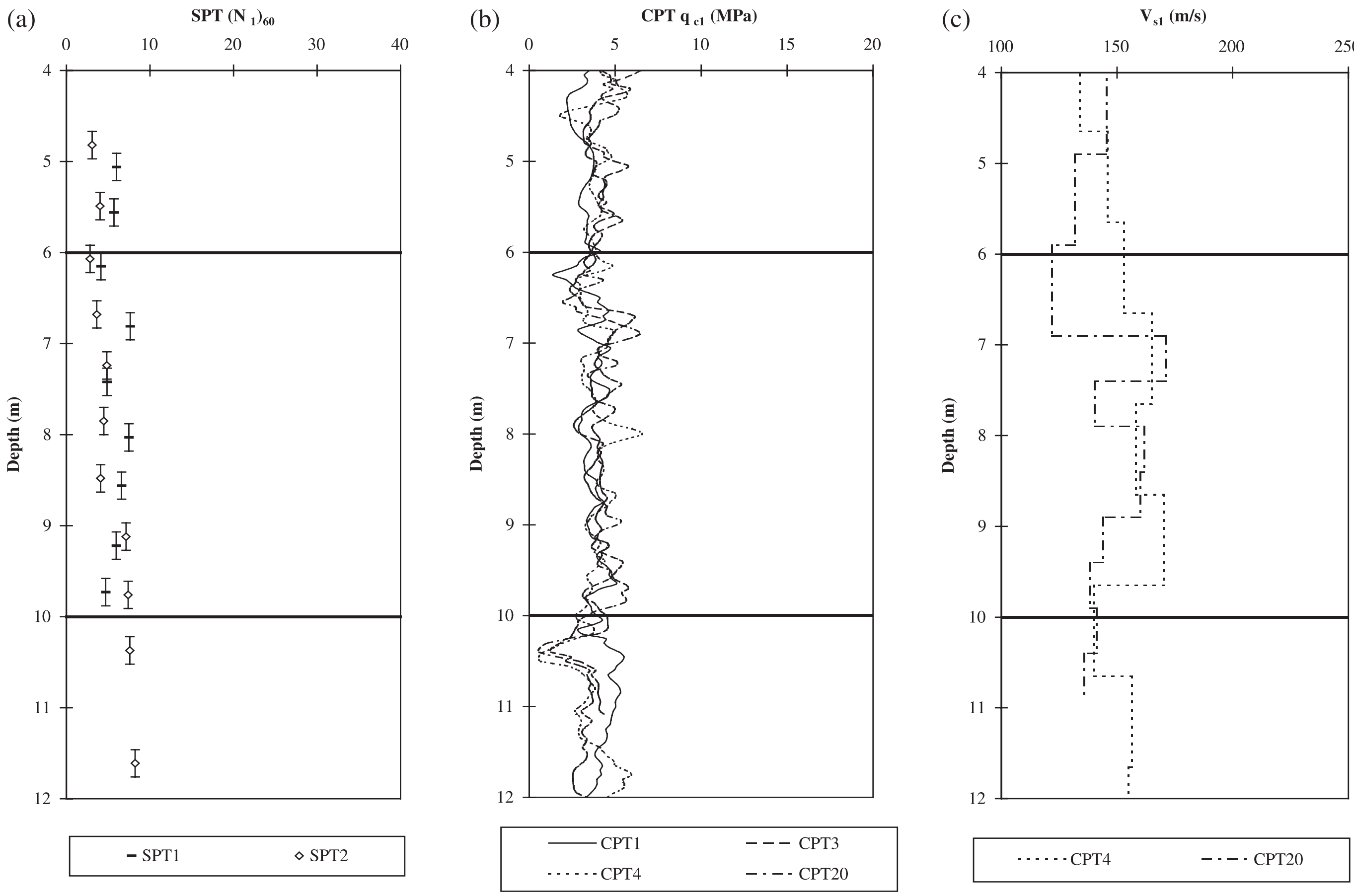


Table 2. Summary of comparisons between various in situ tests at each CANLEX site.

Site data			Comparison of in situ tests		
Phase	Location	Site	$q_{c1}/(N_1)_{60}$	X	Y
I	Syncrude	Mildred Lake	0.44 (0.15)	74.8 (9.0)	95.6 (12.1)
II	Fraser River Delta	Massey	0.58 (0.17)	94.7 (7.7)	110.2 (4.6)
		Kidd	0.45 (0.07)	88.4 (6.1)	110.8 (5.0)
III	Syncrude	J-pit	0.51 (0.25)	89.2 (7.5)	101.1 (6.3)
IV	HVC Mine	LL Dam	0.82 (0.29)	102.1 (10.7)	107.8 (11.4)
		Highmont Dam	1.08 (0.58)	98.9 (13.3)	99.3 (7.5)

Note: The numbers given in the table are overall average values in the target zone, with standard deviations in parentheses. *X*, parameter linking shear wave velocity (V_{s1}) and SPT $(N_1)_{60}$, as defined in eq. [5]; *Y*, parameter linking shear wave velocity (V_{s1}) and CPT q_{c1}, as defined in eq. [6].

and would be classified as a sand mixture, ranging from a silty sand to a sandy silt; however, some of the data fall into zones 6, 4, and 3 and would be classified as a sand, a silt mixture, and a clay, respectively. The majority of both the Massey and Kidd data (Fig. 9) fall into zone 6 and would be classified as a sand, ranging from a clean sand to a silty sand. Both the LL Dam data and the Highmont Dam data (Fig. 10) straddle zones 5 and 6 and would be classified as partly a sand mixture and partly a sand. For Highmont Dam, the data for CPT13 have been plotted as open circles because CPT13 appears to indicate some zones in the target zone with lower tip resistances (and associated lower friction ratios) which are not evident in the other CPT profiles (see Fig. 6).

These CPT-based classifications are consistent with the soil profiles based on boreholes and samples. In general, the soils were uniformly graded, fine sands with some silty zones (Robertson et al. 2000*a*). The soils at the phase III (J-pit) and phase IV (Highmont Dam) sites were generally finer grained below the target zones.

Comparisons between SPT, CPT, and V_s

Table 2 summarizes the comparisons between in situ tests at each site in terms of the average (and standard deviation)

Fig. 6. Corrected (*a*) SPT, (*b*) CPT, and (*c*) V_{s1} profiles at the Highmont Dam site (phase IV).

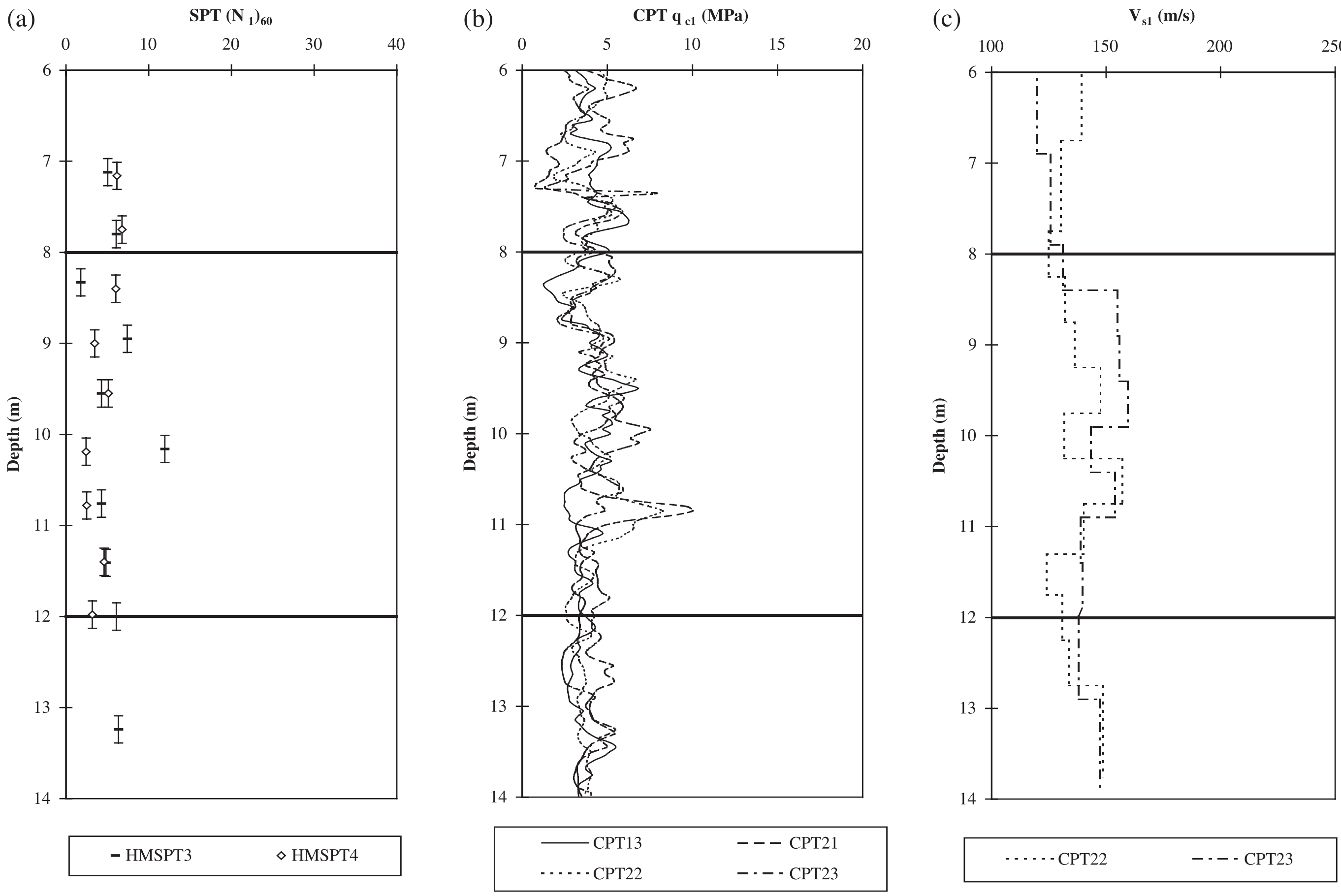


Table 3. Overall average comparison of void ratios from geophysical logs and ground-freezing samples.

Site data			Void ratio *e* interpreted from geophysical logs*	In situ state based on ground-freezing samples			
Phase	Location	Site		No. of trimmed samples†	Void ratio *e*	Relative density D_r (%)	State parameter Ψ
I	Syncrude	Mildred Lake	0.788 (0.053)	41 (33 TX, 8 SS)	0.768 (0.040)	43.6 (9.2)	–0.064 (0.040)
II	Fraser River Delta	Massey	0.99 (0.07)	43 (25 TX, 18 SS)	0.97 (0.05)	32.5 (12.5)	–0.029 (0.048)
		Kidd	0.78 (0.06), very poor	18 (10 TX, 8 SS)	0.981 (0.076)	29.8 (19.0)	–0.002 (0.082)
III	Syncrude	J-pit	0.721 (0.068), based on one good log	47 (34 TX, 13 SS)	0.762 (0.053)	42.7 (10.1)	–0.106 (0.053)
IV	HVC Mine	LL Dam	0.929 (0.120)	18 (16 TX, 2 SS)	0.849 (0.041)	40.3 (8.0)	–0.007 (0.041)
		Highmont Dam	0.862 (0.074)	22 (16 TX, 6 SS)	0.825 (0.075)	37.4 (14.8)	–0.023 (0.076)

Note: The numbers given in the table are overall average values in the target zone, with standard deviations in parentheses.
*Comment indicates the quality of the geophysical log based on measured compensation values.
†SS, simple shear specimen; TX, triaxial specimen.

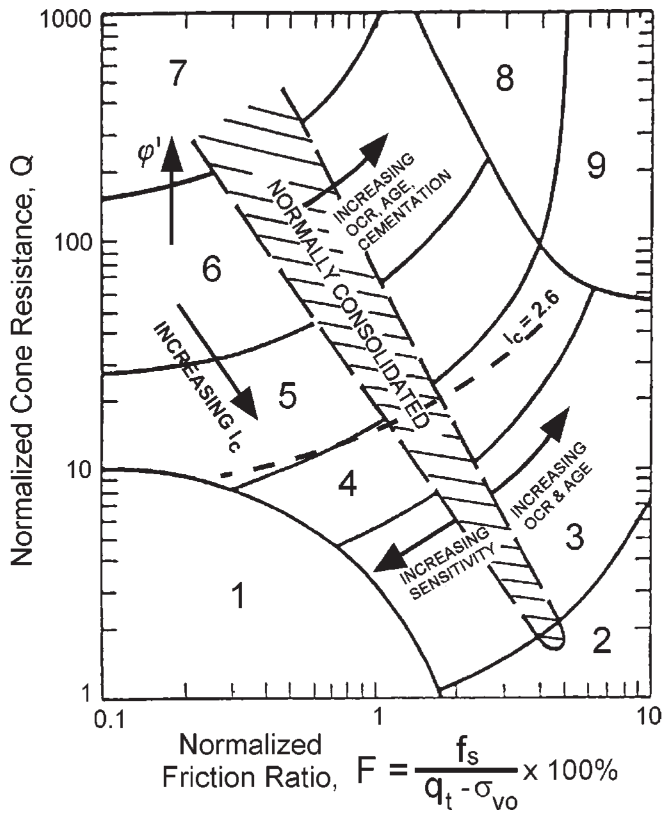
values of parameters $q_{c1}/(N_1)_{60}$, X, and Y. The values X and Y are defined by the following equations (after Fear and Robertson 1995):

$$[5] \qquad (N_1)_{60} = \left(\frac{V_{s1}}{X}\right)^4$$

where $(N_1)_{60}$ is the corrected SPT blow count (see eq. [1]), V_{s1} is the corrected shear wave velocity (in m/s; see eq. [4]), and X is a conversion factor between SPT and V_s; and

$$[6] \qquad q_{c1} = \left(\frac{V_{s1}}{Y}\right)^4$$

Fig. 7. Normalized CPT soil behaviour type chart after Robertson (1990): 1, sensitive, fine grained; 2, organic soils, peats (soil behaviour type index $I_c > 3.6$, where $I_c = [(3.47 - \log Q)^2 + (\log F + 1.22)^2]^{0.5}$); 3, clays, silty clay to clay ($2.95 < I_c < 3.6$); 4, silt mixtures, clayey silt to silty clay ($2.60 < I_c < 2.95$); 5, sand mixtures, silty sand to sandy silty ($2.05 < I_c < 2.60$); 6, sands, clean sand to silty sand ($1.31 < I_c < 2.05$); 7, gravelly sand to dense sand ($I_c < 1.31$); 8, very stiff sand to clayey sand (heavily overconsolidated or cemented); 9, very stiff, fine grained (heavily overconsolidated or cemented). OCR, overconsolidation ratio; φ′, friction angle.



where q_{c1} is the corrected CPT tip resistance (in MPa; see eq. [2]), V_{s1} is the corrected shear wave velocity (in m/s; see eq. [4]), and Y is a conversion factor between CPT and V_s.

Lunne et al. (1997) proposed that the ratio $q_{c1}/(N_1)_{60}$ could be estimated based on the soil behaviour type index (I_c) from the CPT using the following equation:

$$[7] \qquad \frac{q_{c1}}{(N_1)_{60}} = 0.85\left(1 - \frac{I_c}{4.6}\right)$$

Figures 11–13 present a comparison between $(N_1)_{60}$ values predicted from CPT results at each site (using eq. [7]) and the actual SPT $(N_1)_{60}$ results from each site. In general, on an overall profile basis, the equation appears to work well at the phase I, II, and III sites, producing good agreement between SPT and CPT results (see Figs. 11, 12). However, at the phase III site, the CPT interpretation overpredicts the SPT results over the 3 m region beneath the target zone. This may be partially due to the application of a single energy ratio (ER) to all of the SPT blow counts at the phase III site, when calculating values of measured $(N_1)_{60}$. In addition, at the two phase IV sites (see Fig. 13) interpretation of the CPT using eq. [7] appears to overpredict SPT $(N_1)_{60}$ values on an overall profile basis. The poor agreement at the phase IV sites may be at least partially due to the fact that the deposits at these two sites were angular in nature, whereas the other CANLEX deposits were generally subrounded in nature (Robertson et al. 2000*a*). This may also explain why the phase IV deposits had much higher values of $q_{c1}/(N_1)_{60}$ than the other CANLEX sites (see Table 2).

Estimations of void ratio, relative density, or state parameter from SPT, CPT, or V_s

Interpretation of the in situ test results was carried using existing published interpretation methods. Due to length restrictions, only the major interpretation methods are presented and discussed.

Void ratio

Void ratios were calculated (using volume calculations) for each sample obtained using ground freezing which was trimmed for testing. Table 3 presents the overall average values and overall standard deviation of void ratio of the ground-freezing samples at each site. The ground-freezing and sampling procedures used at the CANLEX test sites are described in detail by Hofmann (1997).

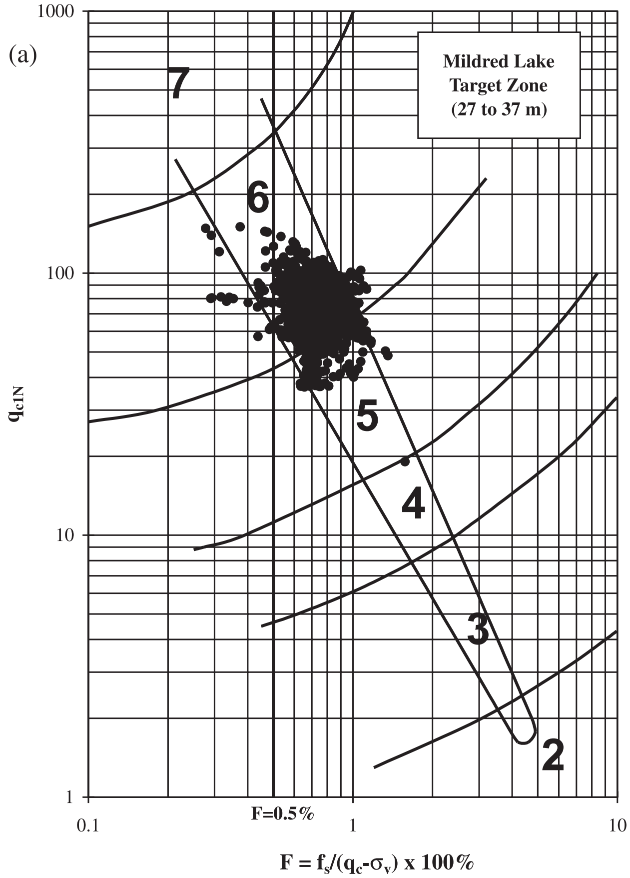
Cunning et al. (1995) proposed correlations between normalized shear wave velocity and void ratio, based on reconstituted, isotropically consolidated (i.e., $K_0 = 1$) samples of sand and shear wave velocity measurements made in the laboratory using bender elements. Ottawa sand, Alaska sand, and Syncrude sand (from the beach of the phase I CANLEX site) were studied. Alaska sand contains approximately 32% fines composed of a large amount of carbonate shell fragments and is much more compressible than either Ottawa sand or Syncrude sand. Cunning et al. proposed the following equation to estimate void ratio e from normalized shear wave velocity:

$$[8] \qquad V_{s1} = (A - Be)K_0^{0.125}$$

where V_{s1} is the normalized shear wave velocity (see eq. [4]), and A and B are material-specific constants.

Based on the three sands tested in the laboratory ($K_0 = 1$), the average relationship between V_{s1} and void ratio is defined by $A = 359$ and $B = 231$ (Cunning et al. 1995). An upper and lower bound relationship can be defined by keeping B constant and allowing A to change by approximately plus or minus 20, respectively. Figure 14 compares the relationships between V_{s1} and e at the six CANLEX sites and the Duncan Dam site with the average relationship proposed by Cunning et al. (1995), adjusted to $K_0 = 0.5$. The CANLEX data are shown in terms of the average values plus and minus one standard deviation. The Mildred Lake, LL Dam, and Highmont Dam data appear to fit within the band proposed by Cunning et al.; however, the other sites do not. At the Kidd, Massey, and Duncan Dam sites, aging may have an effect on the measured V_{s1}; this effect will be discussed in more detail later in this paper.

Fig. 8. CPT-based soil behaviour type classification of (*a*) the phase I (Mildred Lake) site, and (*b*) the phase III (J-pit) site.



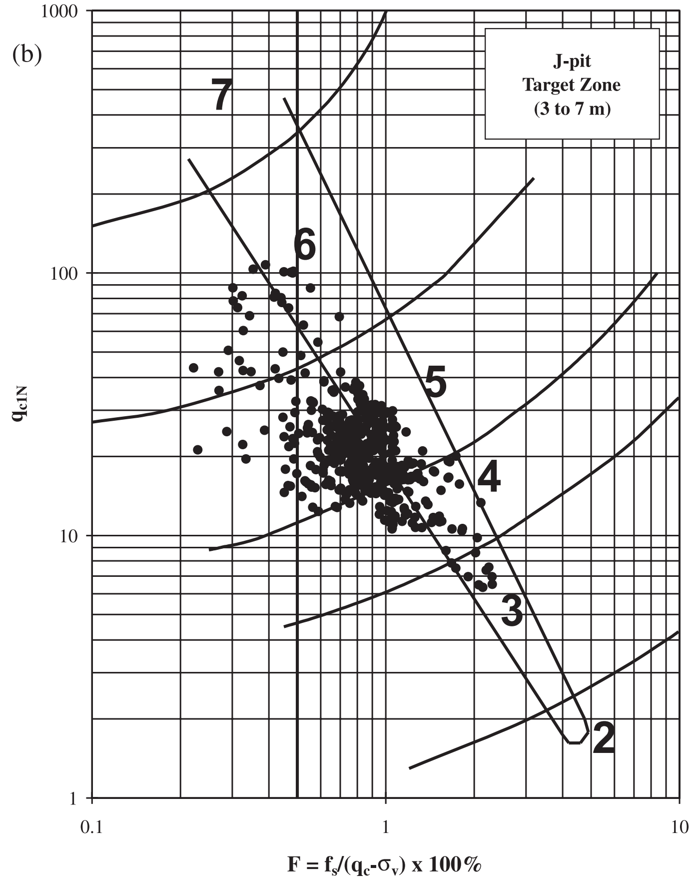
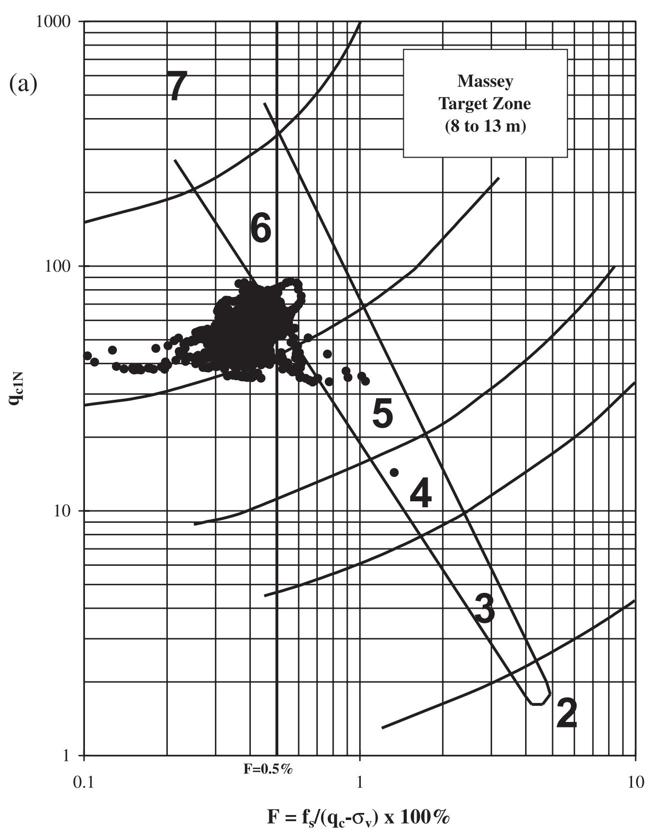


Fig. 9. CPT-based soil behaviour type classification of the phase II sites: (*a*) Massey, and (*b*) Kidd.



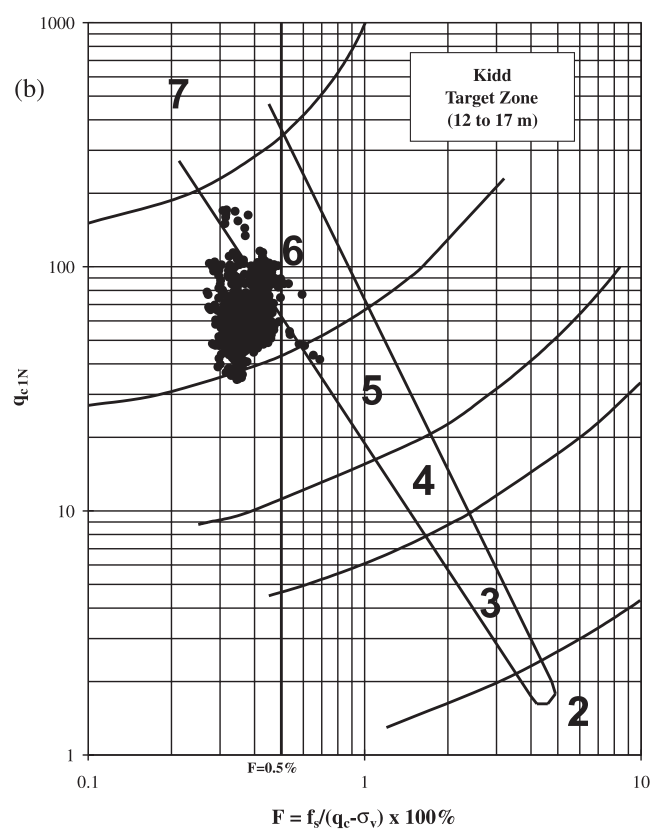
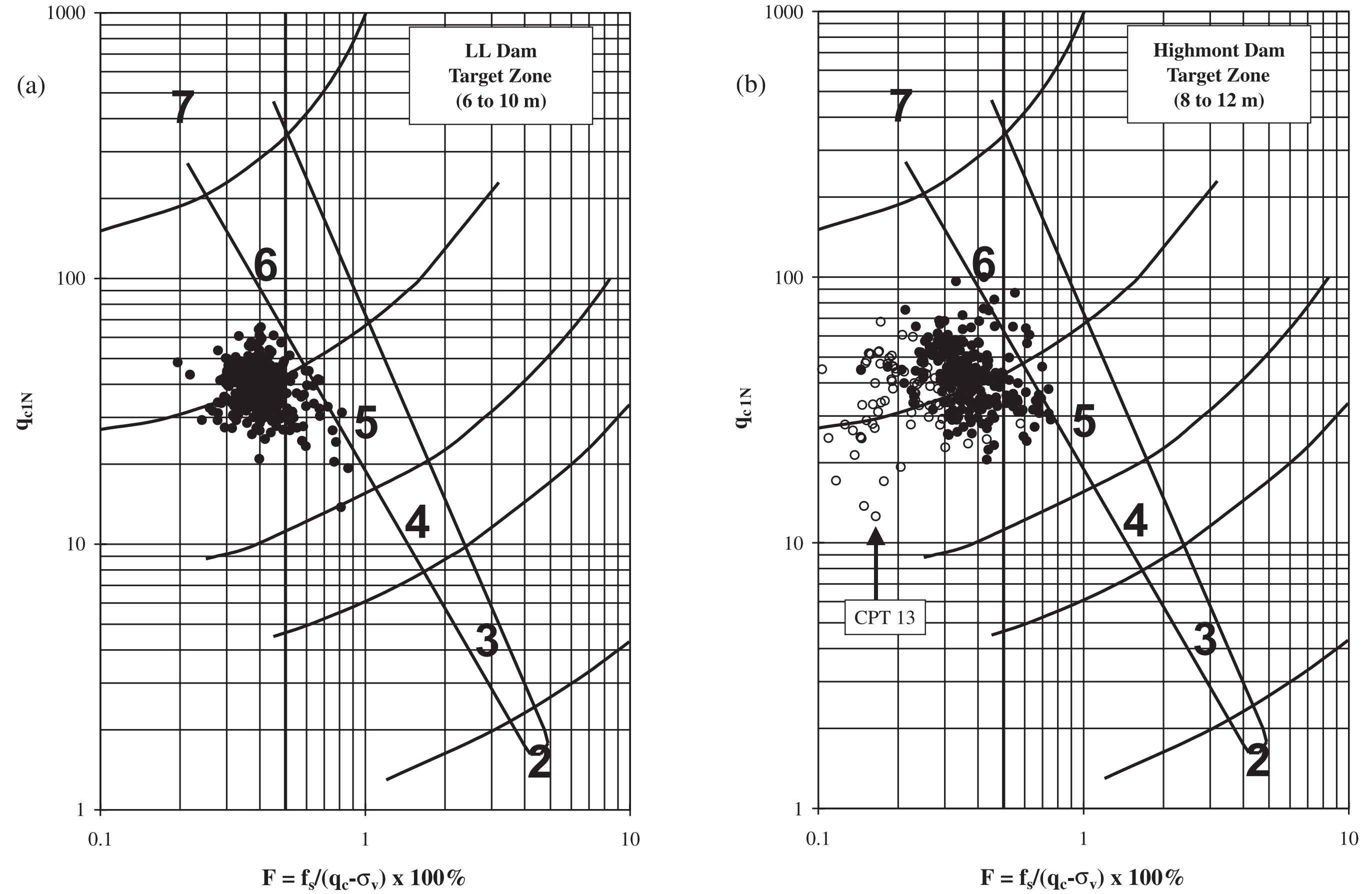


Fig. 10. CPT-based soil behaviour type classification of the phase IV sites: (*a*) LL Dam, and (*b*) Highmont Dam.



Relative density

Minimum and maximum void ratios (e_{min} and e_{max}, respectively) for each site are given in the companion paper by Robertson et al. (2000*a*). Therefore, values of relative density (D_r) can be computed from the void ratios of the ground-freezing samples at each site. Table 3 presents the overall average values of D_r for the ground-freezing samples at each site.

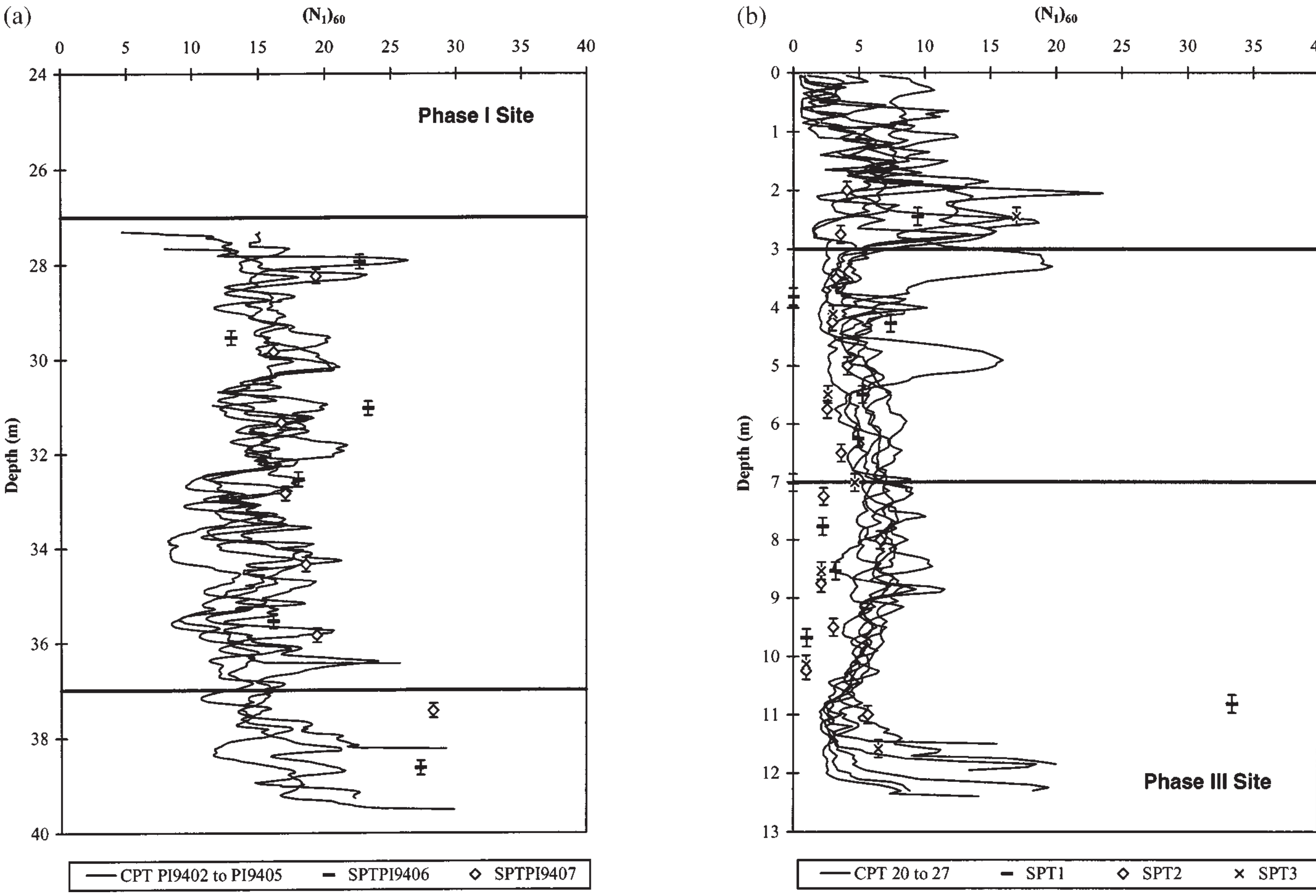
Skempton (1986) proposed the following relationship between SPT $(N_1)_{60}$ and relative density:

$$[9] \qquad \frac{(N_1)_{60}}{D_r^2} = \text{constant}$$

A constant of 40 was recommended by Skempton (1986) for young, fine-grained sands and was selected by the CANLEX project as being representative of a loose, young sand. Figure 15 presents a summary of how well the constant of 40 fits the data from the six CANLEX sites and the Duncan Dam site. The data are shown in terms of overall average values in each target zone plus and minus one standard deviation. The trend of the data is similar to that for shear wave velocity (Fig. 14) in that LL Dam and Highmont Dam fit close to the recommended value of 40. The variation of most of the other sites is consistent with the observations of Skempton (1986) and Jamiolkowski et al. (1988) that the constant should increase with age, since the phase II deposits are significantly older than the other deposits. However, compared with the other sites, the phase I (Mildred Lake) site has a higher average Skempton constant than expected, based on its age. However, the Mildred Lake target zone was very deep (27–37 m); consequently, the values of $(N_1)_{60}$ may be unduly high, as no correction has been made for excessive rod length. Aging effects will be discussed in greater detail later in this paper. In general, a constant of 40 in eq. [9] appears to work fairly well for the CANLEX sands that are in the range of 10–100 years in age.

Figure 16 presents a comparison of the relationships between normalized CPT tip resistance and relative density at the CANLEX sites with the range of relationships proposed by Jamiolkowski et al. (1988), based on the results by Lancellotta (1983). The solid line in Fig. 16 is essentially the same relationship as that proposed by Baldi et al. (1986). Lancellotta investigated the relationship between normalized CPT tip resistance and relative density for five different sands, including Ticino sand. Note that the normalization used by Lancellotta and shown in Fig. 16 uses different units than are used elsewhere in this paper. In general, the CANLEX data fit within the suggested band; however, the trend of the data appears to indicate that aging may tend to increase the normalized CPT tip resistance for a given relative density. The effects of aging will be discussed in greater detail later in this paper. In general, the CPT methods by Baldi et al. and Lancellotta appear to estimate relative

Fig. 11. Comparison of $(N_1)_{60}$ predicted from the CPT using the equation proposed by Lunne et al. (1997) and actual SPT $(N_1)_{60}$ results from (*a*) the phase I site, and (*b*) the phase III site.



density quite well for the CANLEX sands that are in the range of 10–100 years in age.

State parameter

Full details on the background results required for estimating state parameter Ψ is given in a companion paper (Robertson et al. 2000*b*).

The method proposed by Been and Jefferies (1992) for estimating the state parameter of a soil deposit directly from the CPT was developed based on earlier work by Been and Jefferies (1985) and Been et al. (1987), based on the results of calibration chamber testing. Different soil types were examined and the estimation of Ψ was found to be a function of the friction angle (i.e., M) and the slope of the ultimate (steady) state line (USL) ($\lambda_{\log}$) of the sand deposit. Details on the reference USL selected for each CANLEX sand are given in Robertson et al. (2000*b*). The following equation was proposed to estimate Ψ (Been and Jefferies 1985):

$$[10] \quad q^* = k^* \exp(-m^* \Psi)$$

where

$$[11] \quad q^* = Q_p(1 - B_q)$$

$$[12] \quad Q_p = \frac{q_c - p_o}{p_o'}$$

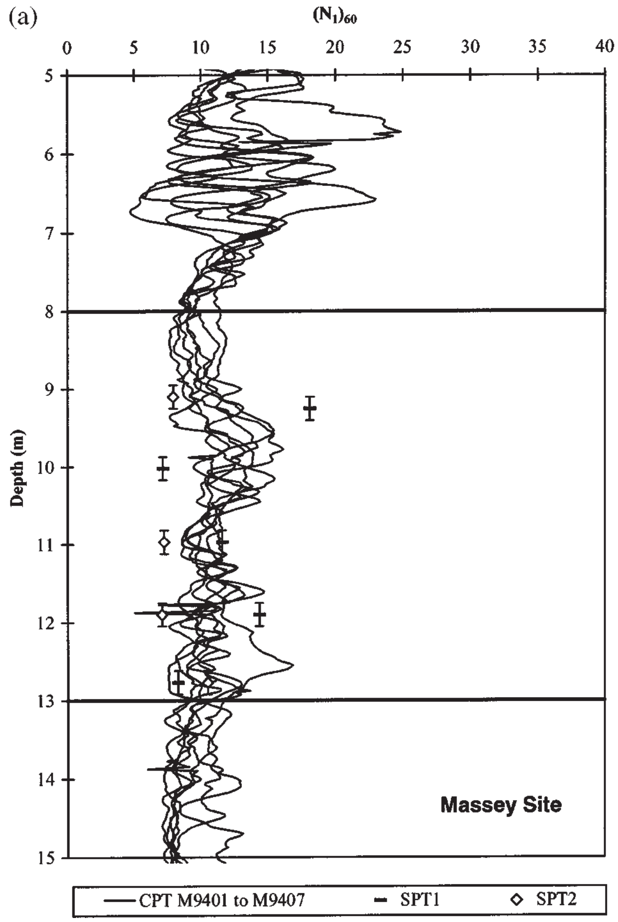
where p_o is the mean in situ stress; p_o' is the effective mean in situ stress; and p' is the effective mean stress;

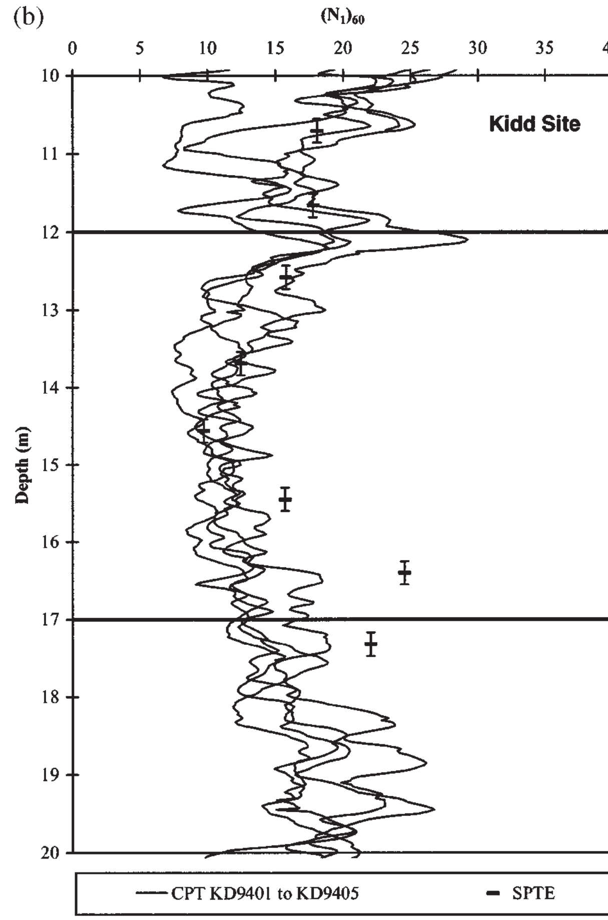
$$[13] \quad k^* = M\left(3 + \frac{0.85}{\lambda_{\log}}\right)$$

$$[14] \quad m^* = 11.9 - 13.3\lambda_{\log}$$

and where $\lambda_{\log} = 2.302\lambda_{\ln}$ ($\lambda_{\ln}$ is the USL slope when the p' axis is plotted in a natural logarithm scale) is the slope of the USL in e–p' space, when the p' axis is plotted in a logarithm to the base 10 scale; B_q is the pore-pressure parameter ratio and is typically very close to zero in sandy soils (therefore $q^* \approx Q_p$ in most sandy soils, e.g., the CANLEX test sites); and M is M in compression (M_C), since the work was based on loading in triaxial compression. Figure 17 compares the relationships between Q_p and the state parameter for the CANLEX sites with the relationships that the Been and Jefferies (1992) method would suggest for each pair of sites, based on the values of $\lambda_{\log}$ ($= 2.302\lambda_{\ln}$) and M. For each of the CANLEX sites, the value of $\lambda_{\ln}$ was taken as the slope of the flatter (low stress)

Fig. 12. Comparison of $(N_1)_{60}$ predicted from the CPT using the equation proposed by Lunne et al. (1997) and actual SPT $(N_1)_{60}$ results from (*a*) the Massey site, and (*b*) the Kidd site.





portion of the bilinear reference USL (see Robertson et al. 2000*b*), and M was taken as the average value of M_C from triaxial compression test results (Wride and Robertson 1997*a*) (all sites had M somewhat greater than 1.2, typically around M = 1.5; Wride and Robertson 1997*b*, 1997*c*, 1997*d*). In general, the CANLEX data do not agree well with the relationships based on the Been and Jefferies (1992) approach. Application of the Been and Jefferies (1992) method appears to overpredict the state parameter at the two Syncrude sites but underpredict the state parameter at the four other sites. The poor agreement may be partly due to some uncertainty in determining the USL and the fact that, in reality, each reference USL is not a single straight line with a single slope, but a continuous curve, with a continuously increasing slope (λ_{log}) (Ishihara 1993), which can only be approximated by a bilinear relationship. The poor agreement may also be due to the age of the deposits, similar to that observed in estimating relative density.

Plewes et al. (1992) expanded upon the work by Been et al. (1987) by estimating contours of the state parameter directly on the CPT soil classification chart, as proposed by Jefferies and Davies (1991). According to Plewes (personal communication 1996), this method is a screening method applicable only to construction of tailings dams, which are strongly dominated by compression loading. The Plewes et al. method was based on the assumption that the value of λ_{log} to be used in eqs. [13] and [14] could be estimated as one-tenth of the normalized CPT friction ratio F (in percent). The method also assumes a value of M_C = 1.2 (friction angle at ultimate state, ϕ_{us}' = 30°) in eq. [13]. Plewes et al. commented that M_C = 1.2 (ϕ_{us}' = 30°) "will fit most sands typically within ±10%, although it may be slightly high for plastic clays." Since the soil classification chart by Jefferies and Davies uses Q_p (normalized with respect to *mean normal* stresses), an estimate of K_0 is required to apply the method. A value of K_0 = 0.5 was used for all of the CANLEX sites (see later section entitled Estimations of K_0 from the pressuremeter).

Figure 18 summarizes the CANLEX data in the soil classification chart by Jefferies and Davies (1991). Superimposed on the soil classification chart are the contours of the state parameter, as proposed by Plewes et al. (1992), based on M_C = 1.2. In general, the Jefferies and Davies soil classification chart predicts soil behaviour types similar to those from the chart by Robertson (1990).

Figure 19 presents an example of comparisons between the values of the state parameter predicted using the method by Plewes et al. (1992) and those for the undisturbed samples obtained using ground freezing for two of the sites

Fig. 13. Comparison of $(N_1)_{60}$ predicted from the CPT using the equation proposed by Lunne et al. (1997) and actual SPT $(N_1)_{60}$ results from (*a*) the LL Dam site, and (*b*) the Highmont (HM) Dam site.

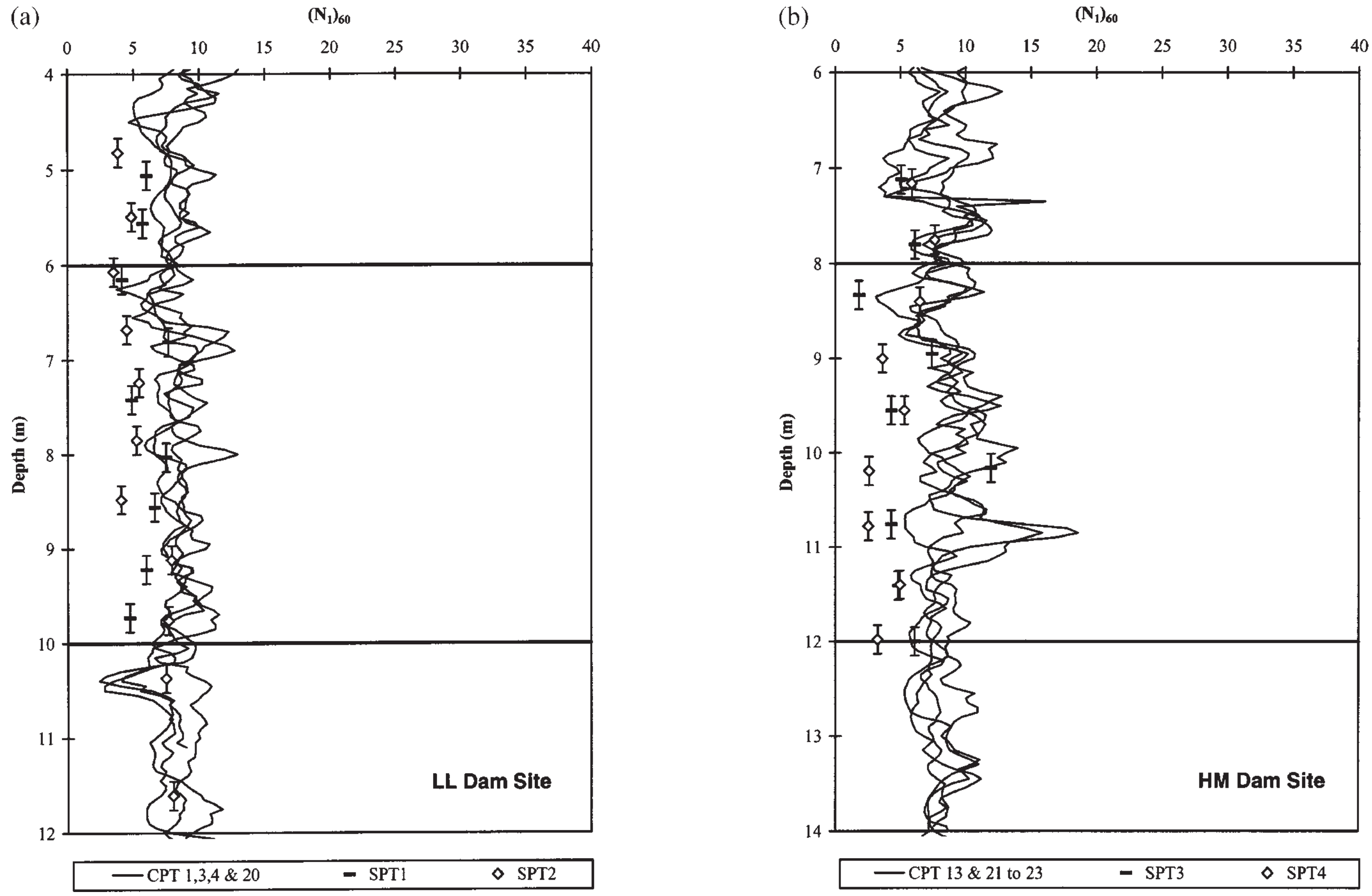


Fig. 14. Comparison of the relationship between void ratio and shear wave velocity at the CANLEX sites with the average relationship suggested by Cunning et al. (1995), adjusted to K_0 = 0.5. Values given are averages ± 1SD. D Dam, Duncan Dam.

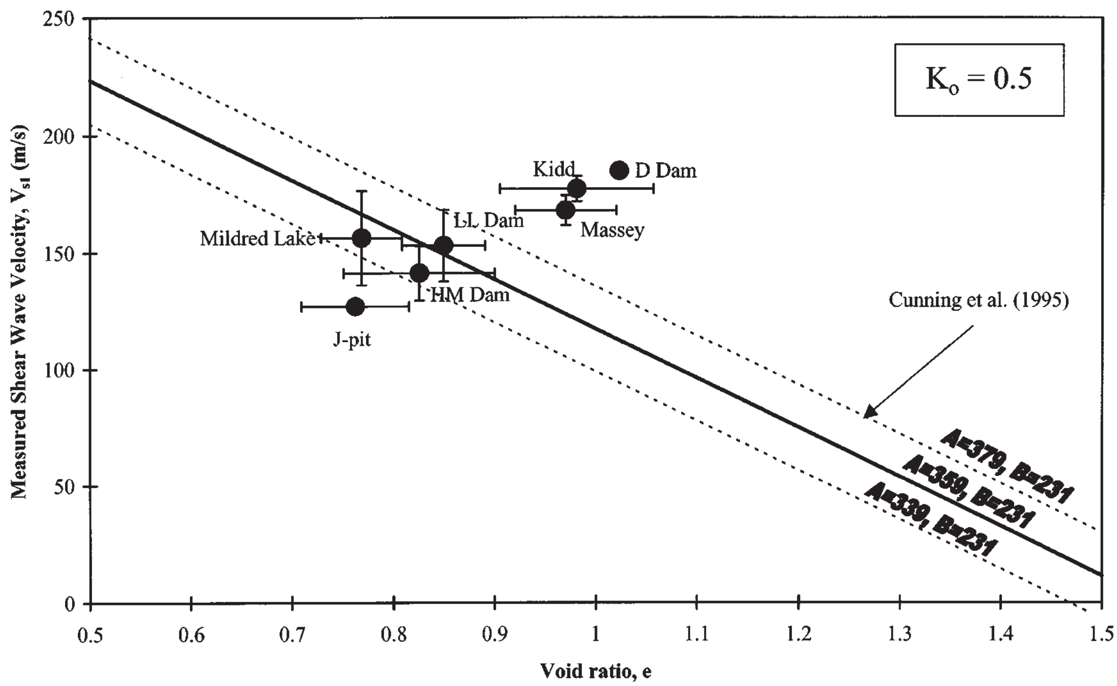


Fig. 15. Comparison of CANLEX data with relationships between SPT $(N_1)_{60}$ and relative density (D_r) suggested by Skempton (1986). Values given are averages ± 1SD.

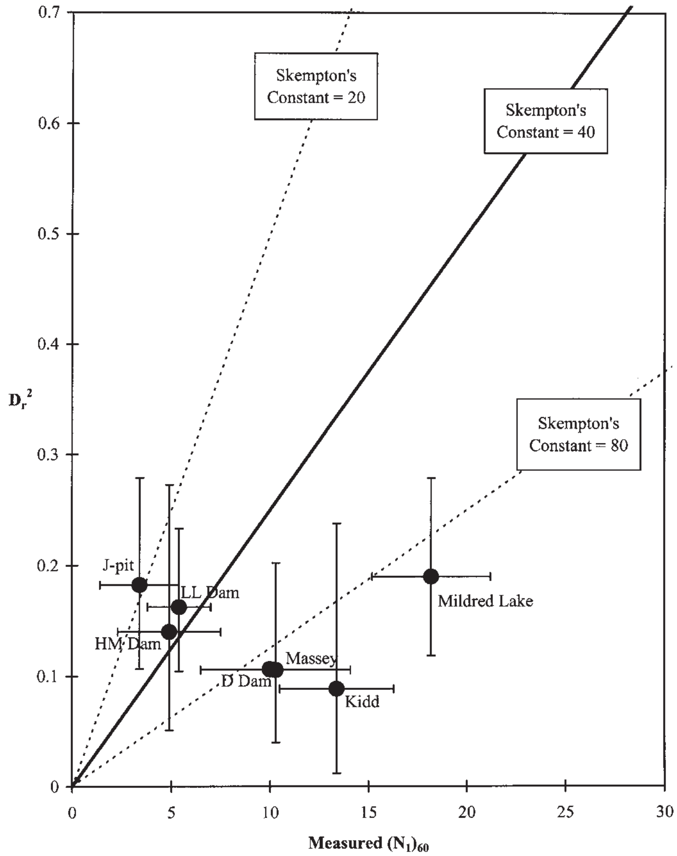


Fig. 16. Comparison of the relationship between normalized CPT tip resistance and relative density at the CANLEX sites with the relationships suggested by Jamiolkowski et al. (1988) after Lancellotta (1983). Note that the normalized tip resistance is in units different from those used elsewhere in this paper. Values given are averages ± 1SD.

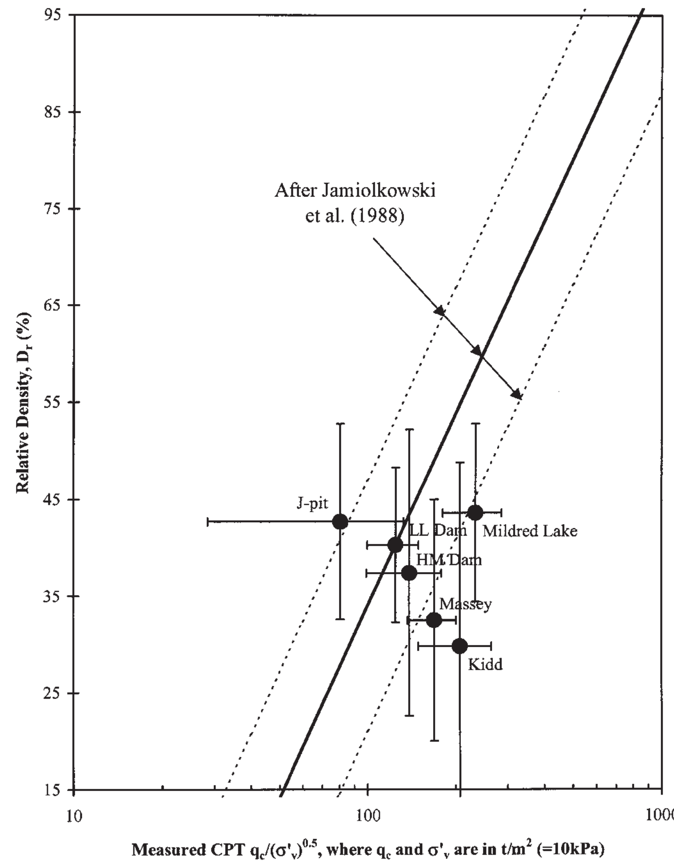


Fig. 17. Comparison of the relationships between CPT Q_p and state parameter (Ψ) at the CANLEX sites with the relationships based on the method by Been and Jefferies (1992), which depend on both the value of λ_{log} ($=2.302\lambda_{ln}$, where λ_{ln} has been taken as the slope of the flatter portion of the reference USL) and M (which has been taken as the value of M_C) for the particular soil.

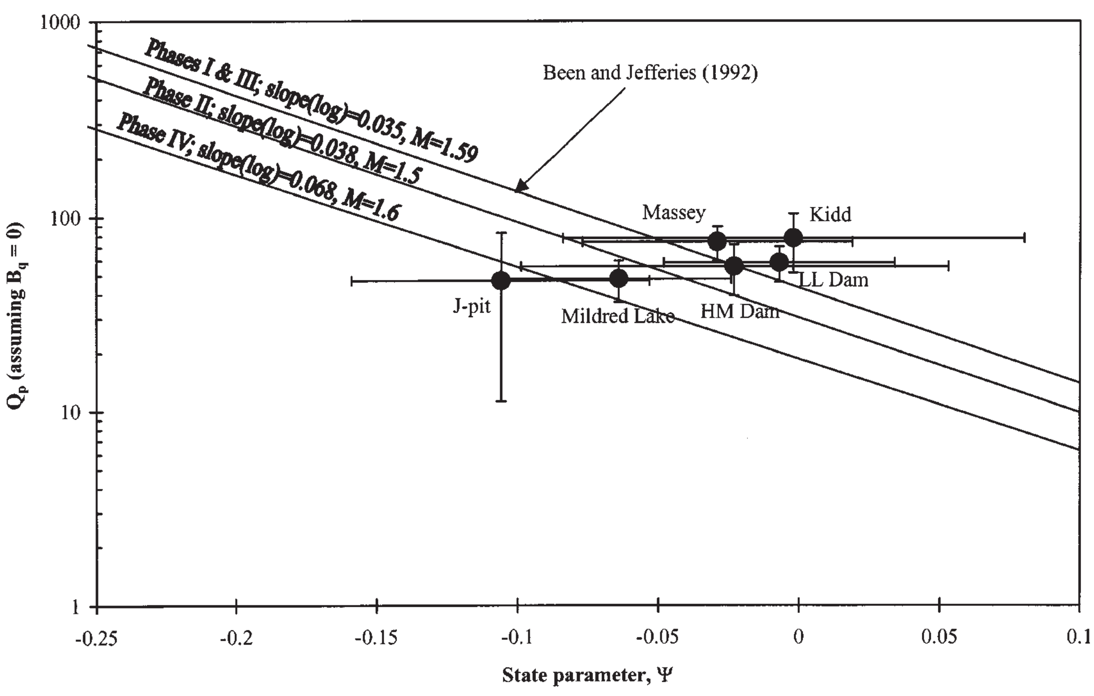


Fig. 18. Summary of the CANLEX data on the soil classification chart by Jefferies and Davies (1991), as recommended by Plewes et al. (1992) for estimating state parameter: (*a*) Syncrude sites, (*b*) Fraser River Delta sites, and (*c*) Highland Valley Copper sites.

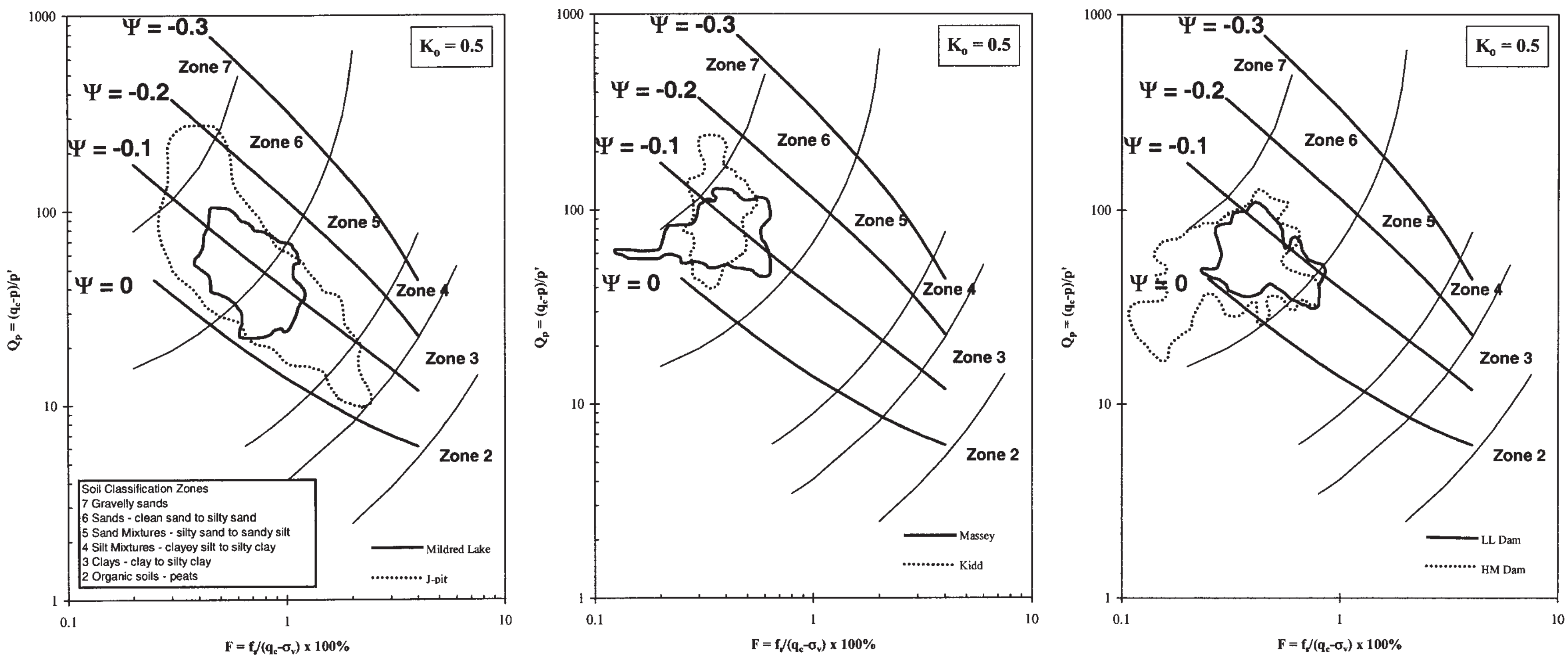
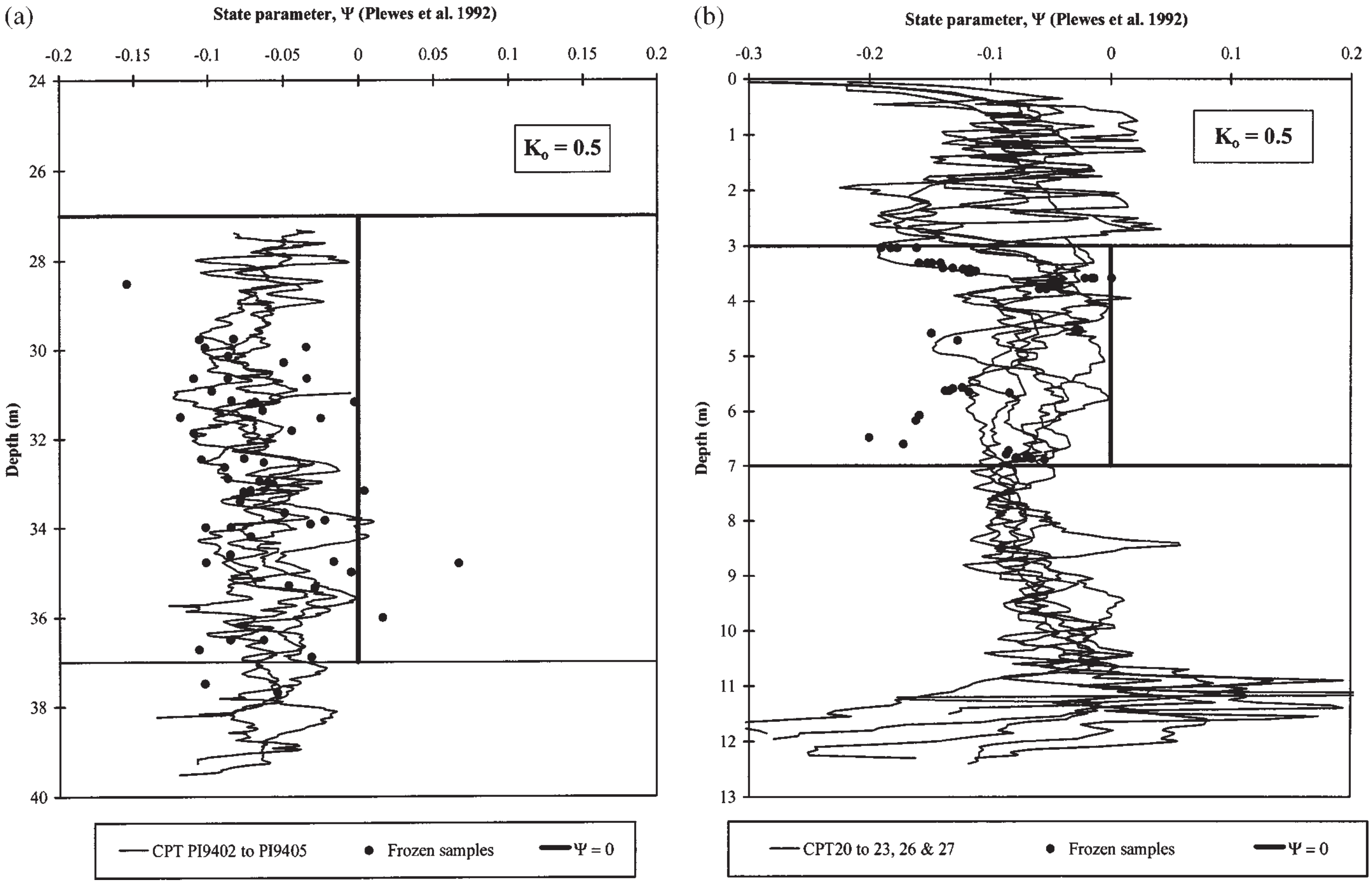


Fig. 19. Comparison of prediction of state parameter, Ψ, for Syncrude sand using the method by Plewes et al. (1992) with values of Ψ for undisturbed ground-freezing samples at (*a*) the phase I site, and (*b*) the phase III site.



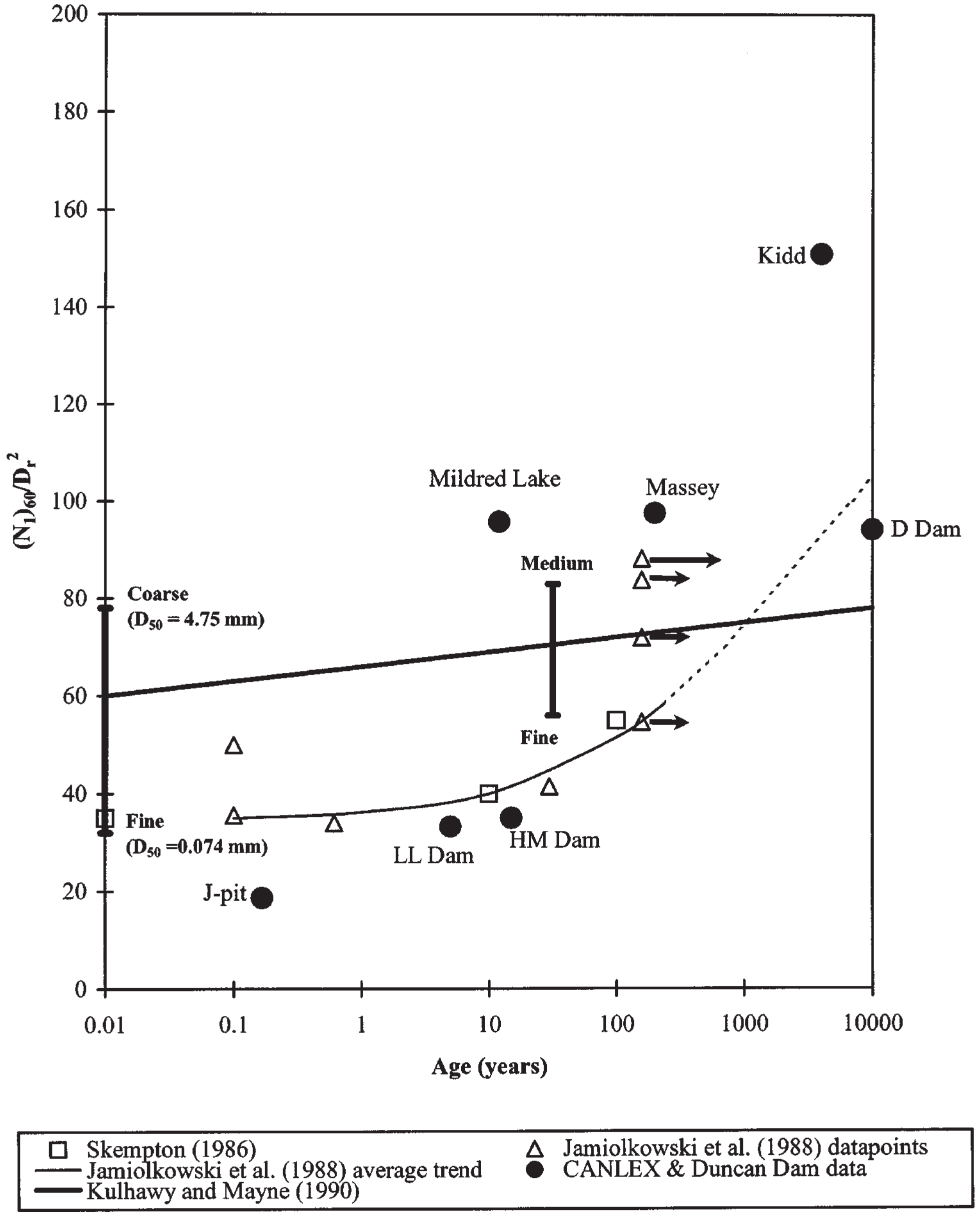
(Mildred Lake and J-pit). The horizontal lines shown in Fig. 19 identify the selected target zones at each site. The vertical lines identify the Ψ = 0 state. In this figure, the Plewes et al. method was applied using $K_0 = 0.5$ and the appropriate value of M for the particular site, based on laboratory testing, rather than $M = 1.2$. In general, when applied in this way, the Plewes et al. method gave good predictions of the average state parameter at each site. However, at some sites (especially at Kidd and Highmont Dam, not shown here) the range in state parameter from the frozen samples was larger than predicted, based on the CPT. Again, age appears to have an influence on the interpretation, with the older deposits (Kidd and Massey) both predicting slightly denser states. In general, the CPT-predicted in situ state was slightly dense of the reference USL (i.e., Ψ = 0) at each site. The CPT also confirmed the large variability in in situ state at each site.

Effects of aging on SPT, CPT, and V_s

The CANLEX sand deposits range in age from approximately 1 month (at J-pit) to approximately 4000 years (at Kidd). The unit 3-c deposit at Duncan Dam is approximately 10 000 years old. Therefore, the seven sites provide an opportunity to investigate the effects of aging on various in situ test measurements in sands. Since in situ tests are often used to estimate state, it is important to understand any effects of aging on the in situ test measurements themselves. Increasing age can also include factors such as overconsolidation, desiccation, groundwater fluctuations, and creep.

Figure 20 illustrates the possible effects of deposit age on SPT penetration resistance, normalized for relative density, based on average data from the six CANLEX test sites and the Duncan Dam site. Shown for comparison are the data suggested by Skempton (1986), the data and average trend proposed by Jamiolkowski et al. (1988), and the relationship proposed by Kulhawy and Mayne (1990). The relationship by Jamiolkowski et al. has been extrapolated to 10 000 years, as indicated by the broken line. The phase III and phase IV CANLEX data and the Duncan Dam data agree fairly well with the relationship proposed by Jamiolkowski et al. The phase II sites would indicate larger values for sands older than 100 years. Figure 20 indicates a significant influence of aging on the link between relative density and $(N_1)_{60}$ beyond about 100 years. Compared with the other sites, the phase I (Mildred Lake) site plots higher than expected, based on its age. However, the Mildred Lake target zone was very deep (27–37 m); consequently, the values of $(N_1)_{60}$ may be unduly high, as no correction has been made for excessive rod length (Farrar et al. 1998). Kulhawy and Mayne also suggested that grain size (D_{50}) and compressibility would have an effect on the ratio between $(N_1)_{60}$ and D_r^2. The effect of grain size is illustrated by the thick vertical

Fig. 20. Possible effects of age of deposit on SPT penetration resistance.



bars shown in Fig. 20. All of the CANLEX sites had values of D_{50} less than or equal to 0.25 mm and would be classified as uniformly graded fine sands. The unit 3-c sand at Duncan Dam had a D_{50} value of approximately 0.20 mm. The average values of $(N_1)_{60}/D_r^2$ for the phase III and phase IV CANLEX sites and the Duncan Dam site appear to be consistent with those which would be predicted for a fine sand, based on Kulhawy and Mayne.

Figure 21 illustrates the possible effects of age of deposit on CPT penetration resistance, normalized for relative density, based on average data from the six CANLEX test sites and the Duncan Dam site. Shown for comparison is the simplified relationship suggested by Kulhawy and Mayne (1990). Also shown is the relationship by Jamiolkowski et al. (1988) for the SPT (see Fig. 20) which has been converted to an equivalent CPT relationship using a $q_{c1}/(N_1)_{60}$ value of 0.50 (see Table 2). The trend of the converted Jamiolkowski et al. relationship appears to agree with the trend of the CANLEX and Duncan Dam data better than the simplified relationship proposed by Kulhawy and Mayne. Figure 21 indicates a significant influence of aging on the relationship between relative density and q_{c1} beyond about 100 years.

Robertson et al. (1995) suggested that aging has the effect of increasing the measured shear wave velocity for a given void ratio. Figure 22 illustrates the possible effects of age of deposit on measured shear wave velocities, normalized for relative density, based on average data from the CANLEX sites and the Duncan Dam site. Also shown is the relationship by Jamiolkowski et al. (1988) for the SPT (see Fig. 20), which has been converted to an equivalent shear wave velocity relationship using an average X value of 90 (see eq. [5] and Table 2). Despite some scatter, in general, the trend of the converted Jamiolkowski et al. line appears to agree with

Fig. 21. Possible effects of age of deposit on CPT penetration resistance.

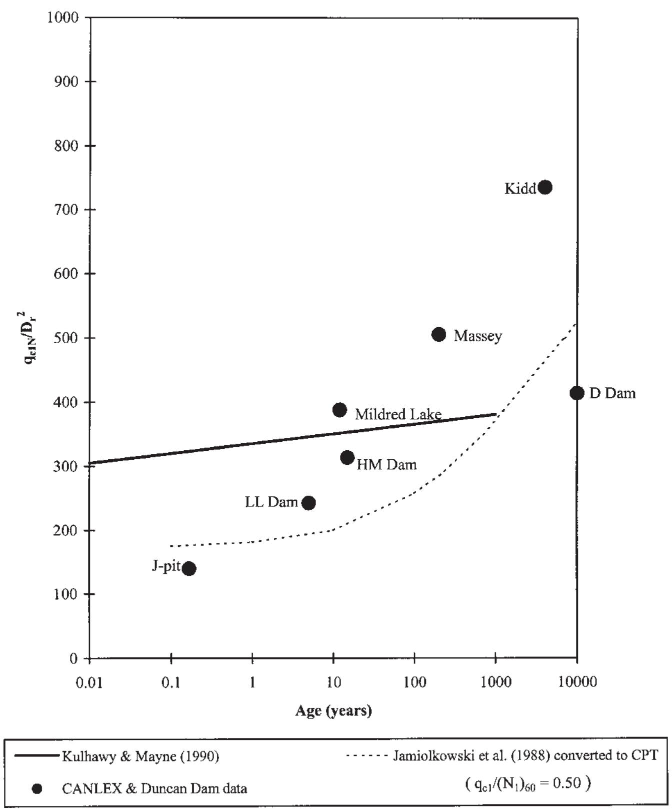
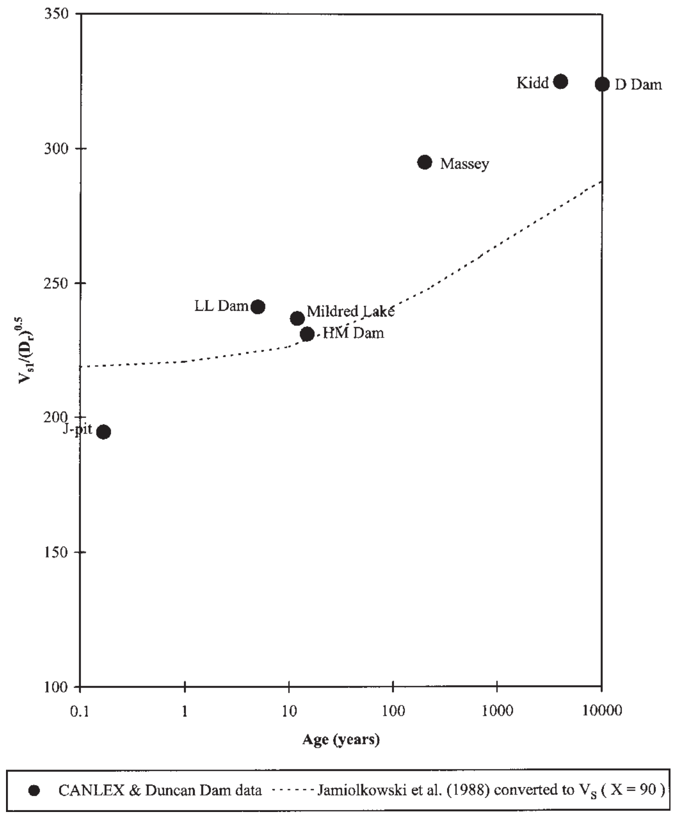


Fig. 22. Possible effects of age of deposit on measured shear wave velocity.



the trend of the CANLEX and Duncan Dam data. The shear wave velocity measurements at the J-pit and Mildred Lake sites may be less reliable due to the fact that the downhole techniques used in the seismic CPTs were conducted at shallow and very deep depths, respectively. Based on a comparison of Figs. 20 and 22, shear wave velocity appears to be slightly more sensitive to aging than either the SPT or CPT penetration resistance.

Geophysical logging

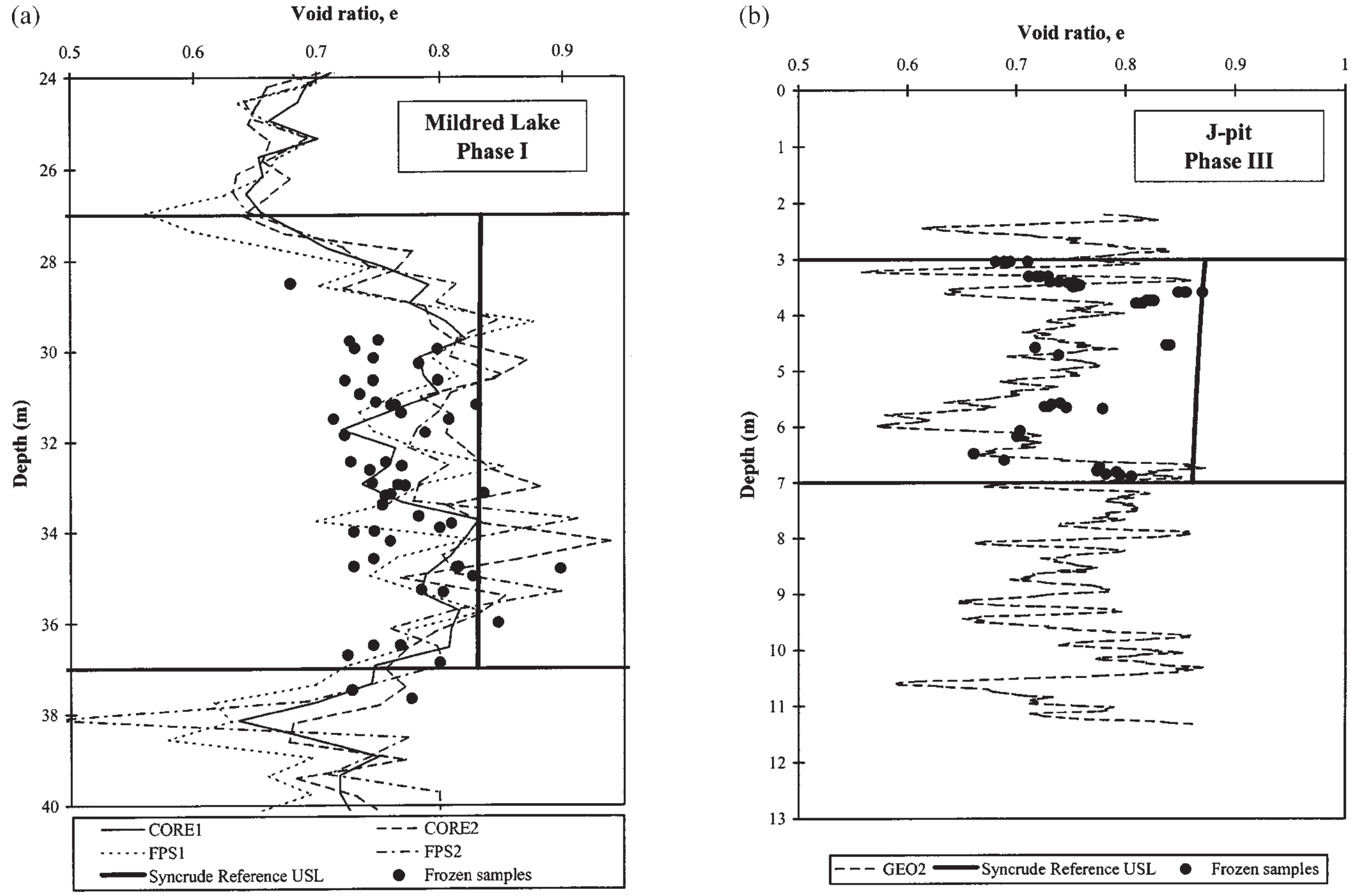
The results of the geophysical logging were interpreted to produce profiles of estimated void ratio. These profiles are compared with the void ratios of the ground-freezing samples in Figs. 23–25. In these figures, the void-ratio scale has been plotted from approximately $e_{\min}$ to $e_{\max}$ for the particular site; therefore, values of relative density (D_r) can be estimated directly from each figure. The thick semivertical line in each figure represents void ratios corresponding to the relevant reference ultimate state line (USL), as given by Robertson et al. (2000*b*) at the effective stresses present over the depth of the target zone, based on a K_0 value of 0.5.

Table 3 presents an overall average comparison of the void ratios predicted by geophysical logging at each site with those of the ground-freezing samples at each site. This is a simplistic comparison, since it is recommended that the complete profiles given in Figs. 23–25 be examined. An important feature to note at all of the sites is the large variability in void ratio both vertically and horizontally. The presence of such variability is indicated by both the ground-freezing samples and the interpretation of the geophysical logging. At all of the sites, the interpretation of void ratio from geophysical logging assumed that the sand was fully saturated (i.e., degree of saturation S_r = 100%). However, at some sites (phase I and LL Dam) the sand was not fully saturated. If, in reality, a given sand was not fully saturated, an S_r = 100% interpretation of geophysical logs would slightly overpredict the actual in situ void ratios. In addition, the void ratios of the frozen samples and those estimated from geophysical logging are sensitive to the value of specific gravity, G_s. Therefore, it is important that G_s be determined carefully.

At phase I (see Fig. 23*a*), in general, the geophysical logs appear to slightly overpredict the overall trend and range of the ground-freezing sample void ratios; the largest differences appear to occur between approximately 29.5 and 31 m, at which depths the geophysical method predicts significantly higher void ratios. At phase III (see Fig. 23*b*) only one of the geophysical logs was considered to be reliable. Interpretation of this geophysical log appears to slightly underpredict the average but captures the range of ground-freezing sample void ratios.

At Massey (see Fig. 24*a*), the interpreted void ratio profiles from the geophysical logs seem to capture the overall trend and range of the frozen sample void ratios; the greatest differences appear to occur between approximately 11.7 and

Fig. 23. Comparison of void ratio interpretation of geophysical logging results with void ratios of undisturbed ground-freezing samples from (*a*) the phase I site, and (*b*) the phase III site. FPS, fixed piston sample borehole.



12.5 m, at which depths the geophysical method predicts significantly higher void ratios. At Kidd (see Fig. 24*b*), the interpretation of the geophysical logs appears to consistently underpredict the void ratios from the ground-freezing samples; however, this is likely due to the unacceptably higher borehole rugosity than those obtained at Massey.

At LL Dam (see Fig. 25*a*), in general, the interpreted void ratio profiles from the geophysical logs seem to overpredict the frozen-sample void ratios. At Highmont Dam (see Fig. 25*b*), the interpretation of the geophysical logs appears to predict the void ratios from the trimmed ground-freezing samples quite well. The geophysical logs predict a relatively rapid variation of void ratio and indicate slightly looser zones near the top and bottom of the target zone. However, the CPT and sampling indicate higher fines contents in these regions, especially below a depth of 12 m.

At the phase I and LL Dam sites, the interpretation of the geophysical logs slightly overpredicted the void ratios of the ground-freezing samples. However, results of laboratory testing have shown that these two sites were not completely saturated. This is consistent with the fact that the S_r = 100% interpretation of the geophysical logs slightly overpredicted the void ratios.

Some of the differences between the geophysical-based predictions of void ratio and the values of void ratio associated with the frozen samples may be due, in part, to the effect of physical scale on the measurement. The geophysical logs are influenced by a volume of soil which is significantly larger than that of the individual frozen samples and, therefore, may produce more subdued variations in void ratio compared with the samples. Image analysis (Hanzawa 1980) has shown that void ratio measurements in sands can vary significantly, depending on the size of the sample. Similar comments based on scale effects apply to either the comparison between void ratio estimates from shear wave velocity and sample void ratios or the comparison between SPT- or CPT-based estimates of relative density and sample relative density.

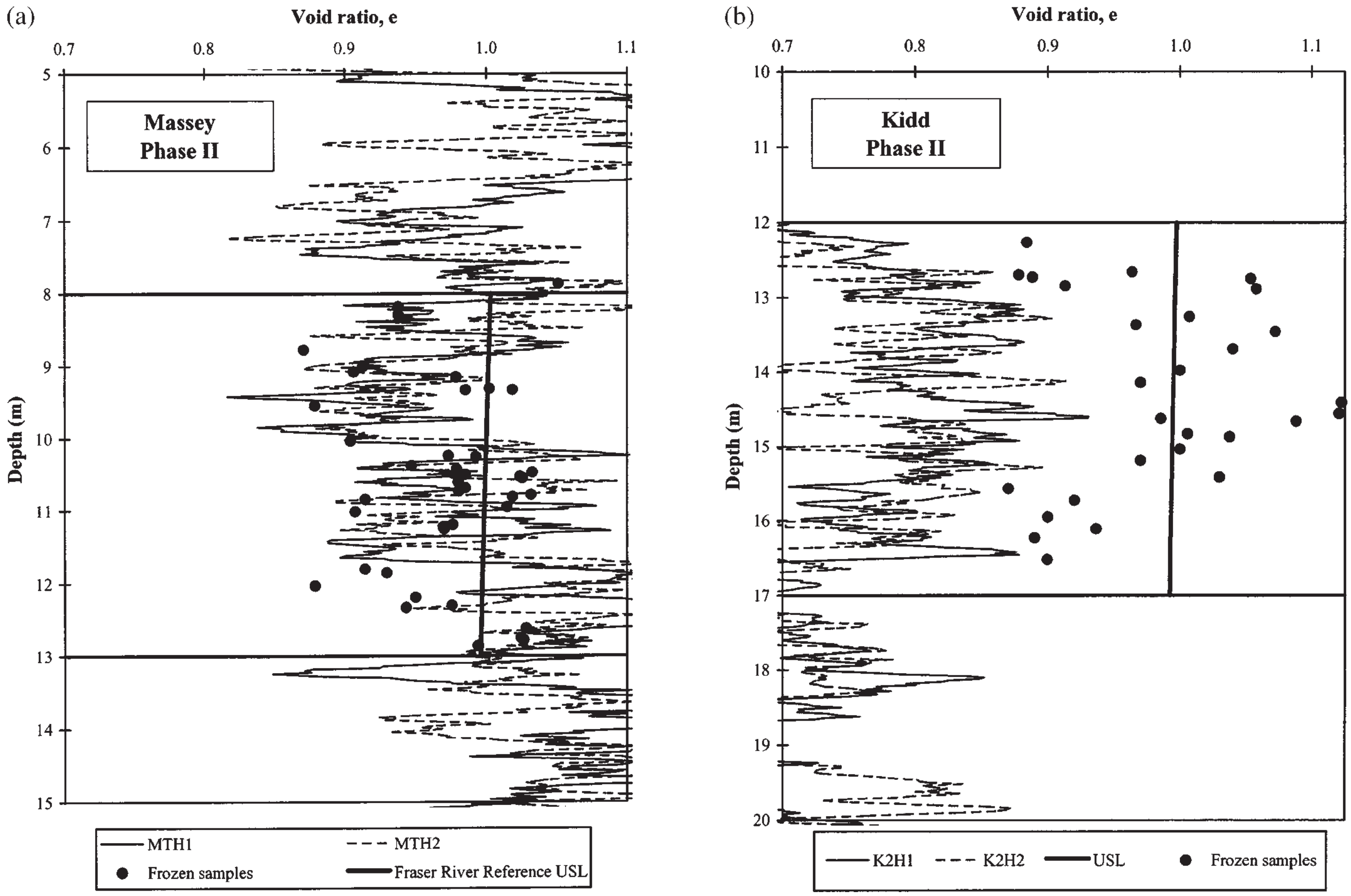
Gamma–gamma logging was also carried out using a new radio-isotope CPT (RI-CPT; Mimura et al. 1995) at the two phase II sites. Figure 26 presents a comparison of the RI-CPT interpretations of void ratio with the void ratios of the frozen samples at the two phase II sites. In general, the comparisons are very good.

Pressuremeter

Estimations of K_0 from the pressuremeter

Only two of the three prebored pressuremeter tests in the phase I target zone were successful; the deepest test was in an oversized hole and, consequently, the membrane failed upon expansion. Interpretation of the phase I prebored

Fig. 24. Comparison of void ratio interpretation of geophysical logging results with void ratios of undisturbed ground-freezing samples from (*a*) the Massey site, and (*b*) the Kidd site. USL, ultimate state line.



pressuremeter results by Hughes (1994) suggests an approximate average K_0 value in the target zone of about 0.60, whereas interpretation of the self-boring pressuremeter test results suggests an average K_0 value in the target zone of about 0.4. At the phase III site, interpretation of the pressuremeter results by Hughes (1996*a*) suggests an average K_0 of about 0.50. There was some uncertainty in the interpretation at both sites.

At the Massey site, interpretation of the nine pressuremeter results by Campanella (1995*b*) suggests an average K_0 value of about 0.40; the three tests in the target zone were also interpreted as having an average K_0 value of about 0.40. These interpretations were based on a groundwater table that was slightly deeper than the average measured depth, resulting in an overestimation of K_0. At the Kidd site, interpretation of the 10 pressuremeter results by Campanella (1995*a*) suggests an average K_0 value of about 0.55; the one test in the target zone was interpreted as having a K_0 value of 0.64. These interpretations were based on a groundwater table depth of 1.0 m for both boreholes, except for the one test in the target zone, which was interpreted using a groundwater table depth of 2.0 m. The average groundwater table depth at the site is in the order of 1.5 m. However, the groundwater table at both phase II sites was affected by tidal fluctuations of approximately 0.6 m per tidal period in the main branches of the Fraser River, located just 200 m from the sites.

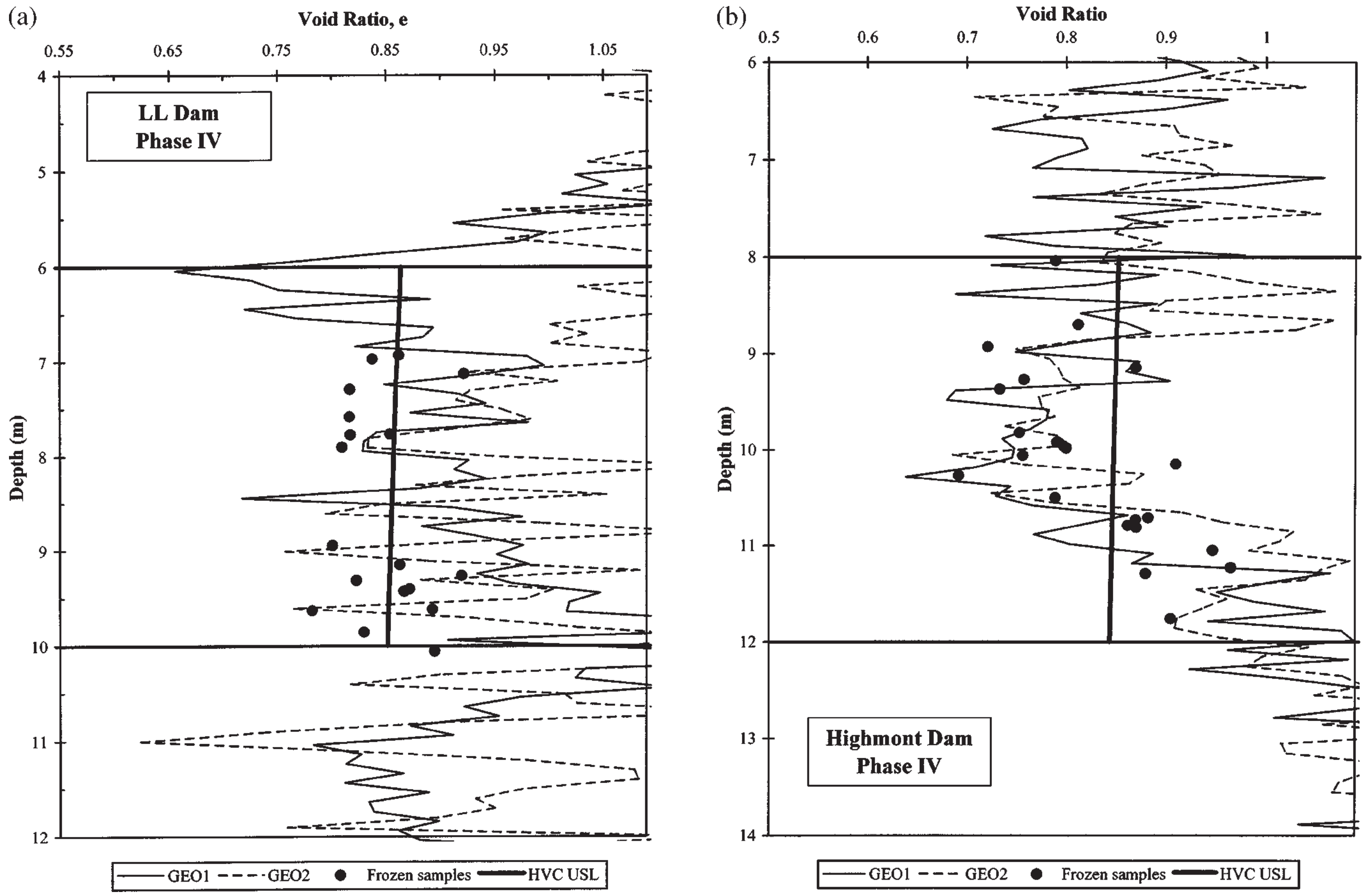
At the LL Dam site, interpretation of the self-bored pressuremeter results by Hughes (1996*b*) suggests an average K_0 value in the target zone in the order of 0.45–0.65. At the Highmont Dam site, interpretation of the self-bored pressuremeter results by Hughes suggests an average K_0 value in the target zone in the order of 0.55–0.70. There was some uncertainty in the interpretation at both sites. More variability between the better quality pressuremeter curves in the target zone was noted at Highmont Dam than at LL Dam (Hughes 1996*b*).

The CANLEX project adopted an average K_0 value of 0.5 for interpretation of all six test sites. An average K_0 value of 0.5 was also used to determine the stresses to impose on most of the undisturbed samples from all six sites during laboratory testing. K_0 is just one of several parameters that can be estimated from pressuremeter results. The pressuremeter can also be used to estimate the state and stress–strain behaviour of a sandy deposit (e.g., Yu et al. 1996; Hughes et al. 1997; Roy et al. 1998). A discussion of the Yu et al. (1996) method for estimating state is presented in the next section. Further details regarding other applications at the CANLEX site are discussed by Robertson et al. (2000*b*).

Estimations of the state parameter from the CPT and pressuremeter

As shown in Fig. 27, after testing several sands, Yu et al. (1996) proposed an average relationship between the state

Fig. 25. Comparison of void ratio interpretation of geophysical logging results with void ratios of ground-freezing samples from (*a*) the LL Dam site, and (*b*) the Highmont Dam site. HVC, Highland Valley Copper.



parameter and the ratio of effective cone tip resistance to effective pressuremeter limit pressure. The work by Yu et al. was based on using a cone pressuremeter, whereas at the CANLEX test sites separate, but adjacent CPT and pressuremeter testing was performed.

Superimposed on Fig. 27 are the average data from the six CANLEX sites. The values of state parameter are the average plus standard deviation values for the ground-freezing samples in the target zone at each site (see Table 3). For each pressuremeter test, the end of the expansion part of the pressuremeter curve was taken as the limit pressure and the corresponding cone tip resistance was determined by averaging all CPTs at the site over a 0.5 m depth range (0.25 m above and below the pressuremeter test depth). In Fig. 27, for each site the ratio represents the average ratio of all pressuremeter tests were performed at that site when compared with the corresponding CPT data. The CANLEX data appear to follow a line having a slope similar to that of the Yu et al. (1996) average relationship but shifted upwards in the plot. Thus, it appears that at each of the CANLEX test sites the Yu et al. relationship slightly underpredicts the state of the sand (i.e., predicts a denser state), based on ground-freezing samples.

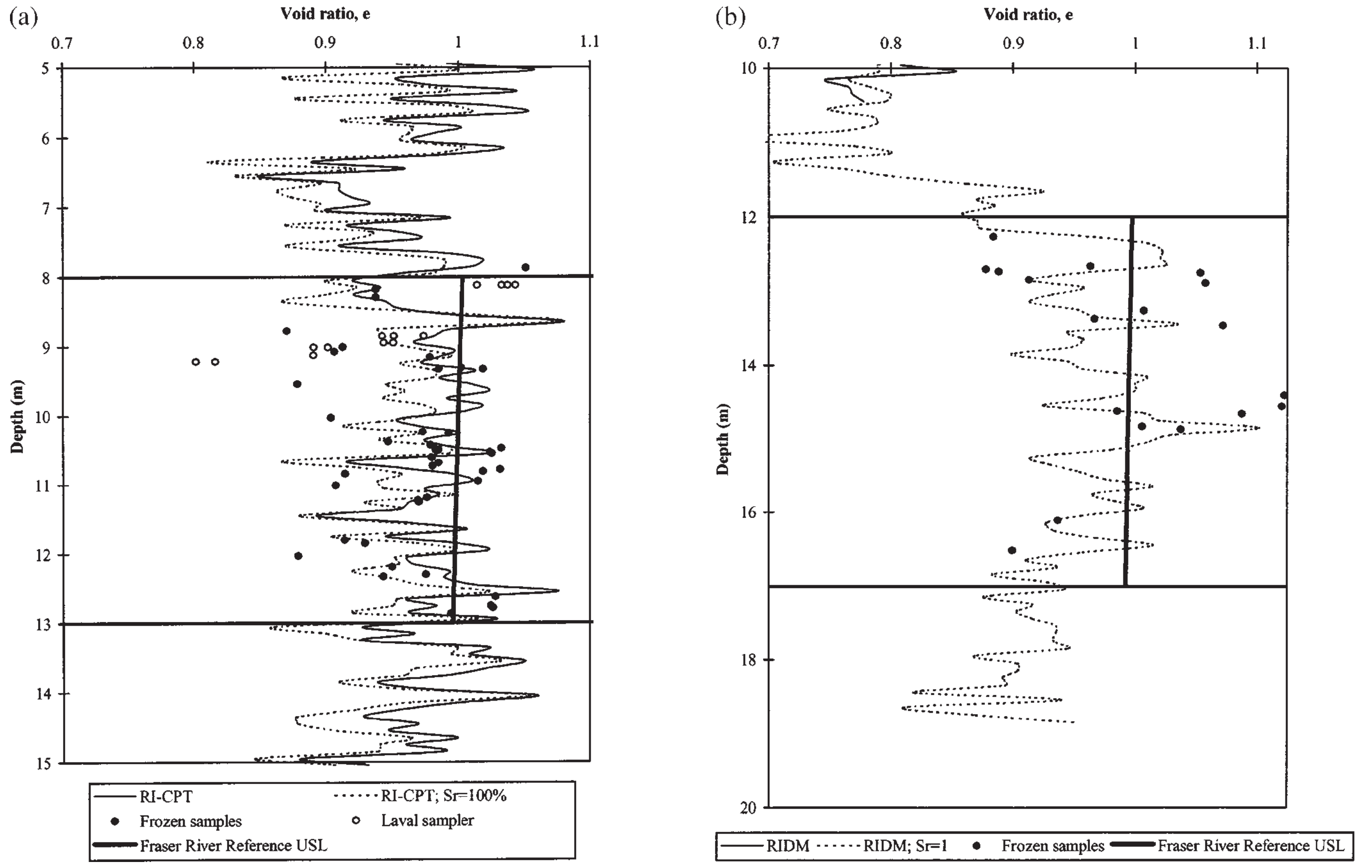
Summary

One of the primary objectives of the CANLEX project was to evaluate in situ testing techniques and existing interpretation methods as part of the overall goal to focus and coordinate Canadian geotechnical expertise on the topic of soil liquefaction. Six sites were selected by the CANLEX project in an attempt to characterize various deposits of loose sandy soil. The sites consisted of a variety of sand deposits including hydraulically placed sand deposits associated with the oil sands industry, natural sand deposits in the Fraser River Delta, and hydraulically placed sand deposits associated with the hard-rock mining industry. At each site, a target zone was selected and various in situ tests were performed. These included standard penetration tests (SPTs), cone penetration tests (CPTs), seismic CPTs (giving shear wave velocity measurements), geophysical logging, and pressuremeter testing.

Based on the results of this study, the sands at the CANLEX sites are either young manmade or of Holocene age (i.e., less than 10 000 years old), are essentially normally consolidated and uncemented, and are composed primarily of quartz minerals. These sands are uniformly graded with a mean grain size (D_{50}) of 0.16–0.25 mm and a fines content, in general, less than 12%, with some less than 5%.

The SPT results indicate that energy corrections for the SPT are important to allow comparisons to be made at and between sites. The CPT appears to provide a more reliable and continuous profile of penetration resistance than the SPT. Shear wave velocity measurements appear to be somewhat less reliable when obtained using a downhole technique from seismic CPTs conducted at very shallow

Fig. 26. Comparison of void ratio interpretation of radio-isotope CPT (RI-CPT) results (Mimura et al. 1995) with void ratios of ground-freezing samples from (*a*) the Massey site, and (*b*) the Kidd site. RIDM, radio-isotope CPT sounding.



(less than 5 m) or very deep (greater than 30 m) depths. However, at intermediate depths, the advantage of the seismic CPT is that both conventional penetration measurements and V_s measurements are made in the same sounding and allow for two independent in situ assessments of a given soil deposit in the same location. At most of the CANLEX sites, reasonable predictions of relative density were made from SPT, CPT, and V_s measurements, although the age of the deposits appears to have an important influence on the correlations, especially for deposits older than about 100 years. In addition, in processing the data it became apparent that conversions between void ratio and relative density are sensitive to the values of e_{min} and e_{max}. Therefore, it is important that these terms be determined carefully.

At the Massey, J-pit, and Highmont Dam sites the interpretation of the geophysical logs gave predictions of void ratio that agreed well with those of the ground-freezing samples. At the Kidd site, the geophysical logs considerably underpredicted the void ratios of the ground-freezing samples; however, this was not surprising because the logging did not meet acceptable criteria for borehole rugosity. At the phase I and LL Dam sites, the interpretation of the geophysical logs slightly overpredicted the void ratios of the ground-freezing samples. This was likely due to the fact that, although the geophysical data were interpreted assuming S_r = 100%, the deposits at these sites had degrees of saturation slightly less than S_r = 100%. At all of the sites, the geophysical logging results, CPTs, and ground-freezing samples indicated that the sand deposits appear to be highly heterogeneous, with large variations in density over short distances, both vertically and horizontally. This observation was somewhat surprising, since the sites had been selected based on criteria of density and uniformity. The void ratios of the frozen samples and those estimated from geophysical logging are sensitive to the value of specific gravity, G_s. Therefore, it is important that G_s be determined carefully.

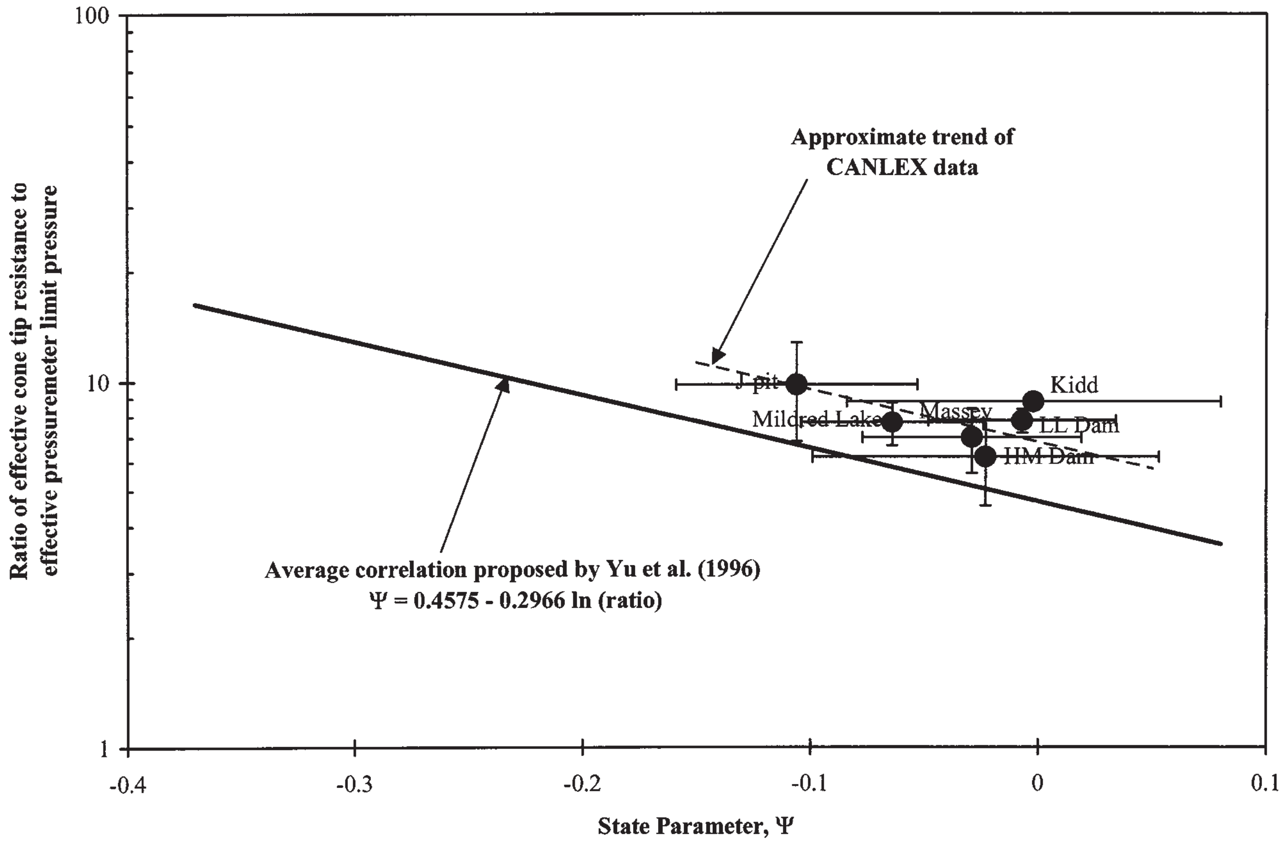
Gamma–gamma logging was also carried out using a new radio-isotope CPT (Mimura et al. 1995) at the two phase II sites and the results were very good.

Some of the differences between the in situ test based predictions of void ratio or relative density and the values of void ratio or relative density associated with the frozen samples may be due, in part, to the effect of physical scale on the measurement. All of the in situ tests are influenced by a volume of soil which is significantly larger than that of the individual frozen samples and, therefore, may produce more subdued variations in void ratio compared with those of the samples.

The self-boring pressuremeter provided reasonable estimates of in situ stresses, although interpretation of the results was difficult. The pressuremeter testing results indicated a range of in situ K_0 values at each site. However, based on results from all of the sites, a K_0 value of 0.5 appears to be an appropriate value for these loose, essentially normally consolidated, sandy deposits.

The overall objective for the CANLEX project was to obtain an improved understanding of the phenomenon of soil liquefaction. This paper has described the results of in situ

Fig. 27. Comparison of the average correlation for estimating state parameter from cone pressuremeter data, as proposed by Yu et al. (1996), with the average (±1SD) data from the six CANLEX test sites.



testing at each of the CANLEX sites. At each of the six sites, ground freezing and sampling were carried out adjacent to the in situ testing to obtain undisturbed samples of sandy soil (see companion paper by Wride et al. 2000). These samples were then carefully logged, trimmed, thawed, and tested under various directions of loading in the laboratory. The companion paper by Robertson et al. (2000*b*) summarizes the results by linking the results of the in situ testing at each site with the results of laboratory testing on the high-quality ground-freezing samples.

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