Ground sampling program at the CANLEX test sites

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Abstract: One of the primary objectives of the Canadian Liquefaction Experiment (CANLEX) project was to develop and evaluate undisturbed sampling techniques 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 methods of ground sampling were performed. These included ground freezing and sampling, fixed piston tube sampling, Christensen double-tube core sampling, large-diameter sampling using the Laval sampler, and sonic (rotary–vibratory) continuous coring. Ground freezing and sampling was performed at all six sites; the other methods were used at only some sites. Geophysical (gamma–gamma) logging was also performed in boreholes near the freeze pipe to independently measure in situ void ratios. This paper describes the techniques used in the ground-freezing and various sampling programs and presents a summary of the results. Comparisons of void ratios measured for various types of samples and using geophysical logging are also made.

Key words: CANLEX, ground freezing, sampling, geophysical logging, void ratio.

Résumé : Un des principaux objectifs du projet CANLEX était de développer et d'évaluer les techniques d'échantillonnage non remanié 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 sable mis en place par méthode hydraulique et reliés à l'industrie minière des roches fragiles. Sur chaque site, une zone cible a été sélectionnée et diverses méthodes d'échantillonnage de terrain ont été exécutées. Celles-ci comprenaient l'échantillonnage des sols après gel, l'échantillonneur à piston fixe, l'échantillonneur Christensen à double tube de carottage, l'échantillonneur à grand diamètre de Laval, et l'échantillonnage sonique continu (rotatoire–vibratoire). L'échantillonnage après gel du sol a été réalisé sur tous les sites; les autres méthodes ont été utilisées seulement sur quelques sites. Le profilage géophysique (gamma–gamma) a aussi été exécuté dans des trous de forage près des tuyaux de gel pour mesurer indépendamment les indices de vide in situ. Cet article décrit les techniques utilisées pour le gel des sols et divers programmes d'échantillonnage, et présente le sommaire des résultats. On compare également les indices de vide mesurés pour divers types d'échantillons et avec le profilage géophysique.

Mots clés : CANLEX, gel du terrain, échantillonnage, profilage géophysique, indice de vide.

[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) are 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) are natural sand deposits in the Fraser River Delta of British Columbia. The phase IV sites (LL Dam and Highmont Dam) are hydraulically placed sand deposits associated with the hard-rock mining industry at the Highland Valley Copper (HVC) Mine in British Columbia.

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. Various methods of ground sampling were performed at each site. These included ground freezing and sampling by coring the frozen sand, fixed piston tube sampling, Christensen double-tube core sampling, large-diameter sampling using the Laval sampler, and sonic continuous coring. Ground freezing and sampling were performed

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Table 1. Summary of ground freezing and sampling conducted at the six CANLEX sites.

Site data		
Phase	Site	Sampling procedure and comments
I	Mildred Lake	Liquid nitrogen was used to radially freeze a 2 m diameter by 10 m long column of the sand deposit; dry coring with a CRREL barrel was used to sample the frozen soil (Hofmann et al. 1994) (see Fig. 1 for illustration of ground freezing and sampling configuration at the phase I site); a total of 20 m of sandy soil core was obtained (Hofmann 1997)
II	Massey and Kidd	Liquid nitrogen was used to radially freeze a 2 m diameter by 5 m long column of the sand deposit; dry coring with a CRREL barrel was used to sample the frozen soil (Hofmann et al. 1995); a total of 40 m of sandy soil core was obtained from the phase II sites (Hofmann 1997)
III	J-pit	Liquid nitrogen was used to radially freeze a 2 m diameter by 4 m long column of the sand deposit; dry coring with a CRREL barrel was used to sample the frozen soil (Hofmann et al. 1996); a total of 6.9 m of 200 mm diameter and 3.9 m of 100 mm diameter sandy soil core was obtained (Hofmann 1997)
IV	LL Dam	Liquid nitrogen was used to radially freeze a 2 m diameter by 4 m long column of the sand deposit; dry coring with a CRREL barrel was used to sample the frozen soil (Biggar and Sego 1996); a total of 18 m of 100 mm diameter sandy soil core was obtained (Biggar and Sego 1996)
IV	Highmont Dam	Liquid nitrogen was used to radially freeze a 2 m diameter by 4 m long column in each sand deposit; dry coring with a CRREL barrel was used to sample the frozen soil; a total of 16 m of sandy soil core (13 m of 100 mm diameter core and 3 m of 200 mm diameter core) was obtained (Biggar and Sego 1996)

at all six sites; the other methods were used at only some sites. This paper describes the techniques used in the ground-freezing and sampling program at each site and presents a summary of the results. The location, geology, and target zones and typical layout for each of the six sites are described by Robertson et al. (2000*a*). Frozen samples of sand were obtained from the target zone at the centre of each of the six sites (Hofmann 1997). In addition, along a typical 5 m radius circle around the central ground-freezing location, the following conventional sampling was performed: fixed piston tube sampling at the phase I and phase II sites, Christensen double-tube core sampling at the phase I site, Laval large-diameter sampling at the phase II site and the LL Dam site, and sonic continuous coring at the phase II sites.

Ground sampling procedures

Table 1 summarizes the ground freezing and sampling that was performed at the six CANLEX test sites. Table 2 summarizes the fixed piston, Christensen core barrel, and Laval large-diameter sampler methods of sampling. Table 3 summarizes the sonic continuous coring. These tables provide details as to the test procedures that were followed in the field and summarize the length of core or number of samples obtained using each method. Additional details for each sampling method are provided in the following sections. To preserve the quality of the samples retrieved from the time they were removed from the ground to the time they were placed in storage at the University of Alberta, careful procedures for handling, preserving, and transporting the samples were developed for the phase I site and used at the subsequent sites. These procedures are also described in the following sections.

Ground freezing and sampling

The risk of disturbance caused by freezing soil is related to soil characteristics (e.g., grain-size distribution, fines mineralogy, and hydraulic conductivity), drainage conditions at the freezing front (affected by both soil characteristics and site conditions, such as stratigraphy and overburden stress), and the geometry of the freezing system. A complete description of the general effects of these factors is provided by Hofmann (1997). Some details of particular importance are described below.

The grain-size distribution and fines mineralogy of a soil deposit affects the ability to perform successful ground freezing and sampling with minimal disturbance to the void ratio and fabric of the soil. Table 4 summarizes the average fines content and mineralogy of the fines for the sand deposit at each CANLEX test site. Based on the mineralogy of the fines, frost heave susceptibility evaluations of various CANLEX test sites were performed, using the criterion developed by Davila et al. (1992), which is dependent on both the amount and type of fines present in the soil. Some sites had relatively high fines contents (e.g., up to as high as 22% in certain zones at the phase III site); however, based on the mineralogical composition of the fines, the criterion suggested by Davila et al. indicated that the risk of frost heave during ground freezing in all of the deposits would be negligible. Frost heave tests that were performed on bulk samples in the laboratory confirmed these findings. In addition, the sand deposits were found to be sufficiently permeable (compared with the expected rate of freezing) that pore-water expulsion would be uninhibited during ground freezing.

Figure 1 illustrates the configuration of ground freezing and sampling that was performed at the phase I test site. At the centre of each test site, liquid nitrogen was used to radially freeze a column of soil (typically 2 m in diameter) over a specified depth range (the target zone). The target sampling zones at the CANLEX test sites were located at different depths in sand deposits with different densities; therefore, the freeze pipes at the various sites were installed utilizing different techniques. Resistance temperature devices (RTDs) were used to monitor temperatures within and around the freezing system to confirm that the frozen

Table 2. Summary of other methods of sampling conducted at the six CANLEX sites.

Fixed piston tube

Truck-mounted Failing 1500 Special mud rotary drill supplied by Elgin Exploration Company Ltd. of Calgary; mechanically operated 76 mm fixed piston sampler manufactured by Sprague and Henwood, Inc.; Assembly No. WA15119 was used (purchased by Klohn-Crippen Consultants Ltd. in 1979; since then, some modifications have been made); Shelby tubes (76 mm 16 gauge stainless steel, 0.76 m long, nominal inside diameter of 73 mm and wall thickness of 1.6 mm) used with the sampler were manufactured by Acker Inc. and supplied by Elgin Exploration; ends of tubes were crimped inward by a machine press to create sharp cutting edges and positive inside clearance; average inside clearance and area ratios of 1.1 and 11.1% just met the American Society for Testing and Materials (ASTM) D1587 standards of 1.0% clearance and 11.4% area ratio for thin-walled tubes; to avoid disturbance during handling and shipping, the fixed piston tube samples were frozen unidirectionally on site

Site data		
Phase	Site	Comments
I	Mildred Lake	Performed in 4 boreholes: FPS-1, FPS-2, FPS-3, and FPS-4; cold temperatures (–5°C to –30°C) reduced efficiency of the sampling work; 22 samples in total, with 14 considered to be of high quality (types I and II; Plewes 1993)
II	Massey	Four samples in total, with 2 considered to be of high quality (Plewes 1995)
II	Kidd	Twenty-six samples in total, with 17 considered to be of high quality (Plewes 1995); 8 of the high-quality samples in the target zone

Christensen double-tube

Wireline 1.5 m long Christensen double-barrel core sampler (Elgin Exploration Company Ltd.); inner barrel assembly retrieved from the outer barrel assembly at the hole bottom by a wireline through the drill rods, eliminating the need to withdraw the drill rods between core samples; inner barrel has a swivel head that fixes the inner barrel while the outer barrel rotates and cores, minimizing possible core disturbance and improving recovery; PVC core liner to retain core (73.0 mm inner diameter)

Site data		
Phase	Site	Comments
I	Mildred Lake (Plewes 1993)	Performed in 2 boreholes, CORE-1 and CORE-2; a total of 24.55 m of sand was cored; a total of 15.86 m of core was recovered (average total recovery 65%); 9.8 m of core was preserved in PVC core liner for inspection and testing; coring the sand was hampered by the tendency of the core barrel to meet refusal in frequent dense sand layers which have CPT q_t values >20 MPa; refusal was caused by the high penetration resistance of the dense sand layers and the tendency for the dilative sand to jam in the core shoe; the core samples were disturbed within the PVC tube due to handling

Laval large-diameter sampler

Sampler 200 mm in diameter (see Fig. 3 for schematic of sampler and illustration of operation in sands); 218 mm outside diameter, cutting edge sharpened to a 5° angle and no inside clearance; the sampling tube is fixed to the sampler head which has a central hole (75 mm diameter) connected to lateral openings that allow mud to flow out of the sampling tube and into the overcoring tube when it is pushed into the soil

Site data		
Phase	Site	Comments
II	Massey (Konrad et al. 1995*a*, 1995*b*)	Four tubes were successfully obtained at depths between 8.3 and 10.6 m; dry ice used to unidirectionally freeze samples on site (required about 8 h); sample lengths 42, 55, 46, and 34 cm; void ratios were calculated for 14 specimens trimmed from these samples
II	Kidd	Occasional gravel-sized particles that were encountered within the sand deposit just above the target zone prevented advancement of the sampler
IV	LL Dam (Konrad 1996)	Sampling was attempted but various problems were encountered, particularly with circulation of bentonite mud; out of three attempts to sample the soil, a total of 35 cm of good quality core and another 15 cm of questionable quality core were obtained

Table 3. Summary of sonic (rotary–vibratory) sampling conducted at the phase II CANLEX sites.

Site	Sampling procedure and comments (Monahan et al. 1995)
Massey and Kidd	Sonic boreholes located 6–7 m from central freezepipe; one borehole at each site, drilled to 48 m at Massey and 20 m at Kidd; vibrating system that liquefies sediment along the cutting edge of the drill was used; 10.8 cm diameter cores were cut continuously in 3 or 6 m increments; after each core was cut, a steel casing was advanced to the base of the core and the drill string was tripped to the surface; the core was extruded by vibrating the core barrel and letting the core slide into a long plastic bag (12.7 cm diameter) slipped onto the outside of the core barrel; permanent PVC casing was installed upon removal of the steel casing to facilitate geophysical logging; natural gamma ray and conductivity logs were run by the Geological Survey of Canada; for preservation and transportation, the core was placed into 1.5 m lengths of split PVC pipe (10 cm diameter), the plastic bag was then cut open, and the core was split; the cores were described and photographed in the field and then relogged and rephotographed in the sediment laboratory (Pacific Geoscience Centre, Sydney, B.C.) to capture some of the finer scale features which were more visible after some drying; core recoveries generally exceeded 75%

Table 4. Summary of mineralogy of fines for the sand deposits at the six CANLEX sites.

Site data			Mineralogy of fines (percent passing No. 200 sieve)						
Phase	Site	Average FC (%)*	Quartz	Feldspar	Kaolinite	Mica	Chlorite and smectite	Illite	Calcite
I	Mildred Lake	~10	90	5	5	Trace	—	—	—
II	Massey	<5	70	15	5	5	5	—	—
II	Kidd	<5	70	15	5	5	5	—	—
III	J-pit	-15	Assumed to be the same as that for phase I						
IV	LL Dam	-8	36	9 plagioclase feldspar, 2 potassium feldspar	3	27	5 smectite, trace chlorite	15	3
IV	Highmont Dam	-10	57	21 plagioclase feldspar, 5 potassium feldspar	4	1	2 smectite, trace chlorite	7	5

* Approximate average fines content (percent passing No. 200 sieve) in the target zone, based on limited SPT samples.

column of soil had reached the desired radius prior to sampling. Sampling was then carried out in several boreholes at each site (typically at a 0.6 m radius from the freeze pipe). These boreholes had been preadvanced using wet rotary coring to just above the target sampling zone, lined with large-diameter (260 mm) casing, filled with water to replace the drilling fluid, and sealed with bentonite plugs (see Fig. 1). The installation was designed to ensure that the bottom of the casing was surrounded by frozen soil prior to sampling. Following the completion of ground freezing and prior to sampling, the water was blown out of each casing. Coring of the in situ frozen sand was performed using a dry coring technique utilizing a Cold Regions Research and Engineering Laboratory (CRREL) core barrel with tungsten carbide tipped cutting shoes. A core catcher at the bottom of the CRREL barrel was used to prevent loss of the frozen core as the barrel was brought to the ground surface. Both 100 mm and 200 mm inside diameter CRREL core barrels were used during the CANLEX project, as indicated in Table 1.

Core runs of approximately 0.6 m long were recovered, extruded at the ground surface using a hydraulic core extruder, measured for length, wrapped in plastic bags, then placed in an insulated box filled with dry ice. The specimens were later placed in freezers for temporary storage on site and for transportation between layers of insulation and dry ice, and subsequently transported to cold rooms (–20°C) at the University of Alberta where they were carefully catalogued and preserved for long-term storage. Samples were then trimmed from the frozen core for laboratory testing, as required by the CANLEX participants.

Fixed piston tube sampling

Fixed piston tube sampling was performed at the phase I and phase II sites using thin-walled (Shelby) tubes with a nominal diameter of 75 mm (see Table 2). At the phase I site, two samples were also attempted using an hydraulic-piston sampler; however, the sampler was not able to push the tube the full 0.62 m stroke into the sand. Thus, the percent recovery could not be accurately calculated and the sampler was no longer used. As will be discussed later, the fixed piston tube samples were shown to be generally slightly denser than samples obtained using ground freezing. As a result, fixed piston tube sampling was not used at other CANLEX test sites.

Figure 2*a* illustrates the configuration of the fixed piston (Shelby) tubes at the end of the sampling procedure. The tubes were weighed, measured, and stored vertically in a heated work trailer immediately upon retrieval. The piston tube samples were then frozen on site to prevent disturbance of the sand fabric during subsequent shipping and handling. Figure 2*b* illustrates the setup that was used to freeze the soil samples at the phase I site. These samples were frozen unidirectionally in a “top-down” direction using dry ice. As

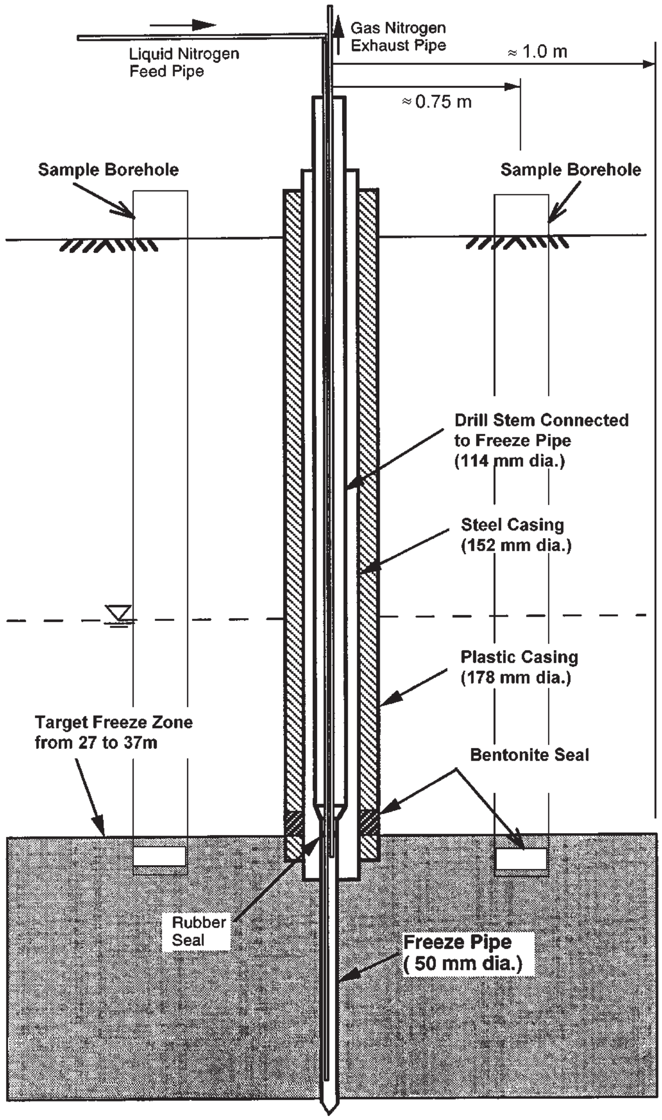


Fig. 1. Schematic diagram of ground freezing and sampling at the phase I CANLEX test site (after Hofmann et al. 1998*b*).

the freezing process took place, the expelled pore water was allowed to drain via perforated packers in the bottom of the tubes. At the phase II test site, some of the fixed piston samples were frozen unidirectionally from the bottom upwards and the excess pore-water volume that was expelled during freezing was collected and measured. This was done to confirm that only the 9% excess pore water was expelled during freezing and that, therefore, the freezing process did not disturb the samples. Freezing the samples from the bottom upwards also ensured that the samples maintained their in situ degree of saturation. Once frozen, the fixed piston samples were packed in dry ice and then transported to the University of Alberta at the end of the field program for long-term storage in cold rooms (–20°C).

The fixed piston tube samples were classified, in terms of quality, using a qualitative classification system (Plewes and Hofmann 1995). The classification system was based on sampling conditions, tube damage, and sample recoveries. Five sample classifications (I–V) were developed, with type I being the highest quality. Type I and type II samples were given the highest priority for testing. These samples had high sample volume recoveries (meeting a target criterion of 98–102%) and experienced no damage, in the case of type I, or minor damage (e.g., minor nicks on the end of the tube), in the case of type II.

Bulk densities of the piston tube samples were determined immediately after recovery, calculated as the initial weight of soil and unfrozen water in the tubes divided by the in situ volume of the sampled soil. Soil samples were trimmed from the bottom of each recovered tube and preserved in glass jars to be analyzed for water content (and bitumen content in the case of phase I samples). Dry densities and void ratios (prior to preservation by freezing) were then calculated for the type I and type II fixed piston tube samples.

Christensen double-tube sampling

The Christensen double-tube sampling method was performed at the phase I site. In this deposit, coring the sand with the Christensen double tube was hampered by the tendency of the core barrel to meet refusal in frequent dense layers (see Table 2). Due to problems with coring and observed sample disturbance due to handling, this method was not used at the other CANLEX test sites. A total of 9.8 m of core from the phase I site was preserved in the PVC core liners. The core retained in the core shoe after each core run was carefully preserved in glass jars and analyzed for water and bitumen content.

Laval large-diameter sampler

A schematic diagram of the Laval large-diameter sampler is given in Fig. 3*a*. Additional details about the Laval sampler can be found in La Rochelle et al. (1981). Figure 3*b* illustrates the general operation of the sampler in sand deposits, such as those at the CANLEX sites where the sampler was used. A special fish-tail drill bit was used to mix soil and bentonite mud in the borehole to maintain borehole wall stability. The sampler assembly was then lowered into the borehole with the sampler attached to the coring tube (208 mm i.d.) and the head valve open, allowing mud to flow freely through the sampler. When the lower edge of the coring tube reached the bottom of the borehole, it was kept at this position, and the sampler was unhooked and pushed down into the soil. When the head of the sampler was about 50 mm above the top of the sample (Fig. 3*b*, step *iii*), the head valve was closed and the soil was overcored while mud was injected under pressure through the wireline drill rods; the mud flowed between the sampling and overcoring tubes and removed the cuttings up into the borehole. Overcoring was stopped at about 20 mm below the sample. The coring device was then pulled out of the ground. The sampler was then gently rotated through 90° and slowly and carefully brought to the surface to minimize any vibrations or shocks which would disturb the sand fabric.

At the Kidd site, occasional gravel-sized particles that were encountered within the soil deposit just above the target zone prevented advancement of the Laval sampler. At the LL Dam site, difficulties were encountered on site with circulation of bentonite mud and overcoring the sampling tube with sufficient water flow was impossible. As a result, overcoring was not executed over the full length of the

Fig. 2. Fixed piston tube sampling: (*a*) preservation of Shelby tubes; (*b*) setup for freezing of soil samples in Shelby tubes (after Plewes and Hofmann 1995).

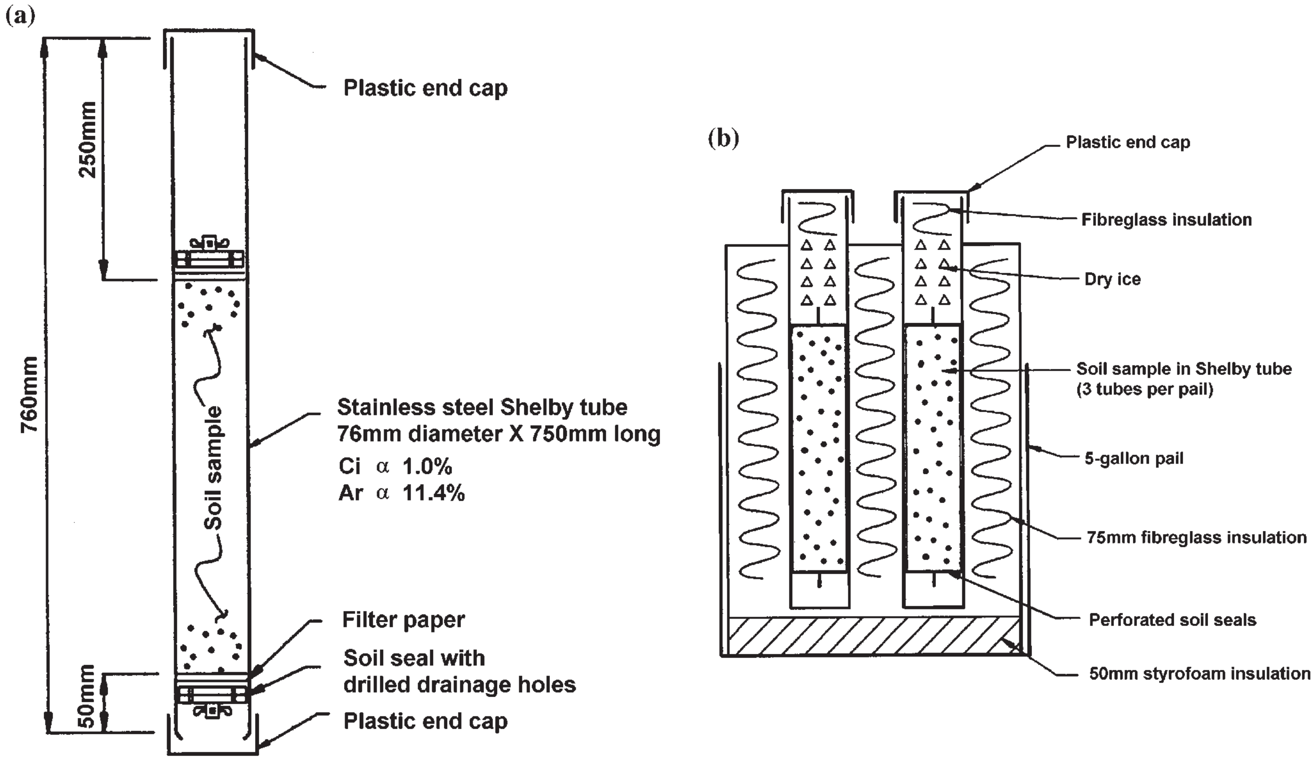


Fig. 3. The Laval large-diameter sampler: (*a*) schematic diagram of the sampler (after Konrad et al. 1995*a* and La Rochelle et al. 1981); (*b*) general operation (steps *i*–*v*) of the sampler in sands (after Konrad et al. 1995*a*).

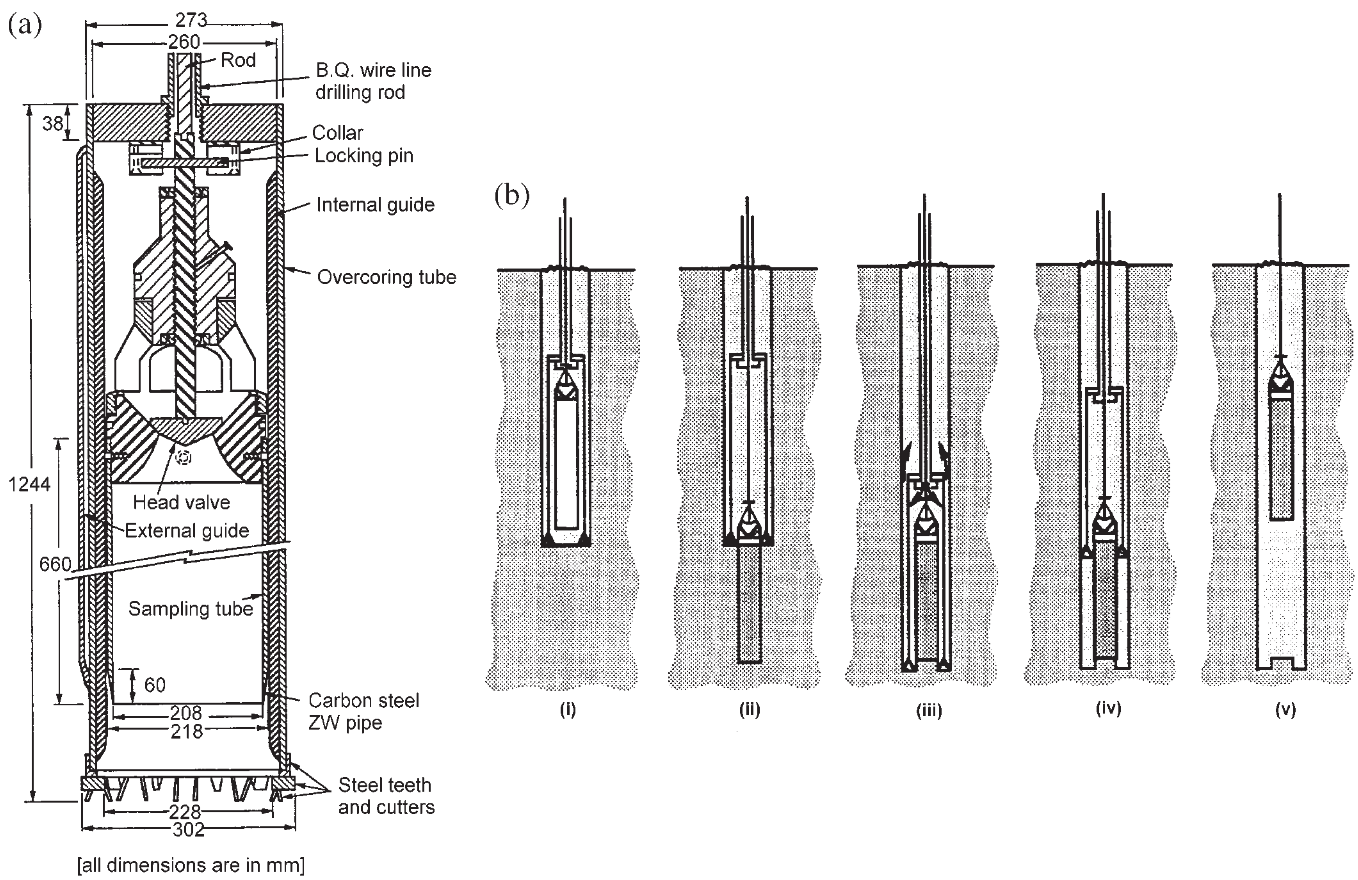
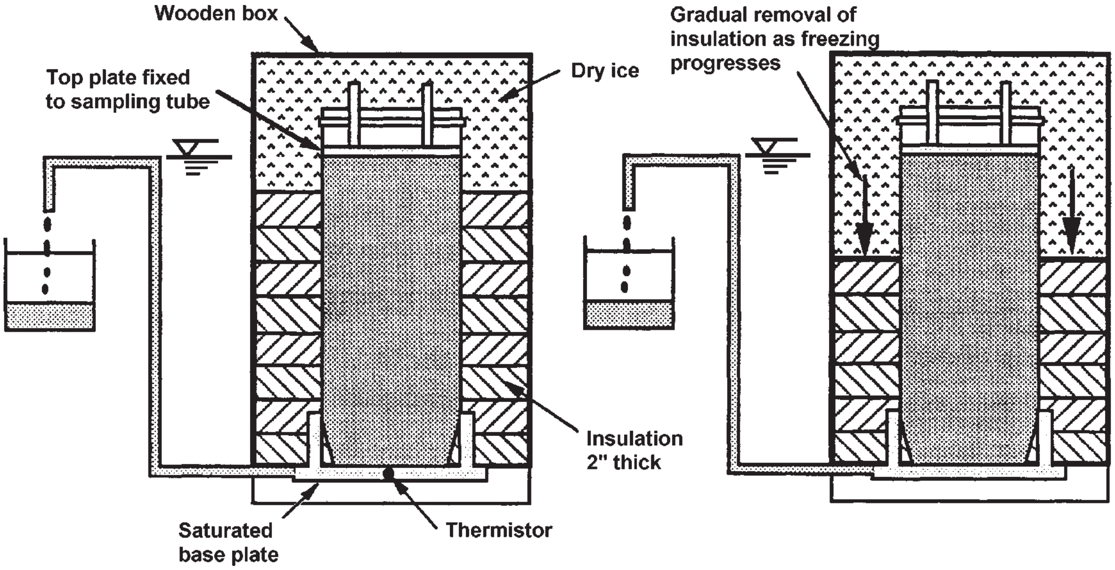


Fig. 4. Setup for freezing of Laval large-diameter sampler soil samples (after Konrad et al. 1995*a*).



sampling tube and soil was lost during retrieval. Adequate mud flow during overcoring was therefore found to be a key factor in successful sampling using the Laval large-diameter sampler.

Once retrieved, the Laval large-diameter samples were then frozen unidirectionally, as illustrated in Fig. 4, to prevent disturbance of the sand fabric during subsequent shipping and handling. First, a special base plate was attached to the end of the tube to keep the sampler vertical. This base plate was connected to a flexible tube through which a back pressure was applied to the sampler. The samples were frozen unidirectionally from the top downwards and the volume of pore water expelled at the base of the samples during freezing was collected and measured. This was done to confirm that only the 9% excess pore water was expelled during freezing and that, therefore, the freezing process did not disturb the samples. Once frozen, the samples were extruded on site, wrapped in plastic, placed into a portable freezer with dry ice, and shipped to the University of Alberta for long-term storage in cold rooms (–20°C).

Sonic (rotary–vibratory) continuous coring

One sonic borehole was also drilled at each of the phase II sites (Massey and Kidd) (see Table 3). At each site, the sonic borehole was located approximately 6–7 m from the central freezepipe. The sonic holes were continuously cored in 3–6 m intervals and the cores were preserved in split PVC tubes and reexamined in the laboratory. The cores were depth corrected by correlation with natural gamma ray geophysical logging, grain-size samples were analyzed, and comparisons were made with CPT data from each site. Based on these comparisons, the natural deltaic deposits at each site were then subdivided into distinct units. Details are provided by Monahan et al. (1995).

Void ratio

Void ratios (e) were calculated (using volume calculations) for each sample trimmed for laboratory testing from core obtained by ground freezing, as well as for each Laval large-diameter sample from the Massey site and each sample obtained using the fixed piston sampler. These void ratios are summarized in Table 5, which provides comparisons between the samples obtained using in situ ground freezing and those obtained using other methods. Detailed comparisons on an overall profile basis are also shown in Figs. 5–7. In each of these figures, the void-ratio scale has been plotted from approximately minimum (e_{min}) to maximum (e_{max}) for the particular site (as given by Robertson et al. 2000*a*); therefore, values of relative density (D_r) can be estimated directly from each figure. The average values of relative density for each site are also summarized in Table 5. 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.

Also given in Table 5 is a summary of the void ratios (and relative densities) predicted by geophysical (gamma–gamma) logging at each site. Comparing these data with the void ratio data for the samples, as given in Table 5, is a simplistic comparison. Because of the variation of soil density with depth in the target zone, it is strongly recommended that the data be examined and compared on a complete-profile basis. The interpretations of void ratio from geophysical logging assumed that the sand was fully saturated (i.e., S_r = 100%). Further details are given by Wride et al. (2000).

Ground freezing and sampling

In general, at the CANLEX sites, when the sand deposits were fully saturated and there were no difficulties in conducting geophysical (gamma–gamma) logging, the void ratios of samples obtained using ground freezing and sampling agreed quite well with the interpreted void ratio profiles from the geophysical logs. At all of the sites, both the geophysical logging results and ground-freezing samples indicated that the uniformly graded sand deposits are actually highly heterogeneous with large variations in density over short distances, both vertically and horizontally. This is an important finding of the CANLEX project.

Table 5. Comparison of void ratio (e) and relative density (D_r) for samples obtained using different sampling methods.

Site data		Ground freezing and sampling			Fixed piston tube sampler			Christensen	Laval large-diameter sampler			Geophysical logging*	
Phase	Site	e	D_r (%)	$n^\dagger$	e	D_r (%)	$n^\ddagger$	double-tube	e	D_r	$n^\dagger$	e	D_r (%)
I	Mildred Lake	0.768 (0.040)	43.6 (9.2)	52	0.694 (0.034)	60.6 (7.8)	14	Samples disturbed due to handling	na	na	na	0.788 (0.053)	40.0 (12.2)
II	Massey	0.970 (0.050)	32.5 (12.5)	42	0.984	29	2	na	0.942 (0.077)	39.5 (19.2)	14	0.99 (0.07)	27.5 (17.5)
II	Kidd	0.981 (0.076)	29.8 (19.0)	28	0.922 (0.046)	44.5 (11.5)	8	na	na	na	na	0.78 (0.06)	80.0 (15.0; very poor)
III	J-pit	0.762 (0.053)	42.7 (10.1)	47	na	na	na	na	na	na	na	0.721 (0.068)	50.5 (13.0; based on 1 good log)
IV	LL Dam	0.849 (0.041)	40.3 (8.0)	18	na	na	na	na	Not calculated (only 2 small pieces of core obtained)			0.929 (0.120)	24.6 (23.5)
IV	Highmont Dam	0.825 (0.075)	37.4 (14.8)	22	na	na	na	na	na	na	na	0.862 (0.074)	30.1 (14.6)

Note: Void ratios and relative densities are given as overall average values in the target zone, with standard deviations in parentheses; values of e_{min} and e_{max} used to calculate relative density are given by Robertson et al. (2000*a*). na, not available.

*Based on S_r = 100%; comment indicates quality of geophysical (gamma–gamma) logs based on measured compensation values (Wride et al. 2000).

†Number of samples trimmed from the frozen core for testing.

‡Number of high-quality (types I and II) tube samples obtained from the target zone at each site.

Fixed piston tube sampling

Fixed piston tube sampling was performed at the phase I and phase II sites. At the phase I site (see Fig. 5*a*), the in situ void ratios estimated from the 13 high-quality fixed piston tube samples (types I and II) fell on the lower bound (denser side) of the high-quality undisturbed samples obtained using ground freezing. At the Massey site, the void ratios of the two fixed piston tube samples in the target zone compared well with those of the ground-freezing samples. At the Kidd site, seven of the nine high-quality fixed piston tube samples also compared well with samples obtained using ground freezing, with the two samples in the middle of the target zone being denser than the in situ frozen samples. The better correlation of the fixed piston tube samples with the in situ frozen samples at the Massey and Kidd sites may be related to the full saturation of the target zone, whereas the sands at the phase I site were not saturated ($S_r \approx$ 80–97%, average $\approx$ 90%; Hofmann 1997). The unsaturation of the sands at the Mildred Lake site likely contributed to the larger sample disturbance (void ratio decreases of 0.10–0.15) during sampling. The closer correlation of the fixed piston tube samples with the in situ frozen samples at the saturated phase II sites is similar to the results reported by Plewes et al. (1994) at the Duncan Dam. Hence, the use of conventional sampling techniques to determine the in situ density of loose, unsaturated sands should be avoided.

Densification of sand using the fixed piston tube sampler agrees with the work by Yoshimi et al. (1994), who showed that when very loose sand samples were obtained using conventional high-quality fixed piston tube samplers and then tested in the laboratory, they resulted in higher values of cyclic resistance ratio (CRR) (i.e., implying higher densities) than those for undisturbed samples obtained using in situ ground freezing. As mentioned earlier, Plewes et al. (1994) observed that ground-freezing samples were of better quality (0.03 higher void ratio) than those obtained using conventional sampling techniques. Other researchers have also shown that even high-quality tube sampling tends to densify loose sand and loosen dense sand (Broms 1980; Hight 1993; Hight and Georgiannou 1995). Based on the work by Yoshimi et al., the average relative density of the sands at the CANLEX sites would suggest that high-quality fixed piston tube samples should provide reasonable agreement with in situ ground freezing.

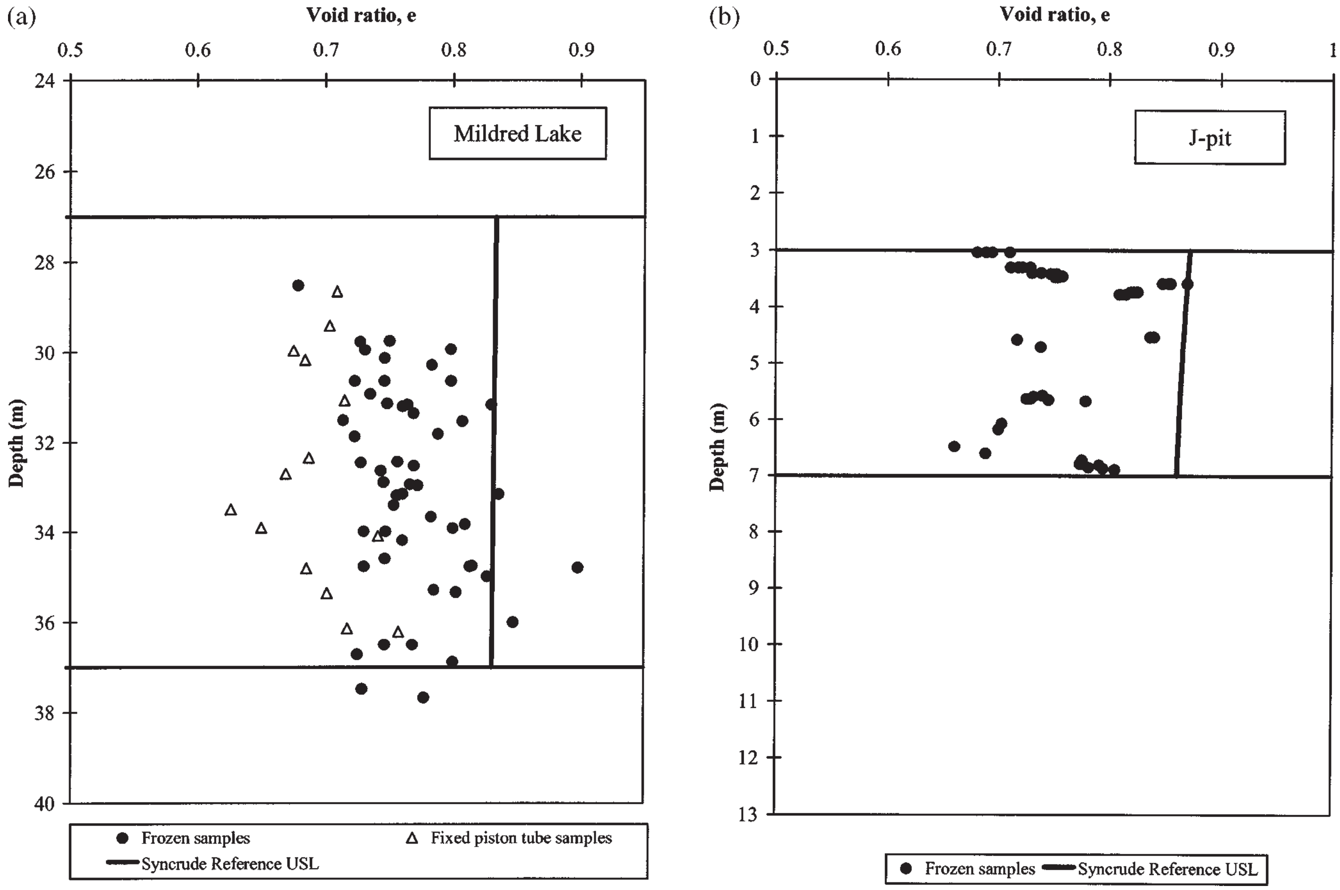
Laval large-diameter sampling

Successful Laval large-diameter sampling was performed at the Massey site. The void ratios of samples at the Massey site obtained using the Laval sampler appear to agree with the undisturbed ground-freezing void ratios except for the two samples at about 9.25 m, which appear to have significantly lower void ratios. At the LL Dam site, insufficient large-diameter samples were obtained (see Table 2) to make specific comparisons with ground-freezing samples.

Costs associated with sampling

Table 6 presents a comparison of the costs in Canadian dollars (Can$) associated with ground freezing and sampling for the various phases of the CANLEX project (Hofmann 1997). As the project progressed and more experience with

Fig. 5. Void ratios of (*a*) undisturbed frozen samples and piston tube samples obtained at the phase I site (Mildred Lake), and (*b*) undisturbed frozen samples at the phase III site (J-pit). USL, ultimate state line.



in situ ground freezing and sampling was gained, the unit costs of ground freezing and sampling (in terms of total soil volume) decreased significantly. By the end of the project, the cost of retrieving samples using ground freezing was about Can$ 0.25 per cm^3. The total cost per site was in the order of Can$ 50 000. It is noted that these costs are based on commercial costs for drilling, sampling, and freezing, but engineering and supervision costs were at government-funded research levels which are generally lower than commercial rates.

Table 7 presents a comparison of the costs associated with the other methods of sampling at the various phases of the CANLEX project. In general, the cost of retrieving samples using these other methods was in the order of about Can$ 0.40 per cm^3. Thus, on a per unit volume basis, the cost of sampling using these methods was similar to the cost associated with ground freezing and sampling. However, the total cost per site was in the order of Can$ 12 000, i.e., significantly less than the cost per site associated with ground freezing and sampling. As noted earlier, the samples obtained using ground freezing were of a superior quality and can be considered as truly undisturbed samples.

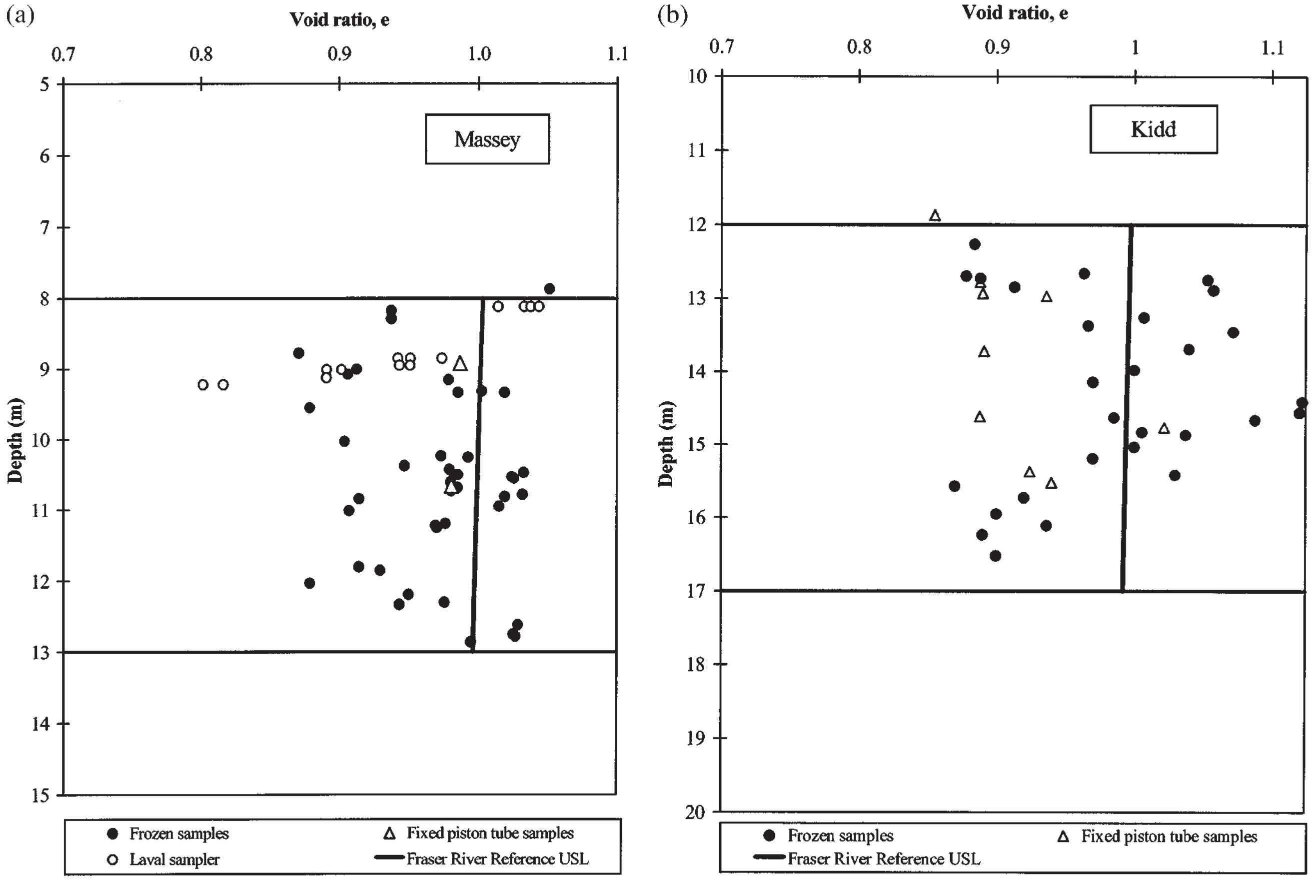
In addition to the sample-retrieval costs presented in Tables 6 and 7, costs associated with subsequent handling, shipping, and storage of all samples were also incurred. These costs were typically in the order of Can$ 14 000 per phase of the CANLEX project. However, the costs are a function of site location, depth of target zone, and equipment availability (cold rooms, etc.) at the storage facility. The costs in a major city will be less than those at a remote site due to lower travel and mobilization–demobilization costs. Again, slightly higher costs may be incurred at industry commercial rates.

Summary

Successful ground freezing and sampling were performed at all six of the CANLEX test sites. Comparisons, in terms of void ratio, with the results of geophysical logging generally confirmed that the samples were of high quality. In addition, as the project progressed and more experience with in situ ground freezing and sampling was gained, the ground-freezing and sampling techniques were refined. As a result, the unit costs of ground freezing and sampling (in terms of total soil volume) decreased significantly. Thus, by following the techniques developed as part of the CANLEX project, high-quality undisturbed samples of sandy soil can be obtained from a discrete target zone at depth in a cost-effective manner.

Factors that affect piston sampling in sandy soils were also evaluated and quantified. Recommendations for successful sampling using this method included very careful sampling techniques, followed by unidirectional freezing (allowing unimpeded drainage to occur) to preserve the sample

Fig. 6. Void ratios of (*a*) undisturbed frozen samples, Laval large-diameter sampler samples, and piston tube samples from the Massey site; and (*b*) undisturbed frozen samples and piston tube samples from the Kidd site.



quality during handling and shipping. Following these procedures, successful fixed piston sampling was performed at three of the CANLEX test sites. However, despite the fact that the sampling and subsequent freezing (for preservation) were performed very carefully, the fixed piston samples obtained at the saturated phase II sites were, on average, somewhat denser ($\Delta e \approx -0.03$ to -0.05, where Δe = change in void ratio) than the samples obtained from the same site using ground freezing and sampling. This agrees with similar data obtained at Duncan Dam and presented by other researchers. Sampling of the unsaturated sand at the phase I site resulted in large density changes ($\Delta e \approx -0.10$ to -0.15), and hence use of conventional sampling methods to determine the in situ density of loose, unsaturated sands should be avoided.

Sampling using the Christensen double-tube sampler proved to be useful for obtaining core for soil identification purposes only. However, various problems were encountered with this method and it appeared to be less successful than the other sampling methods at producing relatively undisturbed samples of soil. Although the sonic cores in the sands at the phase II sites were disturbed, they were very useful for stratigraphic interpretation and detailed correlation with CPTs and other in situ tests (Monahan et al. 1995).

The Laval large-diameter sampler was used at three of the CANLEX sites, with success at the Massey site, little success at the LL Dam site, and no success at the Kidd site, owing to the presence of a gravel layer near the surface. However, the Laval large-diameter sampler was initially developed for sampling of sensitive clay soils (La Rochelle et al. 1981) and the application of the sampler in sandy deposits is a relatively new technique. Adequate mud flow during overcoring was identified as a key factor in successful sampling using the Laval large-diameter sampler in sands. In addition, based on the findings at the Kidd site, it appears that in soils with some gravel, the Laval sampler must be used with a casing and adequate washing to prevent any loose, gravel-sized particles being present at the sampling elevation. Further studies would be useful to improve the sampling technique and in evaluating the quality of the samples which can be obtained using this method.

The overall objective for the CANLEX project was to obtain an improved understanding of the phenomenon of soil liquefaction. This paper has described the various methodologies that were followed at each of the CANLEX sites to obtain the highest sample quality possible for a given sampling technique. In general, the ground-freezing samples were of a very high quality. Overall, they were of higher quality and had void ratios which more closely matched those measured in situ by independent geophysical (gamma–gamma) logging than the samples obtained using conventional sampling techniques. Therefore, the ground-freezing samples were selected to be carefully thawed and tested under various directions of loading in the laboratory. At each

Fig. 7. Void ratios of (*a*) undisturbed frozen samples from the LL Dam site, and (*b*) undisturbed frozen samples from the Highmont Dam site.

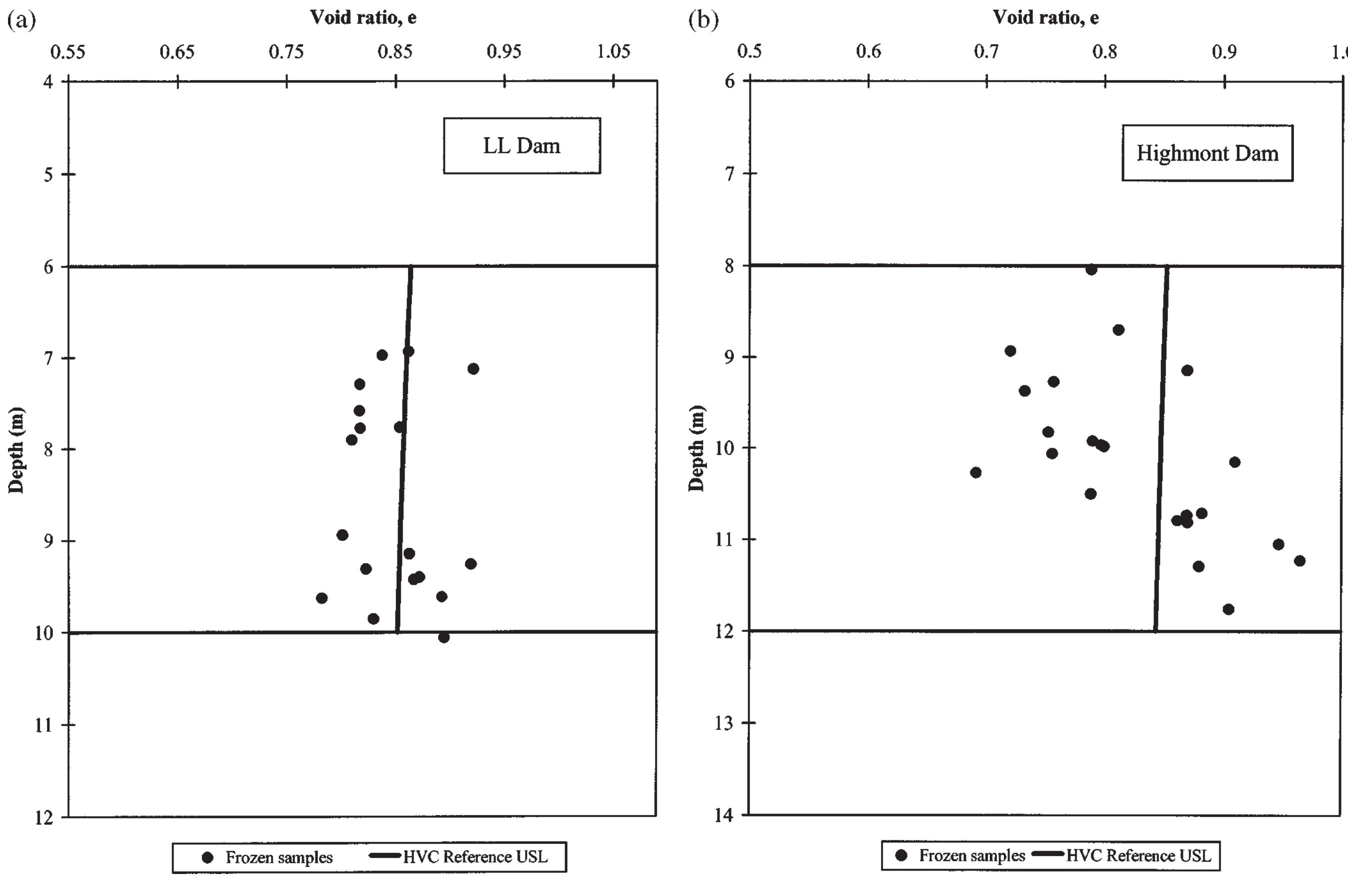


Table 6. Comparison of ground-freezing and sampling costs for the CANLEX project.

		Length of core (m)					Unit cost		
Phase	No. of sites	100 mm dia.	200 mm dia.	Total	Volume of core (cm^3)	Total cost (Can$)*	Site (Can$/site)	Length (Can$/m)	Volume (Can$/cm^3)
I	1	20	0	20	157 080	94 200	94 200	4710	0.60
II	2	40	0	40	314 159	100 100	50 050	2503	0.32
III	1	3.9	6.9	10.8	247 400	48 000	48 000	4444	0.19
IV	2	31	3	34	337 721	81 822	40 911	2407	0.24

* Includes cost of liquid nitrogen, drilling fees, engineering supervision, labour, and equipment, but does not include costs associated with sample handling, shipping, and storage and travel, accommodation, and meals.

Table 7. Comparison of fixed piston, Christensen double-tube, and Laval large-diameter sampling costs.

							Unit cost		
Sampling method	Phase	No. of sites	No. of samples	Total length of samples (m)	Total volume of samples (cm^3)	Total estimated cost (Can$)*	Sample (Can$/sample)	Length (Can$/m)	Volume (Can$/cm^3)
Fixed piston	I	1	22	11.66	48 802	18 000	818	1 544	0.37
	II	2	30	15.90	66 548	20 000	667	1 258	0.30
Christensen double-tube	I	1	—	15.86	66 380	5 000	—	315	0.08
Laval large diameter	II	2	4	1.77	60 144	12 000	3000	6 780	0.20
	IV	1	2	0.50	16 990	10 000	5000	20 000	0.59

* Includes cost of drilling fees, engineering supervision, labour, and equipment, but does not include costs associated with sample handling, shipping, and storage and travel, accommodation, and meals.

of the six sites, in situ testing was carried out adjacent to the ground sampling (see companion paper by Wride et al. 2000). A second companion paper by Robertson et al. (2000*b*) links the results of the in situ testing at each site with the results of laboratory testing on the high-quality ground-freezing samples.

A key observation from the CANLEX project was the large variations in density within deposits of uniformly graded sand. This variation must be recognized in the design of sampling and laboratory testing programs, to properly characterize the deposits, and the interpretation of in situ testing data. This variation must also be considered in the evaluation and understanding of liquefaction case histories. In situ tests, such as geophysical logs and CPT, 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.

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