Ground sampling program at the CANLEX test sites

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December 8, 1998
Canadian Geotechnical Journal

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Abstract

One of the primary objectives of the 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 oilsand industry, natural sand deposits in the Fraser River Delta, and hydraulically placed sand deposits associated with the hardrock 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, fixed piston tube sampler, Christensen double-tube sampler, Laval sampler, sonic coring, geophysical logging, void ratio

Introduction

One of the primary objectives of the 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 (Robertson et al., 1998a). The 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 oilsand 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 B.C.. The Phase IV sites (LL Dam and Highmont Dam) are hydraulically placed sand deposits associated with the hardrock mining industry at the Highland Valley Copper (HVC) Mine in B.C..

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 was performed 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.

Test Sites

The location, geology and target zones for each of the six sites are described by Robertson et al. (1998a). The typical layout of the detailed site characterization at each of the six CANLEX sites is also described by Robertson et al. (1998a). Frozen samples of sand were obtained from the target zone at the centre of each of the six sites (Hofmann, 1997; Hofmann et al., 1994a, 1995 and 1996; Biggar and Sego, 1996). In addition, along a typically 5 m radius circle around the central ground freezing location, the following conventional sampling was performed: fixed piston tube sampling at the Phase I site (Plewes, 1993) and the Phase II sites (Plewes, 1995); Christensen double-tube core sampling at the Phase I site (Plewes, 1993); Laval large diameter sampling at the Phase II sites (Konrad et al., 1995a&b) and the LL Dam site (Konrad, 1996); and sonic continuous coring at the Phase II sites (Monahan et al., 1995).

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. In order 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 (Hofmann et al., 1994b) and used at the subsequent sites. These procedures are also described below.

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 (Hofmann et al., 1998a). A complete description of the general effects of these factors is provided by Hofmann et al. (1998a). Specific effects of these factors on ground freezing at the various CANLEX test sites are discussed by Hofmann et al. (1998b). 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 (Hofmann et al., 1998a). 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, Hofmann (1997) and Hofmann et al. (1998b) performed frost heave susceptibility evaluations of various CANLEX test sites, 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. (1992) indicated that the risk of frost heave during ground freezing in all of the deposits would be negligible (Hofmann et al., 1998b). Frost heave tests that were performed on bulk samples in the laboratory confirmed these findings (Hofmann, 1997). In addition, the sand deposits were found to be sufficiently permeable (compared to the expected rate of freezing) that pore water expulsion would be uninhibited during ground freezing (Hofmann et al., 1998b).

Hofmann et al. (1998b) provide a detailed summary of the ground freezing and sampling that was performed at each of the CANLEX test sites. As an example, 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. Detailed descriptions are provided by Hofmann et al. (1998b). Resistance temperature devices (RTDs) were used to monitor temperatures within and around the freezing system to confirm that the frozen 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 pre-advanced 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 Figure 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 CRREL core barrel with tungsten carbide tipped cutting shoes (Hofmann et al., 1998b). 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.

As outlined by Hofmann et al. (1998b), 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 II sites using thin walled (Shelby) tubes with a nominal diameter of 75 mm (Plewes, 1993 and 1995; 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 (Plewes, 1993). Thus, the percentage 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 (Plewes and Hofmann, 1995). 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 set-up that was used to freeze the soil samples at the Phase I site (Plewes and Hofmann, 1995). These samples were frozen unidirectionally in a "top-down" direction using dry ice. As 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 porewater volume that was expelled during freezing was collected and measured (Plewes, 1995). This was done to confirm that only the 9% excess porewater 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 classification (I to V) were developed, with Type I being the highest quality. Plewes and Hofmann (1995) recommended that Type I and Type II samples be given the highest priority for testing. These samples had high sample volume recoveries (meeting a target criterion of 98% to 102%) and experienced no damage, in the case of Type I, or minor damage (e.g. minor knicks 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) (Plewes, 1993 and 1995). Dry densities and void ratios (prior to preservation by freezing) were then calculated by Plewes (1993 and 1995) 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; Plewes, 1993). Due to problems with coring and observed sample disturbance due to handling (see Table 2), 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 (Plewes, 1993).

Laval large diameter sampler

A schematic diagram of the Laval large diameter sampler is given in Figure 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 (Konrad et al., 1995a). A special fishtail 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 ID) and the head valve open, allowing mud to flow freely through the sampler (i). When the lower edge of the coring tube reached the bottom of the borehole (ii), 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 (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 (iii). The coring device was then pulled out of the ground (iv). 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 (v).

Sampling at the Massey site was performed successfully (Konrad et al., 1995a; see Table 2). However, 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 (Konrad, 1996). As a result, overcoring was not executed over the full length of the 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 (Konrad, 1996).

Once retrieved, the Laval large diameter samples were then frozen unidirectionally, as illustrated in Figure 4, to prevent disturbance of the sand fabric during subsequent shipping and handling

(Konrad et al., 1995a). First, a special base plate was attached to the end of the tube in order to keep the sampler vertical. This base plate was connected to a flexible tube through which a backpressure was applied to the sampler. The samples were frozen unidirectionally from the top downwards and the volume of porewater expelled at the base of the samples during freezing was collected and measured. This was done to confirm that only the 9% excess porewater 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

In addition, at each of the Phase II sites (Massey and Kidd) one sonic borehole was drilled (see Table 3; Monahan et al., 1995; Monahan, 1998). At each site, the sonic borehole was located approximately 6 to 7 m from the central freezepipe. The sonic holes were continuously cored in 3 to 6 m intervals and the cores were preserved in split PVC tubes and re-examined in the laboratory (Monahan et al., 1995). 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 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 Figure 5 to Figure 7. In each of these figures, the void ratio scale has been plotted from approximately e_{min} to e_{max} for the particular site (as given by Robertson et al., 1998a); 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 semi-vertical line in each figure represents void ratios corresponding to the relevant reference ultimate state line (USL), as given by Robertson et al. (1998b) at the effective stresses present over the depth of the target zone, based on a K_o 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 to 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. Such comparisons are provided by Wride et al. (1998). 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. (1998).

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. Figure 8 illustrates this comparison at the Massey site. Comparisons for all the sites and additional details regarding the geophysical logging are provided by Wride et al. (1998). 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.

Some of the differences between the geophysical based predictions of void ratio and the values of void ratio associated with the frozen samples, as illustrated in Figure 8, 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 to the samples. Image analysis (Hanzawa, 1980) has shown that void ratio measurements can vary significantly, depending on the size of the sample.

Fixed piston tube sampling

Fixed piston tube sampling was performed at the Phase I and Phase II sites. At the Phase I site (see Figure 5a), the in-situ void ratios estimated from the thirteen high quality fixed piston tube samples (Types I and II; Plewes, 1993) fell on the lower bound (denser side) of the high quality undisturbed samples obtained using ground freezing. At the Massey site (see Figure 6a), the void ratios of the 2 fixed piston tube samples in the target zone compared well with the ground freezing samples. At the Kidd site (see Figure 6b), 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 ($S_r \approx 80$ to 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 to 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 undisturbed samples obtained using in-situ ground freezing. As mentioned above, 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. (1994), 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. At the Massey site (see Figure 6a), the void ratios of samples 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 (CAD) associated with ground freezing and sampling for the various phases of the CANLEX project (Hofmann et al., 1998b). As the project progressed and more experience with 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 0.25 CAD/cm^3. The total cost per site was in the order of 50,000 CAD. 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 0.40 CAD/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 12,000 CAD; 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 Table 6 and Table 7, costs associated with subsequent handling, shipping and storage of all samples were also incurred. These costs were typically in the order of 14,000 CAD 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 at a remote site due to lower travel and mobilization/demobilization costs. Again, slightly higher costs may be incurred at industry commercial rates.

Summary

One of the primary objectives of the 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 (Robertson et al., 1998a). 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 oilsand industry, natural sand deposits in the Fraser River Delta, and hydraulically placed sand deposits associated with the hardrock 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, and sampling using the Laval large diameter sampler.

As part of the feasibility studies performed during the CANLEX project, factors affecting ground freezing and sampling in sandy soils were evaluated and quantified (Hofmann et al., 1998a and 1998b). The factors include soil characteristics, drainage conditions and the geometry of the freezing system. Based on considerations of grain size distribution, fines mineralogy and hydraulic conductivity, initial studies predicted that the variety of sandy deposits investigated as part of the CANLEX project could be successfully frozen and sampled with negligible disturbance to the soil. Indeed, successful ground freezing and sampling was performed at all six of the CANLEX test sites. Comparisons, in terms of void ratio, with the results of geophysical (gamma-gamma) 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 (Plewes, 1993 and 1995). Recommendations for successful sampling using this method included very careful sampling techniques, followed by unidirectional freezing (allowing unimpeded drainage to occur) in order to preserve the sample 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) 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 (Plewes, 1993). 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, with little success at the LL Dam site (Konrad et al., 1995a; Konrad, 1996), and with 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 (Konrad, 1996). 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.

To avoid disturbance, all of the samples from the CANLEX sites were frozen on site prior to shipment to the University of Alberta for long-term storage. Great care was taken in handling, preserving and transporting the samples obtained from the Phase I test site in order that the quality of the samples retrieved from the ground was not altered from the time that the samples were obtained to the time that they were placed into storage at the University of Alberta. (Hofmann et al., 1994b). Procedures that were developed for the Phase I site were then used at the subsequent sites. These included careful packaging of samples, packing in freezers between layers of insulation and dry ice, monitoring freezer temperatures regularly to ensure subzero temperatures, minimal jostling during shipping, and immediate storage in cold rooms (-20^{o}C) at the University of Alberta.

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 in order 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 of the six sites, in-situ testing was carried out adjacent to the ground sampling (see companion paper by Robertson et al., 1998b). A second companion paper by Robertson et al. (1998b) 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 natural 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 to the samples.

Acknowledgements

This work was supported by CANLEX (Canadian Liquefaction Experiment), which is a project funded through a Collaborative Research and Development Grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), B.C. Hydro, Highland Valley Copper, Hydro Québec, Kennecott Corporation, Suncor Inc., and Syncrude Canada Ltd. The collaboration included the geotechnical consultants, AGRA Earth and Environmental Ltd., EBA Engineering Consultants Ltd., Golder Associates Ltd., Klohn-Crippen Consultants Ltd., and

Thurber Engineering Ltd., as well as faculty and students from the Universities of Alberta, British Columbia, Carleton, and Laval. The CANLEX project also appreciated the participation of the following organizations: the Geological Survey of Canada (GSC), B.C. Ministry of Transportation & Highways (BC MOTH), B.C. Ministry of Energy & Mines, the Centre for Cold Ocean Resources Engineering (C-CORE), ConeTec Investigations Ltd. and Hughes InSitu Engineering Inc. A project of this size can not be carried out without the hard work of many people. The dedication of the main participants from industry, engineering consultants, university researchers, support staff, technicians and graduate students is very much appreciated. The financial support, both cash and in-kind, from the participants and NSERC is also appreciated. Special acknowledgments should also be given to the following people who helped make the ground sampling program at each site a success: G. Cyre, N. Pouliot, F. Gilbert, and S. Saint-Laurent. The work of C. Hereygers and S. Gamble, who catalogued the frozen core, trimmed it in preparation for laboratory testing and coordinated the distribution of trimmed samples to the various testing laboratories, was also greatly appreciated.

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

Site data		Sampling procedure and comments
Phase	Site	
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., 1994a) (see Figure 1 for illustration of ground freezing & sampling configuration at the Phase I site; Hofmann et al., 1998b) • A total of 20 m of sandy soil core was obtained (Hofmann, 1997)
II	Massey & 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 & Sego, 1996) • A total of 18 m of 100 mm diameter sandy soil core was obtained (Biggar & Sego, 1996)
	HM 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 & Sego, 1996)

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

Method	Site data: Phase	Site data: Site	Sampling procedure and comments
Fixed piston tube	Phase I & II (Plewes, 1993 & 1995)		• Drilling equipment: truck-mounted Failing 1500 Special mud rotary drill supplied by Elgin Exploration Company Ltd. of Calgary • Fixed piston sampler: mechanically operated 76 mm sampler manufactured by Sprague and Henwood, Inc., Assembly No. WA15119 was used (purchased by Klohn-Crippen in 1979; since then, some modifications have been made) • Shelby tubes used with the sampler: manufactured by Acker Inc. and supplied by Elgin Exploration; 76 mm 16 gauge stainless steel, 0.76 m long; nominal inside diameter of 73 mm and wall thickness of 1.6 mm; 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 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
	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 • 14 samples were considered to be high quality (Types I & II; Plewes, 1993)
	II	Massey	• 4 samples in total • 2 samples were considered to be high quality (Plewes, 1995)
		Kidd	• 26 samples in total • 17 samples were considered to be high quality (Plewes, 1995) • 8 of these high quality samples were in the target zone
Christensen double-tube	I	Mildred Lake (Plewes, 1993)	• 1.5 m long wireline Christensen double-barrel core sampler (Elgin Exploration); inner barrel assembly which is 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 which 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) • Performed in 2 boreholes: CORE-1 and CORE-2; a total of 24.55 m of sand were 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	Phase II & IV (Konrad et al., 1995a & 1995b; Konrad, 1996)		• 200 mm diameter sampler (see Figure 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 over-coring tube when it is pushed into the soil
	II	Massey Konrad et al. (1995a & 1995b)	• Four tubes were successfully obtained at depths between 8.3 m and 10.6 m • Dry ice used to unidirectionally freeze samples on site (required about 8 hours) • Sample lengths: 42 cm, 55 cm, 46 cm and 34 cm • Void ratios were calculated for 14 specimens trimmed from these samples
		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 with the Laval large diameter sampler 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

Sites	Sampling procedure and comments (Monahan et al., 1995; Monahan, 1998)
Massey & Kidd	• Sonic boreholes located 6 to 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 on to 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		Average	Mineralogy of fines (passing No. 200 sieve), in percent						
Phase	Site	FC (%)*	Quartz	Feldspar	Kaolinite	Mica	Chlorite & Smectite	Illite	Calcite
I	Mildred Lake	≈ 10	90	5	5	trace	--	--	--
II	Massey	< 5	70	15	5	5	5	--	--
	Kidd	< 5	70	15	5	5	5	--	--
III	J-pit	≈ 15	Assumed to be the same as for Phase I						
IV	LL Dam	≈ 8	36	9 (plagioclase feldspar) 2 (potassium feldspar)	3	27	5 (smectite) trace (chlorite)	15	3
	HM Dam	≈ 10	57	21 (plagioclase feldspar) 5 (potassium feldspar)	4	1	2 (smectite) trace (chlorite)	7	5

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

Table 5. Comparison of void ratios for samples obtained using different sampling methods

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

* Numbers are given as overall average values in target zone (numbers in brackets are overall standard deviations in target zone); values of e_{min} and e_{max} used to calculate relative density (D_r) are given by Robertson et al. (1998a).

† The numbers of samples indicated for ground freezing & sampling and the Laval large diameter sampler are the number of samples trimmed from the frozen core for testing; for the fixed piston tube sampler, the number of samples are the number of high quality (Type I & II) tube samples obtained from the target zone at each site.

‡ Based on S_r = 100%; comment indicates quality of geophysical (gamma-gamma) logs based on measured compensation values (Wride et al., 1998)

Table 6. Comparison of ground freezing and sampling costs for the CANLEX project (after Hofmann et al., 1998b)

Phase	No. of Sites	Length of Core (m)			Volume of Core (cm^3)	Total Cost * (CAD)	Unit Cost		
		100 mm ϕ	200 mm ϕ	Total			Site (CAD/site)	Length (CAD/m)	Volume (CAD/cm^3)
I	1	20	0	20	157,080	94,200	94,200	4,710	0.60
II	2	40	0	40	314,159	100,100	50,050	2,503	0.32
III	1	3.9	6.9	10.8	247,400	48,000	48,000	4,444	0.19
IV	2	31	3	34	337,721	81,822	40,911	2,407	0.24

* Includes cost of liquid nitrogen, drilling fees, engineering supervision, labour, and equipment.
(Note: costs associated with sample handling, shipping and storage are not included)
(Note: costs associated with travel, accommodation, and meals are not included)

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

Sampling Method	Phase	No. of Sites	Samples			Total Cost * (CAD) ESTIMATED	Unit Cost		
			Number	Total Length (m)	Total Volume (cm^3)		Sample (CAD/sample)	Length (CAD/m)	Volume (CAD/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	5000	--	315	0.08
Laval large diameter	II	2	4	1.77	60,144	12,000	3,000	6,780	0.20
	IV	1	2	0.50	16,990	10,000	5,000	20,000	0.59

* Includes cost of drilling fees, engineering supervision, labour, and equipment.

(Note: costs associated with sample handling, shipping and storage are not included)

(Note: costs associated with travel, accommodation, and meals are not included)

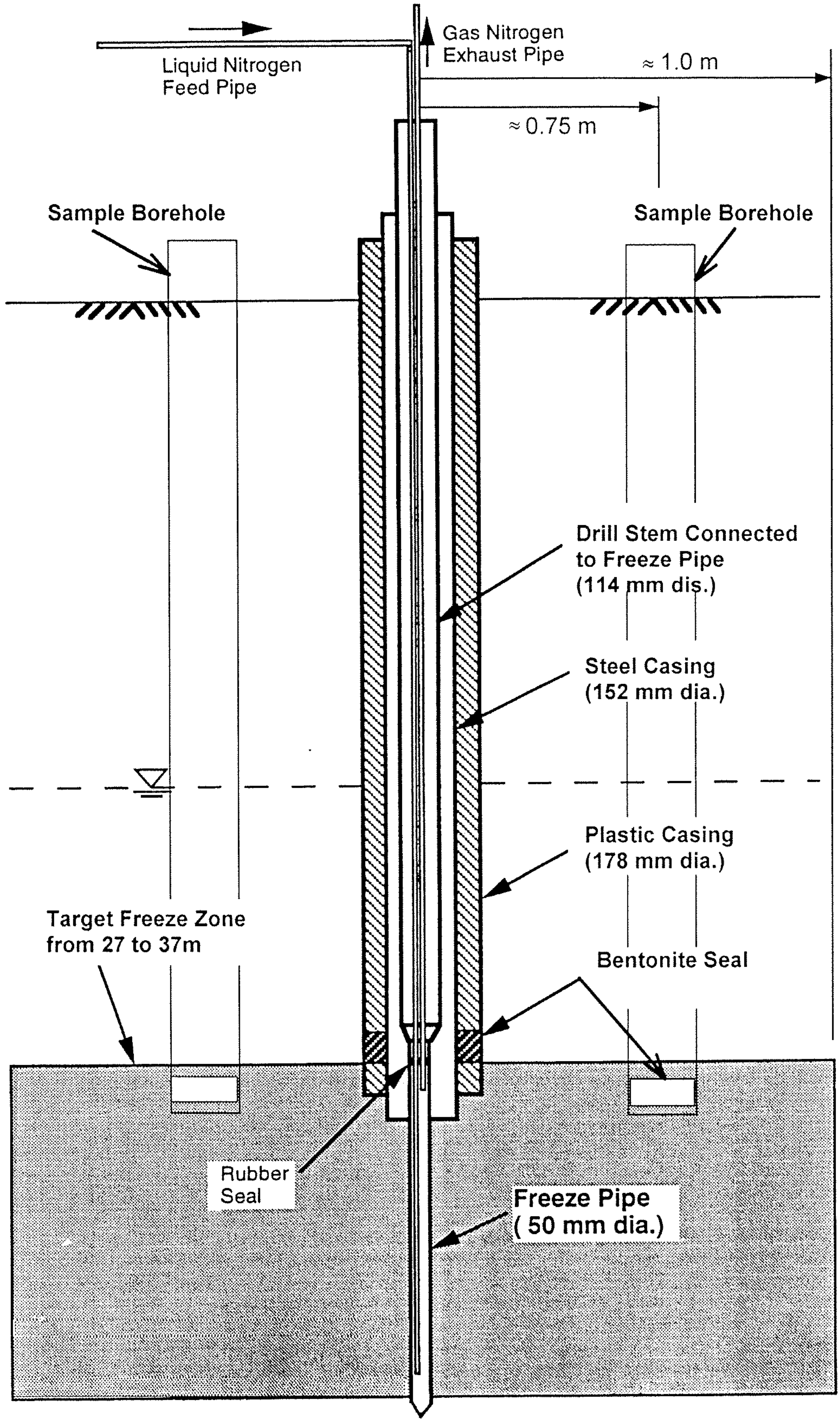


Figure 1. **Schematic diagram of ground freezing and sampling at the Phase I CANLEX test site (after Hofmann et al., 1998b).**

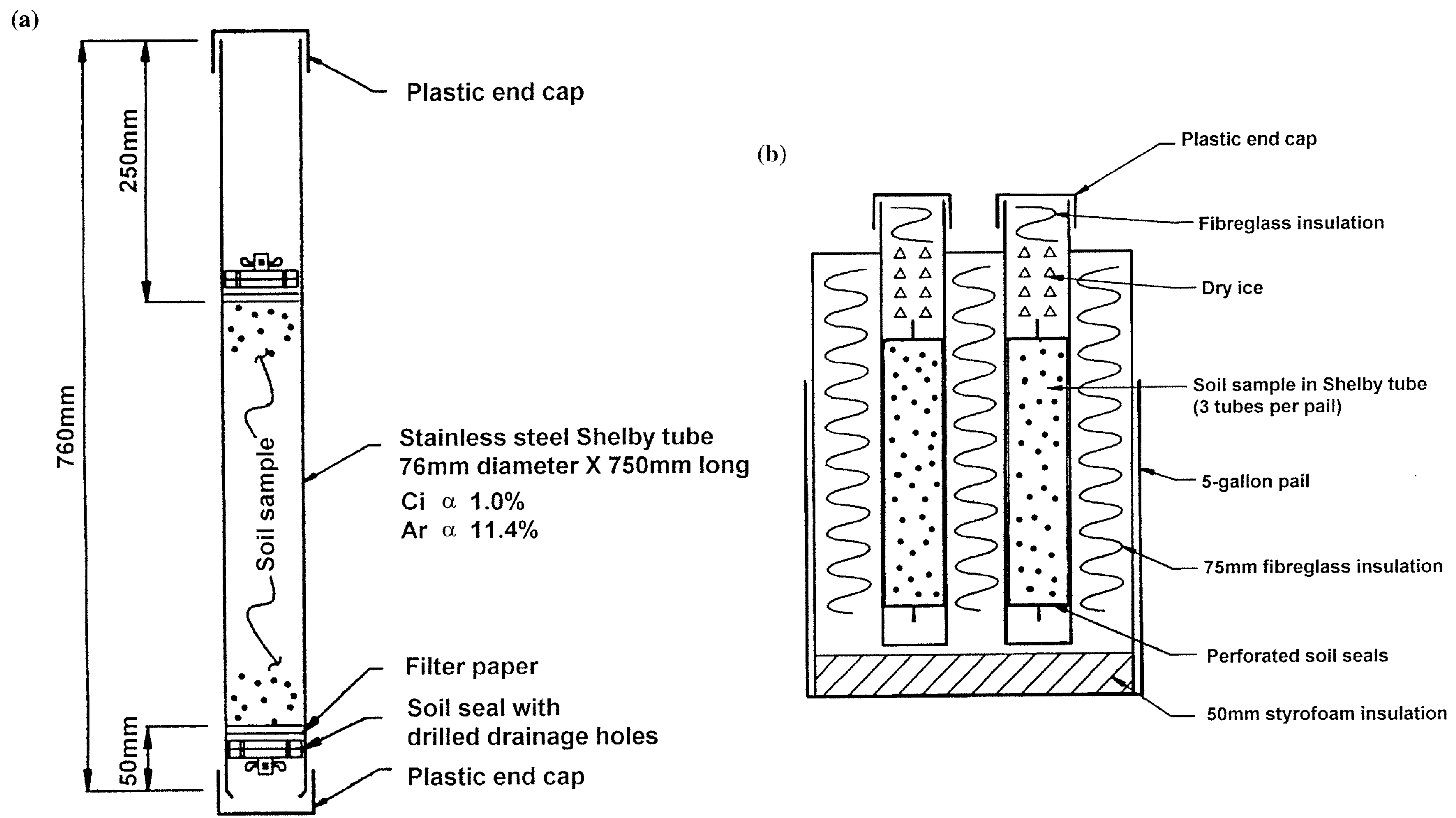


Figure 2. Fixed piston tube sampling: a) preservation of Shelby tubes; b) set-up for freezing of soil samples in Shelby tubes (after Plewes and Hofmann, 1995).

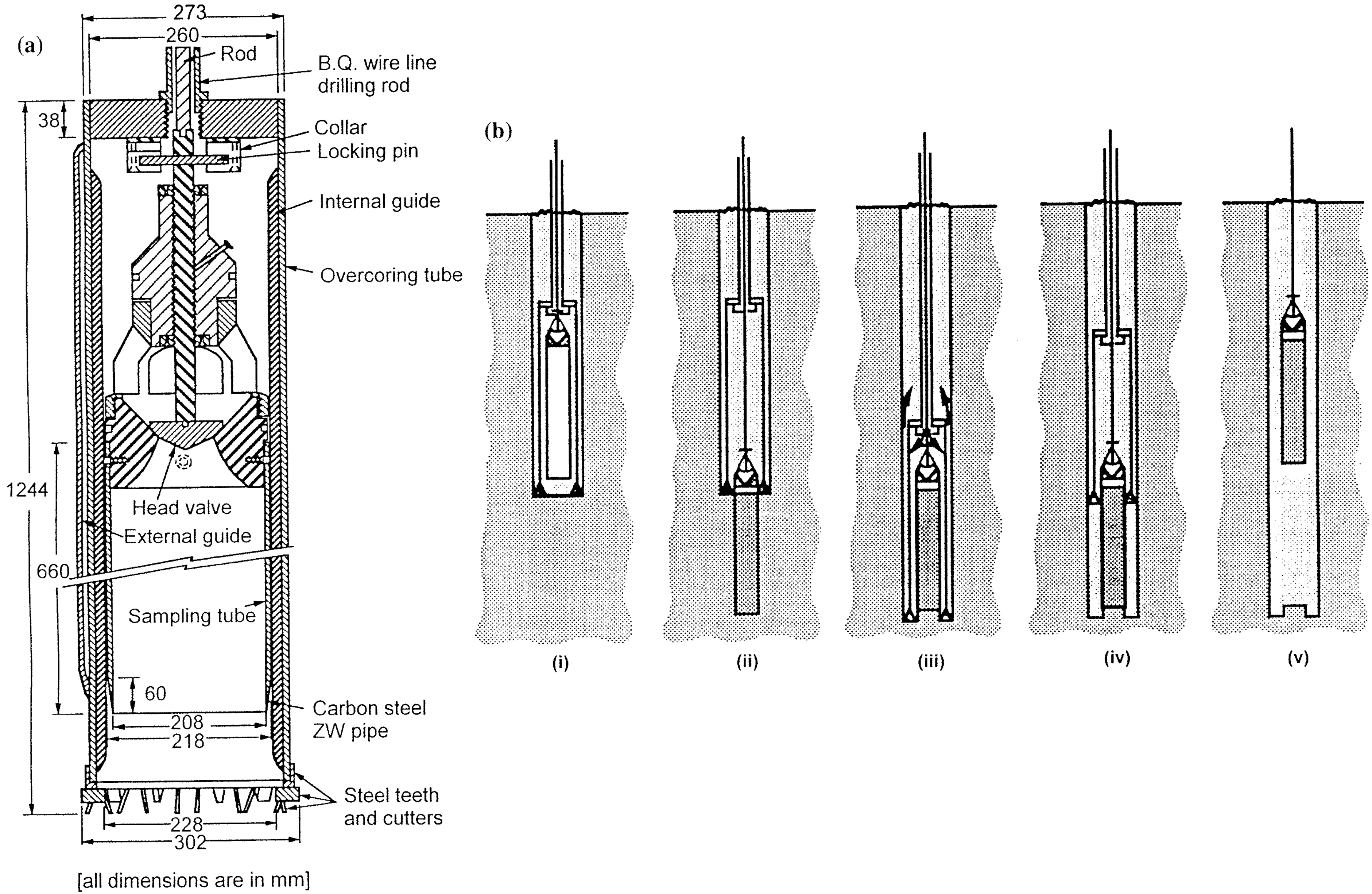


Figure 3. The Laval large diameter sampler: (a) Schematic diagram of the sampler (after Konrad et al., 1995a and La Rochelle et al., 1981); (b) general operation of the sampler in sands (after Konrad et al. 1995a).

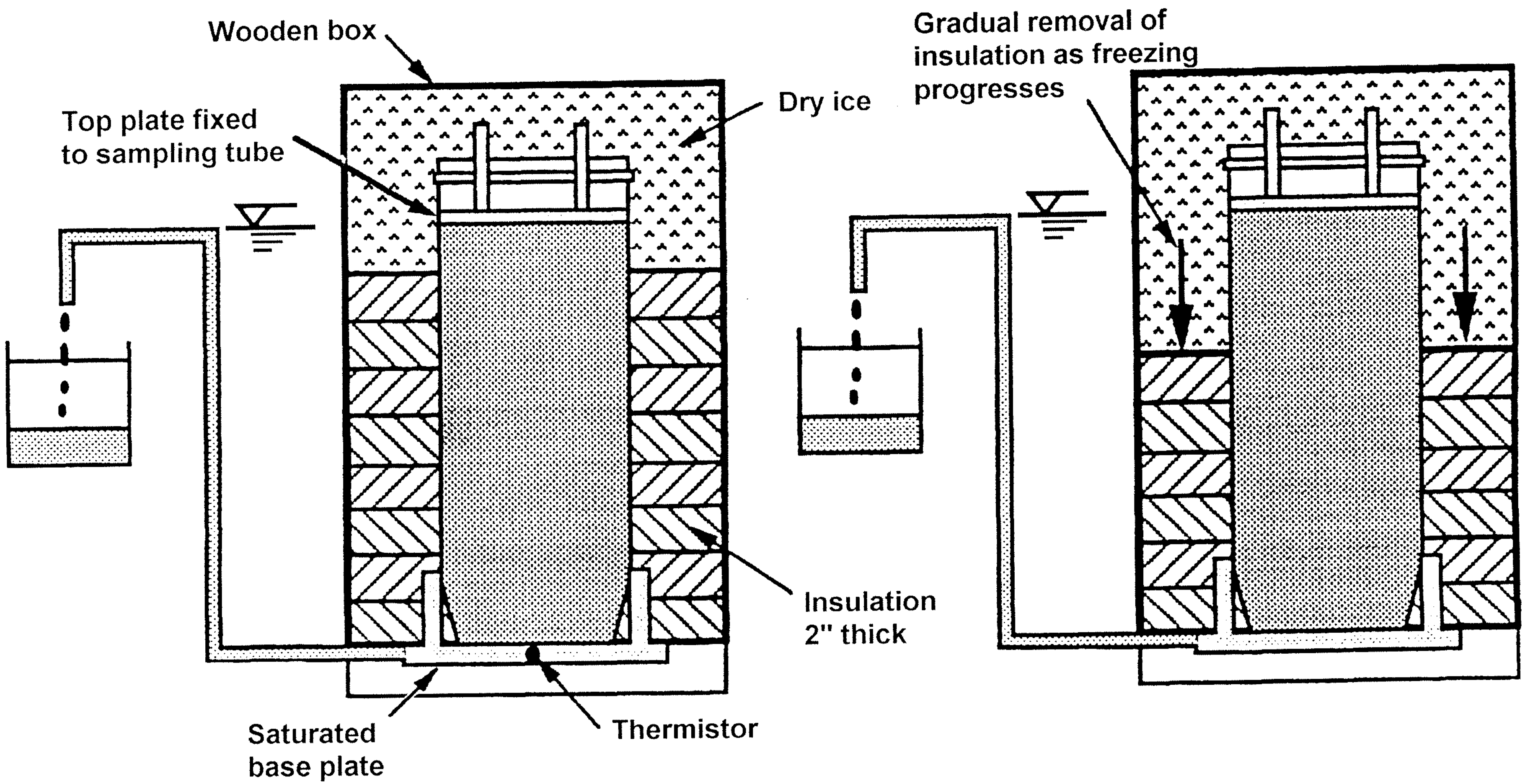


Figure 4. Set-up for freezing of Laval large diameter sampler soil samples (after Konrad et al., 1995a).

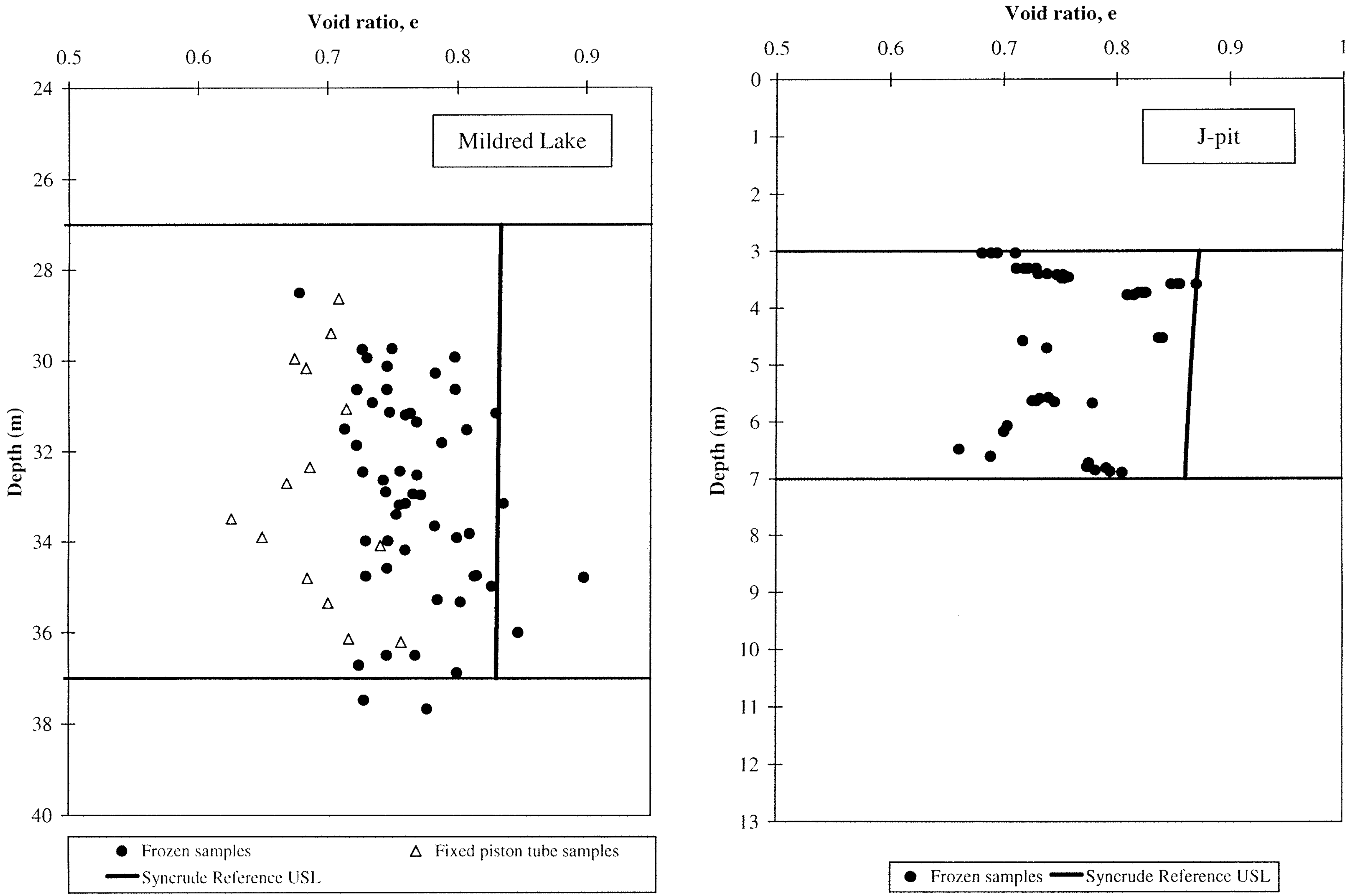
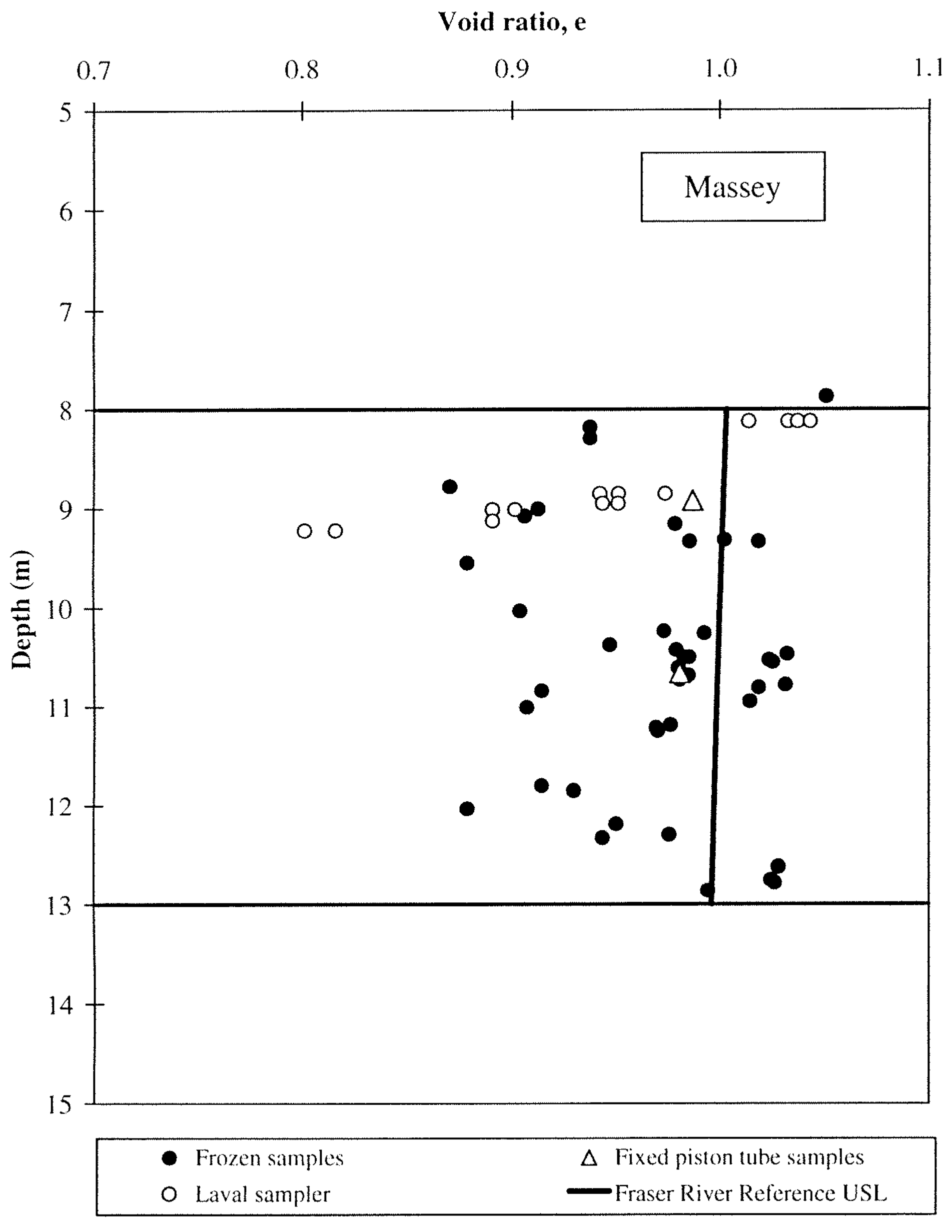


Figure 5. **Void ratios of (a) undisturbed frozen samples and piston tube samples obtained at the Phase I (Mildred Lake) site, and (b) undisturbed frozen samples at the Phase III (J-pit) site.**



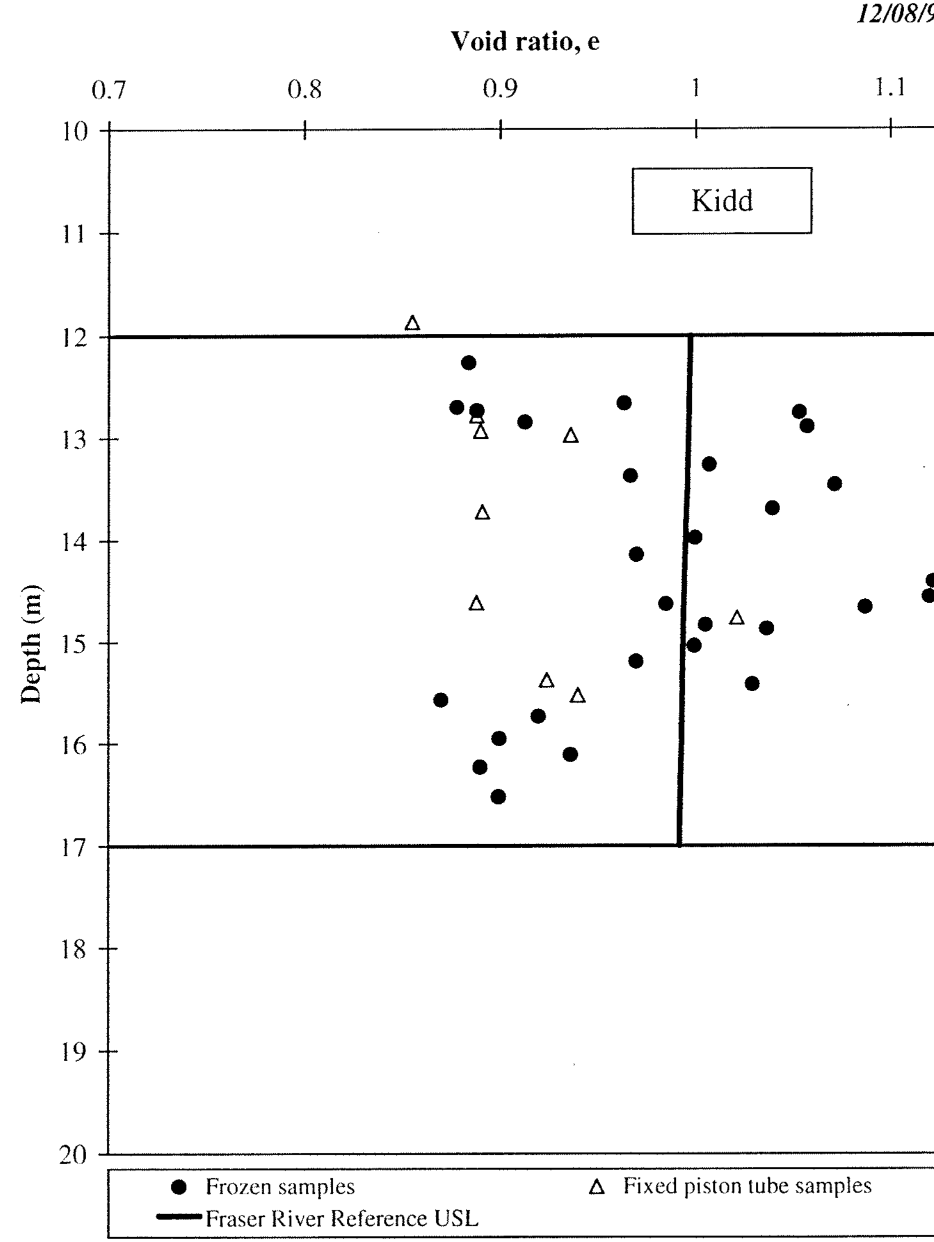


Figure 6. Void ratios of (a) undisturbed frozen samples, Laval large diameter sampler samples and piston tube samples from the Massey site, and (b) undisturbed frozen samples and piston tube samples from the Kidd site.

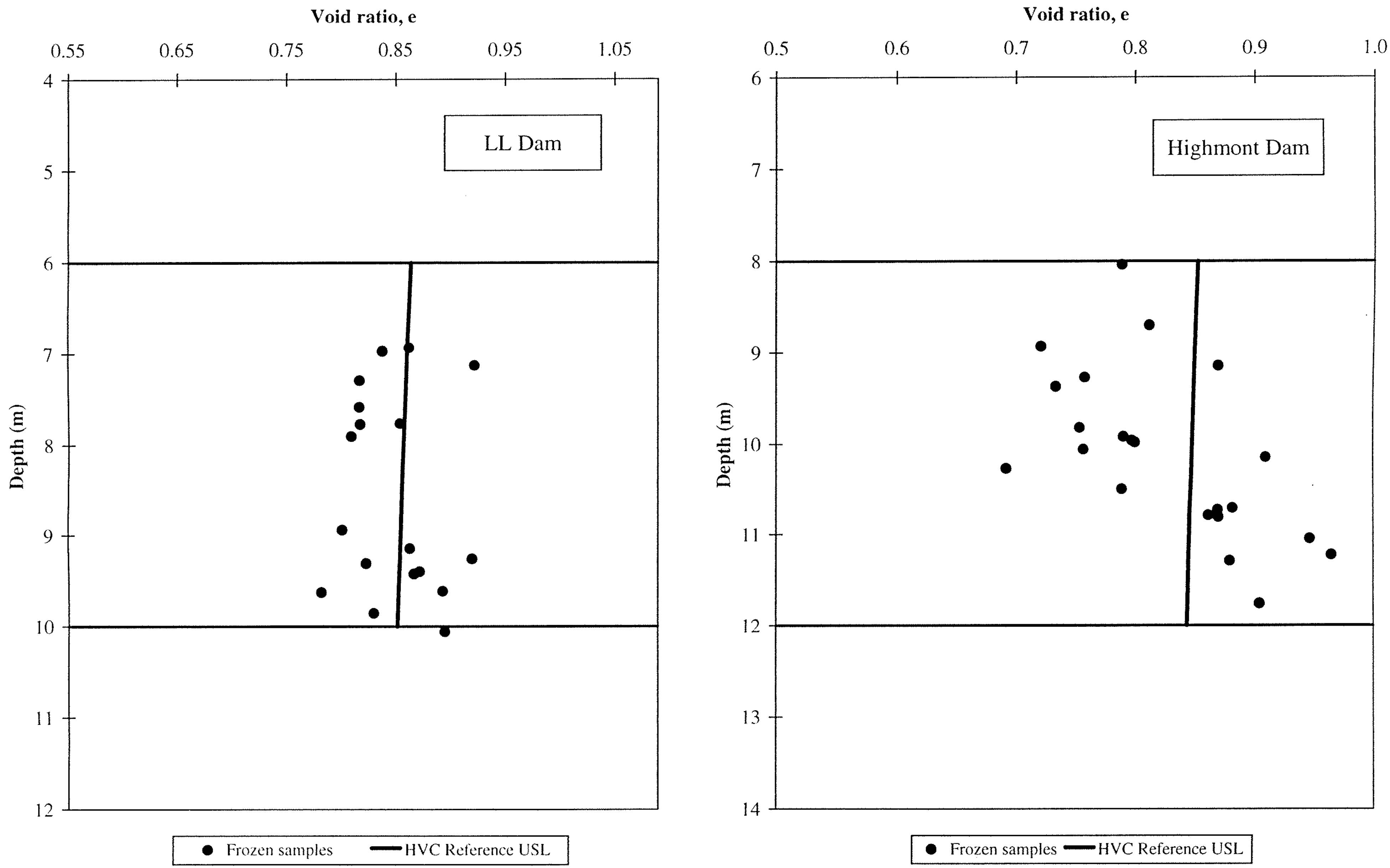


Figure 7. Void ratios of (a) undisturbed frozen samples from the LL Dam site and (b) undisturbed frozen samples from the Highmont Dam site.

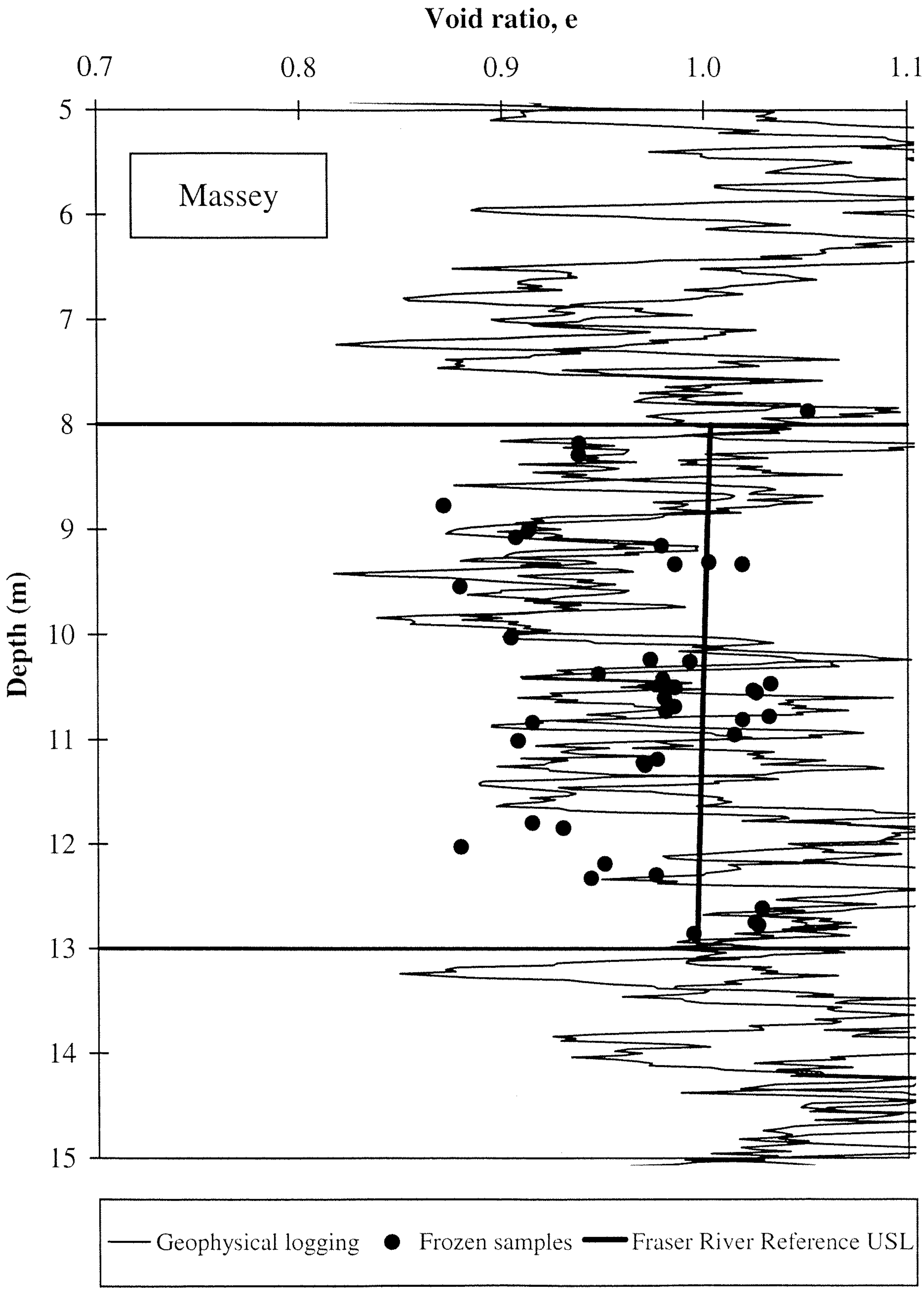


Figure 8. Comparison of void ratio interpretation of geophysical logging results with void ratios of undisturbed ground freezing samples from the Massey site.

List of Figures