GROUND FREEZING AND SAMPLING OF FOUNDATION SOILS AT DUNCAN DAM

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ABSTRACT

Insitu ground freezing to obtain undisturbed samples of a loose sand beneath the Duncan Dam in British Columbia is described. This was the first known use of ground freezing to assist in obtaining samples at depth greater than 10 m in Canada. Once frozen, the sand was cored and brought to the surface using a CRREL core barrel, which is used extensively in permafrost regions.

The design, installation and performance of the liquid nitrogen freezing systems are described in detail. The drilling, sampling and preparation of the frozen core for transport to the testing facility are also outlined. The quality of the core retrieved during the sampling was judged to be excellent and good agreement was found between the void ratios measured using both the frozen core and high quality gamma-gamma density logging techniques, which were performed adjacent to ground freezing and sampling locations.

Keywords: Ground freezing, cohesionless soils, undisturbed sampling

INTRODUCTION

Techniques are currently available to obtain high quality undisturbed samples of cohesive soils. However, little advance had been made in the procurement of undisturbed samples of cohesionless soils such as sands, silty sands and clayey sands. Conventional sampling techniques of cohesionless soils can induce void ratio changes and particle rearrangements due to mechanical disturbance, reduction in confining stress, poor handling during transportation, storage, and trimming prior to testing. The behavior of a cohesionless soil can change from strain softening to strain hardening during undrained loading when small changes in void ratio occur due to this disturbance. In the area of earthquake design and liquefaction, researchers and practitioners are becoming more aware of the importance of obtaining high quality undisturbed samples of cohesionless soils. Plewes *et al.* (1993) describes very careful drilling and conventional sampling of cohesionless sands and then outlines how these samples were frozen at the surface to allow them to be safely transported for later laboratory testing. These sands underwent some disturbance which altered their behavior when subjected to undrained loading.

Efforts have been made to evaluate the degree of disturbance that can take place during conventional sampling techniques (Marcuson *et al.* 1977). However, there are inherent difficulties in correctly assessing the degree of disturbance of natural sand deposits caused by conventional sampling; especially in how the disturbances affect the strain softening behavior of especially loose cohesionless soils.

Ground freezing has been used as a soil stabilization method for excavations and tunnels for many years. However, there have been only a limited number of attempts to use ground freezing techniques to obtain samples of cohesionless soils. The US Corps of Engineers first reported the use of artificial ground freezing to obtain undisturbed samples in a study at the Fort Peck Dam (U.S. Army Corps 1938). Following the work of the Corps of Engineers, there were several other attempts to use ground freezing to obtain undisturbed samples (Bishop 1948; Hanzawa and Matsuda 1977; Marcuson *et al.* 1977).

Several factors affect whether a soil can be frozen without inducing disturbance as it freezes. The suction and expansion of the interstitial water during phase change from water to ice is the primary cause of disturbance to the soil matrix. Hence, the water migration during the freezing process must be understood to determine whether the soil can be frozen without inducing disturbance. These factors are related to the frost heave susceptibility of the natural soil.

An excellent review of frost heave and frost susceptibility of soils was presented by Konrad and Morgenstern (1983) and Horne (1987). Konrad and Morgenstern (1980) presented an engineering model for frost heave that includes the effects of soil permeability, segregational freezing temperature, temperature gradient, suction at the freezing front, rate of cooling and the vertical stress. Yoshimi *et al.* (1978) pointed out that neither the permeability nor the soil gradation alone can account for the disturbance during freezing. They attempted to determine the behavior of sands during freezing by increasing the fines content and concluded that for saturated sands the disturbance induced by freezing increases proportionally to the percent fines.

Davila *et al.* (1992) defined the range of soil types and characteristics in which *insitu* ground freezing can be applied to obtain undisturbed samples. They proposed a new criteria to distinguish between sandy soils that underwent frost heave and those that exhibited no heave. The criterion is based on the amount of clay minerals present and the specific surface area of the clay in the fines portion of the soil. From laboratory uniaxial freezing tests performed on sandy soils with different amounts and type of fines, they established an approximate boundary between a soil that can or cannot be frozen without disturbing its matrix. A summary of the proposed relationship is shown in Figure 1.

Most freezing systems consist of an inner pipe and an outer freezing pipe. Coolant is supplied to the bottom of the freeze pipe through the inner pipe and flows to the surface via the outer pipe. While the coolant flows upward in contact with the outer pipe, heat is removed from the ground by conduction through the wall of the freeze pipe. Coolants used are either, liquid nitrogen (-196 °C), ethanol and dry ice (-70 °C), or brine (liquid calcium chloride -30 °C). Yoshimi *et al.* (1984) used a freezing system shown in Figure 2 to obtain undisturbed frozen samples of a clean saturated sand using liquid nitrogen as a coolant. After the soil was frozen, the soil was over-cored and the complete column of frozen soil was pulled to the surface. Figure 2 illustrates how the frozen column was frozen and retrieved. It was reported that the exterior of the frozen sand column after retrieval appeared to have retained its *insitu* density. This method limits its use to shallow depths and requires heavy lifting equipment.

This paper describes the first known application of *insitu* ground freezing with drilling and sampling to obtain undisturbed samples from a depth greater than 10 m in Canada. The *insitu* ground freezing program was performed at the Duncan Dam in British Columbia for BC Hydro.

INSITU GROUND FREEZING AT DUNCAN DAM

The Duncan Dam, located 8 km upstream of the confluence of the Duncan River, provides storage for hydroelectric generation and flood control in the Columbia River basin (Figure 3). The earth fill Duncan Dam, 39 m high and with a crest length of 792 m, is founded on an approximately 380 m thick sequence of unconsolidated alluvial sands, silts and gravel. Under a recent dam safety evaluation program, BC Hydro assessed the potential for liquefaction within the foundation soils underlying the dam under revised earthquake loading (Little *et al.* 1993). Preliminary screening studies and site investigation identified that the sand unit located in the upper 20 m of the alluvial deposit could become susceptible to liquefaction under the imposed seismic loading (Figure 4). This loose uniform deposit is composed of a fine-grained, saturated sand with up to 20% non plastic fines. A comprehensive sampling program employing state-of-the-art sampling, techniques was conducted in 1990 to retrieve undisturbed samples of the sand layer. The techniques used were *insitu* ground freezing (Sego *et al.* 1993), fixed piston sampling, and Christiansen core barrel with a modified inner core barrel (Plewes *et al.* 1993). *Insitu* ground freezing was performed to freeze a zone of loose uniform sand found between 12 m and 20 m beneath the existing downstream toe berm of the dam. A summary of the soil profile is presented in Figure 5, which shows that the loose uniform sand layer is overlain by 2 m of silty sand and about 10 m of coarse gravel fill that was placed to form a stabilizing toe berm during the original dam construction. The average SPT $(N_1)_{60}$ value for the uniform sand layer was approximately 10. The following sections briefly describe the design of the ground freezing system and the field work to carry out the freezing, drilling and sampling of the frozen soil.

Design Of Ground Freezing System

To obtain undisturbed samples, the ground freezing system must not disturb the sand layer during installation, freezing of the layer, and later drilling and sampling the frozen soil. These prerequisites guided the selection of the freeze pipe configuration that was installed. The overall cost to freeze the ground and the time required to install and operate the freezing system influenced the selection of the coolant and the refrigeration plant that was used. The freezing system consisted of freeze pipes connected to surface piping and the refrigeration system. Hence, the design of the freezing system involved selection of freeze pipe, selection of refrigerant, and determination of the time required to freeze a given volume of soil.

Freeze-pipe Selection

A schematic of the freeze-pipe configuration selected is shown in Figure 6. It consists of a 7 m length of 50 mm diameter steel pipe installed in the zone of soil to be frozen and within the larger casing placed through the 10 m thick toe berm to the surface. The bottom of the freeze pipe was sealed using a bentonite plug. A 13 mm diameter copper pipe was placed in the steel freeze pipe to transfer the refrigerant to the bottom. The tip of the freeze pipe was designed with a special hardened steel cutter which was used to advance the freeze pipe with minimum disturbance to the *insitu* sand. Because of the great depth, a coupler was designed to seal against ground water and to connect the upper copper pipe to the lower steel freeze pipe.

The 50 mm diameter freeze pipe was selected for the Duncan Dam project since it minimized both the radial zone of soil disturbance during installation and the volume that needed to be frozen to retrieve undisturbed samples. The use of this small diameter freeze pipe required longer times to freeze a given volume of soil when compared to more conventional 75 to 150 mm diameter freeze pipes.

Coolant Selection

Both liquid nitrogen and brine refrigeration systems have been previously used for ground freezing. For the Duncan Dam project, liquid nitrogen was selected because of the cost and the additional time required to mobilize and operate a brine refrigeration system. This decision was based on the initial project requirement of a single 4 m length of soil to be frozen. The time required to freeze a volume of soil is longer using a brine system operating at -30°C than a liquid nitrogen system operating at -196°C. The brine system also requires the mobilization of a special power plant, compressor and pumps since the site is remote without a convenient source of electricity, whereas the liquid nitrogen system requires only the delivery of a tanker containing the liquid nitrogen to the site.

Time to Freeze Soil

Detailed heat flow calculations were carried out to determine both the time to freeze the soil and the heat energy to be extracted from the ground. The approaches described by Sanger and Sayles (1978) and Carslaw and Jaeger (1959) were used to compare the design calculations. To check the accuracy of these theoretical approaches, a laboratory freezing experiment was carried out on a small volume of loose sand under controlled conditions. The measured advance of the freezing front was compared to the theoretical predictions. This test supported the time to freeze predictions using the above two calculation methods.

The uniform loose sand at the Duncan Dam site was assigned the following properties for use in all thermal design calculations:

Moisture content = 30%
Dry density = 1.38 Mg/m^3
Unfrozen thermal conductivity = 1.5 W/m•k
Frozen thermal conductivity = 2.8 W/m•k
Unfrozen volumetric heat capacity = 2.9 MJ/m^3•k
Frozen volumetric heat capacity = 2.0 MJ/m^3•k

Volumetric latent heat = 138.3 MJ/m^3

Constant freeze pipe temperature = -190°C

Constant ground temperature = +4°C

The ground temperature was assumed since temperature information was not available during the design stage. Figure 7 shows the predicted radial advance of the freeze front versus time using the two analytical methods. To freeze a 1.0 m radius column of sand requires approximately 180 hours (8.3 days). The radius is measured from the center of the freeze pipe.

The heat energy released by the soil to the freeze pipe during cooling and phase change is calculated to obtain the amount of liquid nitrogen that must be supplied. The predicted liquid nitrogen usage was based on the amount of the heat energy removal that occurs when the liquid nitrogen undergoes phase change. The heat of vaporization to convert the liquid to gas at -195.8°C is 199 MJ/Mg. The additional cooling association with the specific heat of the gas was neglected. Figure 7 shows the amount of liquid nitrogen required to advance the freezing front for a one-metre column length of freeze pipe and frozen sand. The amount of liquid nitrogen needed to freeze the sand was predicted to be between 1200 to 1400 l/m^3. Information provided by Canadian Liquid Air suggested that 1200 l/m^3 was an appropriate design value. The design calculation for the advance of the freezing front and the volume of required liquid nitrogen supported the selection of liquid nitrogen as an appropriate refrigerant based on cost for this project.

Drilling Frozen Sand

It was necessary to obtain information on the strength of frozen sand at cryogenic temperatures to confirm that the sand could be drilled using a Cold Regions Research and Engineering Laboratory (CRREL) core barrel. The temperature at the targeted core sample location, which was at a radial distance of about 500 mm from the freeze pipe, was predicted to be at about -40°C (Figure 8). This required the core barrel to cut through frozen sand at temperatures much colder than previously attempted. The strength of frozen saturated sand at -40°C was estimated to be between 20 and 30 MPa (Bourbonnais and Ladanyi 1985). To evaluate if the core barrel would cut at these temperatures, the sample frozen in the laboratory using liquid nitrogen was cored. This showed that the tungsten carbide teeth used on the core barrel were capable of coring frozen saturated sand at temperatures as low as -100°C. Thus, it was determined that the selected coring system would be capable of advancing through the frozen sand in the field.

FIELD INSTALLATION

Freeze Pipe

A plan view locating the freeze pipes (FP), the various sampling holes (S) and the temperature measuring probes (RTD) is shown in Figure 9. Freeze pipe #1 (FP-1) was installed on May 23, 1990. Freeze pipe #2 (FP-2) was installed on May 24, 1990. A detailed description of their installation is given in the following sections.

The 10-m thick gravel berm at the sampling locations required that 150 mm diameter open ended casings be advanced through the berm for later installation of the freeze pipe and sample holes. The casings for later sampling were located about 500 mm from the freeze pipe. All casings were advanced and stopped at a depth of 10 m to ensure that the uniform sand layer, which began at a depth of 12 m, would not be disturbed by the installation process. Each casing was then cleaned for either installation of a freeze pipe or later sampling. The bottom of each casing set for later sampling was sealed with a bentonite plug prior to having all the ground water removed. All casings were measured for vertical alignment using a removable slope indicator casing system.

Once the casings were installed, the first section of freeze pipe was prepared for installation. The first section consisted of a cutter shoe, a freeze pipe and an internal jetting pipe. The jetting pipe, which was used to self-bore the 50 mm freeze pipe into the sand, was maintained between 100 and 200 mm above the cutter shoe to reduce the potential of washing disturbance of the *insitu* sand. The freeze pipes were advanced by a slow steady push using the chain drive on the drill rig. The freeze pipe sections were 7 m long and were stabilized and centered within the upper casing using evenly spaced stabilization rings with interconnected ropes for later removal. As the freeze pipe advanced into the soil, the rings stopped at the bottom of the surface casing.

Freeze pipe #1 was advanced between 12 and 18 m depths, leaving about a 1 m extension above the plug in the bottom of the surface casing to enable connection to the surface. Freeze pipe #2 was installed using the same procedure, except that the upper casing was advanced to a depth of 16 m and the freeze pipe was advanced to a depth of 21 m. This provided 2 m extension above the bottom of the casing. Additional lengths of copper pipe were connected to the freeze pipe section, to extend it to the ground surface. The couplers were fabricated of brass and were designed to provide a water tight seal. Copper rather than steel was selected for the freeze pipe extensions because of its reduced weight and ease of handling in the field.

Special measures were taken to prevent freezing above the targeted sampling interval and thus minimize refrigeration energy losses. A bentonite seal was placed above the sampling zone to isolate the freeze pipe and the inside of the 150 mm casing from any inflow of ground water. This was accomplished by placing bentonite pellets from the surface to make a seal at the bottom of the casing. After the seal was achieved, the water within the casing was removed using compressed air, and the annulus was back-filled with pelletized vermiculite insulation. The placement of the vermiculite was carried out in early June immediately before the liquid nitrogen circulation system was installed. Figure 10 shows the final locations of seals and the zones to be frozen with each freeze pipe.

Temperature Monitoring Probes

The locations of the temperature monitoring holes are shown in Figure 9. Each hole contained one temperature measuring probe (RTD) placed at the desired depth within a 19 mm plastic tube. The borehole was advanced from the surface without using a casing. The locations were selected to be as close as possible to the sample hole, with the temperature probe to be located at the top of the subsequent freezing zone. This would allow the radial advance of the freezing front to be monitored without disturbing the sand that was to be cored.

FIELD MONITORING OF THE GROUND FREEZING

Liquid nitrogen was first introduced into freeze pipe #1 at noon on June 10, 1990 (day 0) and into freeze pipe #2 at 15:00 hours on day 2. Initially each freeze pipe received liquid nitrogen directly from the tanker to cool down the freeze pipes and to immediately freeze the adjacent soil. This ensured that any small ground-water leaks were immediately sealed. After an initial two days of alternating the liquid nitrogen into one freeze pipe and allowing the cold gas to flow to the other, each freeze pipe received liquid nitrogen directly from the tanker and the exhaust gas was vented to the atmosphere. This was determined to be the best approach since the liquid nitrogen usage in the field was not affected by whether the flow was directed either simultaneously to both pipes or solely to one pipe with the cold gas being circulated to the second freeze pipe.

Figure 11 shows the liquid nitrogen usage versus time with day zero at noon, June 10, 1990. The rate of consumption averaged about 180 l/hr (4320 l/day) throughout the project. A deviation from this usage rate occurred between 220 and 240 hours and is related to changes in the advance of the ground temperature as recorded by RTD #1 adjacent to freeze pipe #1.

Figure 12 illustrates changes in the ground temperature during the freezing period. The radial distances of each RTD from the freeze pipes are given in Figure 9. The initial ground temperature at a depth of 11.5 m for freeze pipe #1 was +8.2°C, which was about 4 C° warmer than anticipated during the design. For the first 40 hours of freezing, the temperature decreased rapidly, but then the rate of temperature drop slowed. The temperature then gradually decreased so that 0°C was achieved at RTD#1 after 260 hours. This compares with a calculated time of about 50 hours. This substantial difference will be discussed in a later section. The initial ground temperature at freeze pipe #2 was about +7.5°C (RTD#6), which shows that heat appears to be flowing downward throughout the soil profile beneath the berm at the sampling location. RTD#6 adjacent to freeze pipe #2 was located 13.4 m below the surface, whereas RTD#1 adjacent to freeze pipe #1 was located at a depth of 11.5 m. The measurements suggest a downward temperature gradient of 0.37°C/m. The soil temperature recorded by RTD#6 gradually decreased with time but at a much slower rate than recorded by RTD#1 since heat was being provided from above.

The slow rate of heat extraction (temperature decrease) had not been anticipated during the design of the freezing system. To investigate the reason for this, a deeper set of temperature probes were installed at location S3 adjacent to freeze pipe #1 (see Figure 9). The S3 location was selected since the bottom of the casing was located such that it would not intersect the frozen column; this was because the casing was deflected away from the freeze pipe during installation. Four temperature probes were installed at depths of 13 m, 14 m, 15 m, and 16 m. These temperature probes were located at a distance of about 770 mm from freeze pipe #1. Figure 13 shows the vertical temperature distribution within the soil adjacent to the advancing frozen column. The cooling of the surrounding sand is illustrated in Figure 13 by the steady decrease in temperatures with time.

The measured ground temperatures illustrate that heat is flowing downward to the column of soil being frozen. The temperature gradients were greater than had been anticipated during the design and resulted in slower rates of heat extraction and freezing front advance throughout the *insitu* ground freezing operation.

DRILLING AND SAMPLING FROZEN SAND

Drilling to retrieve samples of frozen sand was started in the S1 casing (Figure 9). The bentonite plug which had previously been installed to keep out ground water was cored using the CRREL barrel even though it was unfrozen. At a depth of 13.2 m, the barrel encountered a uniform fine gray frozen sand. A total of 10 individual cores were recovered using the CRREL barrel, producing a total core length of 3.4 m out of the 3.5 m of frozen sand drilled. The cores retrieved from S1 were of excellent quality and 100 mm in diameter.

The frozen sand was easily drilled with the tungsten carbide tipped cutting shoe on the CRREL core barrel. Typically during the drilling, the bottom portion of a core would break and then fall back down the hole. This piece of core was retrieved during the next coring operation. To eliminate this loss of core, the barrel was modified on site to install core catchers to improve the recovery. These improvised core catchers improved the recovery throughout the remainder of the sampling operation.

A second sample hole was started adjacent to S1. Drilling was slow since the top 10 m of coarse overburden had to be drilled to set a casing prior to drilling the frozen sand. This sample hole was designated as S1A (S7). Once the casing was set and the coarse material removed, the bit encountered the frozen column at a depth of 12.2 m. The CRREL core barrel was then used to core the frozen column. During the sampling in S1A (S7), water seeped in between the base of the casing and the frozen column of sand. This caused a small amount of melting, which formed a small thawed film on the outer edges of the samples. The cores recovered had frozen diameters greater than 90 mm. Sample hole S1A (S7) produced 14 sections of very good to excellent core with a total core recovery length of 4.0 m from the 4.3 m drilled.

All attempts to core the frozen sand around freeze pipe #2 failed. Drilling was tried in two separate sample casings. The advance of the core barrel did not encounter any frozen sand. Further attempts were stopped since the ground temperature data also indicated that the sand was not frozen.

HANDLING OF FROZEN CORE AT SURFACE

The frozen core required careful handling upon arrival at the ground surface to ensure that its quality did not deteriorate. The following describes the complete process used to remove the core from the CRREL barrel, to store the core at the drill site, to visually describe and log the core, to preserve the core against ablation, and to pack for shipment to Vancouver.

When the CRREL core barrel with a sample reached the ground surface, the barrel was immediately placed in a core extractor. A second barrel was attached to the drill stem for immediate use in the drilling operation. The core was removed from the barrel by slowly heating the outside surface of the barrel to thaw a thin layer of frozen core and remove the adhesion between the sample and the inside of the barrel. The core was then pushed from the barrel onto a plastic tray that was used to support the frozen sample. The core and tray were immediately transferred into an on site trailer to remove it from the direct sunlight. Labels were prepared to indicate the borehole number, the depths of the beginning and end of the drilling, and the top and bottom of the core. The tray and the identified sample were then placed on a bed of dry ice in a freezer to decrease its temperature before further handling. After about 10 minutes on the dry ice, the sample was wrapped with a clear plastic film to inhibit ablation of the pore ice from within the core. The labels were applied to the film and the sample was again wrapped with the film. The two layers of film were for temporary protection of the core until time was available for detailed logging and preparation for storage and shipping.

Upon completion of a borehole and after all core had been placed in temporary storage, the operation of logging and preparing the core for shipping and long-term storage began. The core was never in temporary storage longer than 24 hours. The core was transferred in an insulated box from the freezer at the drill site to the freezers in the nearby BC Hydro Maintenance Building at Duncan Dam. All handling and preparation of the core was carried out within the shade of the building to minimize any thermal disturbance of the core from the direct sunlight.

The core from the bottom of the borehole was placed on a piece of insulated board and the outer temporary wrapping of plastic removed. All labels were carefully aligned to ensure that the orientation of the core was maintained and all borehole information was available. The inner plastic film was removed and the surface scraped with a knife to expose the intact frozen sand. The dimensions of the core and a visual description were recorded. The core was then sprayed with chilled water using a mist bottle to build up a thin layer of sacrificial ice on the outer surface. Care was taken to ensure that all surfaces were coated with a layer of ice. Figure 14 shows a sample after it was described, logged and had been sprayed with the mist bottle prior to being wrapped with the plastic film. The core was then wrapped with two separate layers of plastic film. The layers alternated so that the joints in the film were not aligned. The exposed joints in the plastic film were sealed with tape (Figure 15). The plastic wrapped core was then wrapped in a layer of presoaked paper towels. The water in the paper towels froze on contact with the precooled core to provide additional protection against future ablation of the pore ice (Figure 16). The core was then wrapped in a layer of aluminum foil and sealed with tape. The labels protected with plastic film were taped to the surface of the core. The sample was then wrapped in bubble pack and placed into a 150 mm diameter plastic tube (Figure 17). The ends of the tube were packed with presoaked paper towels and capped. The plastic end caps were sealed to the tube using tape. The core identification information was then written on the surface of the plastic tube for identification in the cold storage facility. The sample and tube were then returned to the chest freezer. The complete logging and wrapping operation for each core required about 10 minutes with three people. A photographic record of the exposed core was also maintained.

In summary, two different types of protection were applied to the core to guard against damage. The protection applied to guard against moisture loss through ablation were:

- Applying a thin film of ice to the surface of the core;
- Double wrapping the surface with plastic film plus sealing the joints of plastic film with

tape;

- Wrapping core in presoaked paper towels to create an additional sacrificial layer of ice;
- Placing presoaked towel, which froze between the bubble pack and plastic end caps; and
- Sealing end caps to plastic tube.

The protection applied to guard against handling and transport were:

- Wrapping of sample within bubble pack and
- Placing bubble pack wrapped sample in plastic shipping tubes.

All of these protections were applied to preserve the samples that were to be stored at temperatures below -10°C while being transported to Vancouver and then while stored in a cold room prior to preparation for testing of the undisturbed samples.

QUALITY OF THE FROZEN SAMPLES

To evaluate the quality of the samples obtained by the *insitu* freezing method, the void ratios determined from the *instu* frozen samples were compared with high quality *insitu* borehole geophysical density measurements. Borehole density logging was carried out using a compensated gamma-gamma density logging tool (Plewes *et al.* 1991 and 1993). The accuracy of the tool was checked by density measurements in large diameter aluminum and magnesium test blocks and bedrock formations with known densities by the geophysical contractor. Multiple tool runs were conducted in the field to assess the repeatability of the measurements. Laboratory testing and X-ray diffraction analyses of the sand were then carried out to determine parameters needed for calculating the density from the gamma-gamma logging. The *insitu* void ratios determined using the geophysical borehole density log are compared with void ratio measurements from the frozen soil samples retrieved from the site in Figure 18. For comparison, the void ratio determined from fixed piston and Christiansen double tube core barrel samples retrieved adjacent to the frozen samples (Plewes *et al.* 1993) are also included in

Figure 18.

Excellent agreement between the void ratio determined from the gamma-gamma density logging and the *in-situ* frozen samples should be noted. The majority of the *insitu* frozen samples experienced minimal changes in void ratio during ground freezing and subsequent drilling and sampling. The void ratios of the samples from the fixed piston and Christiansen core sampler at this location did not compare as well with the *insitu* frozen samples, as can be observed in Figure 18. Hence, ground freezing was considered to be the most successful method of obtaining undisturbed samples of the cohesionless soil at the Duncan Dam. However, the cost of ground freezing is high and the application of this method is therefore limited to projects for which the cost of obtaining undisturbed sampling by *insitu* freezing is justifiable.

In this project, the quality of the samples were determined by comparing the sample void ratio with the void ratio determined from the gamma-gamma density logging. However, the quality of samples can also be determined by comparing the shear wave velocity of the thawed samples with the *insitu* shear wave velocity (Sasitharan *et al.* 1992; Goto *et al.* 1992). However, shear wave velocity measurements of the thawed samples were not made and, hence, a shear wave velocity comparison was not possible for this study .

COMPARISON BETWEEN PREDICTION AND FIELD PERFORMANCE

The retrieval of 7.7 m of excellent quality frozen core from the zone of fine to medium sand was plagued by operational differences between the design and field performance of the liquid nitrogen ground freezing system. This section outlines these differences and attempts to establish why they occurred so that future use of the method can be improved.

The design calculation indicated that two 4 m long columns with a radius of 800 mm from the center of the freeze pipe would develop in about 8 to 10 days. This prediction was based on maintaining a constant temperature of -190°C on the inside wall of the freeze pipe over the zone to be frozen and that the initial ground temperature was 4°C. The predicted liquid nitrogen to freeze these columns would be between 32 000 and 36 000 liters. The ground temperature at 500 mm from the freeze pipe was expected to be between -20° and -30°C once the frozen zone developed.

In the field after 12 days of circulation of liquid nitrogen through the freeze pipes, the radial distance frozen was greater than 500 mm for freeze pipe #1 and less than 500 mm freeze pipe #2.

At freeze pipe #1, RTD #1 indicated that the temperature just prior to drilling was -1.2°C at a radial distance of 490 mm. At freeze pipe #2, RTD #6 indicated that the temperature was 2.8°C at a distance of 600 mm from the freeze pipe. More accurate measurement of the radial distance frozen was not possible since all other temperature measuring devices were located greater than 1 m from the freeze pipe. RTD #2 at a distance of 1.2 m from freeze pipe #1 indicated a temperature of 6°C, while RTD #5 at a distance of 1.8 m from freeze pipe #2 read 7.2°C. These temperatures indicate that substantial temperature gradients existed around the freezing zone. This contributed substantial extra heat which had to be removed during the freezing operation.

The total liquid nitrogen consumed was 68,000 l over the 13-day freezing program. It should be noted that the consumption rate was nearly constant during the freezing period and did not depend on whether both freeze pipes were operating or whether only one was receiving liquid nitrogen.

The difference in the field operation and the design can be attributed to the following:

- Ground temperature at 11.5 m depth was +8.2°C and at 13.4 m depth was +7.5°C.
- The total depth for which no thermal barrier (insulation) existed between the freeze pipe, sampling zone and the 150 mm casing was as follows:

Freeze Pipe	Design Depth (m)	Actual Depth (m)	% Increase
#1	4	7.0	75
#2	4	6.2	55
Total	8	13.2	65

The ground temperature was about 4 C° warmer than anticipated in the design as well as having a downward gradient of 0.37°C/m near the top of the zone of interest. This gradient added heat to the zone being frozen and required that this additional heat be extracted during freezing. The major contributor to the increased use of liquid nitrogen and to the reduced zone that was frozen was the increase in the depth of the zone to be frozen from the original 8 to 13.2 m.

The efficient extraction of heat from the surrounding soil requires that the liquid nitrogen be in contact with the inside wall of the freeze pipe so that it absorbs the heat released as the soil freezes. The design of the freeze pipe allowed for the liquid nitrogen to flow down the interior 13 mm diameter pipe to the bottom of the freezing zone. The liquid then flowed up the outer annulus absorbing the heat, changing phase and then rising up through the annulus as chilled nitrogen gas to be vented at the surface through the exhaust valve. The exhaust gas temperature at the exhaust valve on each freeze pipe was measured and was below -75°C and usually below -100°C.

The reduced radius of soil frozen experienced was likely because part of the liquid nitrogen underwent phase change within the surface piping due to heat absorbed from the sun and as the liquid nitrogen flowed down through the interior delivery pipe by absorbing heat from the rising warmer nitrogen gas. These heat sources would cause the liquid nitrogen to undergo phase change outside of the required freezing zone and thus liquid nitrogen was not in contact with the pipe in the zone to be frozen. Thus the assumed freeze pipe temperature boundary condition in the design was not met during the field operation.

These are the major sources of discrepancy between the design and field performance, along with a physical explanation of processes that caused these differences.

CONCLUSIONS

Ground freezing using liquid nitrogen of a fine uniform sand between a depth of 12 and 17 m at the Duncan Dam was completed. A total of 7.7 m of excellent quality frozen core was obtained and transported to a laboratory in Vancouver for later testing. The void ratio of the frozen samples showed good agreement with the *insitu* void ratio measured by gamma-gamma density logging.

The variation between the prediction of the design of the freezing system and its field performance have been outlined to assist in future projects.

The extensive experience gained during the ground freezing at the Duncan Dam has subsequently assisted in the redesign of the ground freezing system for the Canadian Liquefaction Experiment (CANLEX). Substantial cost reductions in the *insitu* freezing have occurred for the CANLEX project because of the lessons learned at the Duncan Dam and during a controlled experiment carried out to improve on the freezing system for the CANLEX project. Details of the modified freezing system will appear in subsequent publications.

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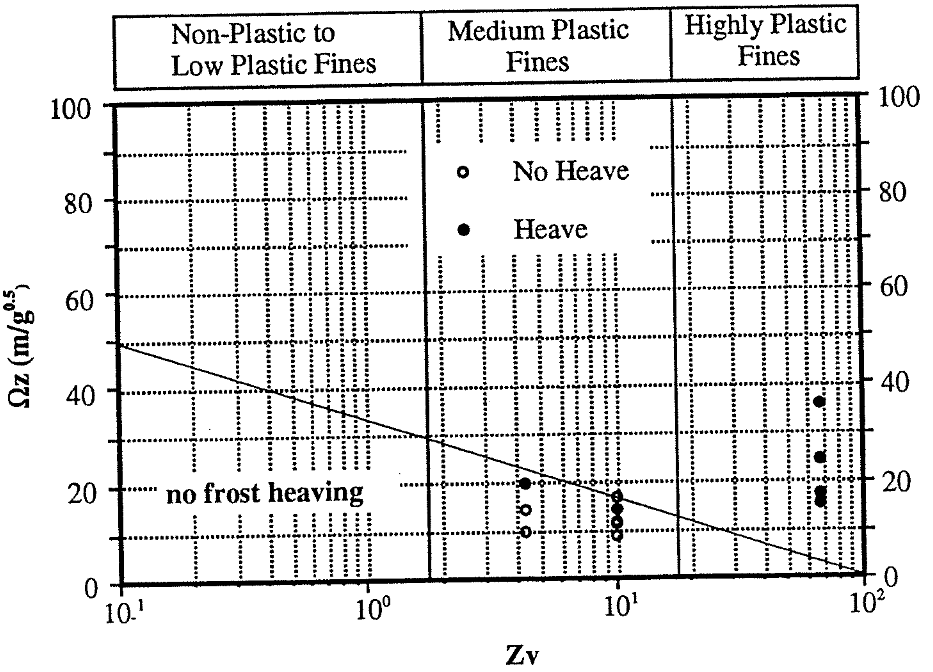
List of Figures

Figure 16	Frozen core showing ablation protection of wrapping the core in soaked paper towels which have refrozen.
Figure 17	Frozen core showing protection for handling and transport consisting of bubble pack and plastic tube.
Figure 18	Void ratio from borehole logging is compared with void ratio measurements from soil samples.



Test Boundary Conditions:
Temperature Gradient = 0.4 °C/cm
Minimum Time Period = 50 hours

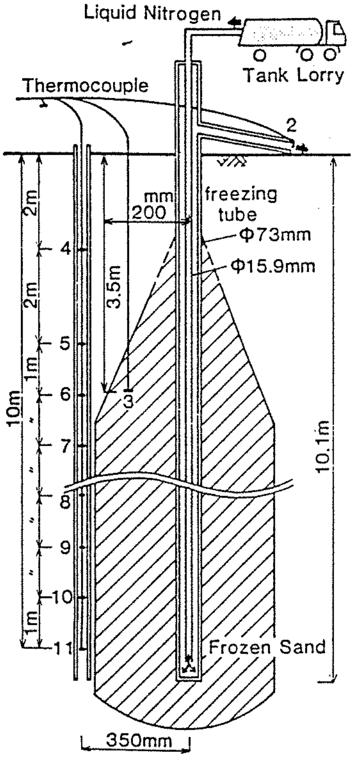
1) **The Fines Mineralogy Ratio** $Zv = \frac{CM_f}{I_{SSA}}$

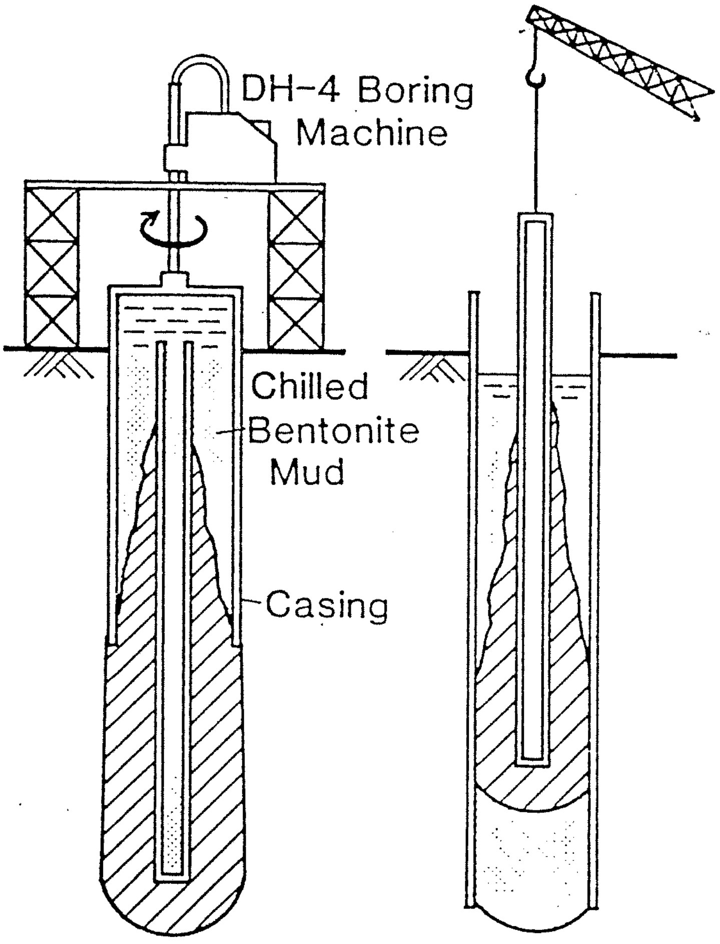
CMf = Clay Mineral Fraction < 75 µm (%)
ISSA = Intensity of the Specific Surface Area $I_{SSA} = \frac{S_c}{S_f}$

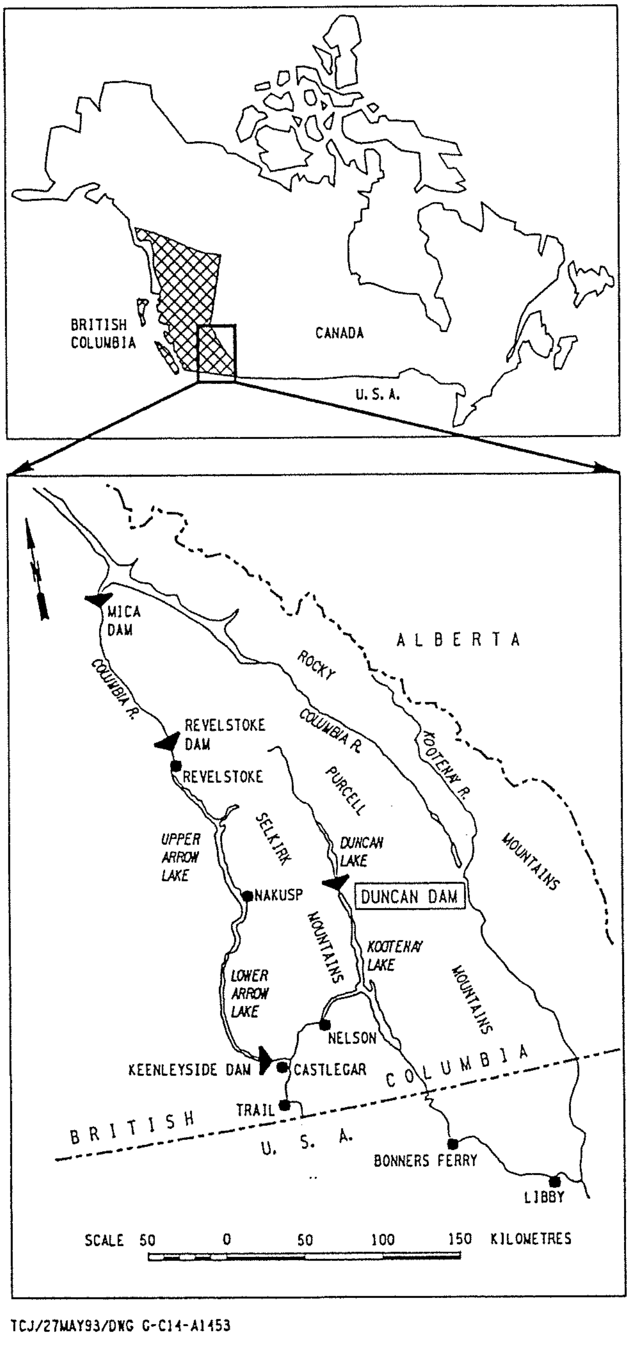
Sc = Specific Surface Area Fines < 2 µm

2) **Surface Area Index** $\Omega z = \sqrt{CM \times S_f}$

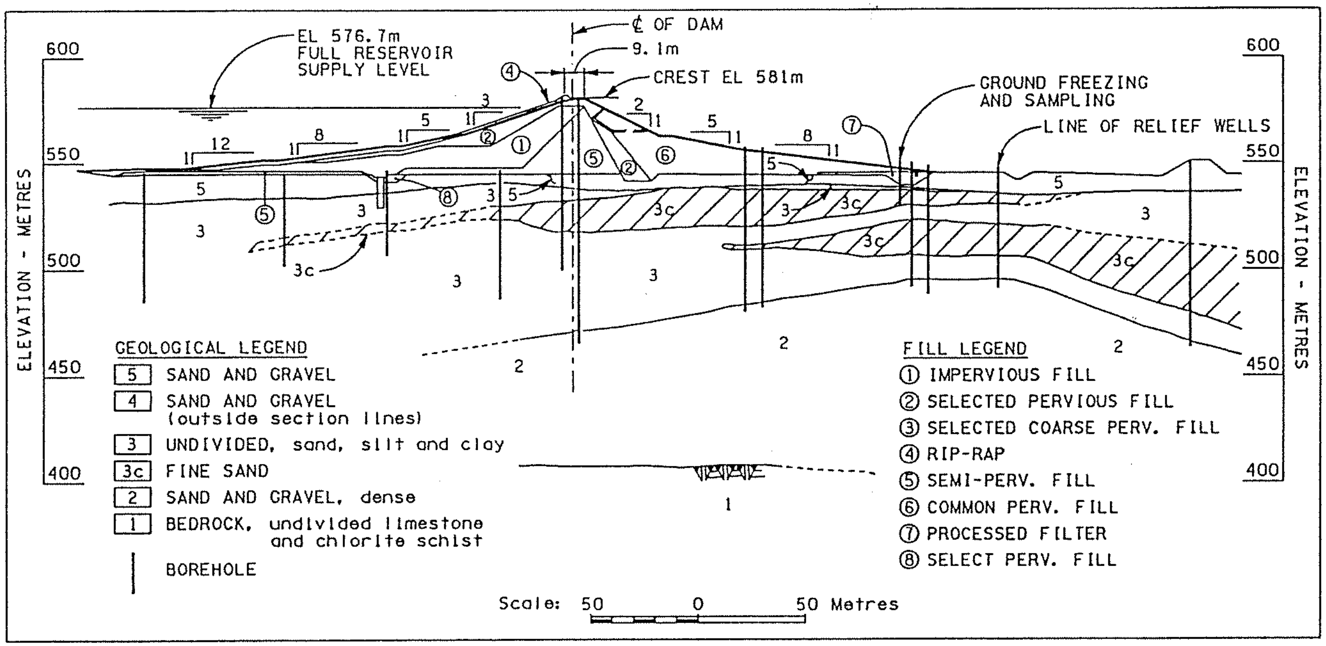
CM = Clay Mineral Fraction in the Soil (%)
S_f = Specific Surface Area Fines < 75 µm


Liquid Nitrogen
Tank Lorry
Thermocouple
2
mm
200
freezing tube
Φ73mm
Φ15.9mm
2m
2m
3.5m
1m
1m
10m
4
5
6
3
7
8
9
10
11
10.1m
Frozen Sand
350mm


DH-4 Boring Machine
Chilled Bentonite Mud
Casing



TCJ/27MAY93/DWG G-C14-A1453



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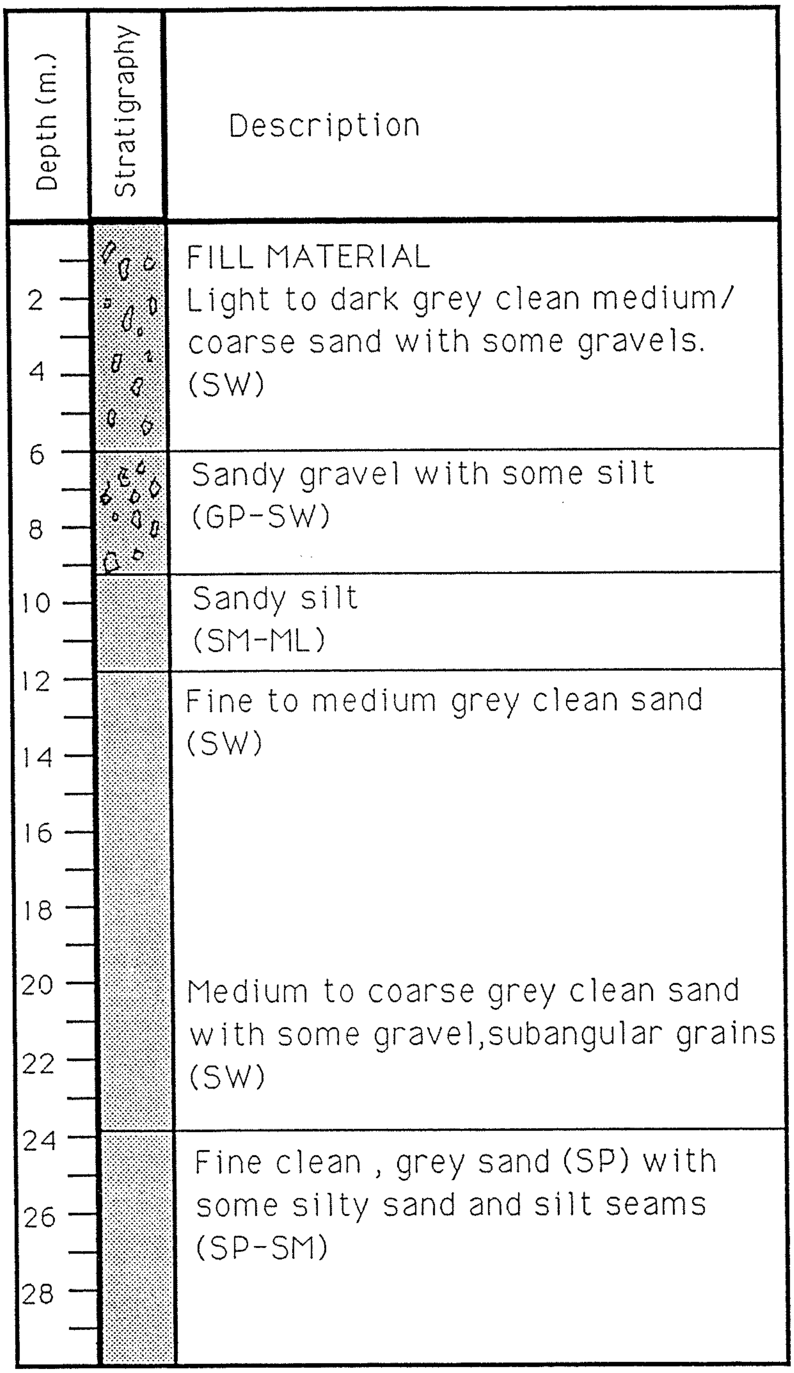


FILL MATERIAL
Light to dark grey clean medium/ coarse sand with some gravels. (SW)

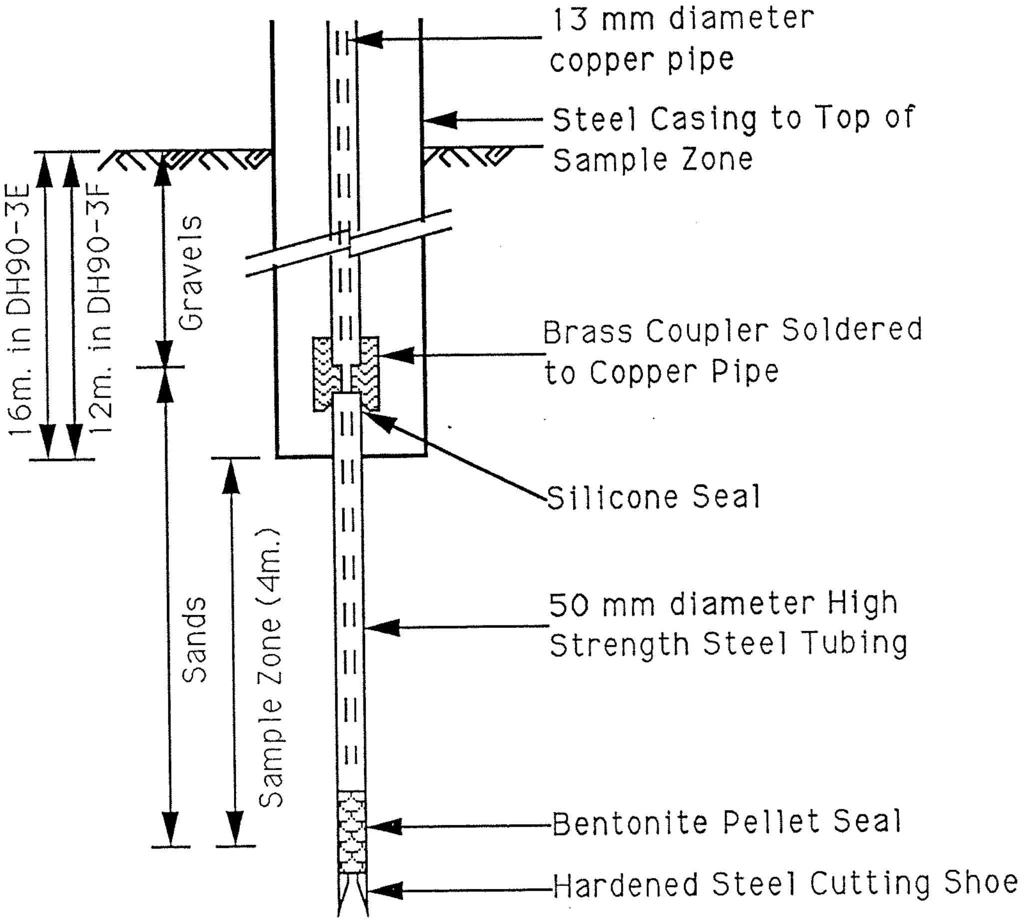
Sandy gravel with some silt (GP-SW)

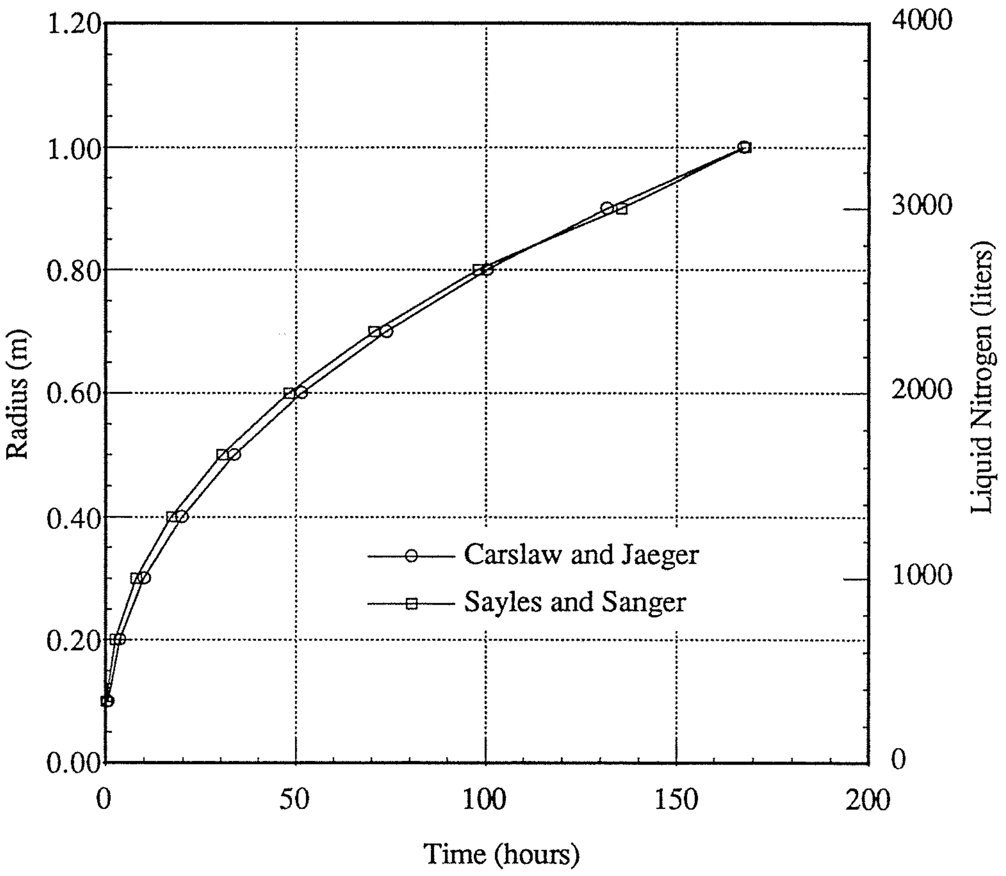
Sandy silt (SM-ML)

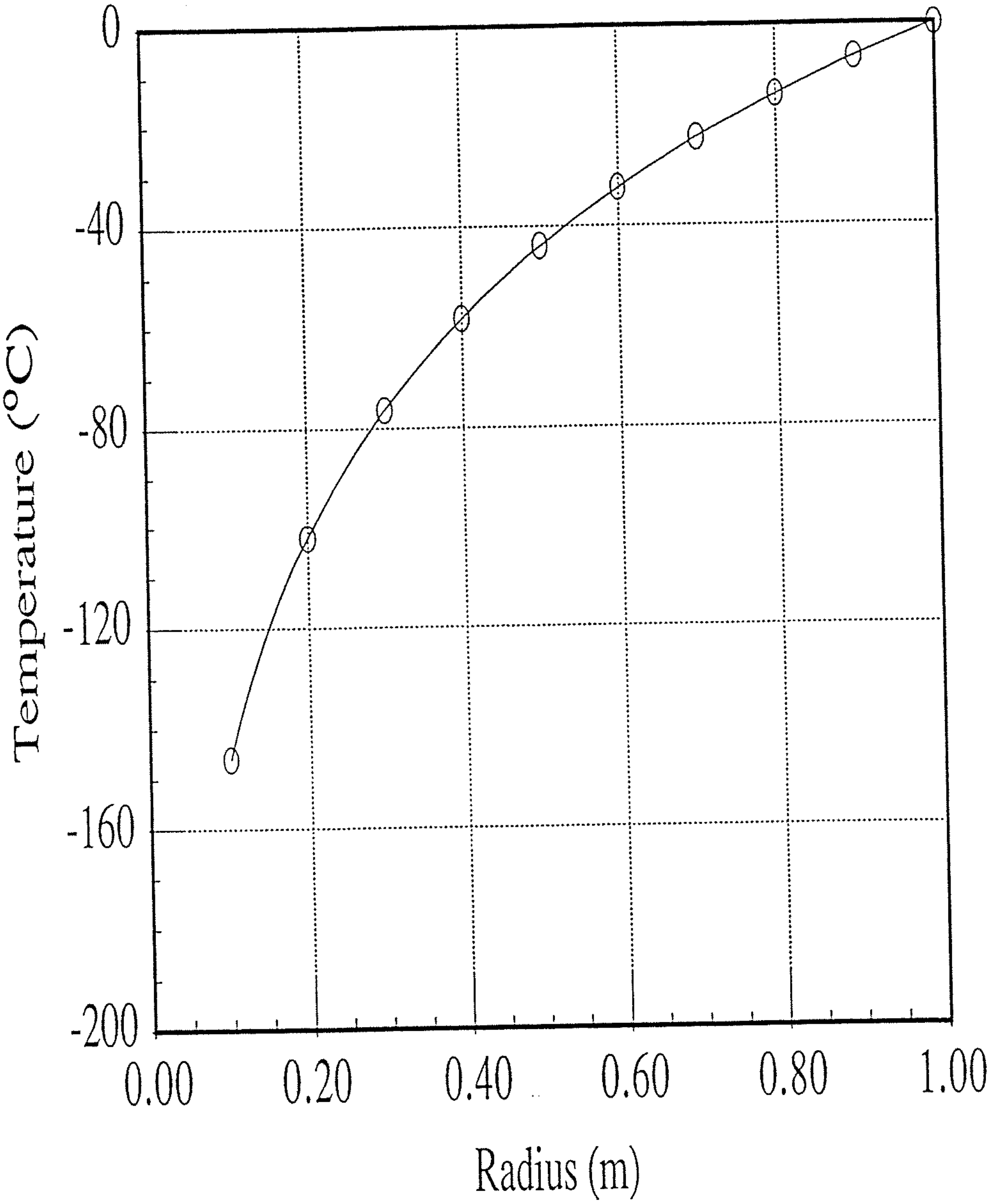
Fine to medium grey clean sand (SW)

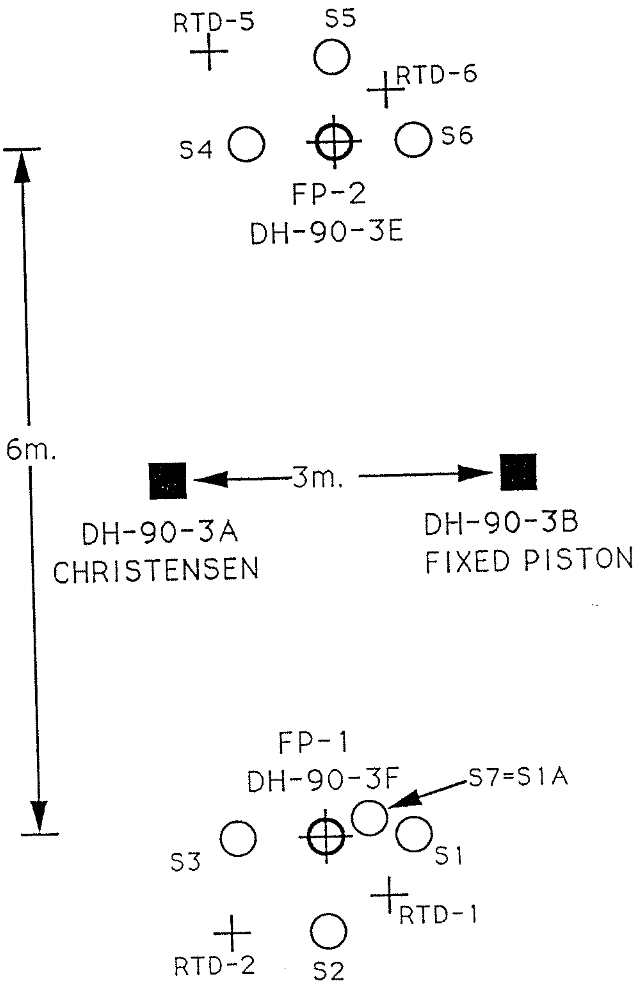
Medium to coarse grey clean sand with some gravel,subangular grains (SW)

Fine clean , grey sand (SP) with some silty sand and silt seams (SP-SM)

13 mm diameter copper pipe
Steel Casing to Top of Sample Zone
Brass Coupler Soldered to Copper Pipe
Silicone Seal
50 mm diameter High Strength Steel Tubing
Bentonite Pellet Seal
Hardened Steel Cutting Shoe
16m. in DH90-3E
12m. in DH90-3F
Gravels
Sands
Sample Zone (4m.)

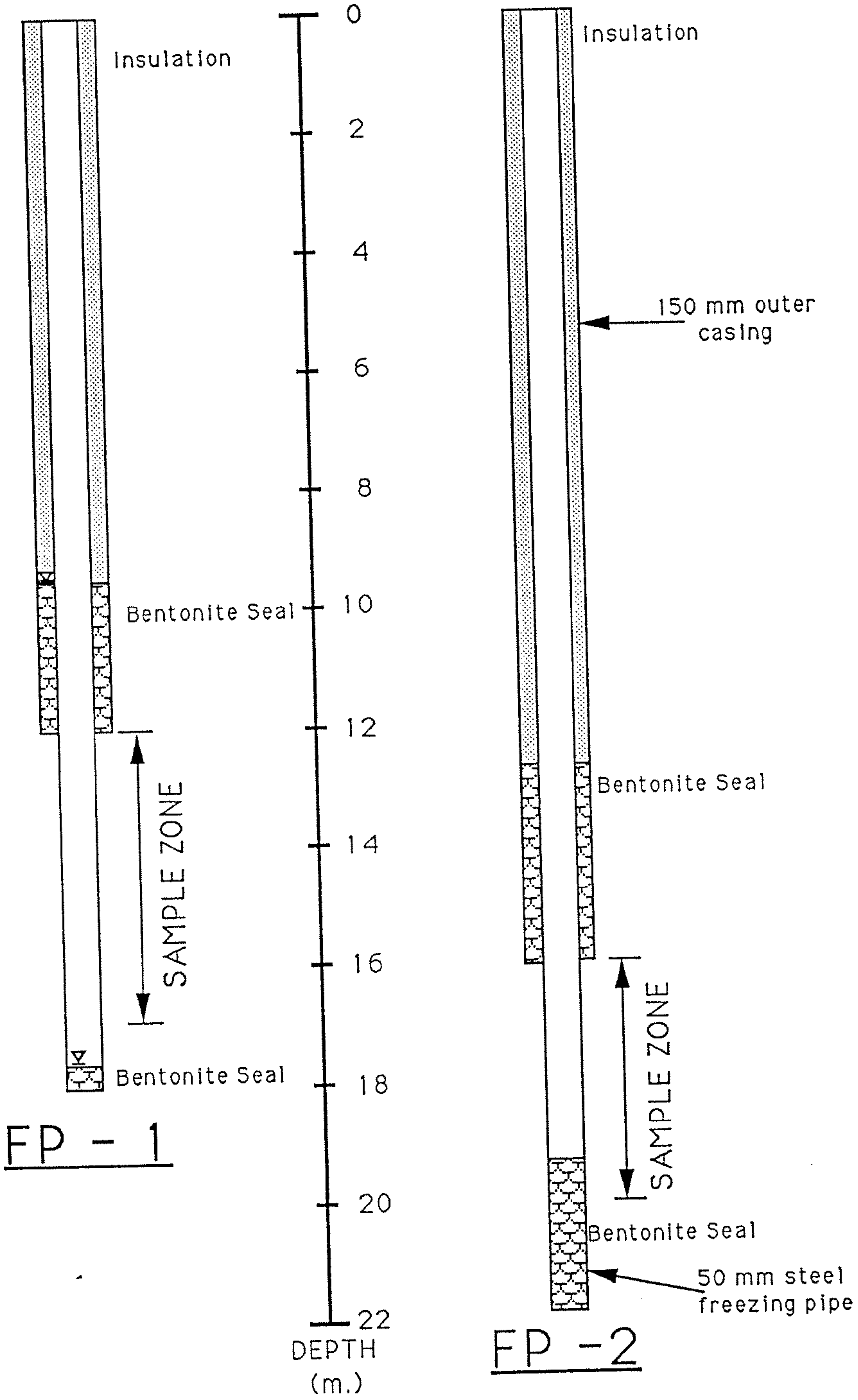

1.20
1.00
0.80
0.60
0.40
0.20
0.00
Radius (m)
4000
3000
2000
1000
0
Liquid Nitrogen (liters)
0
50
100
150
200
Time (hours)
Carslaw and Jaeger
Sayles and Sanger

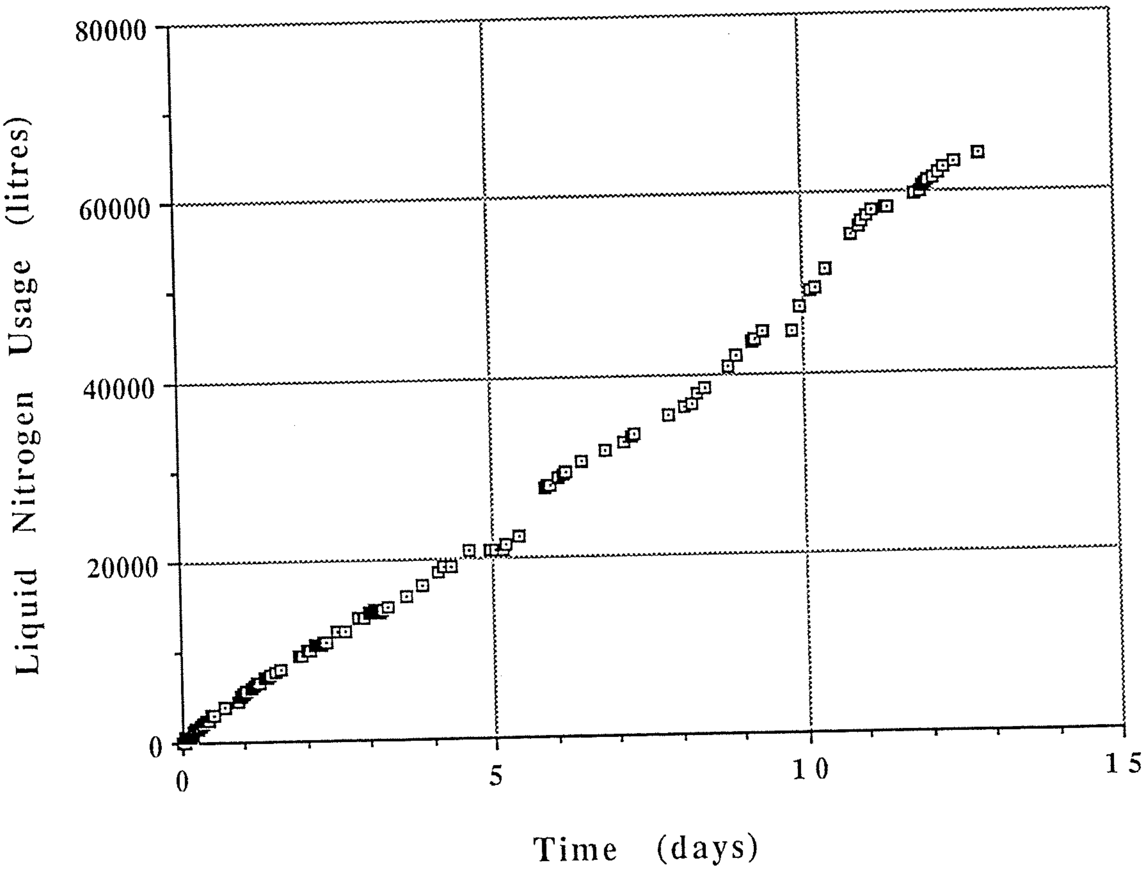

0
-40
-80
-120
-160
-200
Temperature (°C)
0.00
0.20
0.40
0.60
0.80
1.00
Radius (m)

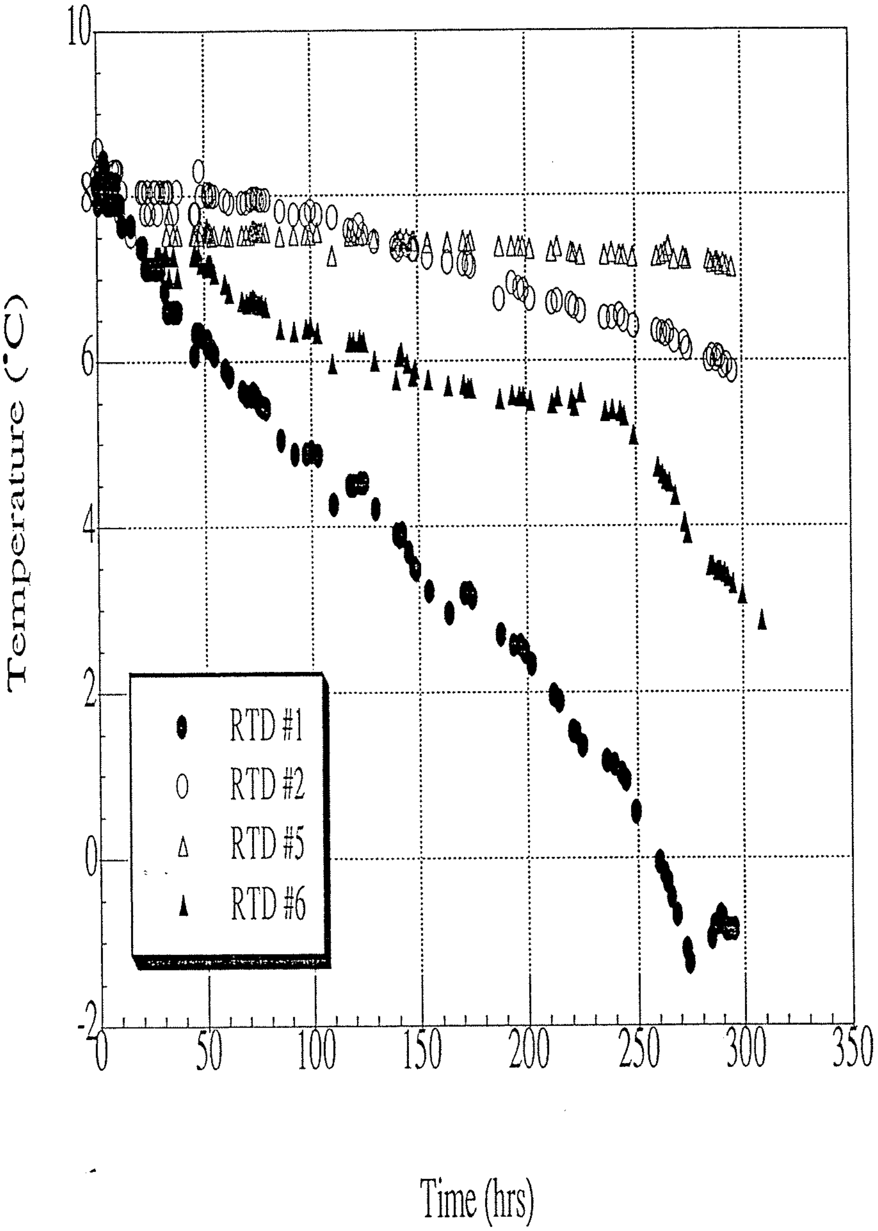


Distances (metres)
@ ground surface

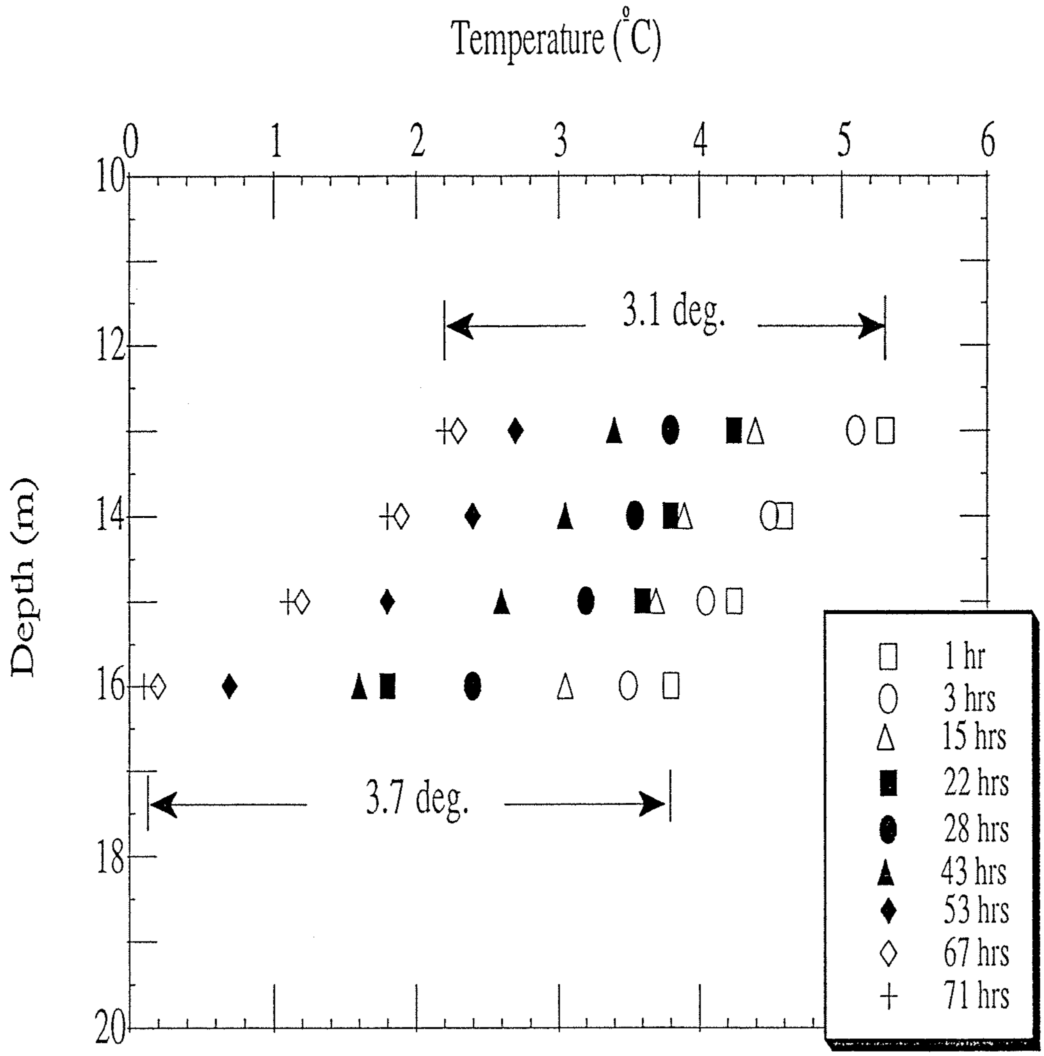
FP-1 to S1	0.57
FP-1 to S2	0.51
FP-1 to S3	0.44
FP-1 to RTD-1	0.42
FP-1 to RTD-2	0.99
FP-2 to S4	0.48
FP-2 to S5	0.54
FP-2 to S6	0.45
FP-2 to RTD-5	0.92
FP-2 to RTD-6	0.55


Insulation
Bentonite Seal
SAMPLE ZONE
Bentonite Seal
FP - 1
0
2
4
6
8
10
12
14
16
18
20
22
DEPTH
(m.)
Insulation
150 mm outer casing
Bentonite Seal
SAMPLE ZONE
Bentonite Seal
50 mm steel freezing pipe
FP -2

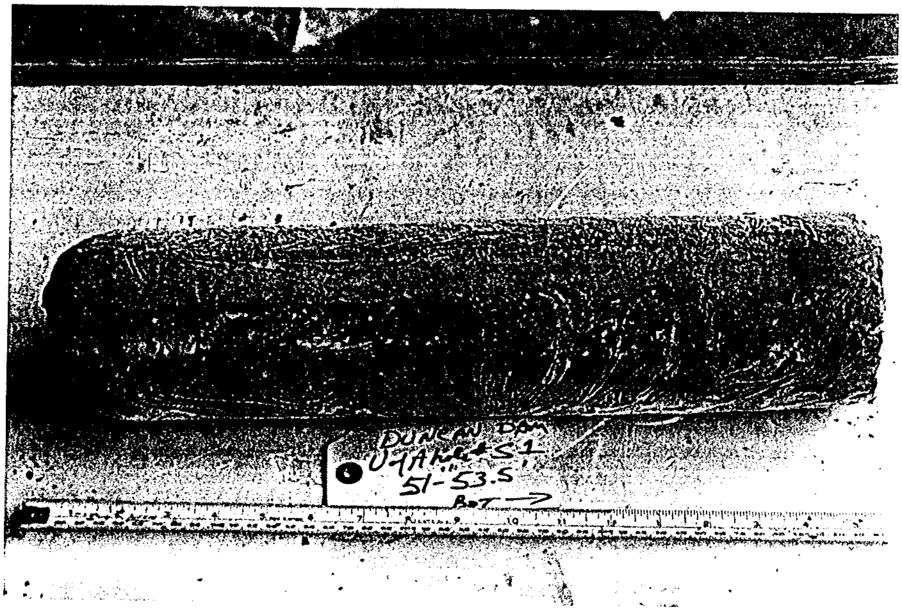

80000
60000
40000
20000
0
Liquid Nitrogen Usage (litres)
0
5
10
15
Time (days)

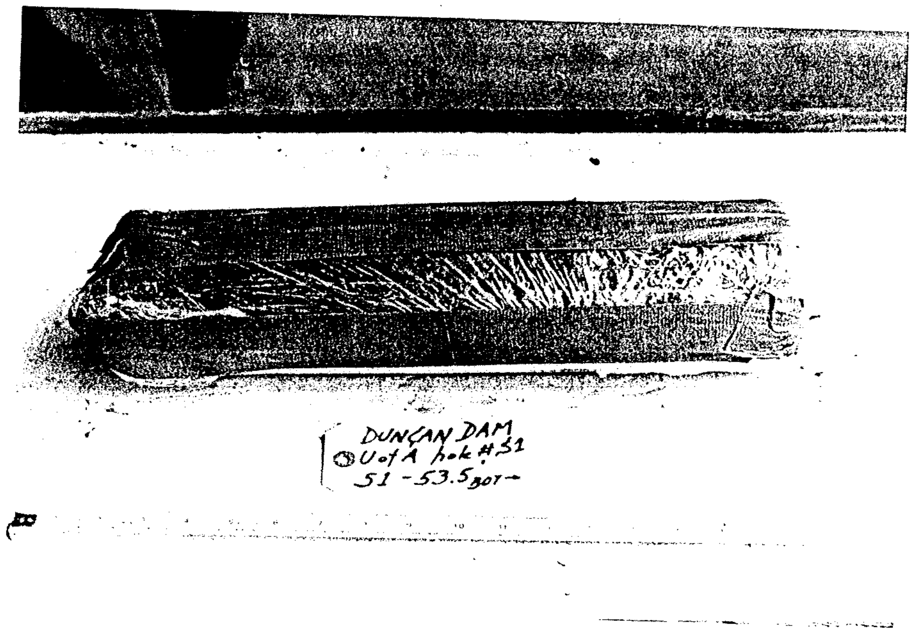


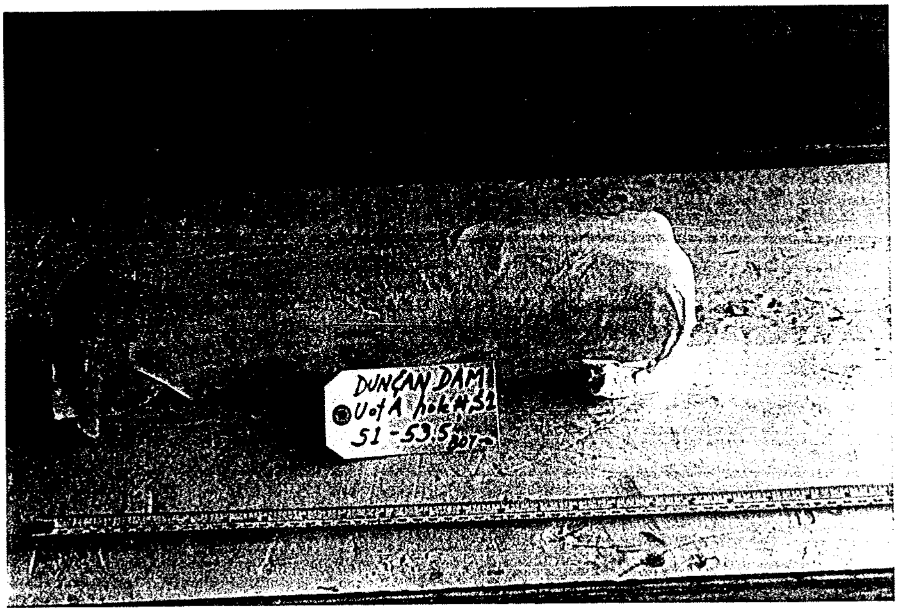
10
8
6
4
2
0
-2
Temperature (°C)
0
50
100
150
200
250
300
350
Time (hrs)
● RTD #1
○ RTD #2
△ RTD #5
▲ RTD #6

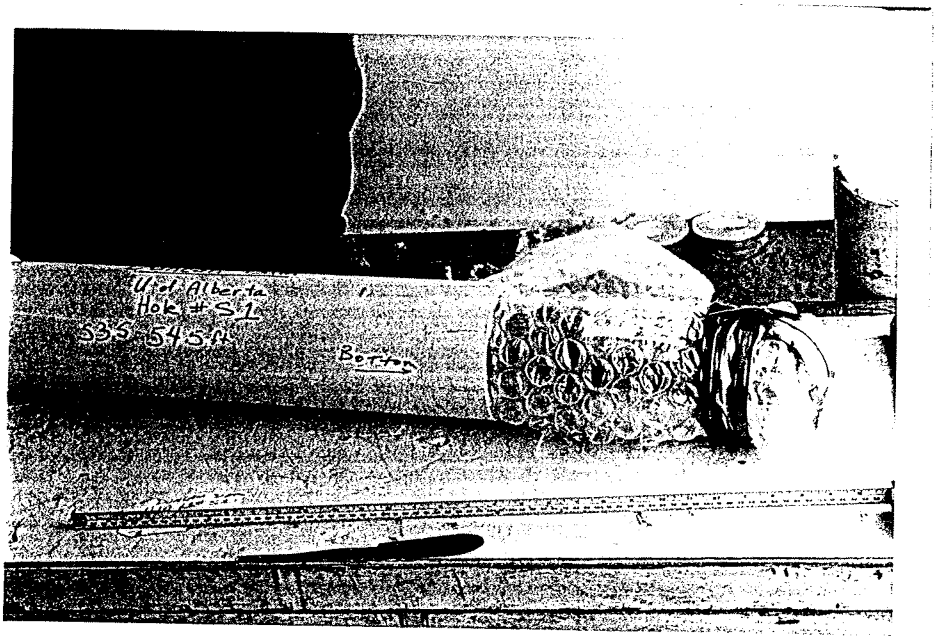


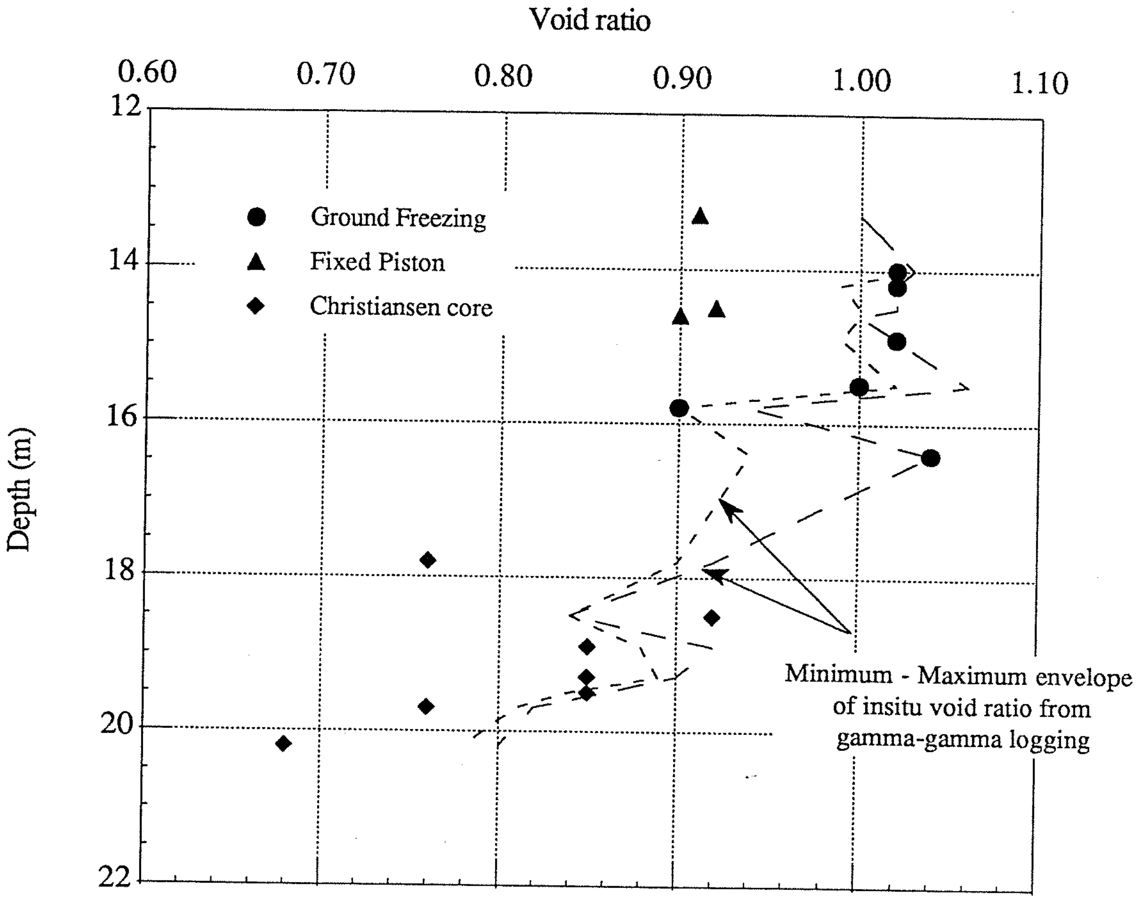
Temperature (°C)
0
1
2
3
4
5
6
10
12
14
16
18
20
Depth (m)
3.1 deg.
3.7 deg.
□ 1 hr
○ 3 hrs
△ 15 hrs
■ 22 hrs
● 28 hrs
▲ 43 hrs
◆ 53 hrs
◇ 67 hrs
+ 71 hrs


DUNCAN DAM
U7A S1
51-53.5'
BOT →


DUNCAN DAM
U of A hole #51
51 - 53.5 bot →


DUNCAN DAM
U of A hole #S2
51 - 53.5


U of Alberta
Hole # S1
53.5-54.5 ft
Bottom


Void ratio
0.60
0.70
0.80
0.90
1.00
1.10
12
14
16
18
20
22
Depth (m)
● Ground Freezing
▲ Fixed Piston
◆ Christiansen core
Minimum - Maximum envelope
of insitu void ratio from
gamma-gamma logging