**PDHonline Course C330 (3 PDH)**

# Sampling Frozen Soils

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# Appendix F-2 (of EM 1110-1-1906)
# Artificial Ground Freezing for Undisturbed Sampling of Cohesionless Soils

## D-1. Introduction

The critical importance of high-quality undisturbed samples of cohesionless soils for earthquake analysis procedures has been well documented (Horn 1979; Marcuson and Franklin 1979; Poulos, Castro, and France 1985; Seed 1979; Singh, Seed, and Chan 1982).[1] Unfortunately, the development of technology or methodologies to obtain truly undisturbed samples of sand has been rather elusive. Hvorslev (1949) suggested several methods which included thin-walled, fixed-piston samplers in mud-filled holes; open-drive samplers using compressed air; freezing; and impregnation. Marcuson and Franklin (1979) and the U.S. Army Engineer Waterways Experiment Station (1952) reported studies using the thin-walled, fixed-piston sampler; these studies documented that loose samples were densified and dense samples were loosened. Seed et al. (1982) reported an investigation of the effect of sampling disturbance on the cyclic strength characteristics of sands; they reported that the Hvorslev fixed-piston sampler caused density changes while advance trimming and sampling techniques caused little change in density, although some disturbance due to stress relief was reported. Other methods have included hand--trimming samples from test pits or shafts. Occasionally, samples obtained by fixed-piston sampling or hand-trimming methods have been frozen after sampling at the site (Torrey, Dunbar, and Peterson 1988; Walberg 1978) in an attempt to preserve the sample. However, studies have consistently demonstrated that stress relief and/or void ratio changes may have occurred during sampling operations.

More recently, studies have demonstrated that high quality undisturbed samples could be obtained by impregnation or freezing techniques, although both methods were fairly expensive and difficult to apply. A study using the impregnation technique was reported by Schneider, Chameau, and Leonards (1989). The premiere consideration of this study was the concern that the impregnating material would readily penetrate the soil, protect the soil structure during sampling operations, and could easily and effectively be removed from the specimen at a later date. Singh, Seed, and Chan (1982) reported a laboratory investigation which employed an "in situ" freezing technique. For this study, a large triaxial specimen of sand which had been subjected to a known stress history was frozen and sampled; the experimental data demonstrated that unidirectional freezing with no impedance of drainage could be used to obtain laboratory samples which maintained the characteristics of the in situ formation.

Based upon the research by Singh, Seed, and Chan (1982), a methodology, which consists of one-dimensional ground freezing followed by core sampling, should be considered whenever very high-quality undisturbed samples of cohesionless materials are required. The in situ freezing method is contingent on the requirements that the soil is free draining and that the freeze front advances one-dimensionally; the one-dimensional movement of the freeze front permits drainage away from the front in response to the change of volume caused by the phase change of water to ice.

## D-2. Historical Development

Ground freezing for construction purposes has been conducted for more than 100 years (Sanger 1968). In situ freezing to obtain undisturbed calyx samples was done at Fort Peck Dam following the upstream slide of the embankment in 1938 (Middlebrooks 1942; U.S. Army 1939a, 1939b; Hvorslev 1949). Other

[1] References cited in this appendix are included in Appendix A.

instances of ground freezing have included operations to obtain in-place densities in sands, gravelly sands, and gravels (Osterberg and Varaksin 1973, Vallee and Skryness 1979). For each of these operations, a cylindrical-wall freezing technique was employed. Because one-dimensional freezing was not satisfied, specimens may have been disturbed as a result of ice expansion.

More recently, Japanese investigators (Yoshimi, Hatanaka, and Oh-oka 1978) reported an in situ radial freezing technique. The methodology consisted of the use of a single freeze pipe which is subsequently used to pull a frozen column of soil from the ground. While the "popsicle" technique satisfied the one-dimensional freezing criteria, it is likely the technique is limited to shallow depths and would not be appropriate for many locations, such as the downstream toe of a dam where the piezometric levels may be very high. A one-dimensional freezing technique which allows sampling at depths greater than 15 m (50 ft) which should not jeopardize the structural safety of the dam or embankment is presented herein.

## D-3. In Situ Freezing and Testing Rationale

*a. Site selection and layout.* As previously mentioned, a site must be selected in which the soil is freedraining; the freeze hole layout must be designed to ensure that the freeze front advances across the prospective sampling area in one dimension without trapping water. Although this in situ freezing procedure is generally applicable to saturated, relatively clean sands and gravels, it could be used in partially saturated materials provided that sufficient ice is formed during the freezing process to give the material adequate strength (cohesion) to allow coring. The presence of too many fines (silts and clays) could result in impeded drainage, in which the pore water would expand during the phase change to ice and seriously disturb the sand structure, or could cause migration of pore water toward the freeze front, which would result in the formation of ice lenses with subsequent volume change. In either case, Tsytovich (1955) and Gilbert (1984) have shown that in sands with free drainage, the porosity remains constant because excess water is squeezed out as the freeze front advances.

Provided that a suitable candidate site has been identified, typical examples of a site layout are illustrated in Figures D-1 and D-2. According to the literature, spacings for the holes are typically 0.6 to 0.9 m (2 to 3 ft), although Vallee and Skryness (1979) reported a hole spacing of 2.1 m (7 ft). Initially, a coolant, such as a chilled brine, is circulated through vertical freeze holes identified by the symbol "F." Freezing progresses radially from each hole and eventually makes closure between the freeze holes to form a continuous frozen mass, as idealized in the figures. The location of the freeze front can be determined by symmetry from monitoring the temperature in holes identified by the symbol "T."

If additional freeze holes are needed to obtain a thick mass of ice around the proposed sampling area, circulation of the coolant in the secondary freeze holes should not begin until freezing of the initial area is completed. Furthermore, the layout of the freeze holes should ensure that freezing will always progress radially outward from the initial freeze zone. If one-dimensional freezing does not occur, disturbance of the soil in zones between the freeze fronts may occur because of the expansion of groundwater upon freezing. Additionally, freeze holes and temperature monitoring holes should be located as far as practical from the sampling area to minimize the disturbance caused by drilling and installation of the holes.

*b. Coring.* Based upon experience obtained by drilling in frozen soil, coring methods vary with the type of soil, its temperature, and the degree of saturation of ice in the soil voids, i.e., the ice content (Hvorslev and Goode 1960). Soil strength increases with a decrease of temperature and an increase of the ice content, whereas the torsional strength of a core of frozen soil increases with increasing diameter. To obtain good cores and good recovery, a fairly large, e.g., 125- to 150-mm- (5- to 6 in.-) diam doubleor triple-tube core barrel with a diamond or tungsten bit is suggested. Because the temperature of the artificially frozen soil can be expected to be only a few degrees below freezing, the drilling fluid will have to be cooled to prevent the melting of the pore ice during the drilling operations. Cooling of the drilling fluid can be accomplished by circulating it through a chiller attached to the refrigeration plant. Although the use of air as the drilling fluid is perhaps more desirable from an environment consideration, it is not satisfactory if the ambient air temperature is above freezing. Furthermore, the use of compressed air as a drilling fluid is prohibited for drilling in water-retaining embankments, as outlined by ER 1110-2-1807. Consequently, the alternative choices for drilling fluid are ethylene or propylene glycol and diesel fuel, although the potential adverse environmental effects caused by these products must be considered.

*c. Frozen core*. Immediately after the core has been retrieved from the borehole, it should be moved to a cold storage facility where it can be identified, logged, and sealed in a container which will prevent sublimation of ice as well as protect the sample when it is transported to and stored at the laboratory. Once the samples have arrived at the laboratory, further testing can be conducted under more controlled conditions and at much colder temperatures. For example, if the grain size of the material is small enough, samples may be recored to smaller diameter specimens; this operation will tend to eliminate the effects of any disturbance from field coring and/or thawing at the periphery of the field sample. After the frozen specimen has been prepared for testing, it can be placed in the triaxial chamber where the in situ stresses and pore pressure can be reapplied prior to permitting the specimen to thaw. During the thawing process, the specimen should be continuously monitored to detect any evidence of disturbance. After the thawing process is completed and the temperature of the test specimen has stabilized with the ambient conditions, monotonic or cyclic triaxial tests can be performed to determine the in situ static or dynamic strength properties, respectively.

## D-4. Freeze Plant System

Although there is not a “best” or unique system for conducting the in situ freezing and drilling and sampling operations, the design of a suitable freeze plant system can be accomplished by cooperation of refrigeration personnel who are knowledgeable of artificial ground freezing operations and geotechnical personnel who are knowledgeable of the site conditions. In principle, the freeze plant system consists of three separate systems. The refrigerator system which is similar to a refrigerator or freezer home appliance consists of a motor, compressor, condenser, and evaporator. The freeze hole system consists of a chiller, a reservoir for storage of the chilled drilling fluid, a brine pump, and the pipe for circulating the chilled brine to the freeze holes. The monitoring or data acquisition system includes pressure, temperature, and flow rate sensors.

*a. Freeze plant*. The purpose of the freeze plant is to cool the brine, which is circulated through the freeze holes, to a temperature much less than 0 deg C (32 deg F) as well as to chill the drilling fluid sufficiently to prevent thawing of the core during drilling operations. During field operations, the brine is cooled in the chiller by the refrigeration system, circulated through the freeze pipes by the brine pump, returned to the refrigeration plant, and recirculated through the chiller; a similar technique is used for cooling the drilling fluid. Considerations for the design of the freeze plant should include: seepage in the foundation could require a large amount of energy to freeze the formation; and the use of two smaller refrigeration plants, i.e., one for in situ freezing and one for chilling the drilling fluid, would allow more flexibility of the field operations as compared to one large plant. From data published in the cited literature, the refrigerator plants were typically 30 to 60 kilowatts (kw) (100,000 to 200,000 BTU/hr or 8.5 to 17.0 tons), although one system was reported as 260 kw (890,000 BTU/hr or 74.0 tons).

*b. Freeze holes and temperature holes*. Freeze holes and temperature monitoring holes can be drilled and constructed identically, except that temperature monitoring holes do not have to be fitted for brine recirculation. Holes should be drilled slightly larger in diameter than the diameter of the pipes to be placed in the holes. To ensure the vertical alignment of all holes, which is fairly critical, the kelly can be plumbed by sighting through a transit. For example, nonvertical freeze holes could result in a pocket or window of unfrozen material within the frozen mass or the intrusion of freeze holes into the desired sample area. Similarly, the vertical alignment of temperature holes assures that monitored temperatures are always taken at a constant distance from the freeze pipes.

Upon completion of the drilling, freeze or temperature monitoring pipes, which have been previously pressure tested for leakage, can be installed in the borehole. Prior to backfilling the annulus between the pipe and the walls of the borehole with granular material, the vertical deviation of each pipe should be measured by a suitable device, such as a borehole inclinometer. After the boreholes have been backfilled, each freeze pipe can be fitted with valves, insulated supply and return lines, and other equipment or gauges which are required for operation of the system. From the literature, the pipes used in the freeze holes were typically 8 to 10 cm (3 to 4 in.) in diameter while the pipes used in the temperature holes were either the same diameter or slightly smaller.

*c. Monitoring system*. To monitor system operations, a variety of instruments is required. Brine pressures and flow rates should be monitored at the pump (supply line) and before the chiller (return line). The refrigeration plant compressor head pressure and suction pressure should also be monitored. Thermocouples or other suitable temperature monitoring devices should be installed at several locations along the coolant supply and return lines, such as immediately ahead of and behind each freeze hole. A string of thermocouples should be suspended in the brine-filled temperature monitoring pipes at regular intervals, e.g., approximately 1.2- to 1.5-m (4- to 5-ft) intervals, to monitor the cooling and subsequent freezing of the formation. The thermocouples can be connected to a multiple-switch monitoring box with a digital thermometer. All operations data should be routinely recorded at regular intervals, e.g., every 4 hr.

## D-5. Undisturbed Sampling Operations

*a. Coring*. Coring can be accomplished using a conventional double- or triple-tube core barrel equipped with a diamond or tungsten bit. The drilling fluid is cooled by circulating it through a heat exchanger connected in parallel to the refrigeration plant; a time of 1 or 2 hr or more may be required to reduce the temperature of the drilling fluid to below freezing before drilling operations can begin. Although drilling operations must be tempered to the site-specific conditions, it is suggested that rapid penetration of the bit at high revolutions per minute (rpm) will usually produce the best quality samples. Because the frozen ground and drilling fluid temperatures are usually not low enough to prevent thawing of the outermost periphery of the sample during drilling and sampling operations, it is probable that lower penetration rates will generally result in more thawing at the periphery of the core and consequently more erosion of the core by the circulating drill fluid. See Chapter 9 for additional information on sampling frozen soils.

*b. Handling of core*. The length of the core run is dependent upon the dimensions of the core barrel and may be several feet. As soon as the core is taken from the core barrel, it should be placed in a sturdy cradle and carried to a refrigerated van where it can be logged, photographed, and cut into shorter lengths. Cutting of the core can be accomplished by a band saw or a hammer and chisel. The cut core should then be wrapped in two or three layers of plastic wrap followed by two or three layers of aluminum foil and then carefully sealed with strapping tape to prevent sublimation of the ice. After each segment of core has been sealed, it should be placed in a suitable container, such as a section of split PVC pipe, and secured by strapping tape for transport to the laboratory and subsequent storage. The sample should then be identified and boring logs should be updated. See Chapter 13 for guidance on the handling and storage of samples and maintaining sampling records.

## D-6. Precautions

Because of limited experience of the profession regarding in situ freezing, each investigation must be tailored to the site conditions. Therefore, comprehensive guidance and rules governing in situ freezing cannot be established for specific situations. However, several precautions are identified which may enhance the field operations.

- The candidate formation should be free draining and relatively free of silt and clay (lenses) which could result in impeded drainage or migration of water towards the freeze front. Unfortunately, this same characteristic may also cause unanticipated freezing difficulties due to the large seepage gradients or velocities in the formation.

- The freeze hole layout and spacing should be optimized for the foundation conditions. Prior to installation, freeze pipes and temperature pipes should be checked for leaks. Care should be exercised to ensure that one-dimensional freezing of the formation occurs. This operation can be enhanced by carefully drilling vertical freeze holes and checking the verticality of the freeze pipes prior to backfilling the holes.

- The temperature of the brine used in the freeze holes should be monitored at several locations along the pipes of the freeze system, such as at the chiller and the return from each hole. Similarly, the temperature of the brine in the temperature holes should be monitored at selected depths and at regular time intervals to determine the passage of the freeze front.

- The efficiency of the freeze plant operations should be optimized by adjusting the flow rate of the brine and the corresponding temperature, or temperature change, to obtain the maximum energy exchange with the formation. However, care is needed when the method for optimizing the system efficiency is selected. For example, in an effort to increase the rate of freezing of a sand formation at a site in Kansas (U.S. Army Corps of Engineers, Kansas City District 1986), liquid carbon dioxide ($CO_2$) was injected into the brine. Although the temperature of the brine was reduced 5 to 10 deg C (10 to 20 deg F) by the addition of liquid $CO_2$, the highly corrosive $CO_2$ and brine mixture resulted in adverse effects on the freezing operations. Pipe scale clogged the brine chiller and thus caused high pressure losses, damage to brine pump, and excessive maintenance.

- Sampling should be conducted in an area located as far as practical from the freeze holes and temperature monitoring holes to minimize the disturbance caused by the installation of the in situ freezing system. Drilling and sampling should be accomplished as rapidly as possible to minimize thawing and erosion of the core. Two options are available to enhance quality of the frozen core. Since the ice content of the frozen core is independent of the artificial freezing techniques which are employed, the torsional strength can be increased only by decreasing the temperature of the pore ice or increasing the diameter of the core. A refrigerated van, or comparable facility, is needed at the site for logging, sealing, and storage of the frozen cores prior to shipment to the laboratory. After the cores have been received at the laboratory, tests should be conducted to determine if the soil has been contaminated by the drilling fluid and the effect(s) of the contamination on the engineering properties of the soil.

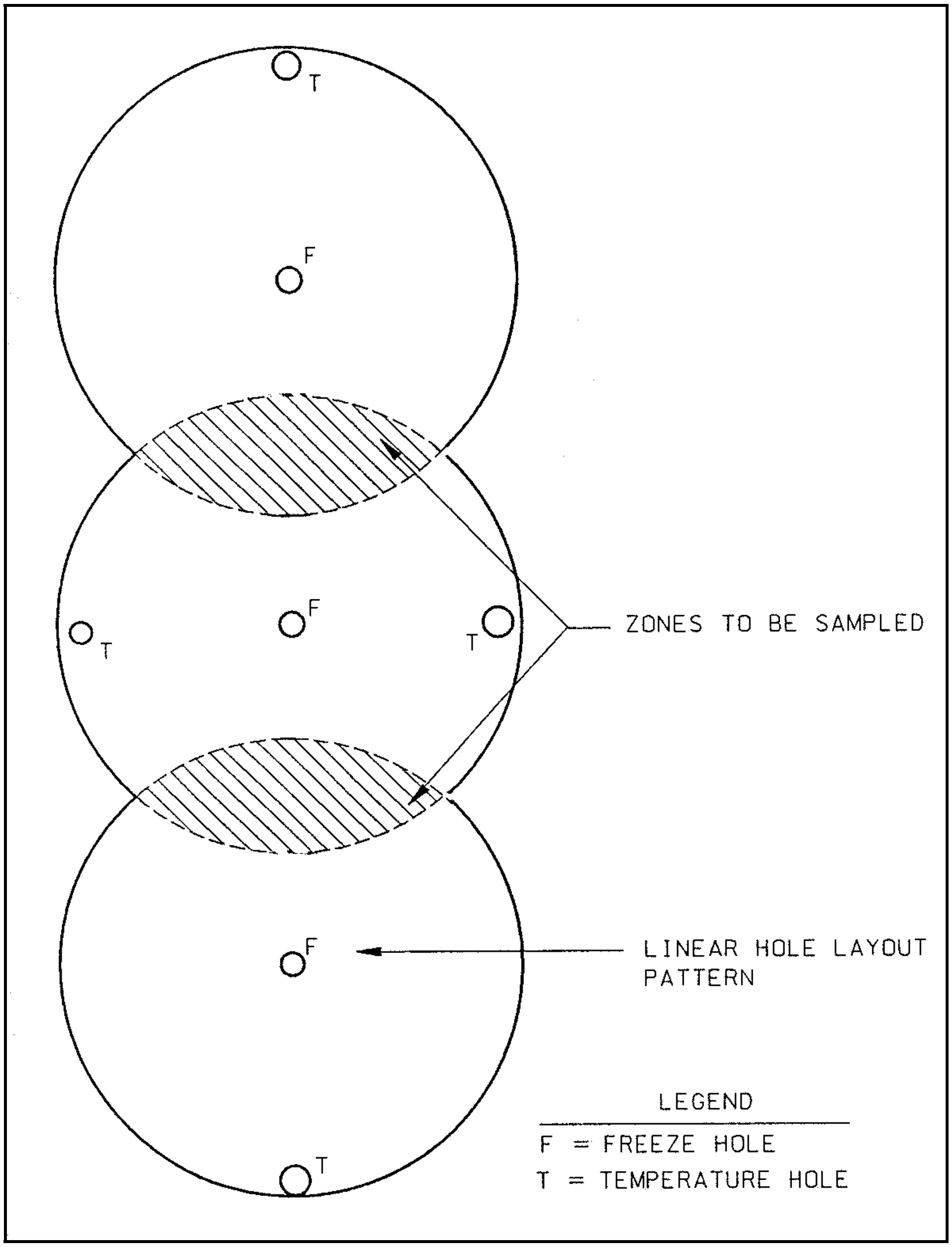


**Figure D-1. Linear layout of freeze holes and temperature holes**

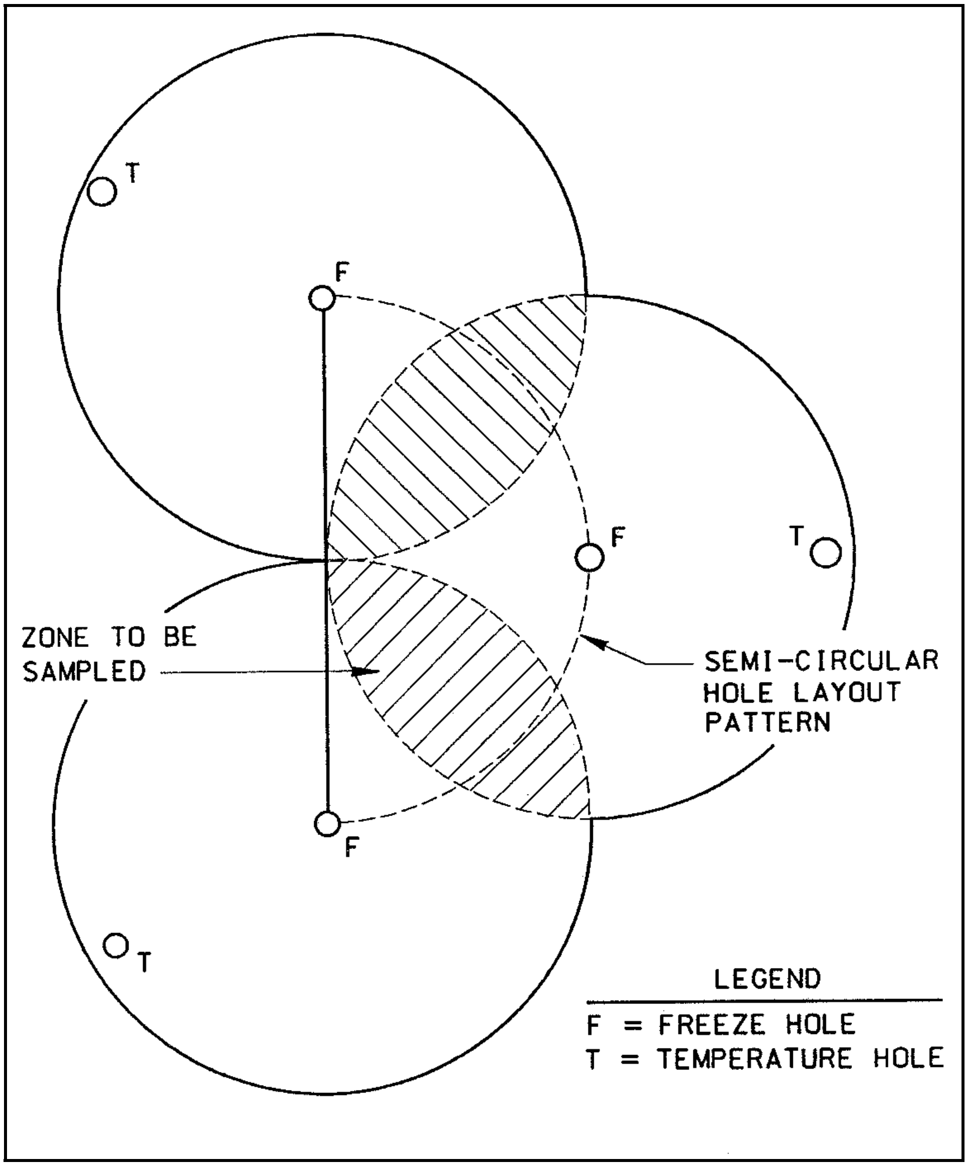


**Figure D-2. Semicircular layout of freeze holes and temperature holes**