In situ frost heave testing using cold plates

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The concept is introduced of a circular cold plate as a device for determining the frost heave characteristics or susceptibility of soils *in situ*. The advantages include (i) the ability to test the *in situ*, undisturbed soil and groundwater conditions, not subjected to possible sampling disturbance, and (ii) the ability to test a much larger volume of soil than is possible in standard laboratory tests. A parallel might be drawn with the use of the plate bearing test in conjunction with standard laboratory compression tests in determining the stress–strain characteristics of soils in conventional geotechnical practice.

The design, fabrication, installation, and instrumentation of several 0.76 m diameter cold plates are described. Instrumentation includes heave measurement rods, thermistors, and earth pressure cells. These plates have been successfully installed and operated in the south Yukon and Calgary. Results from these tests provide a bridging between small-scale laboratory testing and eventual frost heave design for large diameter, buried, chilled gas pipelines.

Results from one of two cold plate installations at the pipeline research facility in Calgary are presented in detail, and brief comparisons are made with the behaviour of full-size pipeline test sections. The *in situ* cold plate test provides valuable test data within a few months that are a valuable aid to long-term frost heave predictions.

La présente étude introduit l'idée de l'utilisation d'une plaque froide circulaire comme dispositif permettant de déterminer les caractéristiques du soulèvement attribuable au gel ou la gélivité des sols *in situ*. Parmi les avantages de cette méthode mentionnons: i) la possibilité d'effectuer des essais sur place dans des sols et des eaux souterraines non perturbés, c'est-à-dire non soumis aux perturbations que peut entraîner l'échantillonnage et ii) la possibilité de faire des expériences sur des volumes de sols beaucoup plus importants que lors des essais habituels en laboratoire. On peut établir un parallèle entre les essais faisant intervenir ces plaques en même temps que les essais habituels de compression en laboratoire, lorsqu'on cherche à déterminer les caractéristiques de déformation des sols soumis à des contraintes, conformément aux procédés géotechniques courants.

On décrit la conception, la fabrication, l'installation et le montage de plusieurs plaques froides d'un diamètre de 0,76 m. L'appareillage inclut des tiges de mesure du soulèvement, des thermistors et des cellules manométriques. Ces plaques ont été installées avec succès et sont utilisées dans le sud du Yukon et à Calgary. Les résultats de ces essais permettent de faire le pont entre les essais à petite échelle en laboratoire et l'éventuelle conception de gazoducs de grand diamètre refroidis et enfouis capables de résister au soulèvement par le gel.

Les résultats détaillés obtenus sur l'une des deux installations équipées de plaques froides à la station de recherche sur les pipelines à Calgary sont présentés ainsi que de brèves comparaisons avec le comportement de sections d'essai de pipelines en vraie grandeur. Les essais *in situ* à l'aide de plaques froides fournissent en moins de quelques mois des données expérimentales précieuses pour la prévision à long terme du soulèvement attribuable au gel.

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Introduction

The Alaska Highway Gas Pipeline Project will involve the operation of a gas pipeline at temperature continuously below 0°C between the Alaska–Yukon border and the first compressor station in the Yukon. Along this 60-km stretch of the pipeline route, most of the terrain is underlain by permafrost, with some unfrozen ground present beneath streams and disturbed areas. Freezing of the ground beneath the pipeline may therefore occur at certain locations.

The assessment of the magnitude of the resulting frost heave that may occur has been the subject of considerable investigations, involving laboratory testing of small samples, and the operation of full-size test pipe sections. These efforts involve not only the pipeline companies involved, but also government and other agencies. Full-scale facilities are operated in the University of Calgary by Foothills Pipe Lines (Yukon) Ltd., and are operated in Fairbanks by Northwest Alaskan Pipeline Ltd. These facilities have provided much valuable data (Carlson *et al.* 1982) for the particular soil types in which they are operated.

They are, however, very expensive facilities to construct and operate. Parallel efforts by the pipeline companies, universities, and government agencies (for example, Penner and Goodrich 1980) in the laboratory have provided considerable advances in our understanding of ice-lensing processes and frost heave behaviour under ideally controlled conditions.

Design of *in situ* Test Procedures

Certain difficulties emerged in bridging the gap between the small-scale laboratory test, and the large, full-size pipe tests. These difficulties became apparent when the range of heat fluxes imposed by each test and the time required to obtain data for long-term design purposes were compared. In addition, the volume of soil frozen by a small laboratory test and a full-scale test or operating pipeline are vastly different (Figure 1).

For these reasons, it was considered desirable to employ a freezing test method that would freeze a much larger volume of soil than a conventional laboratory test, would allow a better representation of the undisturbed soil and groundwater conditions, and would freeze the soil for much longer. All of these conditions would allow a closer representation of freezing conditions in the field adjacent to a large chilled structure. In relation to the Alaska Highway Gas Pipeline Project, this testing method received particular interest when it became necessary to test silty gravels, loose sands, shattered bedrock, and areas having a depressed groundwater table. Any of these conditions would prove very difficult to test adequately in the laboratory.

Methods of inducing freezing using ambient air temperatures were considered, but were discarded due to the lack of temperature control and the widely fluctuating ambient temperatures. Constant temperature baths and circulant systems were required to maintain constant plate temperatures.

The plates could be installed to any reasonable depth, provided that the method of heave measurement was not affected by the overlying soil. In order to overcome problems of variable vertical pressure on the plate as frost heave develops, it was considered necessary to install earth-pressure measuring devices over some of the cold plates. Thermistors were used to monitor the advance of the frost front, and standpipes were necessary to determine the position of the groundwater table.

A major problem at a remote site is, of course, the requirement for a 110-V power supply for the refrigeration and circulation system. This was solved at two remote sites using diesel generator sets, and by using the existing power supply at the Calgary site.

The basic heat exchanger or cold plate is fabricated from a thin metal plate, 0.76 m in diameter, with a metal rim, 5 or 6 cm in depth, welded to the perimeter. Two hex nuts are welded to the outside of the plate for later connection to vertical-heave measurement rods. A spiral of 1.2-cm copper tubing is formed and placed in the circular metal container (Figure 2). The plate is then filled with concrete or some other medium suitable for heat transfer, with the inlet and outlet ends of the copper spiral protruding. Two flexible, insulated, circulant lines connect

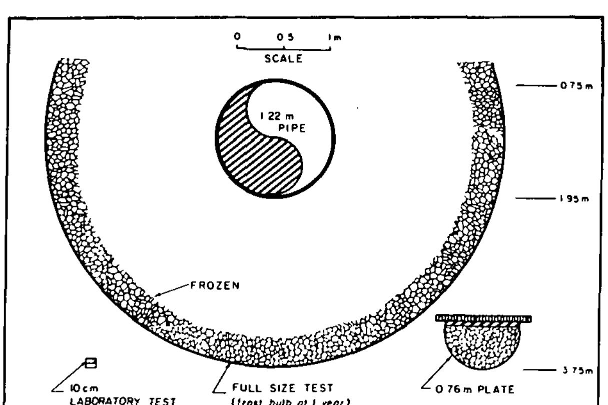


FIGURE 1. Scale drawing to illustrate the relative sizes of sample tested.

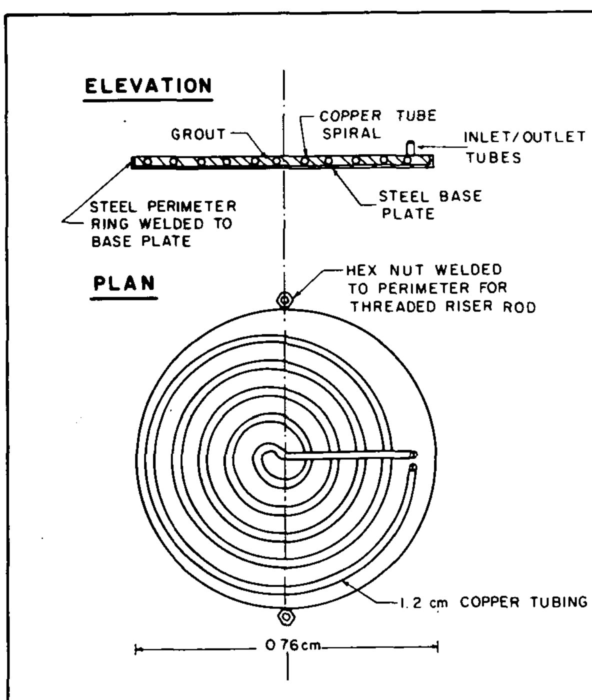


FIGURE 2. Cold plate fabrication.

the plate to the constant temperature circulating unit at the ground surface.

Frost heave is measured using two vertical risers, threaded to connect to the cold plate. These rods protrude about one metre above ground surface, and have metric scales welded or screwed to them. The rods are sleeved with grease-filled PVC tubing to prevent heaving or settling soil from interfering with the heave measurements (Figure 3). The vertical motion of the plate is measured relative to two anchor rods. These are, in effect, shallow benchmarks with a steel base plate, located outside or beneath the possible zone of soil freezing. The steel base plates on the anchor rods are grouted into the base of a hole which may be augered or hand-excavated into the base of the overall excavation for the plate installation.

Excavation for the plates was completed mostly by backhoe. In one case, however, a truck-mounted auger rig excavated a hole 0.9 m in diameter to a depth of 3 m. A variable number of thermistors may be installed beneath the centre and edge of the plate. This is done by pushing or driving a thin steel rod into the base of the plate excavation, and placing the thermistor string into the open hole. The thermistor leads are returned to the surface by taping them to one of the sleeved, heave measurement rods.

The plate is covered with 7.5 to 10 cm of styrofoam insulation, extending some distance beyond the top surface of the plate. This prevents significant frost advance above the plate, and limits heat input from the soil to the topside of the plate.

Following placement of the plate and backfilling with a few centimetres of soil, one or two Gloetzl earth-pressure cells may be installed to monitor the vertical total stress on the test plate. Backfilling to within 0.3 m of the surface may then be carried out. A second layer of insulation, usually 5 cm in thickness, is placed to cover an area of about 3 by 3 m. This prevents deep penetration of seasonal frost, and thermal interference with the performance of the plate.

On completion of backfilling, a copper wire, weight and pulley system is used to measure vertical movement of the heave rods relative to the outer anchor rods (*see* Figure 3). This is generally accurate to 1 or 2 mm. These readings are very convenient to take, but their absolute accuracy is usually checked by occasional precise level surveys, using a stable, deep bench mark. Generally, it has been found that the anchor rods provide a sufficiently stable benchmark for the required accuracy of 1 to 2 mm.

Thermistors are usually read using a portable resistance meter, and pre-calibration in an ice-water bath provides an accuracy of about 0.05°C.

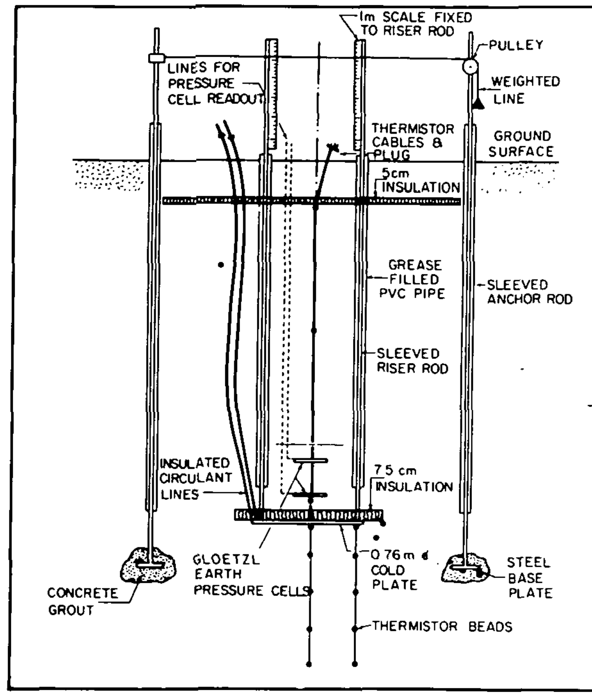


FIGURE 3. Cold plate installation.

Operation

The plates are maintained at near-constant temperatures using one "hot-pack" constant temperature bath for each plate. The fluid is passed through heavily insulated hoses to and from the plate, at a rate of two to three litres per minute. The usual fluid is a 50 per cent volume concentration of ethylene glycol, which can theoretically be controlled by the hot-pack unit to 0.01°C. Practically, due to heat losses by the circulant lines and variable heat demands at the cold plate, plate temperatures can only be controlled to an accuracy of 0.2°C or so. At a remote location, the hot-pack units are housed in a shed or large plywood box to protect them from extreme weather conditions. Over periods of several days or weeks, temperature fluctuations up to 0.5°C may be experienced due to extreme variations in ambient temperature, or other reasons.

At the Beaver Creek and White River locations in the south Yukon, the temperature control units were powered by 4-kw diesel generator sets. These had to be checked and maintained on a weekly basis. Large fuel tanks and additional fuel storage had to be provided at each site. Occasional power cuts or malfunctions of the cooling bath caused interruptions to the maintenance of a constant plate temperature, thereby producing variations in the rate of advance of the freezing front. In general however, the plates at the Yukon location provide data over sufficiently long periods of time (several months in many cases) to meet the test objectives. At the Calgary locations, better power supply and more-regular maintenance have allowed almost uninterrupted operation of two plates there for over a year.

At the Yukon and Calgary locations, readings were normally taken everyday for the first few days, and weekly thereafter. Readings were taken manually, and recorded on standard coding forms for later data reduction. The south Yukon sites were eventually discontinued after 400 days or more of operation. At this time, it was considered that the installations had yielded all data of possible use on the behaviour of these flood-plain gravels. The Calgary plates are still in operation at the time of publication. In October and November of 1980, six new plate installations were completed at the proposed pipeline crossing of Dry Creek, in the south Yukon. These tests are designed to investigate the freezing response of silty sands and silty gravels. In addition one plate was installed in very warm, fine-grained permafrost. To date, no results are available from these installations.

Results

Calgary Installations

Extensive data have been collected from two sites in the south Yukon, and the test site at the University of Calgary. Grain-size curves typical of both areas are given on Figure 4. The Yukon sites are both situated in flood-plain gravel deposits, which have 2 to 3 per cent silt and clay sizes, and 1 to 2 per cent finer than 0.02 mm. The Calgary subsoils are clayey silts, having 85 to 90 per cent silt and clay sizes, and 50 to 70 per cent finer than 0.02 mm. A more complete description of this material is given by Slusarchuk *et al.* (1978).

For the Calgary site, Figures 5, 6, and 7 present the raw data for Plate 7, installed at a depth of 3 m below ground surface. This corresponds to the elevation of the first bulb beneath the full-size test pipeline sections after a few months of operation. Using the temperature profile beneath the plate centre-line for the first four months of operation, the position of the 0°C isotherm can be interpolated to an accuracy of a few centimetres from these data (Figure 5). Examination of the temperature data beneath the centre and

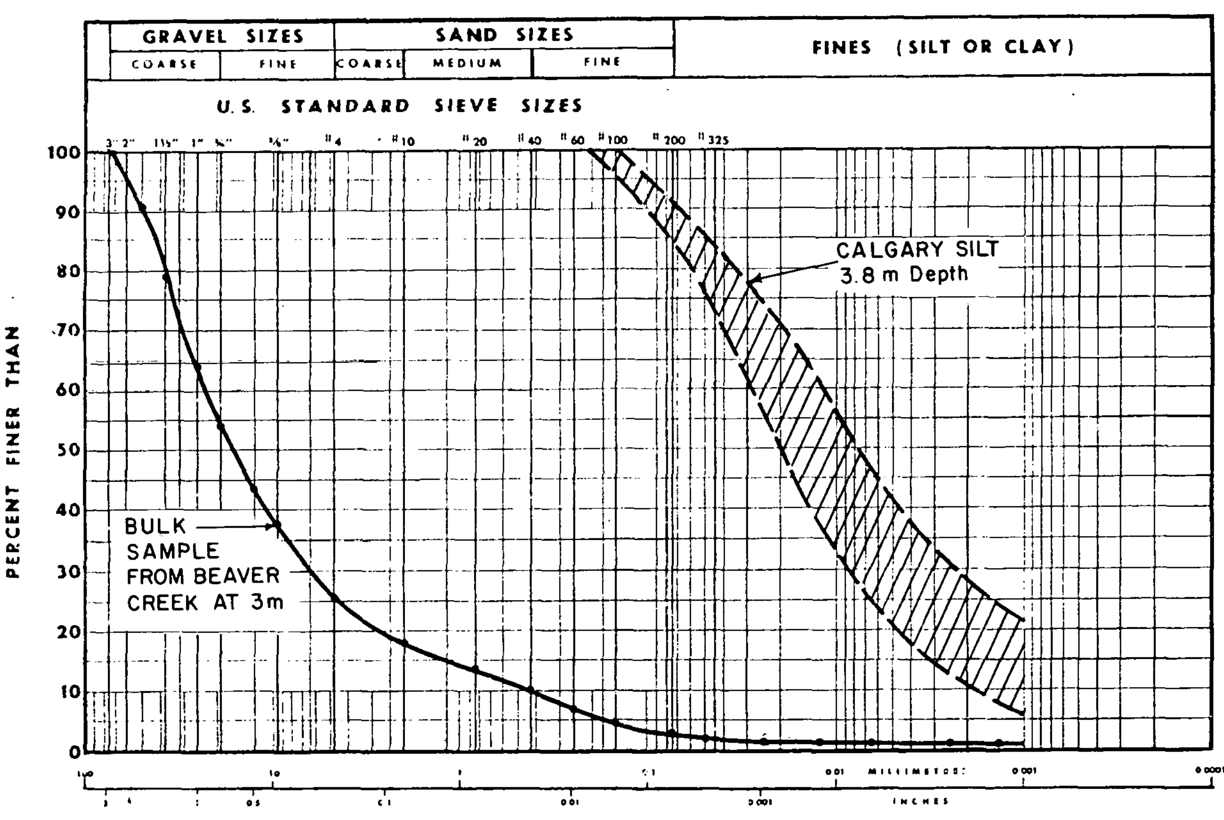


FIGURE 4. Grain-size distribution for soils tested.

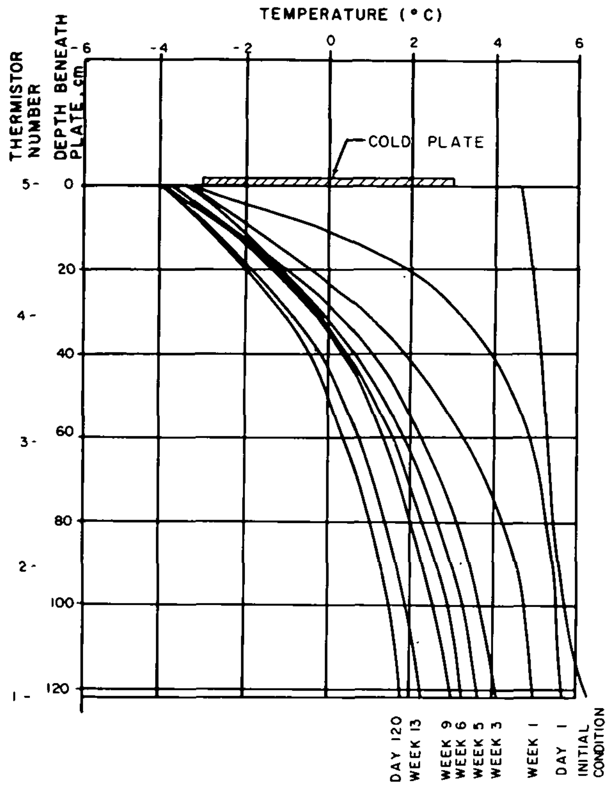


FIGURE 5. Temperature profile beneath centre-line of Calgary Plate 7.

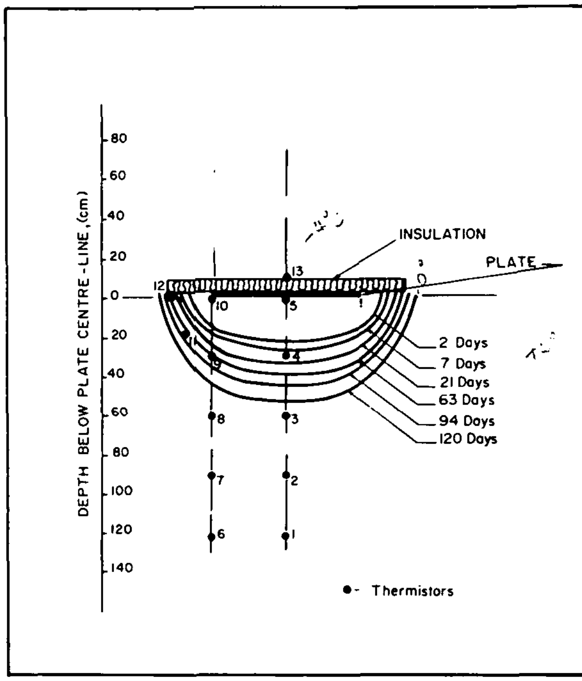


FIGURE 6. Advance of frost bulb at Calgary Plate 7.

edge of the plates allows an estimate of the shape of the frost bulb to be made (Figure 6). The zone of soil freezing approaches a hemispherical shape for the ground and plate temperatures at this site. Colder ground temperatures in a sub-arctic location would allow a greater frost advance.

A composite plot (Figure 7) provides plate temperature, frost depth, frost heave, cumulative ice-segregation ratio, and earth pressure. The data are shown on a common time axis, as many of the features of one relationship are related to another. For the first 200 days of the experiment, the frost line advances monotonically beneath the plate to a depth of about 56 cm. The advance of the frost line compared very favourably with prior predictions for a $-4°C$ plate temperature. These were carried out using the Hardy Associates (HAL) Geothermal Simulator, with the program employing its option to function in 2-D radially symmetric co-ordinates. A frost heave of about 8 cm was noted in the same time period, giving rise to a ratio of heave-to-frost penetration (called here the "ice-segregation ratio") of about 18 per cent. Earth pressure readings stayed at or above the calculated overburden pressure of about 0.56 bars. A sudden drop in vertical pressure on the plate was noted in mid-March, and this can only be attributed to warmer weather, thawing of backfill over the plate, and reduced resistance to upward motion of the plate.

During this entire period, plate temperatures were maintained close to $-4°C$, and did not vary significantly. In late summer, the effects of the warmer summer temperatures had penetrated to plate elevation, causing a steady decrease in the depth of frost to a depth of 20 cm at the end of October, 1980. No effort was made to maintain an advancing frost line by manipulating plate temperatures, however, as the natural thaw-back of the frost bulb was also of interest.

By mid-November, the frost line had started to advance again, and further information on frost heaving associated with the advancing frost line is again being obtained. During the period of retreat and advance of the frost line, although both heave and frost advance decreased significantly, the ratio between the two (as given by the ice-segregation ratio) remained at about 18 per cent, with fluctuations of the order of 2 per cent above or below this level. Of considerable interest was the dramatic decrease in earth pressure well below the calculated level. This is attributed to the settlement of the plate during thaw, and the arching of the looser backfill in the trench with the surrounding undisturbed soil. The pressure cell froze in December 1980, preventing further readings of this cell. A similar pressure reduction was also

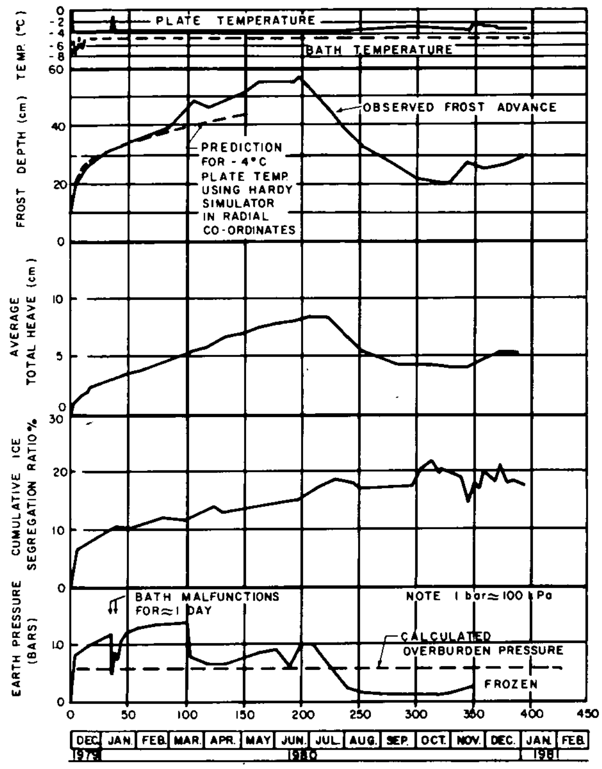


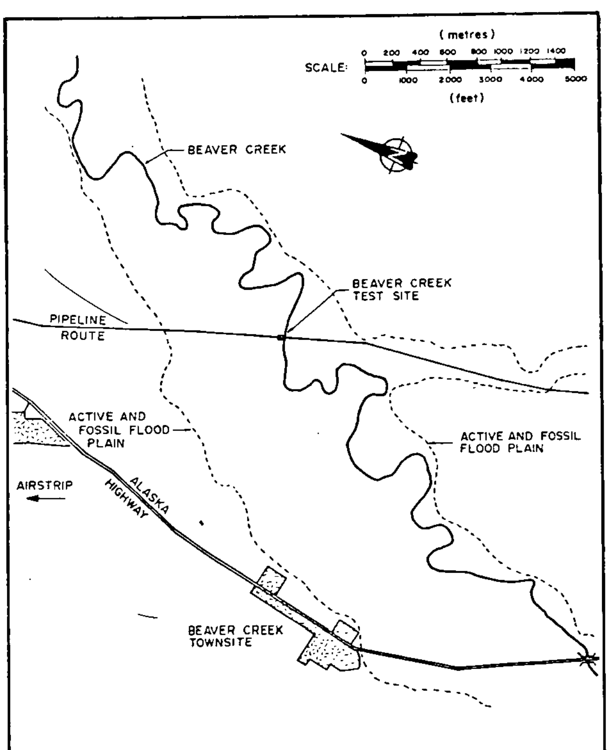
FIGURE 7. Frost heave test data for Calgary Plate 7.

noted for the other plate at this site, and this has since recovered to a value greater than the calculated overburden pressure, as the plate has commenced heaving again.

South Yukon Installations

In October, 1978, six plates were installed by Foothills Pipe Lines and Hardy Associates at two sites in the south Yukon. Two locations, at Beaver Creek and White River, are shown in relation to the Alaska Highway (Figure 8). Both sites were located on gravelly flood-plain deposits, and were designed to investigate the frost-heaving behaviour of granular material with a small fines content. The water table at both sites was close to, or above, the plate elevation. The plates were located at depths of 3.0 and 3.5 m at Beaver Creek and White River respectively.

Results for plate temperature, frost depth, heave, and earth pressure and given (Figure 9) for one plate at the Beaver Creek site. Operation was discontinuous due to power interruptions and equipment malfunctions, but an advancing frost line was maintained for several periods during the test. No significant frost heave was observed during these periods at any of the six plates at the Yukon locations. The results for Plate 2 show positive and negative fluctuations in plate movement of the order of a few milli-



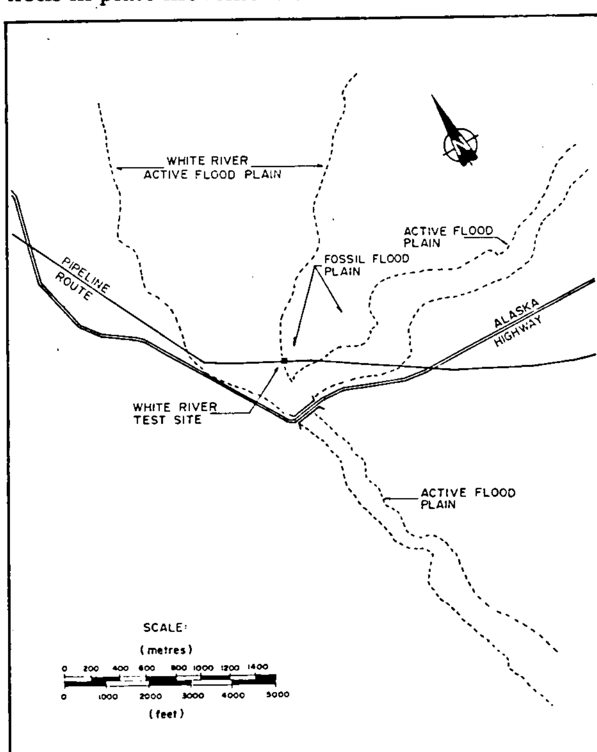


FIGURE 8. Test site locations in the south Yukon: *left* Beaver Creek; *right* White River.

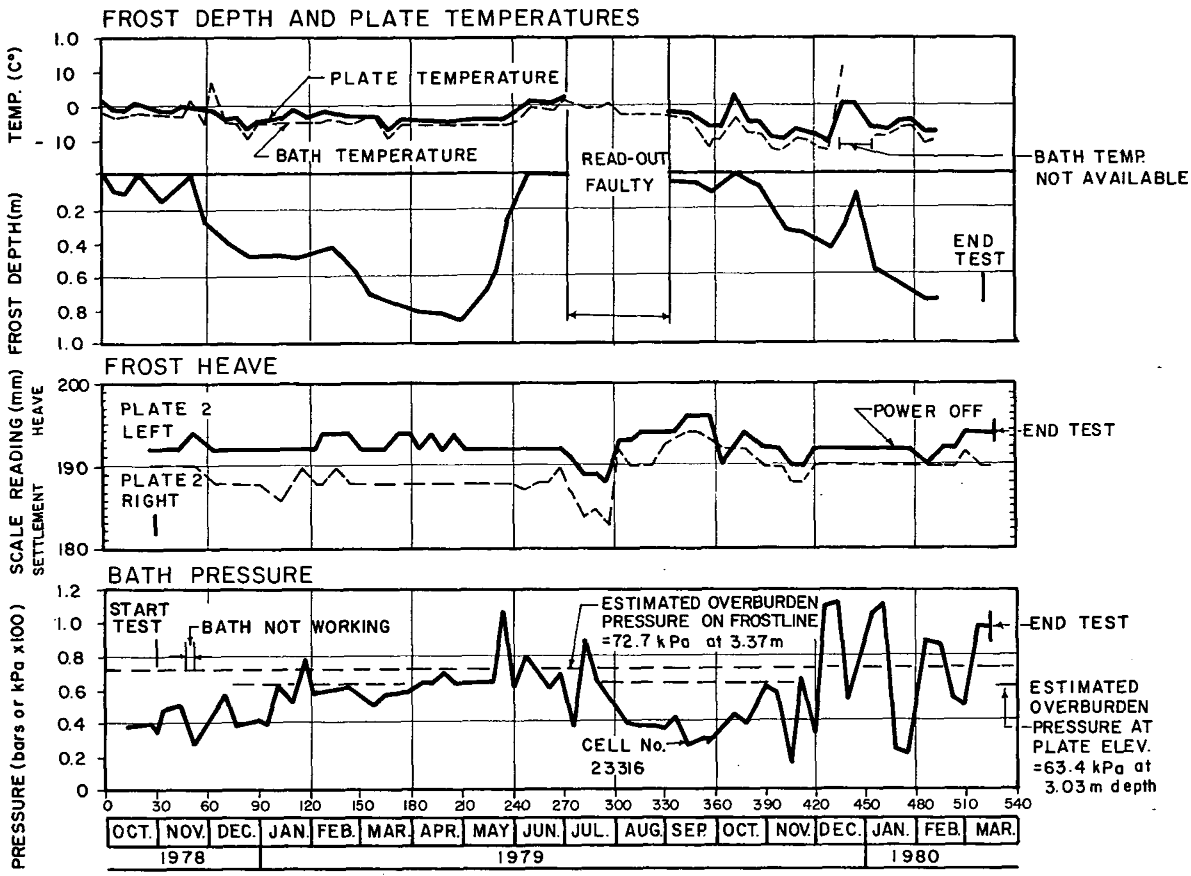


FIGURE 9. Frost heave test data for Beaver Creek Plate 2.

metres, but no trend in plate movement, either heave or settlement was observed.

Interpretation of Results

Calgary Tests

For the Calgary site, average frost heave rates for the first 200 days were in the range of 0.4 mm/day with initial heave rates during the first 20 days in the range of 1 mm/day. These are very similar to the heave rates observed for the full-size test sections, where heave rates of about 1 mm/day were observed for the first year of operation, and lower rates in the several years following.

In order to study in more detail the frost heave behaviour at different times during the test, it is desirable to examine the incremental heave per unit increase in frost depth. This might be termed the instantaneous ice-segregation ratio, and is algebraically given by

$$ISR = \Delta h/\Delta X$$

where $\Delta h/\Delta X$ is the slope of a plot of heave *versus* front penetration.

This quantity expresses the fractional increase in soil volume for some period of the test due to frost heaving. For Plate 7 at Calgary, the heave–frost penetration plot shows some very interesting features (Figure 10). During an early, rapid period of freezing, the slope of the h–X plot is low. After some 20 cm of frost penetration has occurred, the rate of frost advance fell to 10 mm/day or less. For the remainder of the first freezing phase of the test, a period of almost 200 days, the rate of frost advance varied from 10 mm/day to as little as 1 mm/day. During this period, the instantaneous ice-segregation ratio maintained an average slope of about 18 per cent. A similar slope on a heave–frost depth plot was observed for Plate 8 for a lengthy period of time.

During the period of retreat of the frost bulb, some hysteresis was observed initially in the h–X plot. Approximately 10 cm of thaw took place before thaw settlement started to occur. From then onwards, the thaw settlement segment of this plot has a similar slope to the frost heave segment. The re-freezing segment appears to have a similar slope as evidenced by early data.

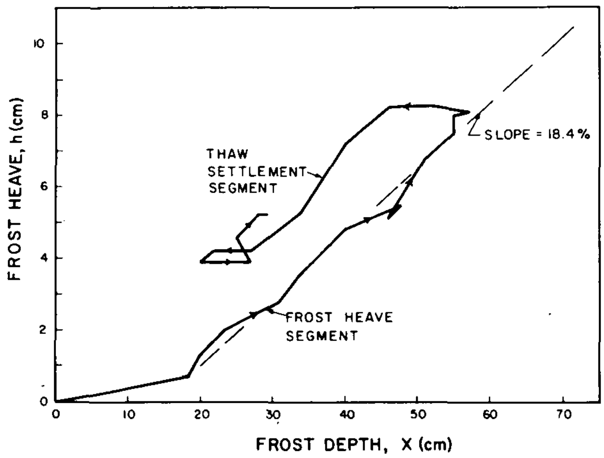


FIGURE 10. Heave–frost depth plot for Calgary Plate 7.

Referring to the data of Carlson *et al.* (1982), these values for ice-segregation are in the same range of values as those experienced beneath the full-size test pipe sections. Therefore, the first few months of data from the cold plate installations can provide an indicator to the performance of a large-scale structure over the first several years of its operation.

Interpretation of this data allows the conclusion that the instantaneous ice-segregation ratio, $\Delta h/\Delta X$, may be relatively constant for a large intermediate range of freezing rates of importance in the long-term design of chilled structures on frost-susceptible soils. At very fast rates (possibly in excess of 10 mm/day), the ice-segregation ratio tends to be much lower. At extremely slow rates of frost advance, as the frost line approaches its position of thermal equilibrium, it is likely that a final ice lens forms, and the instantaneous ice-segregation ratio may become 100 per cent. Under field overburden conditions, this situation would only normally occur at extremely low net heat fluxes, as the frost line approaches its position of final equilibrium, and therefore would only be responsible for relatively moderate amounts of total heave.

Yukon Tests

Continuous monitoring of the behaviour of the south Yukon plates for more than a year have revealed no measurable indication of heave. In order to check and compare these observations with another test method, some laboratory frost heave test data on the same soils have been summarized. These tests were carried out at a variety of test pressures, in cells of different sizes. Several cells, 10 cm in diameter, were used to test screened samples of the gravels from Beaver Creek (Figure 11) and White River. These tests were carried out in Hardy Associates' laboratories, and a range of heave rates were established over several days of freezing. In order to check the effects of freezing non-screened samples, several tests in large cells were carried out[1]. These results generally gave lower (or zero) heave rates than the screened samples. Heave rates for the range of freezing rates used in the tests were generally 0 - 0.03 mm/day, at the field overburden pressure of 80 kPa. If, for example, a heave rate of 0.02 mm/day were maintained for a full six-month period, a total heave of 3.6 mm would be obtained. This heave is likely within the range of accuracy of the field test plates, and no consistent heave of a greater magnitude than this was observed. Therefore, it is concluded that the field test plates heaved a similar, or lesser, amount than that which could be predicted by conventional frost heave tests. This is an indirect, but nevertheless encouraging, correlation of field and laboratory data.

[1]Hardy Associates (1978) Ltd. 1979. Large diameter frost heave testing of granular soils. Report submitted to Foothills Pipe Lines (Yukon) Ltd., Calgary, Alberta.

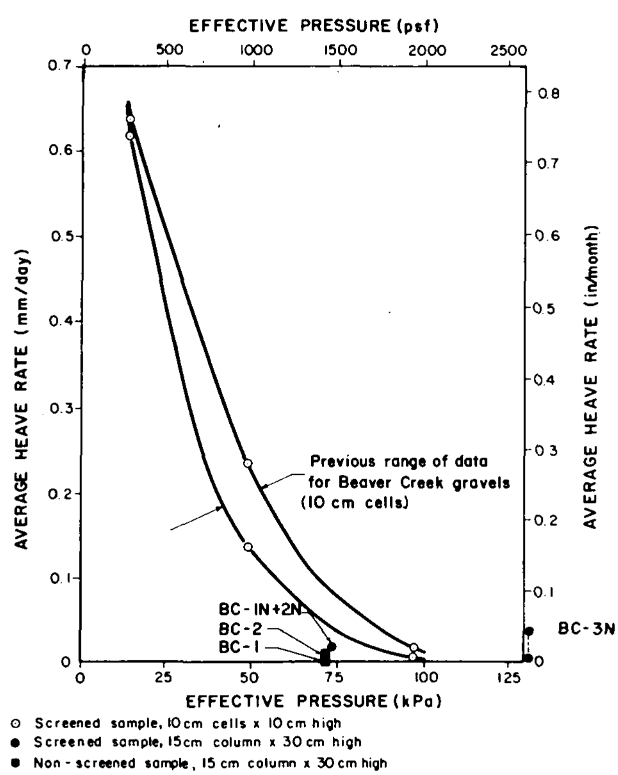


FIGURE 11. Beaver Creek gravel heave rate *versus* effective stress small- and large-diameter lab test data.

Conclusions

1. Several cold plate installations have been successfully installed and operated under field conditions.

2. Data obtained from cold plate tests have provided an important bridging between small-scale laboratory testing and full-scale pipe operation. Comparisons of laboratory and full-scale pipe tests are given in Carlson *et al.* (1982).

3. Just as a plate-bearing test is used to represent larger soil volumes and undisturbed soil conditions in conventional geotechnical practice, the cold plate can be used to assist in predicting the frost heave response of a soil to the continuing presence of a chilled structure.

Acknowledgements

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