Application of heat pipes to design of shallow foundations on permafrost

D.W. HAYLEY

EBA Engineering Consultants Ltd., 14535 118 Avenue, Edmonton, Alberta, Canada T5L 2M7

This paper describes two structures where heat pipes have been successfully used to provide thermal protection for permafrost soils supporting surface foundations. The heat pipes are two different models of "Cryo-Anchors", manufactured by the McDonnell Douglas Astronautics Company.

A school constructed at Ross River, Yukon Territory, in 1975, included heat pipes as an integral part of the foundation design. The site conditions are described in the paper and considerations that led to selection of heat pipes are stated. The heat pipe evaporator sections were installed in aluminum access tubes that extend into a gravel pad supporting a slab-on-grade foundation. Insulation thickness and heat pipe spacing were determined by predicting the maximum extent of seasonal thaw beneath the foundation using two-dimensional geothermal analyses. Performance of the system has been satisfactory over a five-year observational period.

The second heat pipe system described in the paper was installed to stabilize a tramway tower foundation also in the Yukon Territory. Exposed footing foundations were experiencing settlement that could be related to thaw of underlying permafrost gravel. Vertical heat pipes were installed adjacent to the foundation elements to arrest permafrost degradation. Ground temperature records and survey data have shown that the installation has elevated the permafrost table.

Le présent document décrit deux structures pour lesquelles on a réussi à utiliser des caloducs pour protéger thermiquement un pergélisol sur lequel reposaient des fondations de surface. Les caloducs étaient deux modèles différents de marque "Cryo-Anchors", fabriqués par la société McDonnell Douglas Astronautics.

Dans une école construite à Ross River (Yukon) en 1975, les caloducs ont été incorporés aux fondations. Ce document décrit les conditions d'implantation et expose les considérations qui ont conduit au choix des caloducs. Les évaporateurs ont été installés dans des tubes d'accès en aluminium qui pénétraient dans l'appui de gravier sur lequel reposait le radier. L'épaisseur de l'isolant et l'espacement des caloducs ont été déterminés compte tenu de la profondeur maximale du dégel saisonnier au-dessous de la fondation estimée à l'aide d'analyses géothermiques en deux dimensions. La performance du système a été satisfaisante au cours d'une période d'observation de cinq années.

Le second système de caloducs décrit ici a été installé pour stabiliser les fondations d'une tour de tramway également au Yukon. L'affaissement constaté des fondations exposées pouvait être lié au dégel des graviers du pergélisol sous-jacent. Des caloducs verticaux ont été installés le long des éléments des fondations pour arrêter la dégradation du pergélisol. Des enregistrements de la température du sol et des données recueillies pendant l'étude montrent que cette installation a permis d'élever le niveau du pergélisol.

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Introduction

Growth of northern settlements during the past decade has challenged engineers to design effective foundations for permafrost soils. Functional or space limitations are now routinely imposed by developers, who often discourage the use of classical methods for foundation construction on permafrost. When faced with difficult site conditions, design restrictions, or severe space limitation, the geotechnical engineer often finds himself looking for new methods to ensure stability of structures on permafrost.

Thermal piles or heat pipes installed in conventional steel piles have been in use in Alaska for almost two decades (Long 1963, 1973; Womick and LeGoullon 1975). The benefits that can be derived from lowering the ground temperature to improve the adfreeze bond and reduce the risk of frost heave have been well established. Cryo-Anchor heat pipes were adopted from space technology and introduced for geotechnical purposes in the early 1970's by the McDonnell Douglas Astronautics Company. They are an efficient ground-to-air heat exchanger offering design flexibility for shallow foundations that are not available with vertical thermal piles.

The two-phase heat pipe is a relatively simple device that consists of a closed tube charged with an appropriate working fluid. It is installed with one end below ground and the other end exposed to the air. Heat from the soil causes thin-film evaporation of the working fluid within the below ground section. The vapour travels upward and condenses in the above-ground (radiator) segment, releasing the transported heat to the air. The evaporation–condensation cycle is maintained only when the air is colder than the soil, thus heat is not conducted back into the ground during the warmer summer months.

Cryo-Anchor heat pipes received widespread use to improve load carrying capacity of vertical support members on the Trans Alaska Pipeline. The research and development program associated with this project has been described by Heuer (1979). An efficient multi-fin aluminum radiator was developed for the pipeline and experimental programs provided quantitative performance data relating the heat removal rate to the thermal gradient for a particular heat pipe configuration.

Two cases are described in this paper where Cryo-Anchors have been used for design and for restoration of shallow foundations on "warm" permafrost. The objectives are to demonstrate heat pipe configurations that have been used successfully, state the advantages that each system has offered, and describe briefly any unique construction methodology. The geothermal analysis that was used as a design guide is described and available ground temperature data that are indicative of system performance are presented.

Ross River School

The community of Ross River, Yukon Territory, is situated in the Pelly River valley, at the confluence of the Ross River, approximately 200 km by air northeast of Whitehorse. It is predominantly a native settlement, of log or wood-frame houses clustered on a terrace beside the Pelly River. An architect was retained by the Territorial Government in 1974 to design a new school, with a useable floor area of approximately 1325 m^2. The site selected was the playground of the existing temporary school. A routine site investigation, consisting of four borings spaced randomly within the school yard, was carried out by the author during May of 1974. The difficult site conditions that were encountered and the engineering considerations that resulted in a unique heat pipe foundation design are described.

Site Conditions

Site conditions at Ross River are characteristic of many of the large glaciated valleys of the central and northern Yukon. Approximately five metres of dense sand and gravel of recent alluvial origin overlies a very deep deposit of glaciolacustrine silt. The permafrost table was found to be coincident with the gravel–silt contact in all of the borings. One borehole, sampled to a total depth of 28 m, encountered the bottom of the permafrost at a depth of 24 m. The permafrost silt contains excess ice (Vs; Pihlainen and Johnston 1963) throughout its entire depth, although the greatest excess ice content was observed within the depth range from 12 to 18 m where ice was estimated to occupy 20 to 60 per cent of the volume of recovered soil samples. Ground temperature within the permafrost zone was not measured but was anticipated to be very warm; about $-0.5°C$. The unfrozen silt below a depth of 24 m is non-plastic and stiff. Very deep drilling in search of warm water aquifers elsewhere within broad glacial valleys of the central Yukon has shown that this sequence of lacustrine and alluvial deposits can extend to depths of several hundred metres.

Foundation Alternatives

The conventional approach to foundation design on discontinuous permafrost in this region of the Yukon is to carry building loads through the permafrost to unfrozen soils with piles or to excavate and replace soils subject to thaw-settlement. The use of steel pipe piles to support the school was considered but the idea was discarded because an adequate end bearing stratum was not present within the exploration depth of 28 m. Moreover, the design would have to account for large, negative, skin friction loads on the piles caused by subsidence of the thawing silt.

The first alternative to piles that was considered was to provide a breezeway beneath the building in an attempt to preserve the permafrost. Considerable uncertainty and a significant risk of permafrost degradation would have to be assumed by the owner if such a system were used. A contingency plan would be provided by incorporating a jacking system into the foundation to allow periodic relevelling of the structure.

The architect and the owner both objected to the inclusion of a breezeway. The architect desired a slab-on-grade type of foundation for the gymnasium where floor deflections must be minimized. The aesthetics associated with an elevated building were also considered to be undesireable at the site. The owner was most concerned about long-term building maintenance in a community where the work force was very small.

The feasibility of preserving the permafrost by replacing the breezeway with some other type of heat exchanger was examined to satisfy the functional requirements imposed for the structure. Although there was no precedent for the use of heat pipes to maintain permafrost stability below a slab-on-grade foundation, this foundation system was found to be both technically feasible and cost effective. A design was prepared that included Cryo-Anchor heat pipes with long evaporator sections extending into a thin fill supporting a surface foundation.

Design and Construction

A schematic drawing of the configuration adopted is shown (Figure 1). Since the maximum width of the building is 23 m, heat pipes with an evaporator section slightly in excess of one half the width, or 12.2 m, were required. They are spaced evenly along

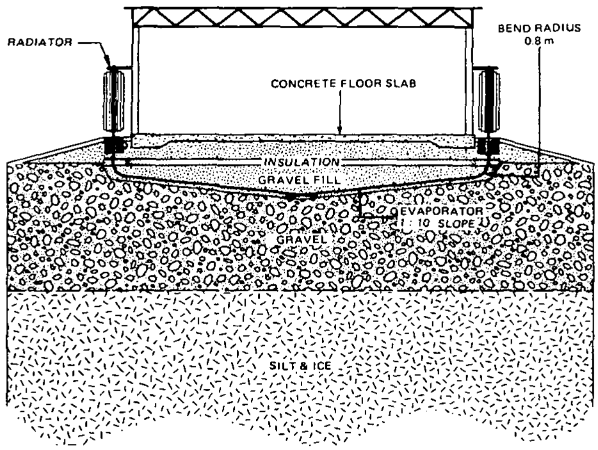

FIGURE 1. Foundation schematic — Ross River School.

both long sides of the building, with the evaporator section extending below the foundation slab at a slope of 1 vertical to 10 horizontal. The radiators have a height of 2.4 m and are mounted vertically along the outside walls.

The design objective was to extract sufficient heat from the foundation to freeze the gravel supporting the structure each winter. After freezeback, the temperature of the ground must be further lowered to create a heat sink that will absorb heat during the summer months when the heat pipes are dormant. Annual thawing and freezing must be confined to the fill and the natural alluvial gravel, a condition that will retain the permafrost table at its present elevation.

A geotechnical difficulty associated with such a design is the necessity to protect the building from frost heave as well as thaw settlement. The gravel fill supporting the slab and the alluvial gravel must be free of silt-sized material and be free draining in order to ensure freeze–thaw stability. This requirement limits the amount of moisture retained in the gravel to a nominally low amount. Unfortunately, such a property is counter-productive for creating a heat sink because the latent heat absorbed during thaw will also be very low. The natural gravels at the site were judged to be thaw-stable as they have a water content of only five per cent and less than ten percent of silt-size particles (less than 0.074 mm).

The variables that were determined by thermal analyses are the heat pipe spacing and the thickness of insulation required beneath the floor. A two-dimensional, finite element, numerical analysis was used to assess the effect of the various design parameters. The numerical model was developed at EBA Engineering Consultants Ltd. (Hwang *et al.* 1972) and has been chiefly applied to problems relating to freezing or thawing around buried pipelines. A description of the method was provided by Hwang (1976). A heat pipe spacing of three metres was chosen for initial analysis and the insulation thickness was varied. The symmetrical distribution of heat pipes allowed the thermal domain under the building to be reduced to a two-dimensional strip, 1.5 m wide, representing one-half the distance between adjacent heat pipes (Figure 2). The strip extended from the concrete surface inside the school, where a steady-state temperature of 21°C was prescribed, to a depth well below the bottom of permafrost. There is no horizontal heat flow across the vertical boundaries of the strip because the thermal gradient at these sections is vertical.

The flux to the heat pipe is proportional to the temperature differential between the air at the radiator and the ground at the evaporator section. The constant of proportionality can be represented by a simple conductivity coefficient or conversely a thermal resistance of the heat pipe. A conductivity coefficient of 5.7 W/(m^2.K) was selected by arbitrarily reducing performance data suggested by the manufacturer in order to build additional safety into the design. This coefficient was assumed to be constant over the range of temperature gradient experienced by the system. Whenever the air temperature went above freezing, the heat pipes were switched off by assigning a conductivity coefficient of zero.

Air temperature records were not available for Ross River before 1974, and, therefore, this important design variable had to be estimated. A design freezing index of 3000 degree Celsius days was chosen after considering data from other central Yukon communities. The air freezing index was converted to a sinusoidal air temperature variation with a mean of −3.9°C and an amplitude of 19.4°C.

The predicted freeze–thaw behaviour on a vertical

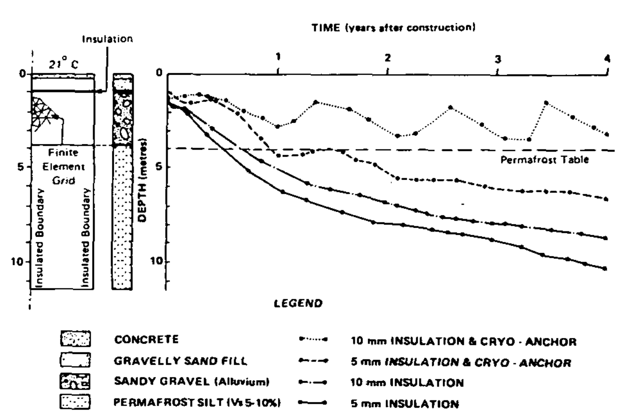

FIGURE 2. Predicted depth of thaw (0°C isotherm).

plane located midway between two heat pipes is shown (*see* Figure 2). The analyses were carried out both with, and without, the heat pipes and for an insulation thickness of 5 and 10 cm respectively. The results clearly demonstrate the contribution of the heat pipes toward retaining the permafrost. A heat pipe spacing of 3 m with 10 mm of insulation met the design objective of limiting thaw to the alluvial gravel.

School construction was planned for the summer of 1975. Construction of the foundation pad was scheduled for the fall of 1974 to provide one full winter of exposure to sub-freezing temperature. This schedule was chosen to offset the undesireable impact that excavation might have on ground temperature. Installation of the heat pipes could not proceed until the structure was essentially complete, as the two rows of 20 radiators each would interfere with building construction. The installation methodology, developed in conjunction with the heat pipe manufacturer, included provision of access tubes that would accept the evaporator sections after the building was complete. Any system involving the use of access tubes must consider possible construction difficulties, heat transfer efficiency, and long-term corrosion protection. The use of access tubes rather than direct burial does have the added benefit of allowing replacement of a unit should it become inoperative.

Thin-wall aluminum irrigation tubing, with an internal diameter of 10 cm, was chosen for the access tubing. The tubing was wrapped with polyethylene tape and cathodic protection was provided by zinc anodes buried in the fill. A single joint was required to connect two 6.1-m lengths and a flexible section was required where the tubes curve upward at a predetermined radius of 0.8 m. Wire-reinforced pump suction hose was chosen for this application. The hose was fastened to the tubing with stainless steel band clamps. The annulus between the evaporator section and the access tube was filled by injecting high-viscosity, bentonite base, drilling mud from the bottom of the tube. Freeze–thaw tests were conducted in the laboratory to ensure that freeze expansion of the mud would not damage the tube.

The site was excavated at a 10 to 1 slope to the maximum depth of the access tubes at the centre of the structure. The tubes were laid on a carefully prepared sand base (Figure 3), and the site was rebuilt to the elevation of the underside of the insulation. School construction commenced the following spring with placement of the insulation and casting of the foundation slab. The Cryo-Anchors were manufactured with a 12-metre long, flexible aluminum evaporator. They were shipped to the site coiled in wooden crates and were installed during November and December of 1975.

FIGURE 3. Installation of access tubes

Handling the units and sliding the evaporators into the access tubes was found to be more difficult than anticipated. Each tube was blown clear of debris with compressed air and then filled with drilling mud prior to installation. The entire procedure was complicated by very cold weather during the working period. Difficulties associated with sliding the Cryo-Anchors into the tubes were resolved by fitting a ball castor to the end of the evaporator to reduce friction at the tip. The long vertical radiators were supported on individual concrete foundations and lateral support was provided at the top of the units with a bracket attached to the school. The completed installation is shown in Figure 4.

Temperature History

A number of thermistor cables were installed in the foundation soil during installation of the aluminum access tubes. Three cables were installed in boreholes

FIGURE 4. Ross River School with Cryo-Anchor radiators at three-metre spacing.

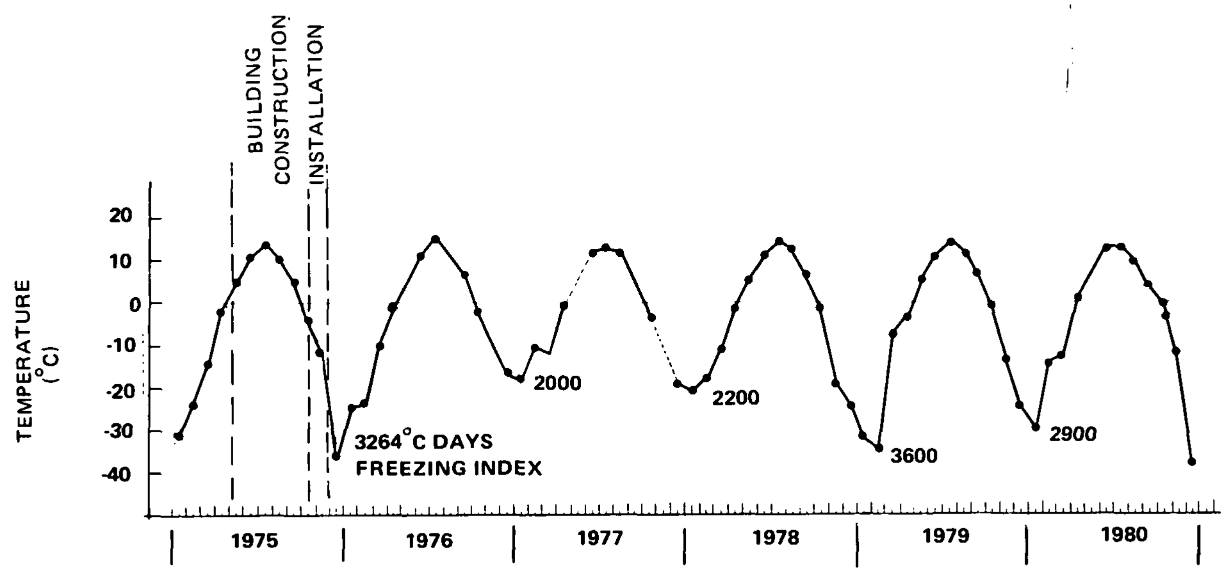

FIGURE 5. Mean monthly air temperature, Ross River.

that extended to a depth of approximately nine metres, two of which were located beneath the building and one outside the building. Horizontal cables were installed at two locations extending between adjacent heat pipes at the midpoint on the evaporator sections. All of the cables were taken to a common readout panel located in the mechanical room.

The temperature records obtained during the past six years of operation are not very complete and a number of the cables were destroyed early in the history of the school. One deep cable under the school and one horizontal cable between heat pipes have provided reliable ground temperature data when readings have been taken. These data have allowed a reasonable assessment of the system's performance.

Mean monthly air temperatures from Ross River since 1974 are shown (Figure 5). It is significant that when the Yukon experienced two particularly mild winters during 1976 and 1977, the freezing index recorded was only seventy per cent of the value used for design purposes. Although the design value of 3000 degree Celsius days seems to be a reasonable long-term average freezing index, the occurrence of sequential warm winters had not been considered in the design calculations.

Temperature records for the first full year following construction and for 1979 are shown (Figure 6). The temperature data for the years 1977 and 1978 are very sparse and therefore have not been included. Three important thermistors, at the locations indicated in Fig. 6 have been chosen to illustrate the range in temperature change recorded in the foundation soils. The temperature changes within the silt have been negligible during the period of record. A relatively constant temperature of $-0.4°C$ has been recorded, with a maximum variation of $\pm 0.2°C$. The thermistors located on the access tube and midway between tubes show characteristic seasonal temperature variations. The thermistor located on the access tube is subject to rapid temperature changes that are not adequately reflected during the course of normal data collection. The data at both of these locations appears to be repeating itself as the temperatures in 1979, four years after installation, are similar to those recorded during the first year. Further analytical work will be required before a direct comparison between predicted and observed ground temperatures can be made.

From the observed freeze–thaw history, determined from the thermistor data (Figure 7), freezing and thawing is confined to the gravel and complete freeze-back seems to occur annually. In general, there

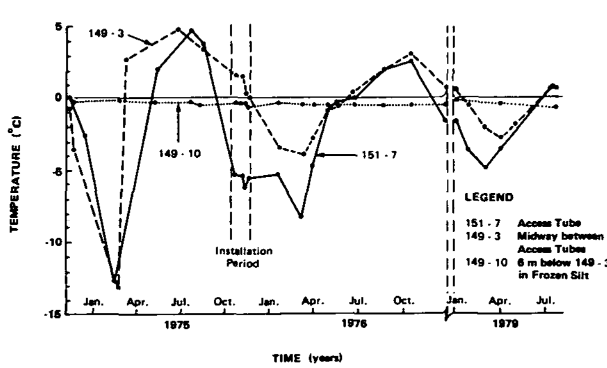

FIGURE 6. Foundation temperature history.

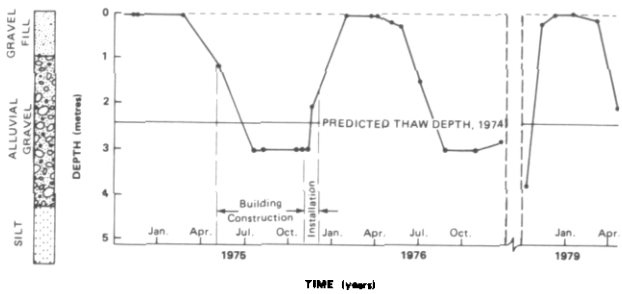

FIGURE 7. Observed freeze - thaw history

is no evidence of thaw of the permafrost silt, although thaw within the gravel is slightly deeper than originally predicted.

A foundation elevation survey that was conducted after the first year of operation did not detect any significant heave or settlement of the slab. Although the survey has not been continued, there has not been any evidence of cracking in the slab-on-grade foundation during the six-year history of the building. The Cryo-Anchors were field checked by the owner during the 1980 winter season and all were reported to be functioning.

Tower Foundation Stabilization

A second example where heat pipes have been used to maintain stability of foundations on frozen ground is at a tramway tower located on the Alaska Highway, approximately 30 km south-east of the Yukon–Alaska border. The tramway was constructed on the south slope of Horsecamp Hill in 1961 by Canadian National Telecommunications (now Northwest Telecommunications) to service an otherwise inaccessible hill-top repeater station. The tramway functioned normally from 1961 to 1977 when settlement of the main tower supporting the tramway cables was observed. The tower settlement caused misalignment of the cable and sheaves resulting in suspension of operation because of an unsafe condition.

Site Conditions

The lower tramway terminal (Figure 8) consists of a machinery building, a counter-weight building, and the main cable support tower. All of the structures were constructed on shallow foundations in a thick gravel pad. The main tower is supported, independent of the buildings, on two, exposed concrete piers. The building foundations have performed satisfactorily whereas the exposed piers have settled differentially, with the south pier sustaining the greatest movement. Total settlement of the south pier has been estimated from survey data to be in the order of 140 mm. A drilling program was conducted during

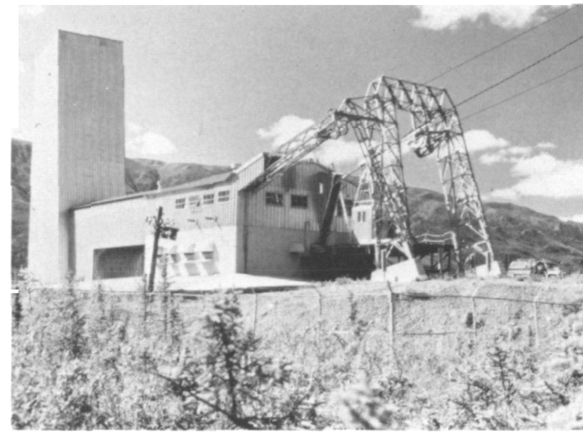

FIGURE 8. Lower tramway terminal, Horsecamp Hill.

September, 1978, to obtain subsurface data in order to determine the cause of the settlements and to develop appropriate restoration measures.

The soil profile, prior to construction in 1961, was inferred from boreholes near, but not on, the foundation pads. The site originally consisted of one to three metres of peat, silt, and organic silt overlying silty sand and gravel of alluvial origin. This alluvial sand and gravel extends to a depth in excess of ten metres. Permafrost is present at a depth of 1.5 m into the silt below undisturbed areas. The alluvial sand and gravel ranges in ground ice classification from non-visible, well-bonded (Nbn) to visible, random ice (Vr) with 10 to 20 per cent estimated volumetric excess ice content. The area surrounding the tower site is thickly wooded with small spruce trees. A bog, indicative of a former lacustrine depositional environment, borders the east side of the site.

Construction records note that the surficial silt and some of the alluvial gravel was excavated below all shallow foundations. Gravel fill was placed and compacted up to footing elevation. Additional uncompacted fill was placed around the foundation elements up to the present surface of the pad.

The stratigraphic section (Figure 9) was constructed from borings placed through the fill in September and December of 1978. The section chosen is referenced on the site plan also included in Figure 9. The position of the permafrost table within the gravel pad was determined from the borehole data and from thermistor cables installed in three of the borings.

Heat Pipe Selection

The observed foundation settlements could be attributed to thaw of the underlying permafrost gravel. Deeper thaw observed under the south pier is consistent with greater pier settlements. This deeper

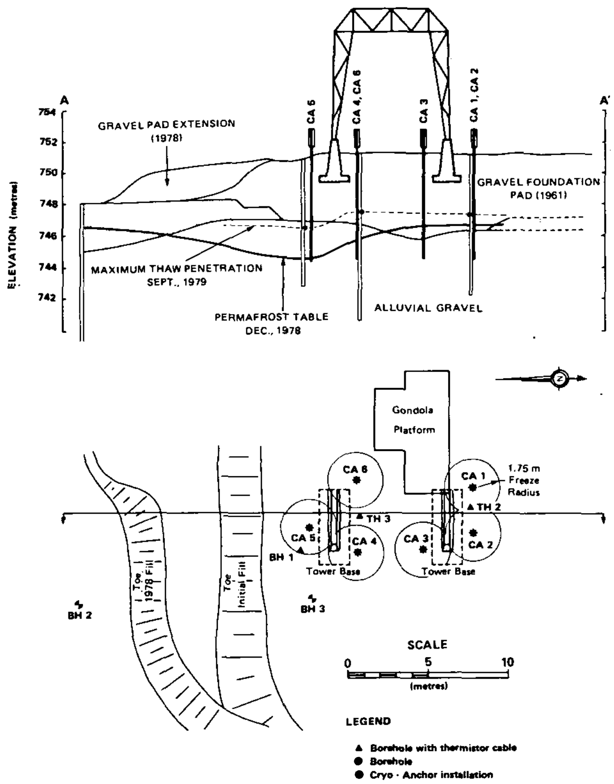

FIGURE 9. Stratigraphic section and tramway tower foundation plan.

thaw could be rationalized by the proximity of the south pier to the edge of the fill and the direct southern exposure. The gravel fill was extended to the south soon after site inspection in order to provide some immediate protection for the permafrost at this location.

Air and ground temperature records were examined in an attempt to explain why thaw-settlement was initiated after approximately 15 years of satisfactory performance. Meteorological data from nearby sites indicated that the long-term freezing index should be approximately 3500 degree Celsius days, whereas the freezing index for the 1976 winter season was only 2720 degree Celsius days. The warm winter of 1976, that was also evident in the temperature records for Ross River, accelerated permafrost degradation at Horsecamp Hill. Approximate, one-dimensional, thermal calculations indicated that the 1976 freezing index would probably not provide sufficient frost penetration to re-freeze the active layer. Once a talik remains, permafrost thaw will continue even during normal winters unless particularly severe conditions reverse the process.

The age of the tower and the growing accessibility of helicopters to service the mountain-top repeater station made expensive restoration measures, such as underpinning with piles, economically unfeasible. Installation of heat pipes adjacent to the foundation elements was considered because they provided a cost-effective means of arresting further permafrost degradation. Model 800 Cryo-Anchor heat pipes, of the same configuration as those used for the Trans-Alaska Pipeline, were selected for vertical installation adjacent to the foundation elements. These particular units were attractive for this project because they are robust, self supporting, and vandal proof.

The design objective was to ensure complete freeze-back of the fill adjacent to the two piers each winter, thereby arresting any further thaw-subsidence. The quantity of heat pipes, their spacing, and the installation procedure were required to meet this objective. Accurate analysis of heat transfer to a heat pipe installed in a vertical borehole is more difficult than the horizontal case described previously because the three-dimensional nature of the heat flow problem that is created. For purposes of this installation, a simplified but conservative approach was adopted to determine the number and spacing of the heat pipes. The extent of growth of a frozen cylinder of soil during a typical winter was predicted based on the capability of an individual heat pipe to freeze the soil around it.

The concept of a cylinder of frozen soil growing around a vertical heat pipe during the winter months is illustrated (Figure 10). The heat removal rate for a single vertical unit can be expressed by the simple equation

$$Q = \frac{T_s - T_a}{R_c + R_s}$$

where Q is the total heat removal rate;
T_s is the soil temperature at the advancing frost front, in this case 0°C;
T_a is the ambient air temperature;
R_c is the thermal resistance of the Cryo-Anchor; and
R_s is the thermal resistance of the frozen soil cylinder.

The thermal resistance of the frozen cylinder can be expressed as a function of the cylinder radius and the soil's thermal conductivity. The thermal resistance of the Cryo-Anchor is dependent on the particular model selected, its radiator to evaporator length ratio, and the estimated average air velocity over the radiator. This information was obtained from the manufacturer and is based on their test data.

In order to simplify the analysis, a constant temperature is assumed within the frozen cylinder thus enabling the volumetric specific heat to be ignored.

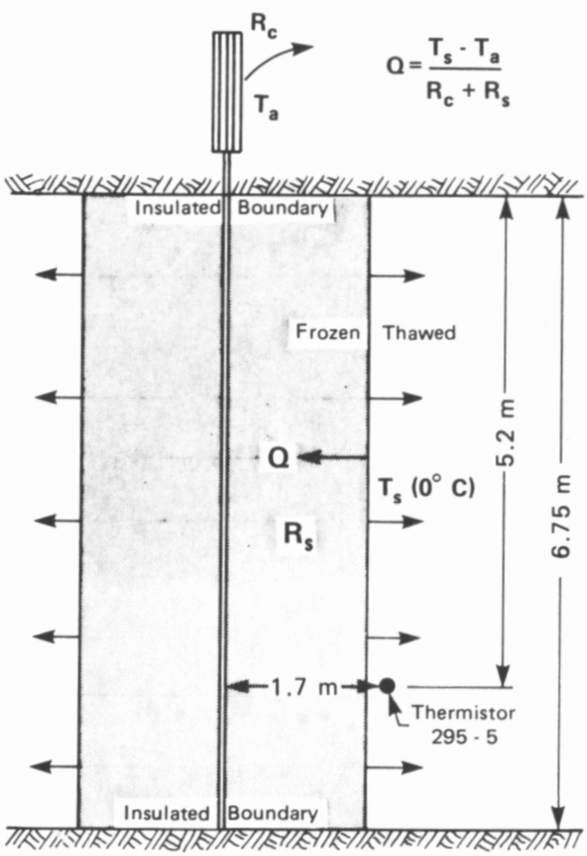

FIGURE 10. Analysis of freezing cylinder growth

Heat removed by the Cryo-Anchor can be equated therefore to the latent heat of a unit volume of soil that is frozen per unit of time at the periphery of the cylinder. The temperature differential between ambient air and the freezing temperature (0°C) is proportional to the air freezing index, allowing a relationship, such as that shown in Figure 11, to be determined. The computed freeze radius is shown as a function of air freezing index for soil conditions specific to the site. From this relationship, a freezing radius of 1.75 m can be expected for the site with an estimated long-term freezing index of 3500 degree Celsius days.

The analysis is highly conservative because it neglects natural freezing that occurs from the surface downward. However, it does provide a guideline for spacing the heat pipes that will ensure freeze-back of adjacent soil within the predicted cylinder radius.

Three Cryo-Anchors per pier were considered sufficient based on the simplified thermal analysis. The actual installation locations were limited by accessibility for drilling equipment and a desire to keep spacing between units close to twice the predicted freeze diameter of 3.5 m (*see* Figure 9).

Heat pipe installation was carried out in early December, 1978. A rotary drill was used to advance a vertical hole to a depth slightly in excess of the desired heat pipe penetration. Drilling mud was required to stabilize the hole within the sand and gravel soils. A polyethylene grout pipe was attached to the bottom of the heat pipe and the unit lowered into the mud-filled hole. The aluminum fins were not attached to the radiator section of the heat pipe during installation and the exposed pipe was wrapped with insulation to inhibit rapid freezing of the drilling mud. When the unit was positioned in the borehole, the drilling mud was displaced by pumping neat cement grout to the bottom of the hole through the grout tube. All of the radiator finned sections were installed just prior to leaving the site in order to allow as much time as possible for the grout to set. The completed installation at the north pier is shown is Figure 12.

Performance

Ground temperature observations were obtained by Northwest Telecommunications personnel during the ten months following installation. An accurate

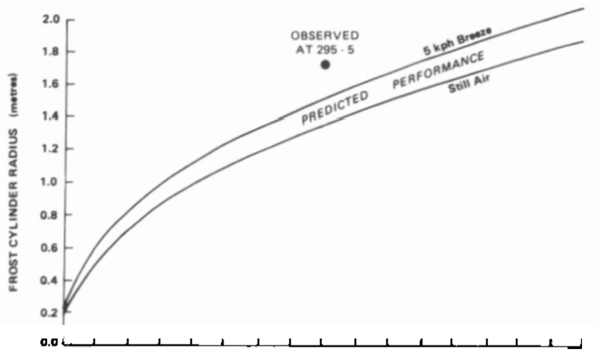

FIGURE 11. Freezing cylinder radius prediction and observation.

FIGURE 12. Heat pipe installation, north pier

elevation survey was also established to monitor any foundation displacement that might occur during the summer season following installation. It was considered imperative to verify that the foundations have stabilized before undertaking re-alignment of structural members.

The temperature data show that complete freezing of the soil in the vicinity of the foundations occurred by January 18th and rapid cooling took place during the ensuing winter months. The time–temperature history of two individual thermistors is shown in Figure 13. Both thermistors are placed at a depth of 5.2 m, which is just above the permafrost table. Thermistor 295-5 is located at the periphery of the predicted freezing cylinder radius, 1.7 m from a heat pipe. The second thermistor (335-6) is located midway between two heat pipes that are spaced at approximately 3 m. Also shown in Figure 13 is the cumulative freezing index computed from mean monthly temperatures for Beaver Creek, Yukon Territory.

The ground temperature data at thermistor 295-5 can be used to provide a crude comparison of predicted and observed performance of the heat pipe. Complete freezing of the soil occurred at thermistor 295-5 on about March 8th, after the heat pipes had

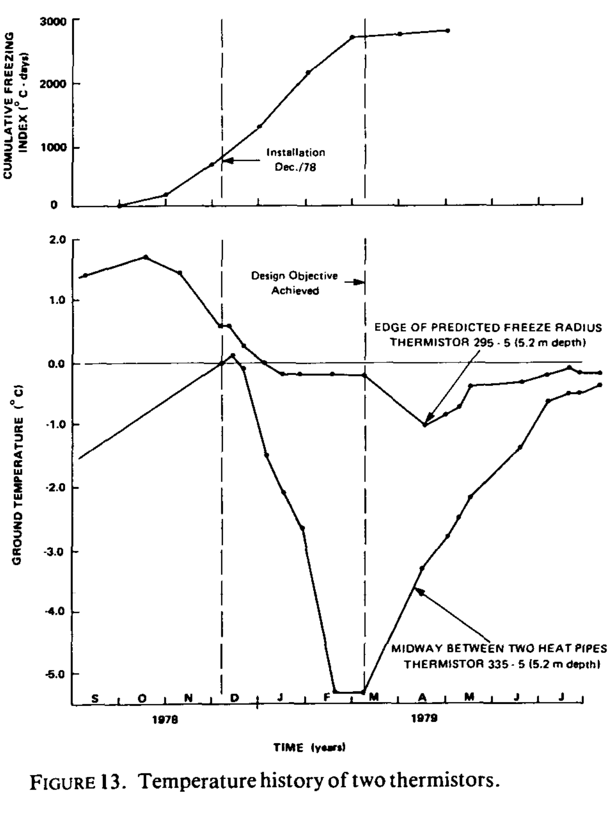

FIGURE 13. Temperature history of two thermistors.

been exposed to 2000 degree Celsius days of freezing. This condition plots above the predicted performance curves (*see* Figure 11), verifying that conservative assumptions have been used for the design calculation. By the end of the summer, 1979, the permafrost table had been drawn up into the fill by as much as two metres (*see* Figure 9).

A precise elevation survey, repeated at several times during the 1979 summer period, did not detect any foundation movements. By the end of the summer, the foundations were considered to have stabilized, allowing repair and realignment of the superstructure to proceed.

Conclusions

Satisfactory performance of the school foundation at Ross River has demonstrated that heat pipes are a viable design alternative to more-conventional heat exchangers for shallow foundations on warm permafrost. The heat pipe system offers certain aesthetic and functional advantages when compared with either a natural convection or forced ventilation system. Recent advances in geothermal analyses have allowed rational procedures to be used for system design. Additional performance data and more-detailed back analyses of existing data are required to improve and generalize the design methodology.

The application of heat pipes for stabilization of a settling tramway tower foundation has been described. The use of free-standing units, grouted into vertical boreholes is a particular application that can be cost-effective for surface foundations where instability is caused by permafrost degradation. There is scope to extend the concept used at Horsecamp Hill to stabilization of embankments on permafrost and to develop rapid techniques for inserting heat pipes into thawing soil.

Acknowledgements

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