Full-Scale Chilled Pipeline Frost Heave Testing, Fairbanks, Alaska, USA

Beez Hazen, P.E.
Northern Engineering & Scientific, Anchorage, Alaska, USA
Ralph M. Isaacs, P.E., PhD
RMI Associates, LLC, Camano Island, Washington, USA
John E. Myrick, P.E.
Myrick International, Tyler, Texas, USA

ABSTRACT
Beginning in 1979 Northwest Alaskan Pipeline Company began operating a multimillion dollar chilled pipeline frost heave test facility near Fairbanks, Alaska. The purpose of the facility was to simulate and record the rate of frost heave and frost-bulb growth for a chilled pipeline and to observe the effectiveness of conceptual mitigation measures. The facility had ten, 1.22 m diameter (48”) test sections. Uninsulated, insulated, and insulated with over-excavation and gravel berm configurations were tested. Frost heave of the chilled pipeline in permafrost was also tested. This paper describes the test facility and presents frost heave and frost-bulb growth measurements for the first year’s operation of the facility.
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RÉSUMÉ
Commençant en 1979, du Nord-Ouest de l'Alaska Pipeline Company a commencé l'exploitation d'une installation de plusieurs millions de dollars réfrigérés test pipeline situé près de Fairbanks, Alaska, USA. Le but de l'installation était de simuler et d'enregistrer le taux de soulèvement par le gel et la croissance du gel à bulbe pour un pipeline réfrigérés et d'observer l'efficacité des modèles d'atténuation théorique. L'installation comprend dix, 1,22 m de diamètre (48 ") sections d'essai. Non isolés, isolés, et isolés avec plus d'excavation et de configurations berme de gravier ont été testés. soulèvement dû au gel du pipeline réfrigérés dans le pergélisol a également été testé. Ce document décrit l'installation et comprend des mesures de soulèvement par le gel et la croissance du gel pour le fonctionnement de la première année de l'installation

1 INTRODUCTION

On October 13, 1979, Northwest Alaskan Pipeline Company and Foothills Pipeline Company began operation of a pipeline frost heave test facility near Fairbanks, Alaska. Both companies were developing designs for a pipeline to transport high-pressure natural gas from Prudhoe Bay, Alaska, along the Alaska Highway to connect with pipeline networks in Alberta, Canada. Along the proposed pipeline route the northernmost approximately 400 km was continuous permafrost (> 90% frozen) and the next approximately 1050 km was discontinuous (50% to 90%) and sporadic (10% to 50%). The pipeline was proposed to be chilled in Alaska and for the first several hundred kilometers in Yukon to preserve permafrost and prevent thaw settlement of the pipeline. The chilled pipeline was expected to frost heave where it transitioned unfrozen soil.

The ten, full-scale test sections at the facility were designed to investigate the frost heave relationships between the sections, to test frost heave in permafrost, to test possible mitigation options, and to advance the predictive capabilities of geothermal, structural and empirical frost heave models. In 1979 Foothills was operating and had recently expanded their pipeline frost heave test site in Calgary (L.E.C. Engineering, 1984). Some of the frost heave mitigation options explored at the Fairbanks site were suggested by the frost heave behavior of the Calgary site.

Until recently no frost heave or frost-bulb growth data for the Fairbanks site was in the public domain. Through a freedom of information act request made by others, data for the first eight months of operation of the test site are now in public domain (Northwest Alaskan Pipeline Company, 1981). This paper is based upon those data and the description of the Northwest Alaskan frost heave design given in Myrick, et. al. (1982).

2 FAIRBANKS SILT

The subsoil consists of loess and retransported deposits that blanket much of the Yukon-Tanana uplands. These soils are often referred to as Fairbanks silt. Laboratory tests of samples from the Site are shown in Figure 1 (EBA Engineering Consultants Ltd., 1980) along with data from Calgary (L.E.C. Engineering, 1984) and Coldfoot/Wiseman (Hazen, et. al, 1993).

The site topography is relatively flat to gently sloping to the south and east. A small, seasonal stream runs near the western and southern sides of the site. Permafrost in undisturbed areas extends to a depth of approximately 30 to 45 meters with an active layer of approximately 1m (Linell, 1973). In the 1950s the western side of the site had been cleared and stripped to prepare the soil (thaw and drain) for farming. The eastern side of the site remained undisturbed. By the late 1970s, soil in the cleared and stripped area had warmed, the permafrost had degraded and the upper approximately 7.5m was unfrozen with a seasonal frost depth of approximately 2m. Figure 2 shows measured soil temperatures and Figure 3 shows idealized soil layering and moisture contents.

3 TEST SITE LAYOUT

3.1 Test Sections

The Fairbanks site included 10, full-scale, 1.2m (48”) test sections. Eight of the test sections were 36.6m (120’) long, one test section was 122m (400’) long and one was 12m (40’) long. Figure 4 is an oblique aerial photograph taken by Crory (1979), shortly before chilled air circulation began on October 13, 1979. The view is toward the northeast. Figure 5 is a plan-view of the facility showing test section layout and the area of the facility with near-surface permafrost (eastern side). The 0.9m test section shown on the northern site was installed and operated by the Japan Science and Technology Foundation and the University of Alaska, Fairbanks (Huang, et. al. 2004).

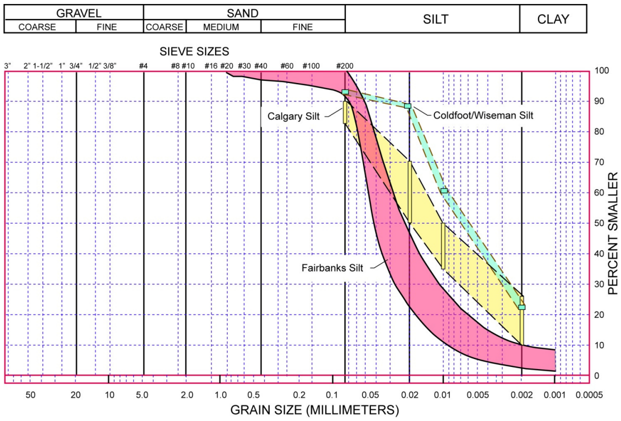

Figure 1. Soil Grain Size Distributions

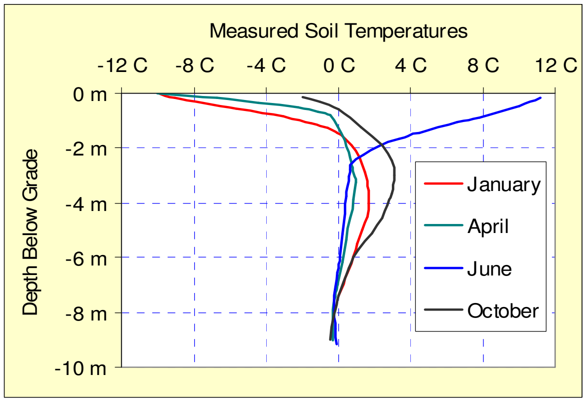

Figure 2. Measured Soil Temperatures

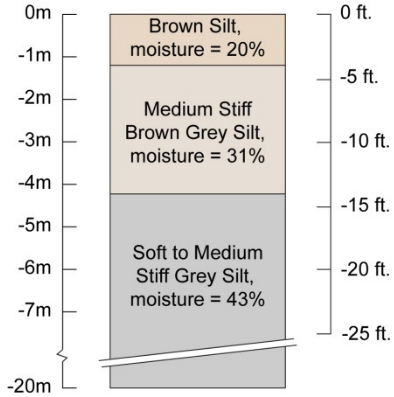

Figure 3. Soil Layering for TS-1

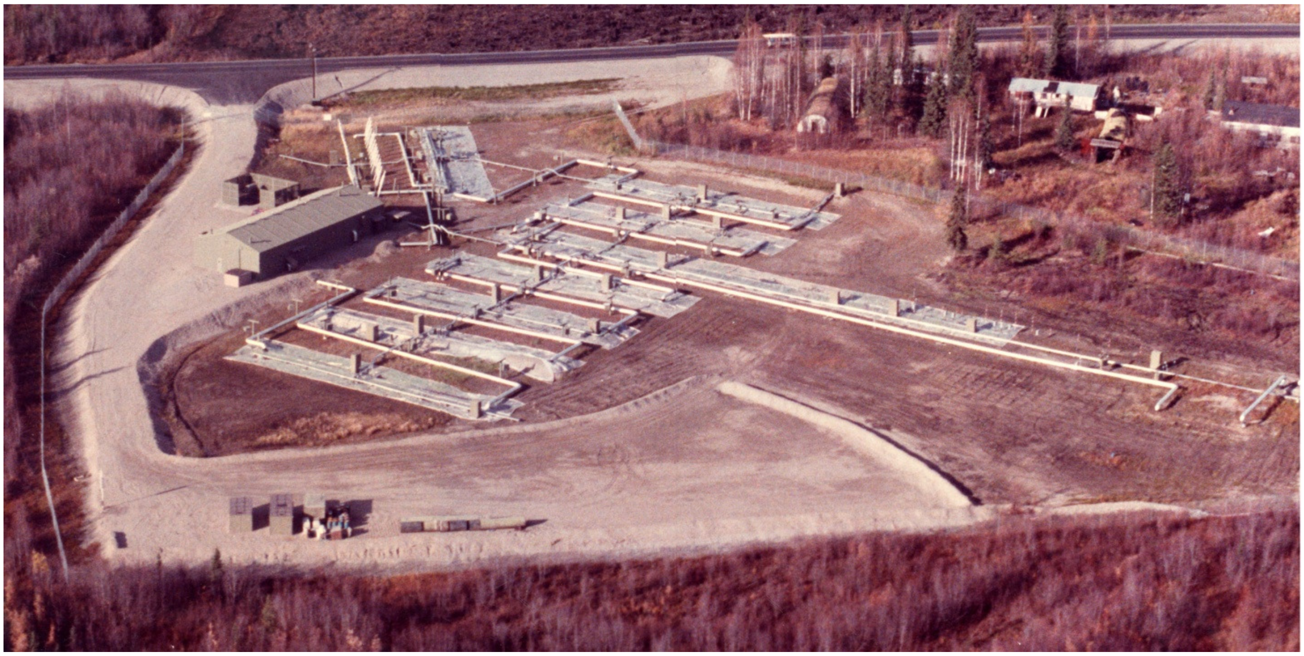

Figure 4. Oblique Aerial Photo of Fairbanks Test Site

3.2 Test Sections

The Fairbanks site included 10, full-scale, 1.2m (48”) test sections. Eight of the test sections were 36.6m (120’) long, one test section was 122m (400’) long and one was 12m (40’) long. Figure 4 is an oblique aerial photograph taken by Crory (1979), shortly before chilled air circulation began on October 13, 1979. The view is toward the northeast. Figure 5 is a plan-view of the facility showing test section layout and the area of the facility with near-surface permafrost (eastern side). The 0.9m test section shown on the northern site was installed and operated by the Japan Science and Technology Foundation and the University of Alaska, Fairbanks (Huang, et. al. 2004).

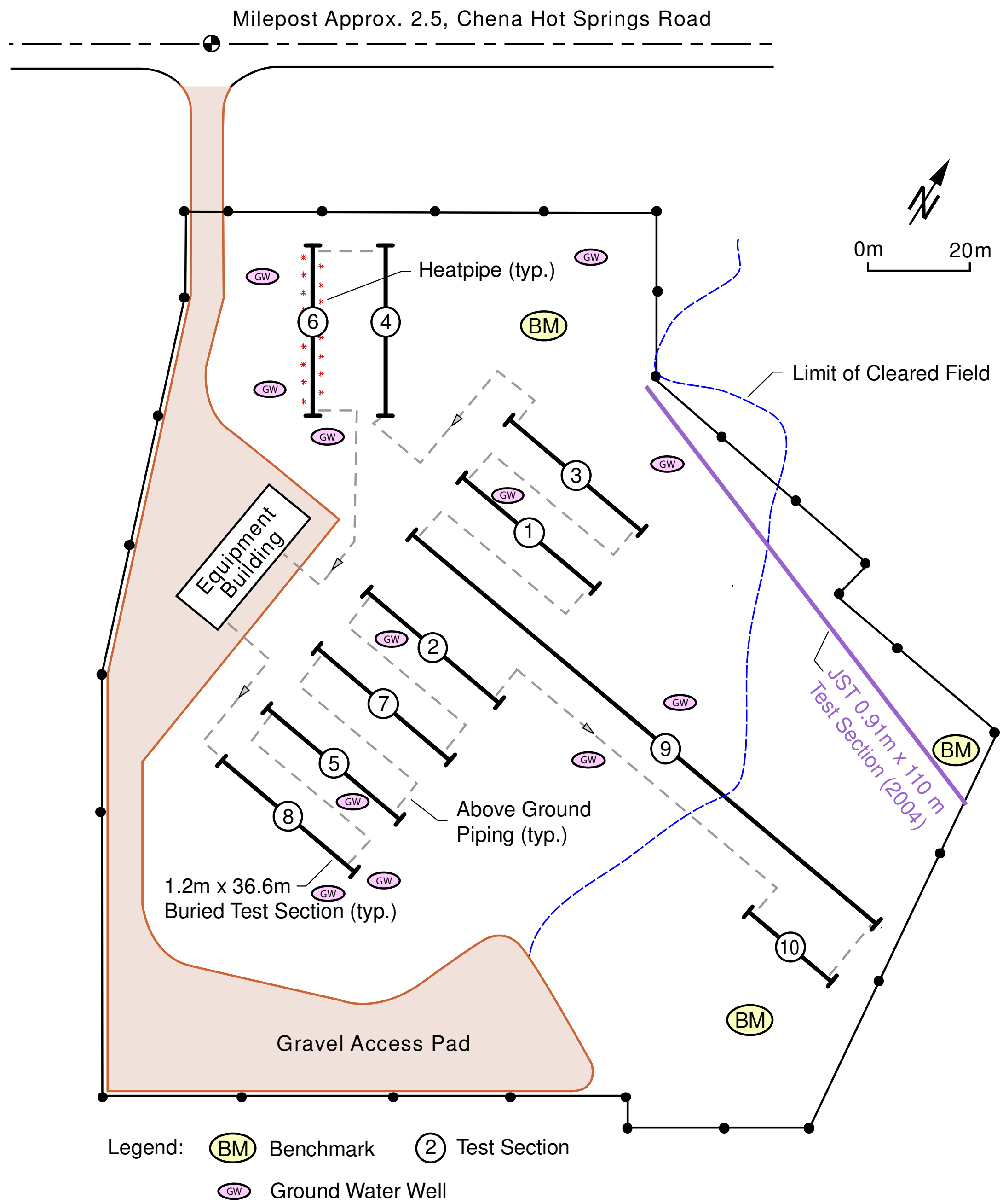

Figure 5. Plot Plan of Fairbanks Test Site

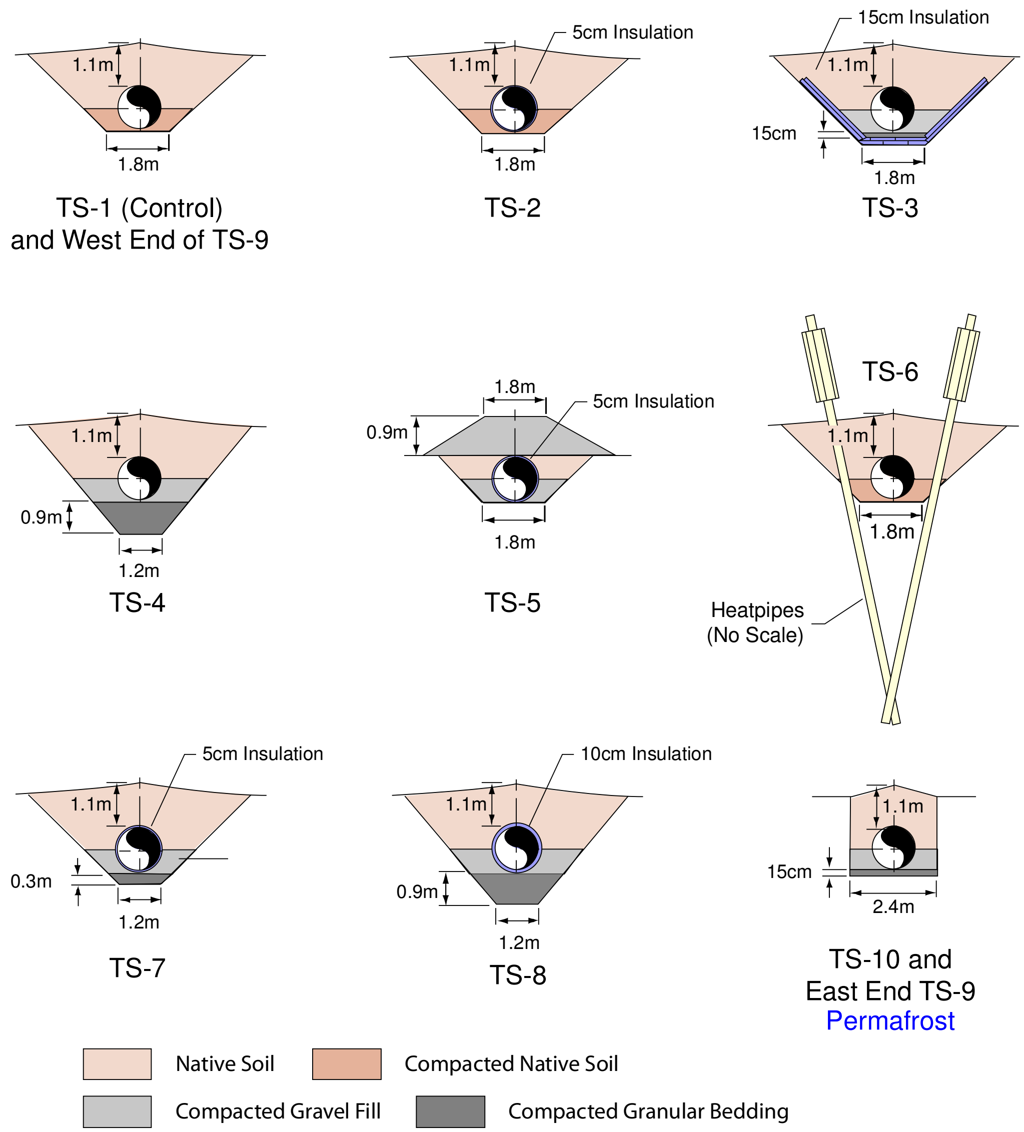

Figure 6 -- Test Section Cross-Sections

Figure 6 shows the burial cross-section for each of the 10 test sections. Test Section 1 (TS-1) was the control section, with standard burial depth, no over-excavation, spoil backfill and no insulation. Similar test sections included the western end of TS-9 (the long-span differential heave test section) and TS-6. Heatpipes (or chill pipes or thermosyphons) alongside TS-6 were installed to show if pre-freezing the soil below the pipe was a viable frost heave mitigation technique. The effects of over-excavation were tested by TS-4 and insulated test sections 7 and 8. TS-3 used boardstock insulation laid along the bottom and sloped ditch sidewalls. TS-10 and the eastern/shallow-permafrost end of TS-9 were buried in a vertical sidewall trench with 15cm of padding. TS-2 had 5cm of insulation and no over-excavation. TS-5 had 5cm of insulation and was buried below a 0.9-m thick gravel berm.

3.3 Instrumentation

Arrays of temperature sensors, heave rods and in some cases heave plates, extensometers and strain gages were placed in and around test sections. Figure 7 shows the instrument layout for TS-1. Table 1 gives a summary all (original) instruments at the Facility. Summary descriptions of instruments are given below.

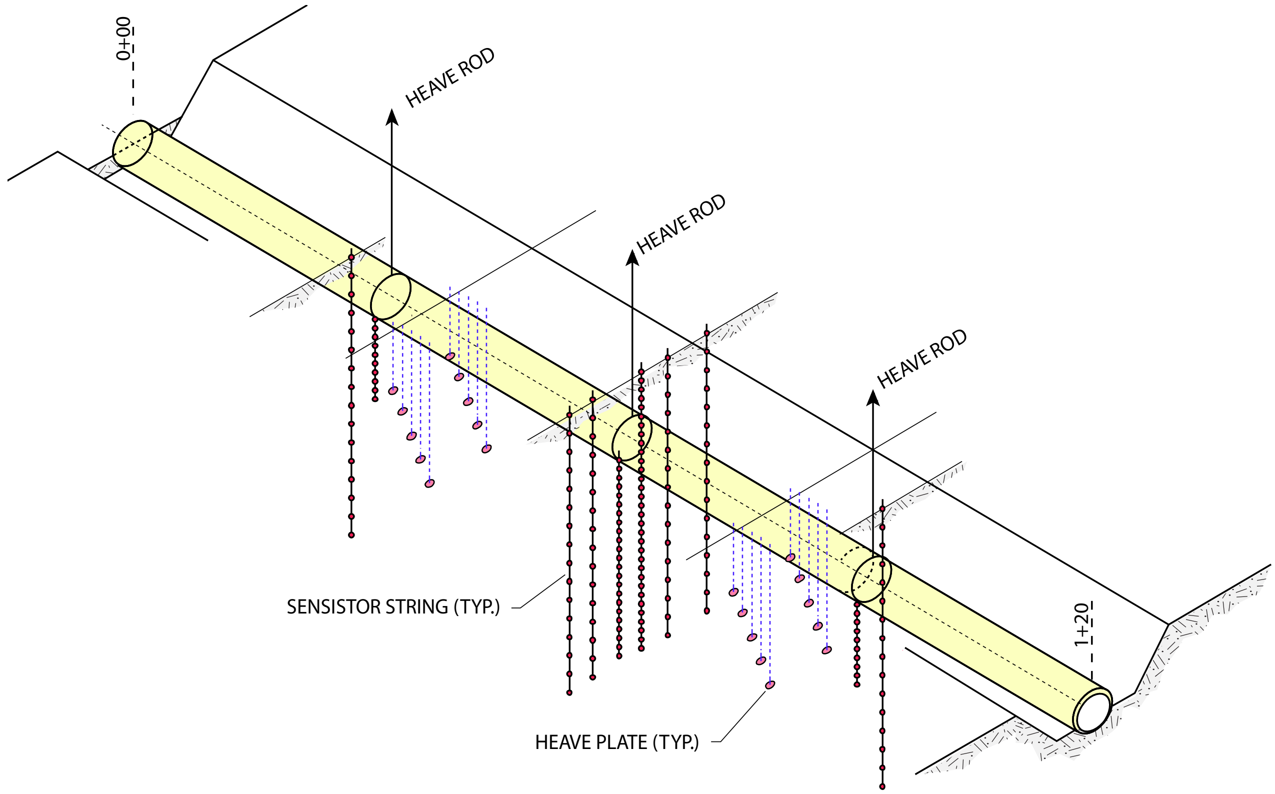

Figure 7 -- Instrumentation Along TS-1

Table 1. Instrument Summary

Instrument	Total
Temperature Sensors (Sensistors)	1850
Groundwater Wells	12
Heave Rods	59
Heave Plates	30
Frost-proof Benchmarks	3
Extensometers	8
Strain Gauges	94
Soil Pressure Gauges	42
Heat Flux Transducers	70
Piezometers	17
Pipe Pressure Gauges	1
Pipe Flow Rate Gauges	1
Chilled Air Temperature Sensors	5
Ambient Air Temperature Sensors	2
Snow Depth Gauges	4

3.3.1 Ground Temperatures

Ground temperatures were measured by "sensistors", a semiconductor chip with a unique, sometimes multiple degree Celsius ice-bath offset for each sensor (where modern thermistor sensors are interchangeable within 0.1 ℃). The sensistors were organized in strings as shown in Figure 7. Cold-room calibrations of the completed strings were provided by the string fabricator. The sensistor strings were connected to custom-made circuit boards that were housed in one of twenty-two small buildings that were located alongside test sections. These circuit boards were connected to a central data acquisition system (DAS) inside the equipment building. Soil temperatures were recorded daily by the DAS. Engineers tracked the growth of the frost bulb alongside and below test sections by finding when the reported temperature of a given sensistor went through the Newtonian transition between unfrozen and frozen, i.e., where the temperature remains nearly constant as the water changes phase from liquid to solid. Because of generally poor sensistor calibration it was not possible to interpret frost-bulb dimensions directly from reported sensistor temperatures. This analysis technique was verified by borehole drilling during summer 1980. New thermistor strings were also installed during summer 1980.

3.3.2 Benchmarks

The Facility had three frost-proof benchmarks patterned after designs proven by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Benchmark elevations were measured twice weekly with a Hewlett-Packard Total Station. Engineers paid close attention to elevations of benchmarks, looking for changes in the relative elevations which would suggest settlement or heave. One benchmark did have to be replaced later in the test.

3.3.3 Heave Rods and Heave Plates

Each test section had three vertical heave rods (see Figure 7) that were connected to the top of the test section and extended above the ground surface where they could be read by the survey instrument (Hewlett Packard Total Station).
Twenty heave plates (10 cm diameter disks) were installed at prescribed depths alongside TS-1 to measure frost heave within the frost bulb. Heave plates were also installed along the unfrozen end and frozen (shallow permafrost) end of TS-9. One heave plate was also placed near one end of TS-5.

3.3.4 Strain Gages

Strain gauges were placed in axial, hoop and triaxial rosettes inside TS-9 to measure pipe strain during differential heave.

3.3.5 Ground Water Wells

Twelve groundwater wells were installed at the site. Data were to be used for frost heave predictions, where the elevation of the groundwater affects the effective stress at the frost front and thereby frost heave.

3.3.6 Circulating Air Temperature, Pressure and Flow

Five temperature sensors (in-line temperature wells) were installed in the 12-inch interconnecting piping. Temperatures for four of the sensors were collected by the DAS and data from one was plotted on a strip-chart recorder which was monitored by site operators. Pressure and flow rate data were also recorded on strip-chart recorders.

3.3.7 Ambient Temperature Sensors and Snow Depths

Two ambient temperature sensors and four snow depth gages were installed to keep track of local weather.

3.3.8 Extensometers

Extensometer (LVDT and C-ring) were placed inside TS-9 and TS-6 to measure ovaling of the test sections and one was connected to the western (unfrozen soil) end of TS-9 to measure longitudinal movement during differential heave.

3.3.9 Misc. Instruments

Electronic piezometers, heat flux transducers and soil pressure gauges installed at the site did not produce useful data, only noise. Problems with these instruments were generally attributed to electronic failures and problems installing the instruments during winter.

4 CHILLED AIR CIRCULATION

The equipment building at the Facility housed the twin, 0.5 m^3/sec, 4.7 MPa (940 cfm, 675 psi) compressors (one an installed spare) and 40-ton refrigeration plant which were used to circulate and chill air for the test sections. Test sections were connected in a closed-loop, daisy-chain configuration. Chilled air from the outlet of one test section was connected to the inlet of the next test section by 30cm, insulated, above-ground piping as shown in Figure 5. Between start-up and August 1st, 1980, the average chilled air temperature entering and returning from the test-section loop was -10.2 °C and -9.1 °C, respectively as shown in Figure 8.

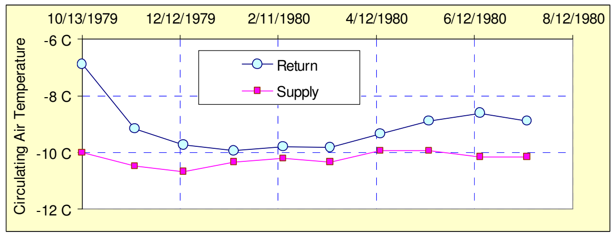

Figure 8. Chilled Air Circulation Temperatures

5 MEASURED FROST HEAVE

5.1 Non Insulated Test Sections

After 10 months of operation the test sections had experienced a full winter cycle, i.e., the potentially restraining effect of seasonal frost, and nearly a full summer cycle including the winter decrease and summer increase in groundwater elevations. The approximately exponential decay shapes of the heave versus time curves for uninsulated test sections were well defined as shown in Figure 9.

When the chilled air flow began approximately 0.75m of soil was unfrozen below TS-6 (with heatpipes) due to natural summer thawing. The heatpipes had been installed the previous winter and had worked through the winter to freeze soil below the test section. Once chilled air flow began, TS-6 began to heave at approximately the same rate as TS-1. When the frost bulb from the pipe coalesced with the frost bulb generated by the heat pipes the heave rate reduced considerably.
TS-10 and the eastern (permafrost) end of TS-9 heaved approximately 0.5 cm shortly after startup, i.e., as the pipes froze soil immediately under their base, then heaved another approximately 0.5 cm by mid August 1980.

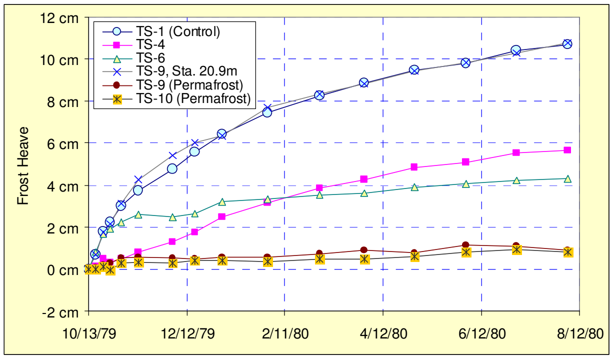

Figure 9. Measured Frost Heave of Uninsulated Test Sections

Figure 10 shows the frost-heave profile measured along TS-9, the long-span differential frost heave test section. Structural engineers used the pipe's profile, pipe strain measured by internal strain gauges and extensometers for pipe deflection and frozen-soil uplift resistance modeling

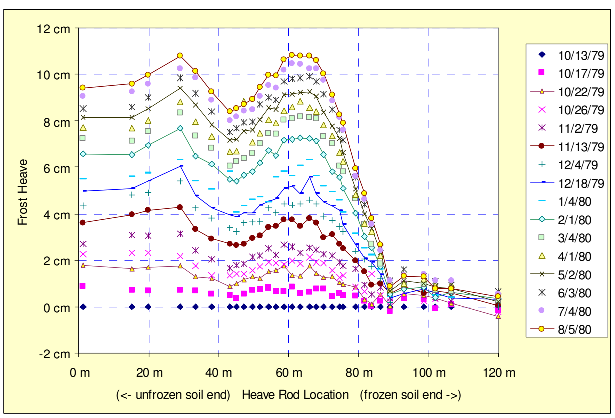

Figure 10. Measured Frost Heave Profile of TS-9, Spanning Unfrozen and Permafrost Soil

5.2 Insulated Test Sections

Comparisons of frost heave for insulated test section are shown in Figure 11. TS-2 and TS-7 were insulated with 5cm of polyurethane foam which was protected with an approximately 6 mm thick polyethylene jacket. The difference between these two test sections configurations is that TS-7 had 30 cm gravel bedding and TS-2 had no bedding.

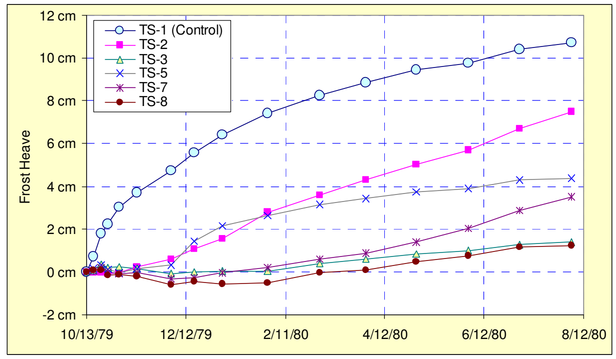

Figure 11. Measured Frost Heave of Insulated Test Sections and TS-1 (Control)

6 MEASURED FROST-BULB GROWTH

Figure 12 shows frost-bulb growth for uninsulated test sections. Depths were inferred from temperature trends for sensistors located beneath the test sections. These trends showed when moisture in the soil surrounding a given sensistor passed through the liquid to solid phase, i.e., the near isothermal period when latent heat was released. This was relatively easy to do with uninsulated test sections as the bulb progressed rapidly and trends were clear; this technique did not work for insulated test sections because of slow bulb growth. During late July 1980 the tops and bottoms of frost bulbs alongside test sections were determined by boreholes drilled approximately 0.9m (3') from the centerlines of the operating, pressurized test sections.

Figure 13 compares predicted frost-bulb shapes and the tops and bottoms of the frost bulbs measured alongside TS-1 and 2 (insulated) during the drilling program. The interpreted depth of the frost bulb under TS-1 from sensistor data at the time of drilling is also shown. The generally good agreement between the interpreted depth and measured depth provided confidence in frost-bulb depth interpretations for uninsulated test sections.

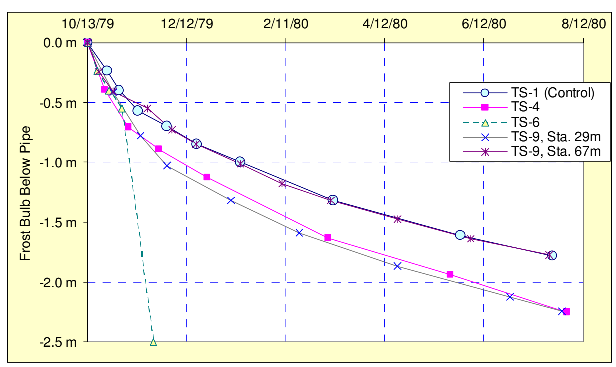

Figure 12. Measured Frost-Bulb Growth for Uninsulated Test Sections

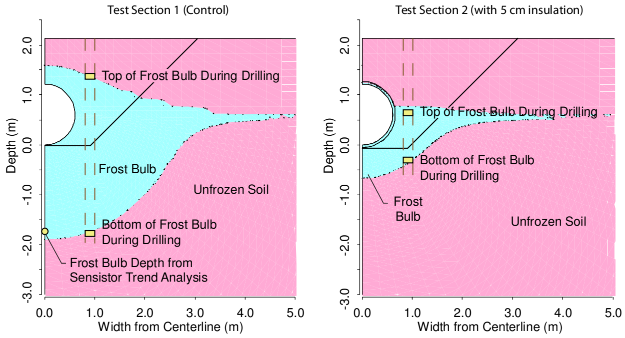

Figure 13. Predicted Shapes of Frost Bulbs around TS-1 and TS-2, late July 1980, and Measured Tops and Bottoms of Frost Bulbs from Borehole Drilling

7 MEASURED GROUNDWATER DEPTHS

Groundwater depths were measured in nine standpipes which were distributed around the test site (see Figure 5). Measured data for the first 8 months are shown in Figure 14. These data are used to calculate the effective stress at the frost front which has a strong influence upon incremental frost heave.

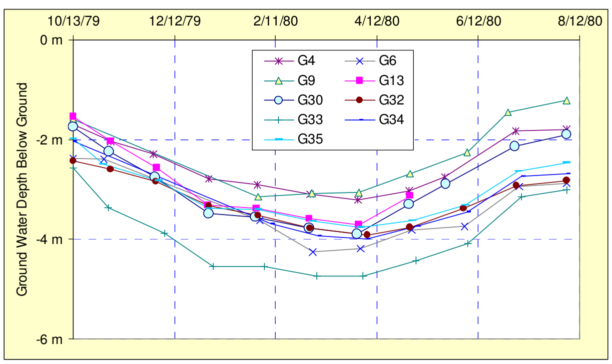

Figure 14. Measured Groundwater Depths

8 PREDICTED FROST HEAVE

Figures 15 and 16 compare measured and predicted frost heave and frost-bulb growth for TS-1. Predictions were made by TQUEST (Northern Engineering & Scientific) using the frost-heave segregation potential (SP) theory developed by Konrad (1980). The SP theory states that the rate water flows to the freezing front is related to the soil's SP and the thermal gradient at the segregation freezing front:

water flow rate (mm/day) to the freezing front = SP * (dT/dx) [1]

Where: SP is the soil's pressure-dependent segregation potential (mm^2/day-°C)
dT/dx is the thermal gradient at the freezing front (°C/mm)

Figure 17 shows SP values for Fairbanks silt measured by Penner (1977) as well as SP values for Calgary silt (L.E.C. Engineering, 1984) and Coldfoot silt (Hazen, et. al. 1993). SP values are interpreted from specialized, 1-dimensional laboratory tests. Within TQUEST the pressure-dependency of SP is calculated using:

$$SP = SP0 * e^{(-SPa * P)} \quad [2]$$

Where: SP is the segregation potential (mm^2/day-°C)
SP0 is the SP value at zero effective stress (mm^2/day-°C)
P is effective stress at the frost front (kPa)
SPa is the coefficient that expresses the pressure dependency of SP (1/kPa)

Measured chilled air temperatures, ground water depths and ambient temperatures and snow depths measured during the time of the field experiment were used for the prediction. The SP for Fairbanks silt is strongly dependent upon effective stress.

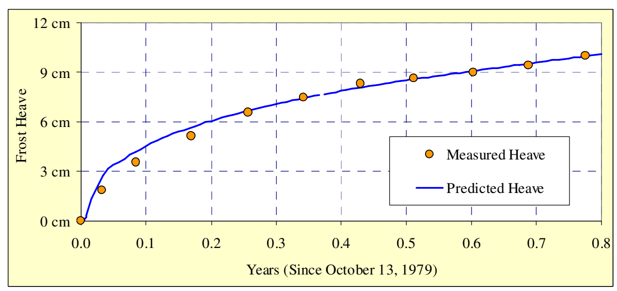

Figure 15. Comparison of Measured and Predicted Frost Heave for TS-1 (Control)

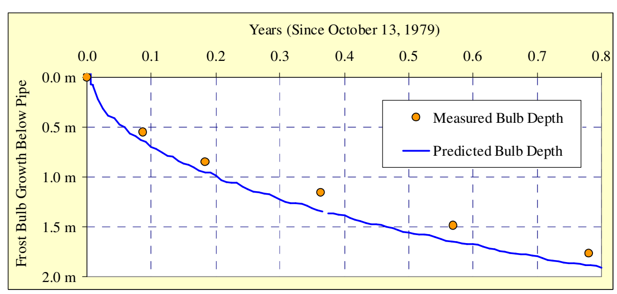

Figure 16. Comparison of Measured and Predicted Frost Bulb Growth for TS-1 (Control)

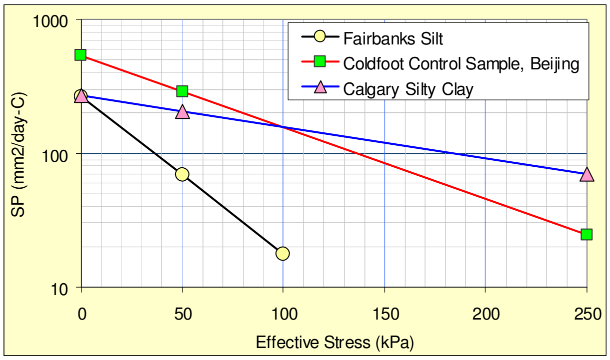

Figure 17. Segregation Potentials for Fairbanks, Coldfoot/Wiseman and Calgary Silt

9 CONCLUSIONS

The Fairbanks test site was designed to measure frost heave of a buried, chilled pipeline in frost-susceptible soil, to show the effectiveness of a wide range of mitigation options, to test frost heave in permafrost, to measure frost heave and pipeline structural response across a transition from frozen to unfrozen soil and to advance geothermal and structural prediction computer models.

Uninsulated test sections in unfrozen soil (TS-1, 4, 6, 9) heaved approximately 50% as much as expected, based upon the pipeline frost-heave prediction approach being used at the time. This approach combined 1-dimensional laboratory testing and geothermal modeling. Modern predictions using the SP theory and pressure sensitivity show generally good agreement with measured data as shown above and as reported by Nixon (1982).

TS-4 tested the mitigation option of over-excavation and TS-6 tested the mitigation option of pre-freezing. TS-4 heaved little as the frost bulb penetrated through the approximately 0.9m thick non-frost susceptible gravel layer underneath the test section. TS-6 heaved little after its frost bulb coalesced with the frost bulb generated by heatpipes the previous winter.

Test sections in frozen soil (TS-10 and the east end of TS-9) showed approximately 1 cm of heave during the first 10 months of test site operation, half of which occurred in the first month of operation as soil immediately under the test sections froze. These test sections show that little to no heave can be expected in permafrost.

No clear, long-term trends were revealed by measured heave and heave rates of insulated test sections in the first 10 months of operation. Although the measured heave rate of TS-2 suggested its heave may ultimately be greater than the uninsulated control test section (TS-1), it is possible that segregated ice that formed under TS-2 during winter and spring would have melted later in the summer and early fall as in-situ ground temperatures warmed, the heave rate may have decreased and possibly the test section may have settled. The relative merits of the various insulation thicknesses, insulation configurations and effectiveness of over-excavation was generally revealed in the heave of insulated test sections. Unfortunately, locations of frost bulbs below and alongside insulated test sections could not be inferred from original ground temperature instruments, a problem solved by installation of new thermistor strings and data-acquisition equipment during August 1980.

Only the first 10 month's data of the 5-year test are in the Public domain, but during that 10-month period many of the goals of the field test site were satisfied and chilled pipeline frost heave trends were strongly defined. Good agreement between predicted and measured frost heave and frost-bulb growth provides confidence in the technology used to measure soil frost heave properties and use of those data for computer model predictions.

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