Field test results of operating a chilled, buried pipeline in unfrozen ground

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In order to study the behaviour of a chilled, large-diameter pipeline buried in frost-susceptible ground, a field test facility was constructed in Calgary, Alberta. This facility, which contained four non-insulated test sections of pipe, 1.2 m in diameter, buried in frost-susceptible soil, has been operational since March 1974. Two insulated sections of pipe 1.2 m in diameter were installed in late 1978. This paper describes the layout of the test site and the geometry of the test sections. Results are presented, of the growth of the frost bulb around the pipe sections, together with the heave of the pipe sections and the soil around the pipe. The results of these full-scale frost heave field tests have aided in developing an understanding of frost heaving around a chilled pipeline. They have indicated the effects of increased overburden pressure and frost penetration rate on the rate of frost heave.

Afin d'étudier le comportement d'un pipeline de grand diamètre, refroidi et enfoui en terrain gélif, on a construit une installation expérimentale à Calgary (Alberta). Cette installation composée de quatre sections expérimentales non isolées de conduites enfouies dans un sol gélif, est en opération depuis mars 1974. Deux sections de conduites isolées d'un diamètre de 1,2 m ont été installées à la fin de 1978. La présente étude décrit le plan de l'installation et la disposition des sections d'essai. Les résultats présentés concernent la croissance de la masse de gel autour des sections de conduite ainsi que le soulèvement de ces sections et du sol autour des conduites. Les résultats de ces essais en grandeur réelle sur le terrain ont aidé à comprendre le mécanisme du soulèvement par le gel autour d'un pipeline refroidi. Ils ont révélé les effets de l'augmentation de la pression exercée par le mort terrain et de la vitesse de pénétration du gel sur le taux de soulèvement attribuable au gel.

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Introduction

Frost heave is one of the main design aspects of the Alaska Highway Gas Pipeline Project. This project entails the designing, construction, and operation of a large-diameter, natural gas pipeline which will transport gas from the north slope of Alaska south across Alaska and through the Yukon Territory and western Canada to markets in the lower United States. It has been decided that the gas will be chilled below 0°C throughout the continuous permafrost zone and partially through the discontinuous permafrost zone. In fact, the chilled gas runs from Prudhoe Bay on the north slope of Alaska to just inside the Yukon Territory. The operation of this chilled pipeline through the non-frozen areas of the discontinuous permafrost region may lead to serious problems of frost heave if these are not addressed in the design and operation of the pipeline system.

Foothills Pipe Lines and its American partner, Northwest Alaskan Pipeline, are operating two full-sized, frost heave research facilities as well as carrying out extensive laboratory testing programs. One of these full-scale, frost heave facilities is at Calgary, Alberta, and the second one is in Fairbanks, Alaska.

This paper presents some data obtained from the Calgary Frost Heave Facility. It will also present a comparison of results from this full-scale, frost heave facility and those obtained from laboratory testing programs. An interpretation of these data is presented followed by a discussion on the development of an empirical engineering model for the prediction of frost heave.

Calgary Frost Heave Facility Layout

The Calgary Frost Heave Test Site (Figure 1) was constructed by Canadian Arctic Gas Study Ltd. in 1974. The construction and operation of the site has been reported by Slusarchuk *et al.* (1978). The operation of the test site was taken over by Foothills at the end of 1977.

The facility consists of six full-size pipe sections. The first four are non-insulated pipe sections 1.2 m in diameter and approximately 12 m long. These sections were installed with the original construction of the site in 1974. In 1977, two pipe sections of identical diameter were installed, each insulated with a 15 mm thickness of polyurethane insulation. The ground around the pipes is frozen by circulating air at about −10°C through the system.

The cross sections for the four non-insulated pipe sections are illustrated (Figure 2). The control section represents the standard burial configurations for a

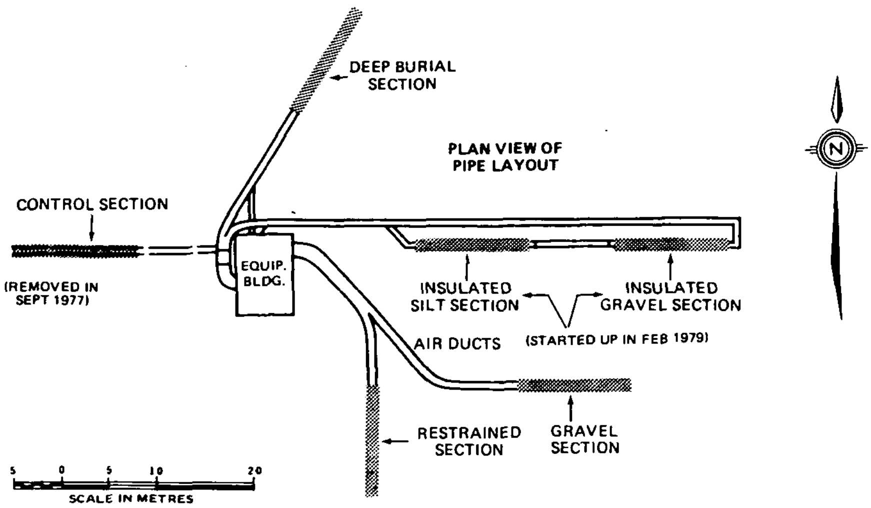

FIGURE 1. Schematic layout of Calgary frost heave test facility.

gas pipeline of this dimension. The base of the pipe is buried at a depth of approximately 2 m from the original ground surface and there is a silt cover over the top of the pipe approximately 0.75 m thick. The deep burial section is similar to the control section except that the base of the pipe is buried to a depth of 2.9 m beneath the original ground surface. The gravel section is, again, similar to the control section with the addition of 0.9 m of gravel placed underneath the pipe. The fourth section in this sequence is the restrained section. It again is similar to the control section but with the addition of restraining devices at each end which provide a constant hold-down pressure for this section. The cross sections for the two insulated pipe sections are illustrated (Figure 3). The insulated silt section has a geometry which is identical to the original control section.

Experimental Results

Of the observed pipe heave for the non-insulation pipe sections (Figure 4), the frost heave of the control section was the largest of the four sections. The effects of the design variations are clearly represented. By mid 1977, at the termination of the control section, the control section had heaved in the order of 0.60 m. The deep burial section at that time had heaved a somewhat smaller value of 0.54 m. The heave of the gravel section was only 0.39 m and that of the restrained section only 0.27 m. The reduction in the heave of the three latter sections provides an indication of the mitigative potential of these types of design. The frost penetration depth for all four sections was approximately the same, being roughly 3 m in depth (*see* Figure 4).

A close look at the pipe heave curve for the gravel section shows a seasonal fluctuation trend over the past three years. The pipe heaves during the mid winter and spring months followed by settlement in the summer and fall period. The average heave over the last two years has been very small.

The frost heave and frost front penetration graphs for the insulated pipe sections (Figure 5) are quite different from those for the non-insulated sections. There are very significant annual fluctuations in both the heave and frost penetration. These data show that the insulation around the pipe has been very effective in isolating the cold air or pipe temperature from the external ground. It is seen from this figure that the insulated silt section heaved roughly 50 mm during its first season of operation and approximately 100 mm during the second season of operation. (It should be noted that the first operating season started in mid February and was only approximately half as long as the second operating season.) The effectiveness of the gravel soil replacement around the insulated pipeline is shown through the much lower heave values for the insulated gravel section. The first operational season had a heave of approximately 20 mm and during the second operational season the frost heave of the gravel section was in the order of 35 mm.

For both insulated sections, the warmer summer ground temperatures have thawed back the frost bulbs, negating the heave accumulated over the winter period.

Interpretation of Results

It is informative to look at the frost heave data in a form which lets one examine the incremental frost heave per unit increase in frost depth. The ratio of these two quantities is the instantaneous ice-segregation ratio, and is algebraically given by:

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

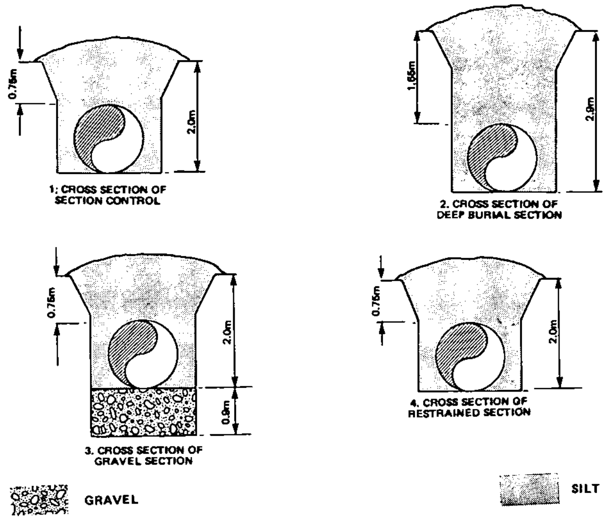

FIGURE 2. Cross sections for the non-insulated test sections at the Calgary frost heave test facility.

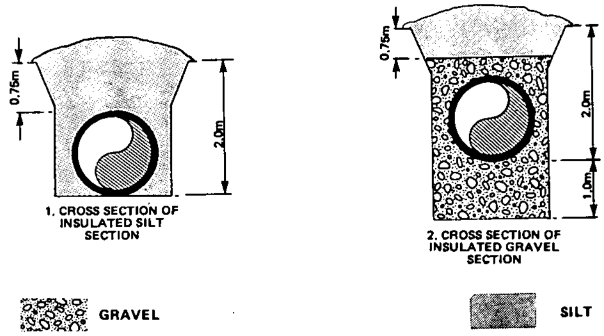

FIGURE 3. Cross sections for the insulated test sections at the Calgary frost heave test facility.

where $\Delta h/\Delta X$ is the slope of a plot of heave *versus* frost front penetration. The incremental ice-segregation ratio value expresses the fractional increase in the soil volume during a given time period of the soil freezing process.

The data for the control, gravel, and deep burial non-insulated pipe sections is presented in this format in Figures 6, 7, and 8. It is seen in these figures that the field data can be divided into three zones. The first, Zone 1, represents the fast initial freezing of the soil, where the frost penetration rate is greater than about 7 to 10 mm/day. The incremental ice-segregation ratio for Zone 1 is less than 11 per cent. This period lasted about three months. Zone 2, which lasted for one to two years, corresponds to frost penetration rates lying roughly between 1 and 10 mm/day. The incremental ice-segregation ratio for Zone 2 is in the order of 20 to 30 per cent. The third, Zone 3, which has lasted for several years, corresponds to very low to zero, frost penetration rates, and has an ice-segregation ratio range from 70 per cent up to the theoretical limit of 100 per cent.

Field results very similar to the above are reported

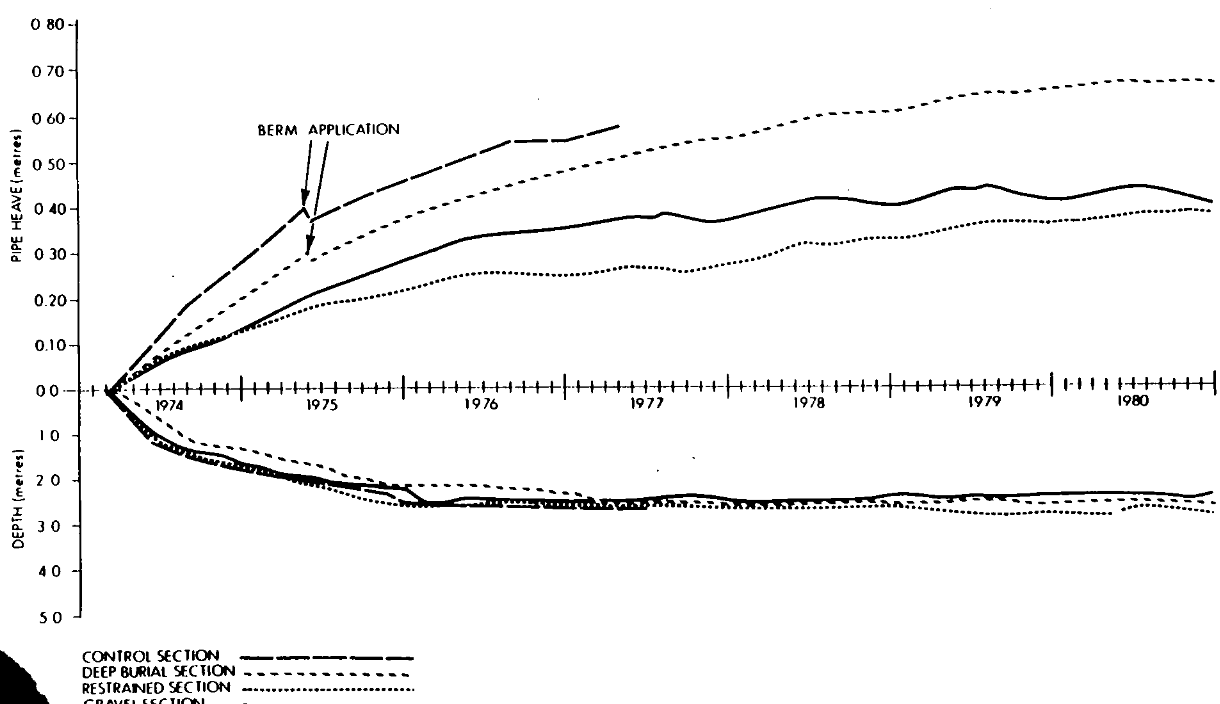

FIGURE 4. Observed pipe heave and depth of frost below bottom of pipe.

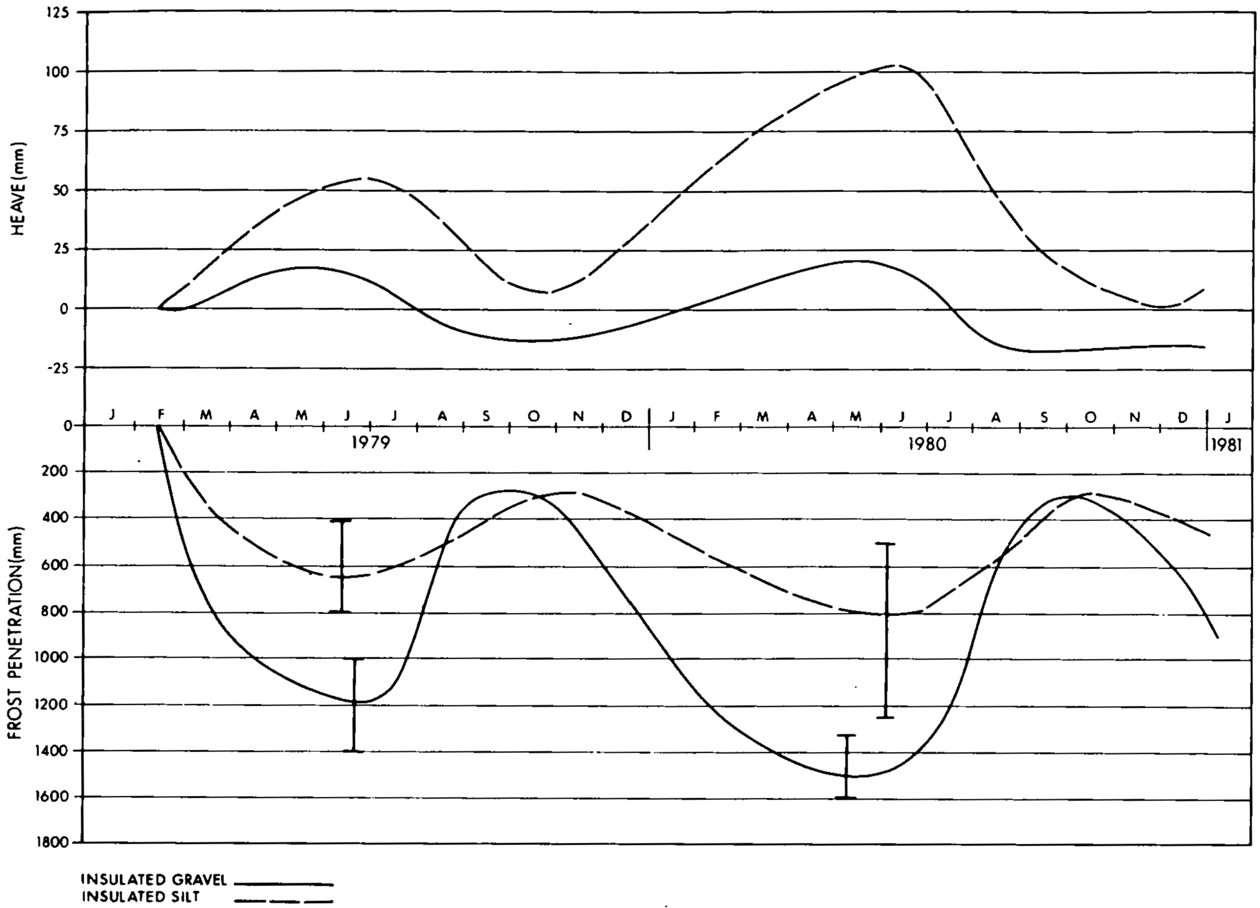

FIGURE 5. Heave and frost penetration for the insulated pipe sections.

by Nixon *et al.* (1982). They report results obtained at the Calgary Frost Heave Site using *in situ* freeze plates 0.76 mm in diameter, to create small frost bulbs. Similar *in situ* freeze plates have been operated in the Yukon Territory and are discussed in this reference.

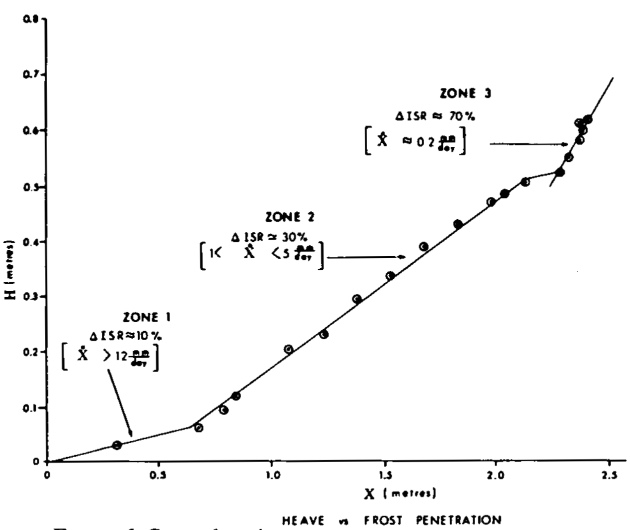

FIGURE 6. Control section.

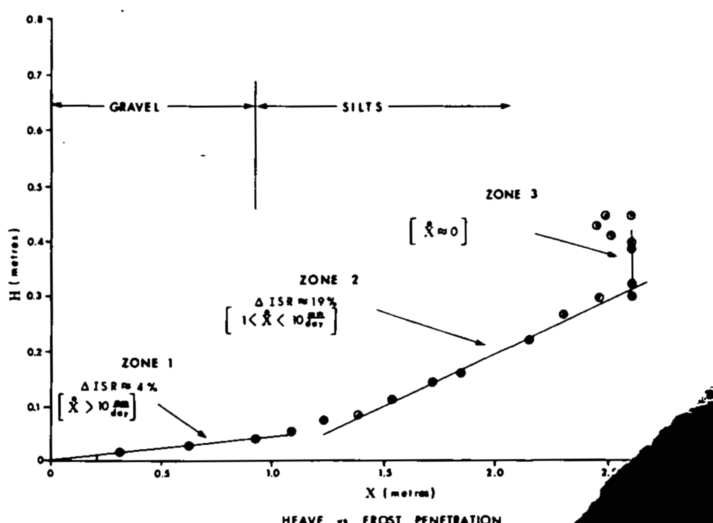

FIGURE 7. Gravel section.

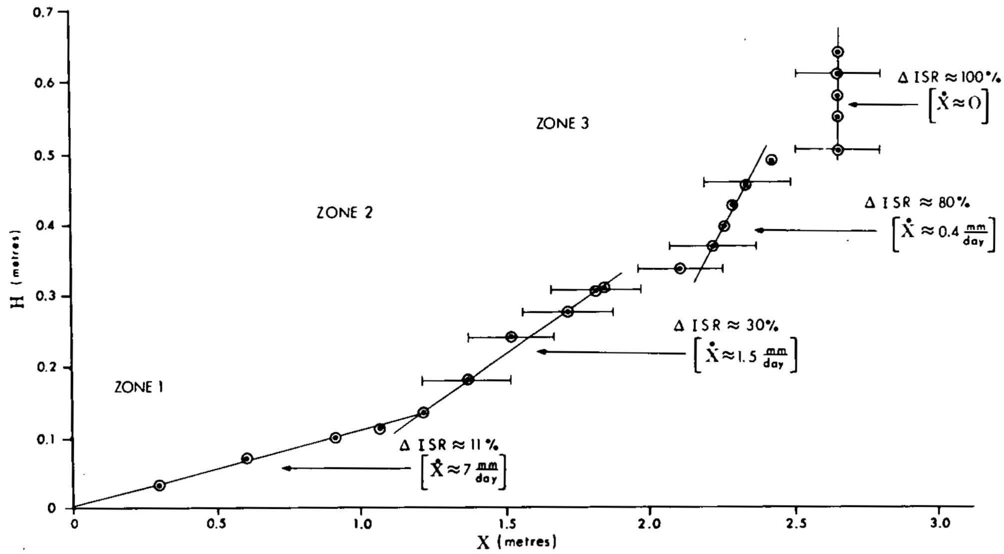

FIGURE 8. Deep burial section.

Comparison Between Field and Laboratory Tests

Foothills Pipe Lines has been carrying out a program of laboratory frost heave testing over the past several years. These tests entail the unidirectional freezing of small soil samples (approximately 100 mm diameter by 100 mm high). Data from one of these tests is presented (Figure 9). In this test, controlled temperatures, as indicated, were applied to both the cold, or freezing, side and the warm side of the soil sample. These temperatures were changed several times during the run in order to form several distinct ice-lensing regions within the soil sample. These regions are apparent in the frost penetration curve (*see* Figure 9).

These laboratory test data are presented as a heave *versus* frost penetration curve (Figure 10) in which an

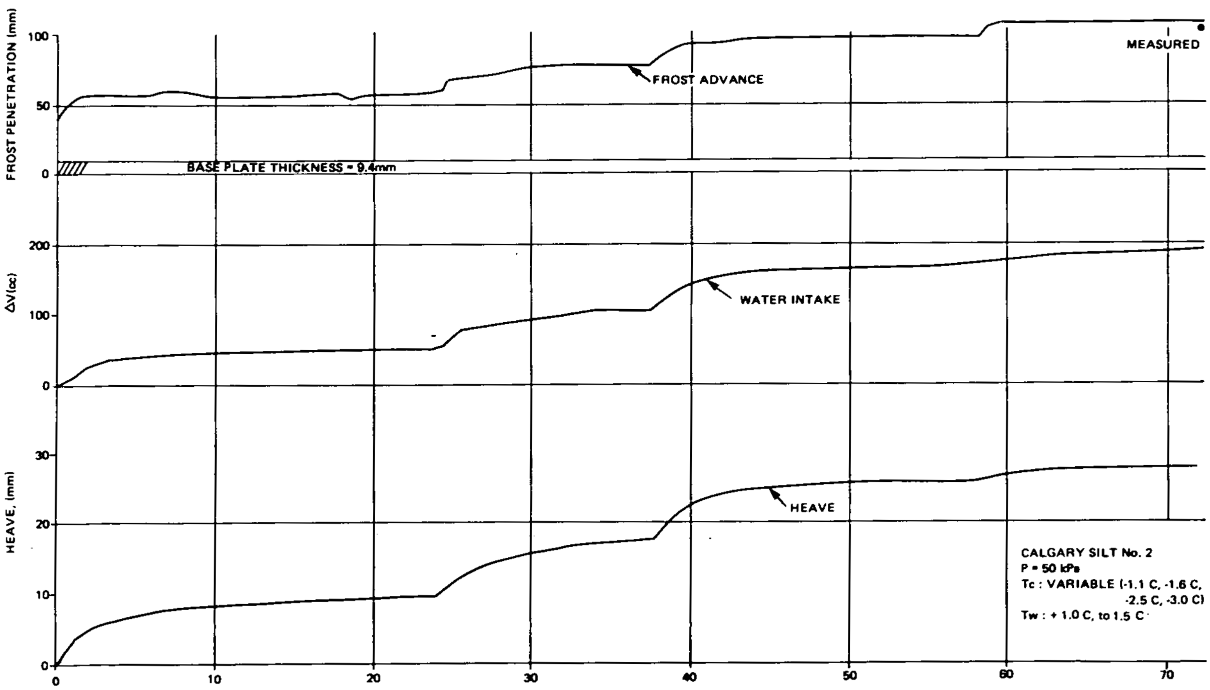

FIGURE 9. Test 2: Heave, water intake, and frost penetration *versus* time.

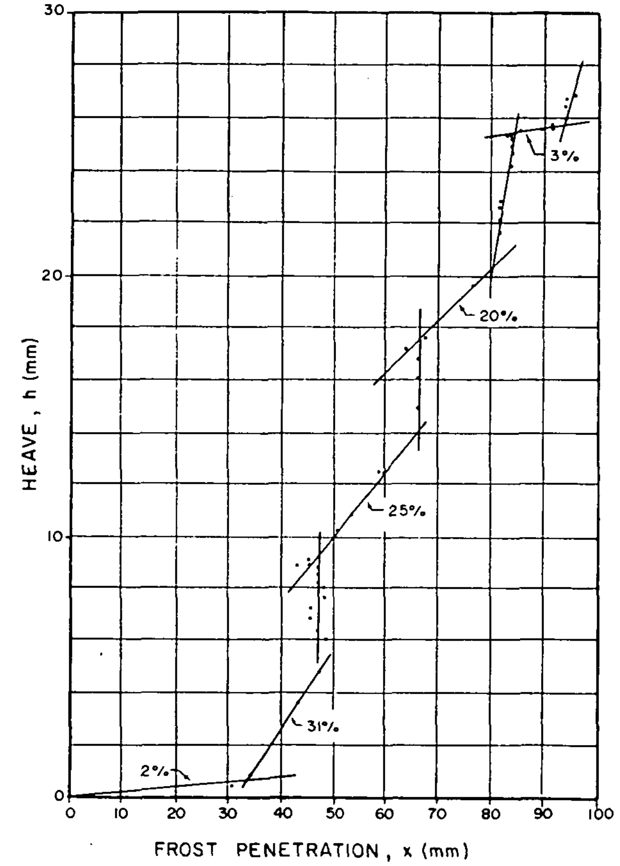

FIGURE 10. Test 2: Heave *versus* frost penetration.

initial period with a large frost penetration and little heave, a Zone 1 region, is followed by three Zone 2/Zone 3 sequences and a Zone 1, Zone 2, Zone 3 sequence. The incremental ice-segregation ratio of the Zone 2 regions is 20 to 31 per cent for these laboratory tests. These values compared very favourably with the Zone 2 values of 20 to 30 per cent for the full-scale field test data.

Empirical Models for Frost Heave

Foothills Pipe Lines and Northwest Alaskan Pipeline are currently developing empirical models for the prediction of frost heave due to the operation of chilled gas pipelines. The two major models are the heave rate model and the ice-segregation ratio model.

In the heave rate empirical model, for a given time period,

$$Heave = (Heave\ Rate) \times (Time).$$

For the ice-segregation ratio *(ISR)* model, when freezing a quantity of soil,

$$Heave = (ISR) \times (Frost\ Penetration\ Depth).$$

The data (*see* Figures 6, 7, 8, and 9) are very helpful in the development of the *ISR*-based empirical model. The full-scale test field data, the *in situ* freeze plate data of Nixon *et al.*, and the laboratory frost heave data support the development of an incremental ice-segregation ratio empirical model. The data presented in this paper, plus other experimental results from our testing programs, indicate that the incremental ice-segregation ratio can be defined, for a given soil type, as a function of the two parameters; first, frost penetration rate, and secondly, pressure at the frost front. Given this formulation, the overall frost heave is calculated as a series of incremental heaves.

$$Heave = \sum \Delta h = \sum \left(\Delta ISR(X,P)\right) \times \left(\Delta X\right).$$

An incremental, ice-segregation ratio, frost heave model requires knowledge of the *ISR* dependence on pressure and frost penetration rate for each soil under consideration. The engineering use of an *ISR* model requires further development of *ISR* data for the soils along the pipeline route. To this end, further laboratory testing, *in situ* freezing plate testing (in the Yukon Territory), and full-scale field testing programs (in Alaska) are currently underway.

Conclusions

The data from the insulated pipe sections have shown that the placement of insulation around the chilled pipe is very effective in limiting the frost penetration depth and related frost heave. In fact the summer warming effects negated the heave built up over the winter season.

The full-scale test site data for non-insulated sections have been compared to data from a laboratory test on soil from the test site. This comparison shows that the general behaviour as seen on the heave *versus* frost penetration plots is very similar. The comparison is taken a step further, to results obtained using *in situ* frost heave test plates by Nixon *et al.* (1982). This close similarity of behavior of the laboratory test results to those from the full-scale tests provides encouragement to carry on with an extensive laboratory testing program.

It was also shown that the data from both the field tests and laboratory tests are helping in the development of empirical models for the prediction of frost heave.

References

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