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Centrifuge modelling of frost heave of arctic gas pipelines

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ABSTRACT: North American Arctic regions contain vast amounts of gas that must be transported through permafrost to reach southern markets. During the 1970s and 1980s, eight full-scale test sites provided information and experience on operating chilled gas pipelines. One site in Calgary investigated frost heave of such buried pipelines. More test sites are unlikely to be constructed because of cost and time constraints. Yet a great deal remains to be learned about frost heave for different soil and groundwater conditions, ditch configurations and potential mitigating measures. Centrifuge modelling of the Calgary short rigid pipelines replicated their behaviour. The heave rate and the amount of heave of a 1.2 m pipeline at two different burial depths at the test site were similar to that recorded in centrifuge tests during 5 hours at 30 g. This paper compares these results to known full-scale behaviour and small-scale laboratory tests for the Calgary site. Small sample frost heave tests and a testbed at Caen are also compared.

1 INTRODUCTION

Large diameter gas pipelines to carry gas from the North American Arctic to southern regions of Canada and the U.S. have been intermittently studied for more than 30 years. During the period from about 1969 to 1985, hundreds of millions of dollars were spent by various proponents on constructing full scale test sites, conducting field investigations including drilling and sampling of soils, geophysical surveys, laboratory test programmes, environmental and socio-economic studies, engineering studies for preliminary designs and preparation of documents for regulatory hearings. The work was discontinued by about the mid-1980's. It has now been reactivated and similar routes, as previously studied, are once again under consideration.

When the work on the Mackenzie Valley pipeline was terminated in 1977, the sponsors turned over all reports to the Arctic Institute of North America (AINA). Tons of documents were examined by representatives of the sponsoring industries and those judged to be most useful were placed with AINA. They have since been archived and are readily available to the public. Unfortunately, much of the material was not included and is now lost along with much of the corporate memory.

Some of the test site data (Yukon and Alaska) remains proprietary to the sponsors but the data from the Calgary frost heave test site and laboratory tests are available. These data provide useful case histories of pipelines operating below freezing temperatures in highly frost susceptible soil. The data have been used extensively in a number of publications and workshops, e.g. Carlson (1984), Nixon (1984) and Carlson & Nixon (1988).

It is unlikely that more full-scale test sites will be constructed to assess the design performance in the future. Costs are exceptionally high but the main issue is that several years are required before significant results are available.

If reliable experimental modelling at an accelerated time scale could be used to replicate full-scale tests, a wide range of potential frost susceptible soils could be investigated within a reasonable time frame. It was to this end that C-CORE initiated an investigation of the viability of conducting frost heave tests in the centrifuge. A 48 inch diameter pipeline (1.2 m) can be replicated by a pipe of about 40 mm diameter with the centrifuge operating at 30 g or by a 24 mm model pipe at 50 g. The major benefit of the centrifuge is that some fluid flow processes scale in proportion to the square of the gravitation field. At 30 g, 5 hours of flight replicates 6 months frost heave of full-scale operations at the same temperature. An entire operating life of 30 years could be replicated at 100 g in about 26 hours of flight.

This paper presents the results of centrifuge model tests designed to replicate the full-scale tests in Calgary. The amounts and rates of frost heave in the centrifuge are compared to the Calgary tests. The rates of heaving for a pipeline at the Caen test bed is also included for comparison. Small-scale frost heave tests carried out at Carlton University and from Calgary for the Caen test bed soil and tests on undisturbed samples of silt from the Calgary test site are also examined with respect to freezing rate.

Cyclic freezing and thawing is being tested as a means of mitigating frost heave, for example, operating at below freezing temperatures in the winter and above freezing in the summer.

2 ARCTIC GAS PIPELINE DESIGN CONSIDERATIONS

A major design consideration is whether or not the gas in the pipeline is chilled to below freezing temperatures to preserve the permafrost or if it is allowed to flow at run-of-the-line temperatures and allow the permafrost to thaw. Even if the gas is not chilled, it will typically be below freezing for some distance downstream from the compressor station due to the Joules–Thompson effect, so frost heave for at least some of the pipeline route must be considered in either case. There is an economic incentive on throughput to chill the gas. The pipeline will hold more gas if it is chilled. Deciding the last point of cold flow was debated extensively in previous regulatory hearings and it remains as an issue to be resolved. When the gas is chilled, frost heave will be experienced where the line traverses unfrozen soil, which is frost susceptible and where water is present. When the line is above freezing temperatures, permafrost will melt and thaw settlement will occur. The design challenge is to define the point when thaw settlement is less troublesome than frost heave.

Other design considerations that are influenced by pipe operating temperature include slope stability, creep at bends, foundations for block valves and compressor stations, drainage and erosion control and reclamation. Given that thawing slopes (and even some slopes that are thawed) tend to be unstable, the stability and ditch erosion resistance is enhanced by freezing the soil around the pipe. The strength of frozen soil at bends is typically greater than the same soil if thawed, and frozen soil has greater resistance to erosion. Hence there is a strong incentive to carry chilled gas as far south into the discontinuous permafrost soil as possible.

Revisiting the previous full-scale field studies is instructive for current engineering design, including sites in permafrost regions and the sites where full-scale pipeline frost heave was studied.

3 THE CALGARY TEST SITE

A description of the Calgary Test Site and initial test results were presented by Slusarchuk et al. (1978) at the 3rd International Permafrost Conference. A very detailed description of the site and initial test results is included in a two volume report to Canadian Arctic Gas Study Limited, CAGSL (1975) and further details can be found in a submission by CAGSL (1976) in response to a request for information from the NEB. A detailed discussion of the 4 test sections (later expanded to 6) will not be presented here. Of particular interest are the results of freezing tests of two sections; one designated the control section and the second the deep burial section. These are shown in Figure 1. They represent practical designs for burial depths.

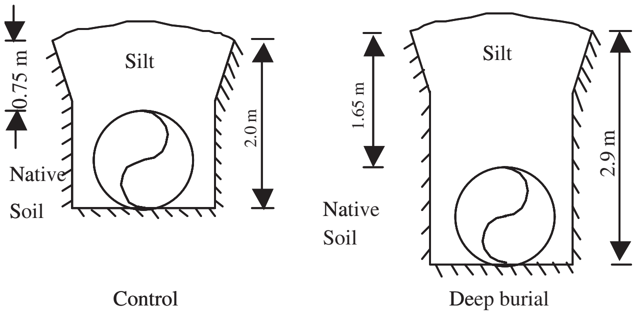

Figure 1. Calgary ditch configurations, after Carlson (1984).

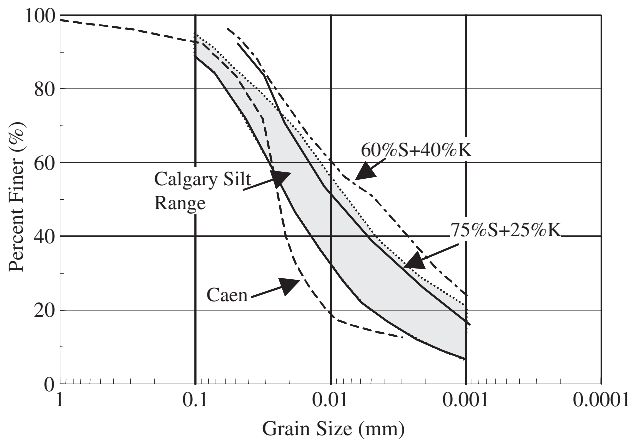

Figure 2. Grain size distributions for the Caen, Calgary and model silts.

4 REPLICATION OF CALGARY TESTS

Three centrifuge tests have been completed on soils similar to the Calgary test site. Figure 2 shows the range of grain size distributions for the Calgary site and for the samples prepared for centrifuge modelling. Also shown is the grain size distribution for the Caen tests.

5 CENTRIFUGE MODELLING

5.1 *Centrifuge technique*

The geotechnical centrifuge modelling technique accounts for the stress-dependent behaviour of soils. Soil models placed at the end of a centrifuge arm can be rotated to achieve an inertial radial acceleration field, which to the model simulates Earth's gravity but many times stronger. If the same soil is used in both the model and prototype and the soils both have similar stress histories, then soil stress similarity is correctly modelled. When the soil model is subjected to an accelerated inertial stress field of N times Earth's gravity, the vertical stress at depth h_m in the model will be equal to the prototype vertical stress at soil depth h_p (where $Nh_m = h_p$). This is the basis of centrifuge modelling and scaling laws, that stress in the model and prototype are equal at a homologous point by accelerating a model of scale 1:N to N times Earth's gravity (g). It has been confirmed that the centrifuge technique is an effective tool for modelling of gravity dependent geotechnical phenomena. The scaling laws for centrifuge modelling of frost heave are presented by Ketcham et al. (1997) and Yang & Goodings (1998).

5.2 *Model preparation*

The soil used in the modelling study for Tests 1 and 2 was a 60–40% mixture of Sil-Co-Sil silt and Speswhite Fine China kaolin clay. Test 3 used a 75– 25% mixture. A summary of the properties of the modelling soil and the prototype field soil, preparation procedure and instrumentation are presented in Phillips et al. (2001).

Three areas of temperature control are required to model pipeline frost heave properly, the temperature in the pipe, ambient air temperature above the model and the soil temperature gradient with depth. The test setup must ensure a free flowing water source with the groundwater level maintained at the pipe invert.

An insulated strongbox with inner dimensions of 1020 × 775 mm was used to contain the model. Covering the box, and enclosing the model, was a thermally insulated lid suspending a refrigeration plate to cool the air at the model surface. A vortex tube was used to circulate chilled or sub-freezing air through the pipeline model.

5.3 *Model testing programme*

Test 1 and test 3 under 30 g were modelled after the control section tested at the Calgary test facility. The rigid pipe section was 41.3 mm in diameter, 700 mm in length and had a 1.59 mm wall thickness for tests 1 and 2. The pipe section was not restrained at its ends, see Phillips et al. (2001), which presents further details for these tests. The pipe section in Test 1 was placed at a depth that gave 25 mm of overburden to simulate 0.75 m in the prototype, which existed for the Calgary control section. Test 2 was modelled after the Calgary deep burial section. Therefore the model was placed 57 mm below the soil surface to represent 1.7 m of overburden in the prototype. Tests 1 and 2 were tested for 5.5 and 6.25 hours respectively and therefore represented the first 201 and 230 days of field test site operation. Test 3 conducted at 55 g, using a 22 mm diameter pipe, represented 790 days of freezing.

The test package was accelerated to test speed. The testbed was consolidated under selfweight. Chilled air at about −10°C was then circulated through the pipe section while the heave displacements of both the pipe and surrounding soil were measured.

To define the advancing cold front from the chilled pipe an array of thermistors were positioned at the pipe mid-section. The pipe/air temperatures along the pipe were measured at the inlet, mid-section and outlet. The outlet temperature was about 4°C warmer than that at the inlet. These temperatures were controlled within 1°C during freezing.

Upon completing the tests, the model container was removed from the centrifuge platform and placed within a cold-room at −5°C where examination of the model could be performed without the thawing of the ice formations generated during testing.

6 TEST RESULTS AND ANALYSIS

6.1 *Model to prototype comparison*

A comparison of the models to the measured field data from the Calgary frost heave test site reveals similar behaviour patterns with respect to heave displacements and time. Furthermore, a similar thermal response to the prototype conditions was also observed.

The pipe temperatures are similar between the model and prototype, but the ambient air temperature at the soil surface is an area of model simplification. The ambient temperature during Tests 1 to 3 was kept at a constant level of about 2°C, whereas the prototype would be subjected to seasonal variation. This would have more of an effect on Test 1 since it had a shallower burial depth.

The surface displacement at mid-length of the pipe model during Test 1, presented at full-scale, is compared to the prototype control section in Figure 3. The prototype control section was measured at the pipe surface, whereas the model was measured at the soil surface.

Test 2 modelled the deep burial condition tested at the Calgary test site. Pipe model displacements at full-scale are compared to the prototype deep burial section in Figure 3.

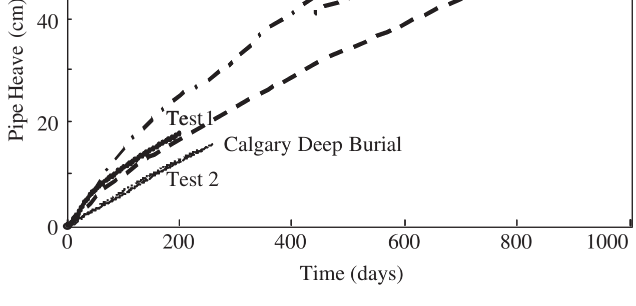

Figure 3. Pipeline heave: comparison for Calgary and model tests.

6.2 *Comparison of rate of heave – full scale and centrifuge*

Figure 4 shows the rate of frost heave plotted against pressure acting on the freezing front for the Calgary test site and for the centrifuge modelling of those sites. This pressure was calculated from the total effective weight of the pipe and a block confined by two lines tangent to the developing frost bulb and rising to the surface at 60° to the horizontal and the frost bulb base. In addition to the Calgary tests, rate of heave for two test cycles of the 250 mm diameter pipe at Caen, France are shown. The Caen tests have a much lower pressure on the freezing front and are presented here for comparison only. The tests designated as the second cycle have a much greater heave rate than the first cycle. This is contrary to other small-scale tests.

The substantial reduction of heave rate due to increased pressure on the freezing front as the frost bulb grows in the full-scale Calgary tests has been replicated by the centrifuge modelling.

6.3 *Small scale laboratory frost heave tests*

As a part of the frost effects study for CAGSL, an extensive laboratory test programme was carried out on samples secured from the Calgary test site and from test holes drilled along the proposed route in the Mackenzie Valley. These tests were made in test cells patterned on those previously used at the University of Alberta (Arvidson & Morgenstern 1974, Arvidson & Morgenstern 1977). The frost heave concept that emerged from the University of Alberta tests was that if sufficient pressure was applied to the freezing front in the sample it would result in water being expelled rather than being sucked toward the freezing front. The pressure where water started to be expelled was designated as the "shut off pressure". At that time the concept of shut off pressure was used as the basis of design of burial depth and mitigative measures for the proposed CAGSL pipeline from the Arctic. This concept cratered when it was discovered by tests on similar cells by National Research Council Canada that air leaked into the sample, particularly at high pressures. Water was forced out by the leaking air giving a "shut off pressure" lower than would have been the case if the cells had functioned properly.

Although the test results were spurious, the results for the low-pressure tests (564 psf or 27 kPa) are probably not seriously affected, given the relatively short test time (about 24 hours).

Konrad & Morgenstern (1982) also carried out small-scale frost heave tests and presented a concept for prediction of heave based on "segregation potential" derived from the small-scale tests. Nixon (1982) had previously conducted laboratory tests to define the "segregation potential" and showed comparisons with the Calgary full-scale tests.

A large number of laboratory freezing tests on small samples (typically about 100 mm diameter) were run on the Caen silt by Carlton University and are reported by Dallimore (1984). The samples tested show a very wide scatter of heave rate, up to a factor of 4 for the same soil and test procedure. The method by which the sample was prepared appears to have a major influence. Dallimore also shows the results of tests on Caen silt carried out at Hardy Associates Ltd., reported by Nixon (1984). The test pressures for the small samples tested by Nixon ranged from about 20 kPa to 200 kPa. The results of the tests in terms of rate of heave versus the applied pressure on the freezing front are shown in Figure 5, along with the results for the full-scale tests and centrifuge modelling previously shown on Figure 4. Two points available from the restrained section at the Calgary site are included. Also included are the results of the tests by Hardy for CAGSL for the Calgary test site soils conducted at a relatively low pressure (27 kPa). It can be seen that in the small-scale tests the rates of heave are much greater for pressures up to about 75 kPa than for the full-scale tests. The scatter recorded for the

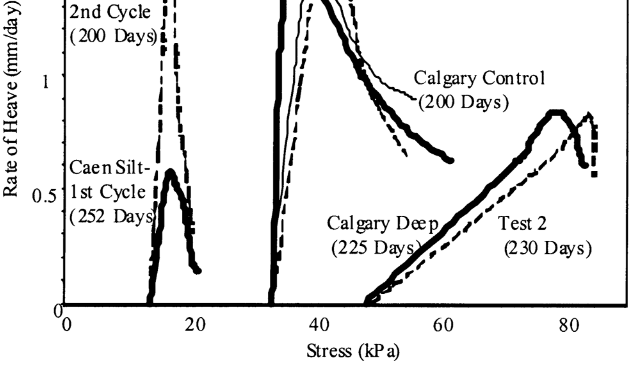

Figure 4. Heave rate with pressure for Caen, Calgary and model tests.

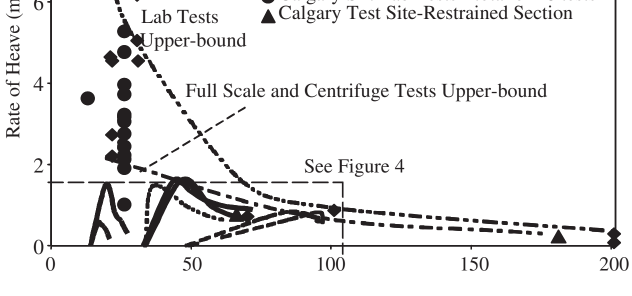

Figure 5. Heave rate with pressure for tests and laboratory data.

various soil types at pressures above about 75 kPa is much less than the scatter for the Calgary silt and Caen tests at low pressures. Figure 2 shows the relatively wide range of grain size curves for the soils tested. An upper-bound of pressure versus rate of heave for small-scale tests can be represented reasonably well by a single line. An approximate upper-bound line can also be drawn for the full-scale tests at the Calgary site as shown on Figure 5.

7 DISCUSSION

Small-scale laboratory frost heave tests show a very wide scatter of heave rate and segregation potential. Dallimore (1984) notes "heave parameters from a single test or a series of tests under identical test conditions may be misleading. A large number of tests under a variety of test conditions seem desirable". This may be acceptable for a small test facility such as Caen but is completely impracticable for pipeline design. The full-scale tests in the Caen test bed also show results that are inconsistent. The first cycle showed a heave rate of only a fraction of that recorded for the second cycle. Other testing has shown that the segregation potential of saturated clayey soils is greatly reduced by repeated freeze thaw cycles (Konrad 1994).

As the pressure on the freezing front increases, the scatter of laboratory test sample results decreases significantly. The same holds true for the various pipelines at the Calgary test site and for the 3 centrifuge modelling tests. The comparison of the heave rate with pressure is good for the two tests replicating the control section at Calgary and the deep burial section.

The Calgary field tests, centrifuge tests, and Caen laboratory tests at higher pressures appear to converge at an equivalent pressure on the freezing front in the range of 75 to 100 kPa, where the heave rate is about 1 mm/day and the rate continues to reduce with increasing pressure. This pressure corresponds to a frost bulb for the deep burial section of less than 1 m from the pipeline and occurs in less than 6 months. The influence of pressure on the freezing front appears to outweigh other factors such as texture variation, permeability, sample preparation and full-scale field tests versus small-scale laboratory tests for the experimental test site data available. Whereas shut off pressure may not be a valid concept for highly frost susceptible soils, there does appear to be a freezing front pressure beyond which the rate of heave is similar for different textures, sample preparation procedures, different test scales, etc.

The soil may experience consolidation outside the frost bulb under the freezing front pressure depending on the soil properties. For soft to medium soils, this consolidation may absorb some of the growth of the soil in the frost bulb due to ice lensing and increased water content. Hence, even though a soil is highly frost susceptible consolidation outside the frost bulb may reduce the heave of the pipeline.

If the upper bound curve for the Calgary field tests, centrifuge tests and high pressure laboratory tests shown on Figure 5 is used with an average rate of heave of 1.5 mm/day for the first 60 days, 1 mm/day for 60 days to 6 months, then 0.5 mm per day to one year and 0.1 mm/day thereafter; the total predicted heave would be about 0.75 m for a 30-year life. The deep burial section at Calgary heaved less than 0.7 m in 10 years. Much greater heave would be predicted if the upper-bound for the small-scale tests was used.

Given the grades of steel and practical wall thickness of present day pipeline now available and the trend to more realistic design codes, it is unlikely that heave would overstress the pipe in a ten year time frame if it was buried in a ditch 3 m deep irrespective of soil type. It is also unlikely that significant heave would occur beyond that time. The Caen tests demonstrated that heave rate at the interface of a heaving/non-heaving soil is greatly reduced. This is due to the much greater pressure on the freezing front, caused by the anchoring effect of the non-heaving (or minor heaving) soil. The pipeline stress at such an interface will be likely to be the most significant experienced by the pipe in areas subjected to frost heave. The previously unfrozen and frozen soil will both experience creep causing stress relief, but creep is not simulated in these centrifuge tests. Stress relief can also be achieved by cycling the pipeline temperature to run below freezing during the winter (when it is most economical to do so) and warm for several months in summer. Temperature cycles over a 30-year period can be examined in 5 days of centrifuge flight time at 50 g. This is a current line of research at C-CORE.

A pipeline operational and maintenance protocol that included, for example, a seven month gas chilling period over the winter months each year, followed by 5 months of run-of-the-line temperatures with the chillers shut down would result in an annual thaw of frost heave zones and likely a reduced heave rate in following years. Permafrost would also thaw at run-of-the-line summer temperatures but freeze back would occur the following year.

Techniques for monitoring of arctic pipelines are presently greatly improved from what existed 30 years ago. The Geo-Pig detects even minor changes of curvature and can readily be conducted on an annual basis (Hektner 1999). Satellite monitoring of surface heave and subsidence is economic and can now be repeated weekly to an accuracy of ±10 mm, Randell et al. (1999). If potential frost heave problem areas are identified by the monitoring programme, the soil types and ground water conditions could be modelled very quickly in a centrifuge and future heave behavior or intervention required could be predicted.

8 CONCLUSIONS

The frost heave of full-scale pipelines carrying gas at below freezing temperatures can be accurately modelled in a centrifuge if soil and groundwater conditions are similar and if the pipeline is scaled proportionally to the gravitational field.

The rate of heave of pipelines modelled in the centrifuge is similar to the rate of heave of the prototype for the same soil.

Small-scale frost heave tests under no or low surface pressure show exceptionally large variations in heave rates even though the samples are identical and test procedures are the same.

The heave rate for full-scale and centrifuge tests tends to converge with small-scale tests conducted at higher pressure.

Limited experimental data suggests that for a 1.2 m diameter pipeline with a burial depth of 3 m, the pressure on the freezing front, after a frost bulb has developed to 1 m below the pipe, outweighs the effects of other variables.

ACKNOWLEDGEMENTS

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