Assessment of Frost Heave Modelling of Cold Gas Pipelines

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ABSTRACT
The design of chilled gas pipelines passing from the Arctic to Canada and the United States through talik zones has resulted in a considerable number of studies to better understand the frost heave mechanisms. This paper discusses reduced scale frost heave tests that have been carried out in a geotechnical centrifuge to simulate 2D frost heave of a buried pipeline. Further, it compares the results to full-scale tests and examines a possible mitigative technique based on a recent centrifuge test with accompanying data analysis techniques. Centrifuge testing allows for measuring and monitoring of a broad range of parameters such as temperature, displacements and pore pressures. Other measurements carried out include soil water contents and post test CAT scans showing the frost bulb. Details of the tests including the setup, procedures and the range of data interpretation that can be carried out are discussed. Centrifuge data has been compared to and shows consistency to semi-analytical methods. Recent centrifuge data analysis has shown the method's ability to quantify both the in-situ and segregational heave components of the process. Further analysis of the type of data produced from these tests combined with such semi-analytical methods will increase the overall understanding of frost heave and development of mitigative measures.

RÉSUMÉ
La conception de pipelines traversant le talik pour acheminer du gaz réfrigéré de l'Arctique vers le Canada et les États-Unis a généré un grand nombre d'études visant à mieux comprendre les mécanismes de soulèvements dus au gel. Cet article présente des modélisations à échelle réduite de soulèvement par le gel entreprissent dans une centrifugeuse géotechnique avec pour but de simuler en 2 dimension le soulèvement d'un gazoduc enterré. L'article inclus une comparaison entre un essai à vraie grandeur, une discussion de techniques d'essais pour des mesures d'atténuations et les résultats d'un essai récent avec une description des techniques d'analyse de données. La modélisation en centrifugeuse a démontré le potentiel de mesurer des températures, des déplacements, la pression des pores, le contenu de l'eau dans le sol et des tomodensitogrammes a posteriori. Une description des essais, des procédures et les possibilités d'analyses de données sont incluses dans l'article. Les données de la centrifugeuse sont convergentes avec les méthodes semi-analytiques. Les données de centrifugeuses les plus récentes démontrent la capacité de quantifier la composante du traitement in-situ et celle du rejet horizontal. Des analyses plus approfondies de ce genre d'essai combiné avec de telles méthodes semi-analytiques démontrent le potentiel d'accroître la compréhension du soulèvement par le gel et aideront au développement de mesures préventives.

1 INTRODUCTION

The design of chilled gas pipelines passing from the Arctic to Canada and the United States through talik zones has resulted in a considerable number of studies to better understand frost heave mechanisms. Frost heave occurs in soil as *in-situ* pore water freezes and additional free water advances to the freezing front leading to the formation of segregated ice lenses. The pipe and soil heave are dependent on several factors including soil type, cooling rate, thermal gradient and the availability of a water source. In northern regions a buried pipeline can pass through talik zones (i.e. zones of unfrozen soil within permanent permafrost). When these pipelines are operated with chilled gas, frost heave can occur in the talik zone and may cause distress to the pipeline.

Over the past three decades significant effort has taken place in predicting pipeline frost heave behaviour. Large-scale test sites, laboratory scale tests and theoretical and numerical modeling techniques have been developed to aid in such research. This paper describes the use of a geotechnical centrifuge for modeling the frost heave process. It also includes a comparison to full-scale tests, discussion of a possible mitigative technique and a recent centrifuge test with accompanying data analysis techniques. Centrifuge modeling facilitates measurement of a broad range of parameters such as temperatures, displacements and pore pressures. Post test CAT scans and soil water contents and also taken.

2 CENTRIFUGE MODELLING

The geotechnical centrifuge modeling technique for frost heave testing has been discussed in detail in Phillips et al. (2002) and Morgan et al. (2004). Centrifuge modelling accounts for the stress dependent behaviour of soils. When a soil model is subjected to a gravitational field of N times the earth's gravity, the vertical stress experienced at any depth in the model is multiplied by N times that measured at 1g. Similarly, certain fluid flow processes scale proportional to the square of the gravitational field, thereby reducing the required testing time by a factor of N^2. This is the basis of centrifuge modeling, which has been applied to the frost heave problem. The scale

effects relating to centrifuge testing in general, and frost heave effects in particular, are discussed by Taylor (1995) and Yang (1997) respectively. Typical scaling relationships are presented in Table 1.

Soil samples representative of the field condition are prepared and a scaled pipe model is instrumented and buried in the soil bed. The soil and pipe models are contained within a thermally controlled and insulated strong box. The surface of the soil can be heated or cooled to replicate summer or winter conditions. Compressed air is supplied to the pipe through a vortex tube to chill the pipe to the required temperature. Up to 64 channels of data acquisition can be used to measure air and soil temperatures, pipe and soil displacements, pipe strains and soil pore pressures. The model is placed on the centrifuge and accelerated to the required g level or acceleration field to create the prototype modelling conditions. The soil body is allowed to consolidate over a 5 to 20 hour period depending on the model tested. Then chilled air is circulated through the pipe to induce the frost heave process. Post test activities include excavating the soil sample to determine water content profiles around the pipe and photographing the frost bulb and ice lenses. Radiographic examination of the model pipe and soil sample can be carried out. A CT Scanner is utilized to examine cross sections through the soil and allows the examination of the frost bulb around the pipe.

Table 1: Centrifuge Scaling Laws

Parameter	Scale Factor
Gravitational Acceleration	N
Macroscopic Length	1/N
Mass	$1/N^3$
Stress	1
Fluid Flow Velocity	N
Heat Flux	N
Time (Diffusion)	$1/N^2$
Time (Conduction)	$1/N^2$
Temperature	1

3 TEST DATABASE

There is now a significant history of centrifuge modelling of chilled gas pipelines. Testing has occurred in a variety of soil types, comparing to full scale testing, studying water table and burial depth affects, examining pipe response to differential frost heave, and the use of mitigative techniques such as thermosyphons and temperature cycling.

3.1 Full Scale Comparison

The use of the centrifuge to model frost heave was validated by C-CORE during a study where centrifuge tests were carried out and compared to full-scale tests carried out at the Calgary test site (Phillips et al., 2002).

Several large and full-scale test facilities were constructed and operated in the 1970s and 1980s to determine the behaviour of pipelines under northern conditions. The Calgary test site in particular is well documented (Slusarchuk et al. 1978, Carlson et al. 1982, Carlson & Nixon 1988). Six full-scale pipes, 1.22m (48″), diameter, 12.2m long were buried and operated under chilled conditions at about -10°C. The pipes were installed with variations in burial depth, bedding materials, restraint and insulation coatings. Among them, the pipe in the "control section" was buried at 0.75m and operated under continuously chilled conditions for 3 years while the pipe in the "deep burial" section was buried at 1.65m and operated under chilled condition for 10 years. These are the two test conditions that were chosen to be modeled in the centrifuge. Monitoring for the Calgary site and in the centrifuge included pipe and soil temperatures and vertical pipe movements. The size of the frost bulb around the pipe and resulting frost heave experienced by the pipe could therefore be quantified.

The conditions at the Calgary test site were scaled for the centrifuge test to allow a direct comparison with the full-scale behaviour. Model pipes were fabricated using copper pipe that gave a model scale of 1:30. Both pipes, the full scale and centrifuge, were designed to be rigid and therefore a material comparison is not needed. The soil bed was made up of 60% sil-co-sil silt and 40% kaolin clay to produce a grain size distribution similar to the mean of what was measured at the Calgary test site. The moisture content and density of soil was similar to the soil at the Calgary test site. The pipe sections in each test were chilled for the appropriate amount of time to scale to the full scale test being considered. Three C-CORE tests are compared in Figure 1 to the full scale tests. The results of these tests show that the observed heave was in good agreement with the full scale tests and demonstrates the use of centrifuge testing as an appropriate tool to model the frost heave behaviour of buried chilled gas pipelines.

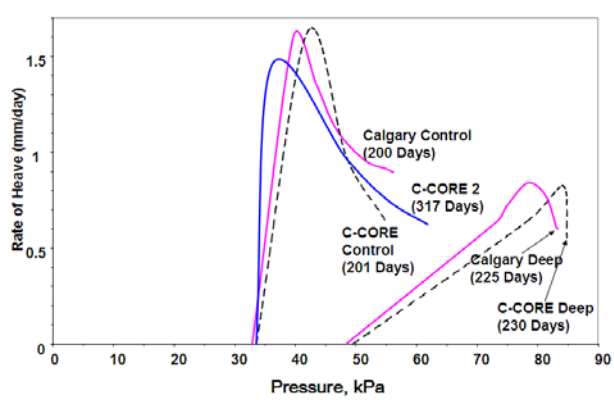

Figure 1: Full Scale Comparison

3.2 Temperature Cycling

The centrifuge has been used to examine the use of temperature cycling as a means of reducing long-term

frost heave of a pipeline. A centrifuge test was carried out with two pipes with different temporal temperature regimes, but with the same overall mean temperature. Further details of this test can be found in Morgan et al., 2006. Both pipes were initially operated at a constant temperature of -10°C for a period equivalent of three years at prototype scale. One of the pipes, pipe B, was then warmed to a constant temperature of -2°C and maintained at this temperature for a period equivalent to the next 10 years. The other pipe, pipe A, was subjected to a cyclic temperature for the next 10 years. The pipe temperature was maintained at +8°C for 5 months of a model year, and -9°C during the other 7 months of a model year. This provided a mean annual temperature of -2°C. Figure 2 shows the temperature conditions in each pipe against time. Figure 3 shows the heave of each pipe and the significant reduction in heave for pipe A. The test results clearly demonstrated that cyclic temperature operation of a chilled gas pipeline can significantly reduce long-term frost heave. In this case, the first two cycles led to elimination of the accumulated frost heave, while the frost heave at the end of 10 years operation was reduced by close to 70% compared to the control pipe section.

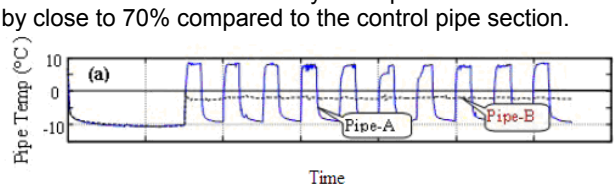

Figure 2: Temperature Conditions Pipe A and B

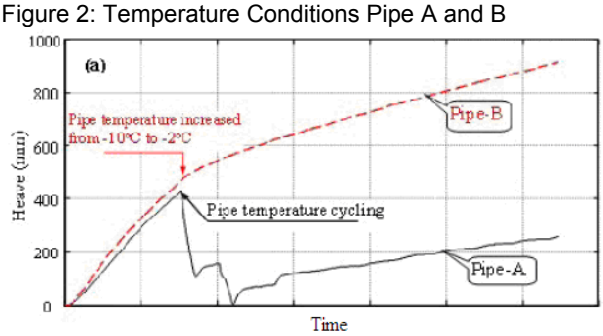

Figure 3: Pipe Heave Comparison

4 PHREATIC LEVEL EFFECT ON FROST HEAVE PROCESS – RECENT EXPERIMENTS

4.1 Test Setup

A centrifuge test was carried out to study the effect of a change in the phreatic surface level on the frost heave of a chilled gas pipeline. Two model pipelines, fabricated from copper tubing, were tested in a soil bed under controlled conditions similar to the previous experiments described by Phillips et al. (2002) and Morgan et al. (2004). The soil used in the test was a mixture of 75% Sil-Co-Sil silt and 25% Speswhite Fine China kaolin clay. The soil had been consolidated to 400 kPa. The initial water content of the soil used in this test was 23%. The soil is classified as a clayey silt and is highly frost susceptible.

The model pipe sections used in this test were 22.2mm in outside diameter and 420mm in length, representing a 1:55 scale model of a 1220mm (48″) diameter pipe. Both pipes had a model cover depth of 0.75D (17 mm). Pipe 1 was installed above the water level so that the distance from the pipe invert to the phreatic surface was 35 mm. Pipe 2 was installed so that the invert of the pipe was at the water level. The initial water level after consolidation was 110 mm above the clay-sand interface. The distance from the pipe invert to the clay-sand interface was 145 mm for Pipe 1 and 110 mm for Pipe 2. The pipe sections were instrumented with thermistors at the inlet, center and outlet of the pipe interior to measure the air temperature as it passed through. Thermistors were also placed within the soil below and aside the pipe to measure the thermal regime as the chilled pipe was operated. See Figure 4 for the instrumentation locations. The pipe and soil displacement response was measured using linear variable displacement transducers (LVDT's). Pore water pressure transducers (PPT's) were also placed below the pipe at 30, 60 and 90 mm from the bottom of the clay to measure suctions induced by freezing. Two PPT's were also installed within the soil bed at clay-sand interface to confirm the level of the water table. Each pipe was cooled individually using vortex tubes connected to a compressed air supply, which were controlled remotely to provide the required air temperature during the test. The experiment was mounted to the centrifuge and after 18 hours of consolidation at 55 times gravity the cooling phase began. Consolidation was considered complete after 90% consolidation when pore pressure reductions showed insignificant change. The pipeline was then operated at –7.3°C for 22 hours or 7.5 years of prototype scaled frost heave. An ambient air temperature of 1°C is maintained in the test box. Figure 5 shows the test bed before testing and post test with pipes and frost bulb formation.

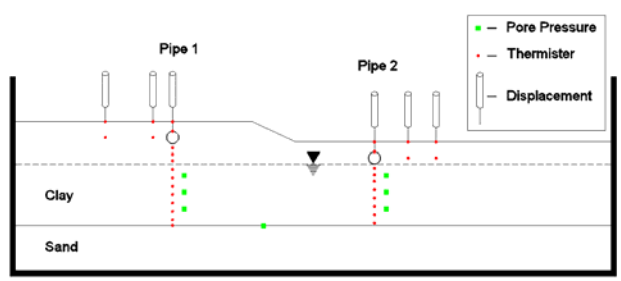

Figure 4: Test Setup

Figure 5: Test Bed Pretest (left) and Post Test (Right)

4.2 Test Data and Analysis

4.2.1 Temperature Data and Analysis

The temperature of soil body was on average +2.5°C before the cooling portion of the test began. After cooling began the soil directly below the pipe began to freeze and the temperatures below the pipe developed as shown in Figure 6, 0mm being pipe invert and 142.5mm being the sand clay interface. The temperature distribution below the pipes shows that the temperature gradient is not linear. Its value is increasing through the depth towards the pipe. This can be explained by the geometric shape of the pipe and the frozen bulb grown around it and the resulting increase in cross sectional area as the frost bulb moves away from the pipe. The isotherms formed around the pipe have a quasi-cylindrical shape, and based on the principle of continuity of heat flux in the unfrozen/frozen zone, the temperature gradient decreases with the distance from the pipe. Figure 7 and Figure 8, with the axis units in mm, shows the temperature fields around pipes 1 and 2 after 22 hours of freezing.

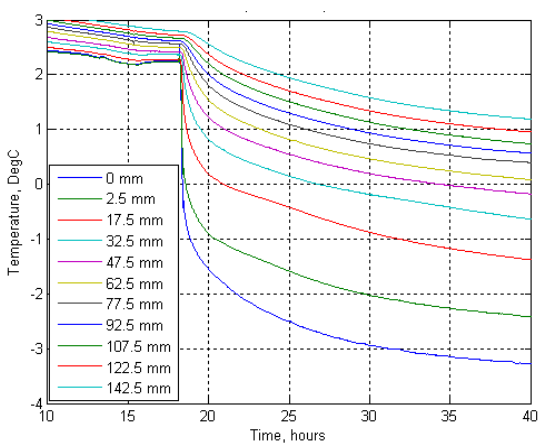

Figure 6: Temperatures below Pipe 1

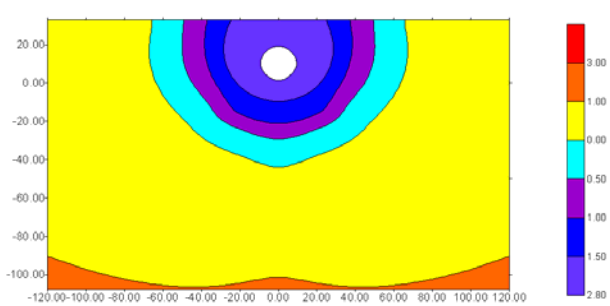

Figure 7: Temperature Field around Pipe 1 after 22 hours of freezing (7.5 years in the field)

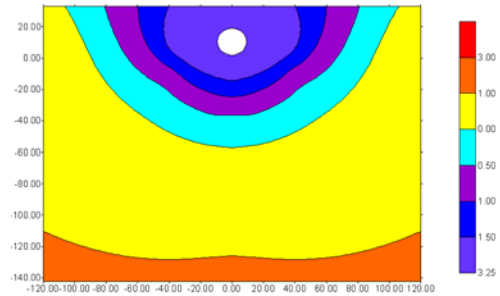

Figure 8: Temperature Field around Pipe 2 after 22 hours of freezing (7.5 years in the field)

4.2.2 Isotherms and the Frost Front Assessment

The temperature and pipe heave measurements are used to assess the progression of the frost front depth during the test. The dynamics of isotherms along the thermistor stacks situated below pipes are shown in Figure 9 (pipe 1), as a typical example of this type of data. Zero isotherms can be interpreted as a frost front (red line) and -0.5 °C isotherms (purple line) as a segregation front. The frost front for pipe 1 penetrated 57mm and pipe 2 penetrated 45 mm below the pipe invert. The penetration rate of frost front was also calculated to be higher for pipe 1 than pipe 2. These calculations are reflected in the calculation of water contents around the pipes from post test excavation. Figure 10 and Figure 11, with the axis units in mm, show the water content profiles and that the water content of frozen soil around pipe 2 was higher than it is around pipe 1.

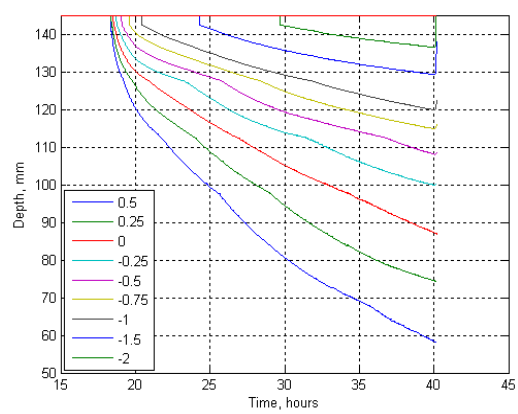

Figure 9: Isotherm Dynamics for Pipe #1

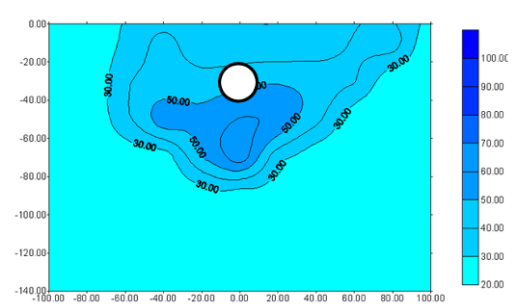

Figure 10: Final water content profile, Pipe #1

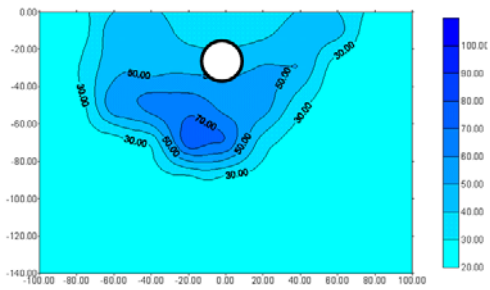

Figure 11: Final water content profile, Pipe #2

The final frost bulb geometry was assessed from CAT scan images after the test. Figure 12 shows the CAT scans from both pipes; Figure 13 shows the CAT scan from pipe 2 with wedge limits identified and Figure 14 shows a photograph of the frost bulb with the ice lenses. The geometry evolves as an axisymmetric frost front below, and centred on, the pipeline. This front is bounded by two passive wedges to either side of the frost bulb inclined at 56° to the vertical, which is consistent with a 22° friction angle for the clayey silt.

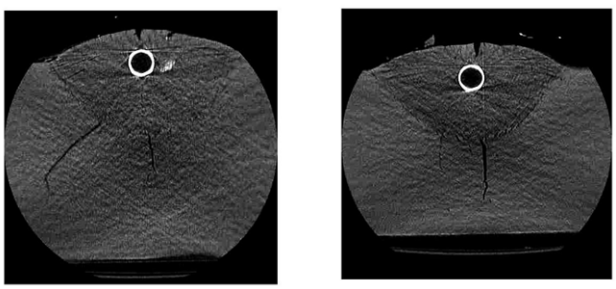

Figure 12: CAT Scan Images Pipe 1 (left) and Pipe 2 (right)

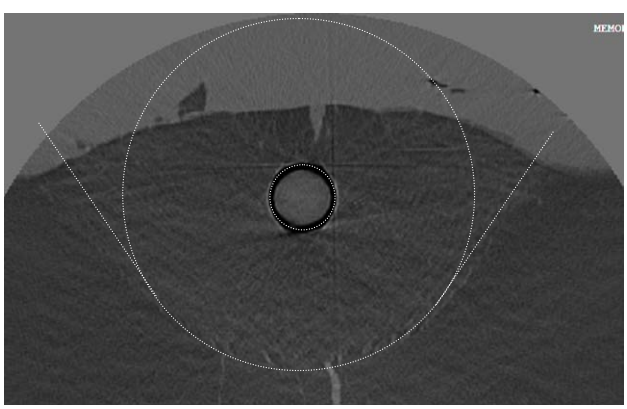

Figure 13: Frost bulb geometry, Pipe 2

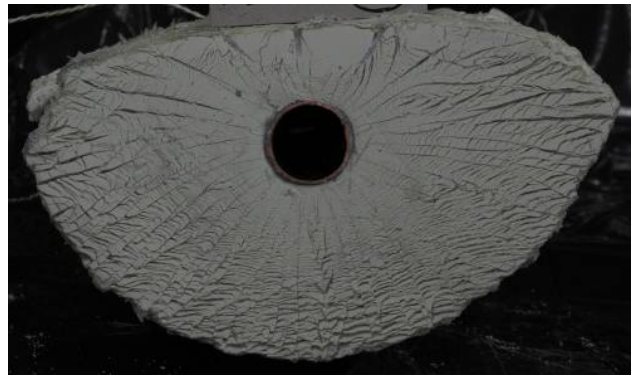

Figure 14: Cross Section Photo, Pipe #2

4.2.3 Heave Data and Analysis

The chilled air operated in the pipeline resulted in frost heave and therefore upward displacement of the soil around the pipe and thus pipe heave. The total heave recorded by the LVDTs was 15 mm for the pipe #1 and 15.6 mm for the pipe #2 after 22 hours of freezing, Figure 15. Pipe #1 heaved less due to a lag in the beginning of freezing. This is explained by the greater distance from the freezing front to the water supply. Calculated heave rates show higher rates for pipe 2 at the beginning of the test due to closer proximity to the initial phreatic surface. Pipe 1 achieved its maximum heave rate 3.5 hours after freezing started, and pipe 2 in 20 minutes after freezing started. After the 20 hour point the heave rates became similar and there was a constant offset in the heave versus time plots for each pipe, as can be seen in Figure 16.

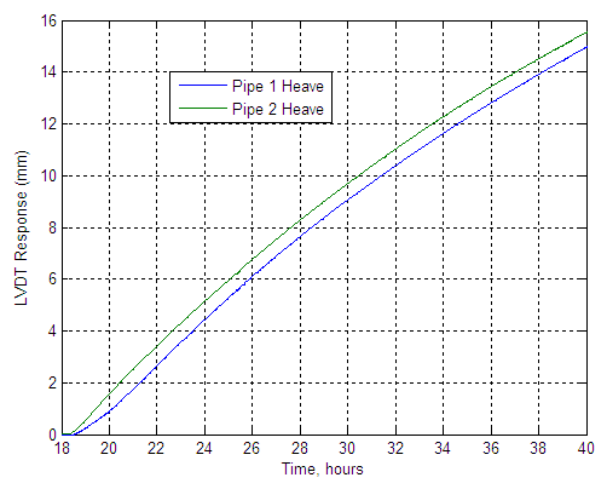

Figure 15: Heave vs. Time

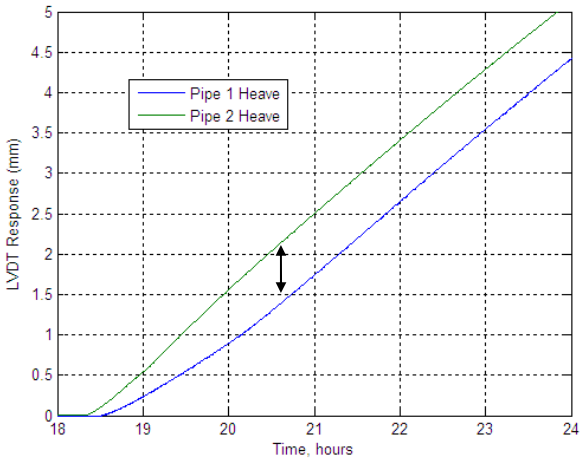

Figure 16: Heave vs. Time (initial)

4.2.4 Pore Pressure and Heave Component Analysis

Pore pressure transducers (PPT's) recorded the change in pore pressure at the same depths (30, 60 and 90 mm from the clay-sand interface) for both pipes. These transducers recorded the reductions in pore pressures that resulted from suctions generated in the soil by the soil freezing process around the pipe.

Hawlader et al. (2004) and others define the total pipe heave in two components: in-situ and segregational heave. The in-situ heave component is estimated from the frost front advance and 0.09*n* where *n* is the soil porosity and 0.09 is the increase in volume resulting from transformation of water into ice. After establishing a frost bulb, the total segregational heave rates decrease as expected with increasing frost front depth, Figure 17. These depth increases are equivalent to an increase in initial total bearing pressure under the pipe from 40kPa to around 120kPa under the developed frost bulb using the calculation method of Clark & Phillips (2003).

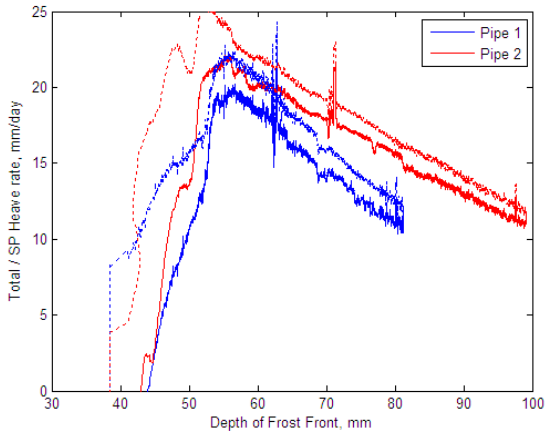

Figure 17: Total and segregational heave rates

The segregational heave is supplied in part by upward migration of water from the underlying sand. Typical pore pressure seepage profiles developed after 3, 12 and 21 hours of freezing (with 22 mm/day corresponding to 3 hours, 17 mm/day at 12 hours and 13 mm/day at 21 hours) for Pipe 2 are shown in Figure 18, together with the elevations of the associated frost fronts and the initial pipe invert, which was also the initial water level. The water level was depressed to about 9kPa below the final frost front due to the seepage development.

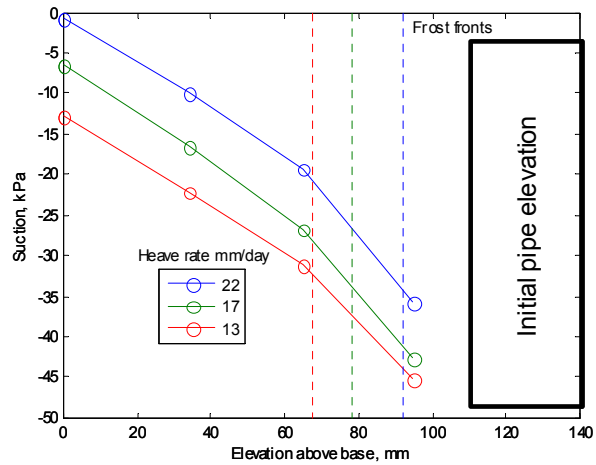

Figure 18: Pore Pressure Seepage Profiles (Pipe 2)

The total pipe heave rates decrease with increasing seepage gradient. This is due to a second diminishing component to the segregational heave beside seepage across the unfrozen zone. The total and segregational heave rates vary with these seepage gradients, Figure 19. Initially the heave rate increases due to in-situ heave alone with no seepage. Finally, after a maximum seepage gradient (shown by the circular dots), the heave is proportional to the seepage gradient alone. In the interim, as shown at 17mm/day for Pipe 1, there is another heave segregational component. Some of this arises from compression of the unfrozen soil below the frost front due to the effective stress increase from increasing total bearing stress and decreasing pore pressures. The water release is drawn towards the freezing front where it freezes and contributes to the pipe heave.

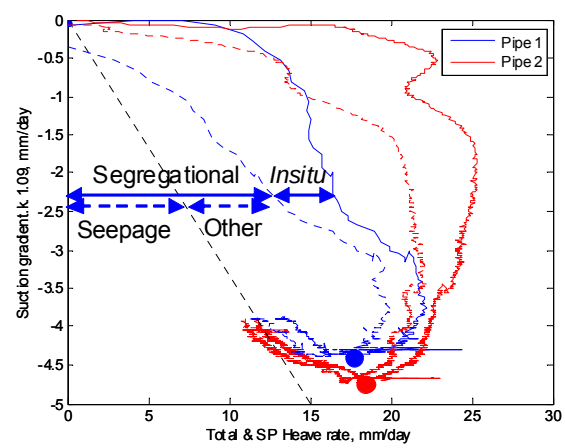

Figure 19: Seepage to heave rate relationships

Hawlader et al. (2004) quantified the seepage induced heave, Δh_s assuming one-dimensional flow as:

$$\Delta h_s = 2\ (.\ 1.09\ SP\ grad(T_f)\ \Delta t) \qquad [1]$$

Where SP is the segregational potential from element tests, grad(T_f) is the temperature gradient in the freezing front and Δt is the time increment. Element tests are laboratory freezing tests on small soil samples where heave rates can be measured, at various soil top and bottom temperatures and various pressure conditions, and SP values can be calculated. The factor of two arises from integration of grad(T_f), which is a function of time. The measured factor was around 3, as shown by the straight dashed line in Figure 19, probably due to the axisymmetric nature of water flow to the frost front below the pipe.

The frost front progression and pipe heave are also expected from this simplified solution to be linear in root time if the soil parameters remain reasonably constant. This is consistent with the observed behaviour, Figure 20 after the maximum suction gradients are exceeded.

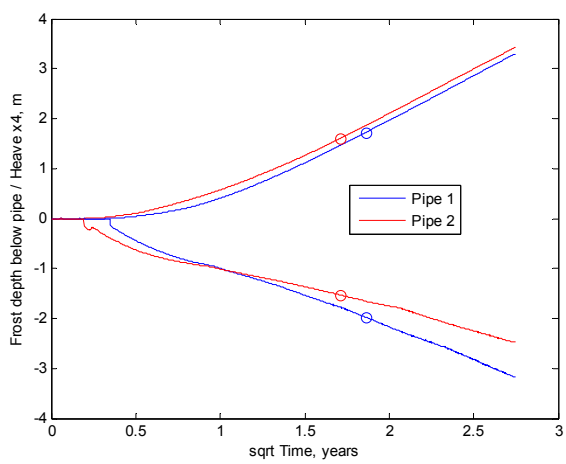

Figure 20: Frost front and heave development

The clayey silt hydraulic conductivity, k and segregation potentials, SP were measured at Universitie Laval averaging at 1.55e-06 mm/sec and 180 mm^2/deg/day for total vertical stresses between 25 and 100kPa, respectively. These SP values are consistent with the final segregational heave to temperature gradient ratios assessed from the two pipe tests, Figure 21, showing heave rate / gradT versus the depth of the frost front, allowing for the geometric factor of 2 to 3 to account for somewhat radial water flow towards the pipe.

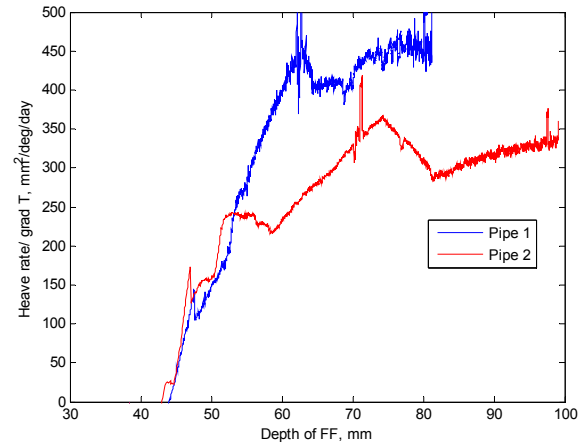

Figure 21: Segregational heave rate to grad.T ratio

5 CONCLUSION

This paper included details of the comparison of a full scale frost heave tests to centrifuge tests and the quality and success of that comparison. A frost heave test was also completed in the centrifuge that demonstrated the technique's ability to compare possible frost heave mitigation techniques against a control condition. In this test it was shown that temperature cycling in a pipe is capable of reducing the frost heave on a buried pipeline. This was one example of mitigative techniques that can be compared and quantified. Changes to burial depth, granular bedding, piled frame anchors and piled geomat covers for pipelines, and thermo siphons / heat pipes for pipeline and/or foundations are other mitigation methods that could be tested using these techniques.

The recently completed test to study the effect of a change in the phreatic surface level on the frost heave of a chilled gas pipeline was presented. These test results showed that the distance between the water level and the pipe invert plays a role in frost heave mainly at the beginning of the freezing process. This test also allowed for the development of analysis techniques relating to the pore pressure response and the suction profile to heave relationships. The two components of heave, in-situ and segregational heave, were demonstrated using seepage profiles derived from test pore pressure data. The frost front progression and pipe heave against root time is shown to be linear as expected from semi-analytical methods.

It has been demonstrated that centrifuge modeling can provide a large range of measurements, including temperatures, displacements, pore pressures, post test CAT scans and soil water contents. Centrifuge data have been compared to and shows consistency to semi-analytical methods. Recent centrifuge data analysis demonstrated the tool's ability to correctly capture the in-situ and segregational heave components of the process. Further analysis of the type of data produced from these tests combined with such semi-analytical methods will increase the overall understanding of frost heave and development of mitigative measures.

ACKNOWLEDGEMENTS

The writers would like to acknowledge the hard work and contribution of the technical staff, Don Cameron, Derry Nicholl and Karl Tuff, of the C-CORE centrifuge center who are pivotal to the success of each centrifuge test. They would also like to thank Dr. Bipul Hawlader, consultant to the C-CORE team.

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