REVIEW OF CENTRIFUGE TESTING APPLICABILITY TO FROST HEAVE

C-CORE Contract Report
R-03-094-285 v3.0

June 2004

Review of Centrifuge Testing Applicability to Frost Heave

Final Report

Prepared for:

Geological Survey of Canada

Prepared by:

C-CORE

C-CORE Report

R-03-094-285 v3.0
June 2004

C-CORE
Morrissey Road
St. John's, NL
Canada A1B 3X5

T: (709) 737-8354
F: (709) 737-4706

Info@c-core.ca
www.c-core.ca

The citation for this report is:

C-CORE. Review of Centrifuge Testing Applicability to Frost Heave. Prepared for Geological Survey of Canada. C-CORE Report R-03-094-285 v3.0, June 2004.

Project Team

Vincent Morgan, Project Manager
Ryan Phillips, Director, Geotechnical Engineering
Jack Clark, J.I. Clark & Associates
Stuart Haigh, Cambridge University

EXECUTIVE SUMMARY

This review summarizes the applicability of centrifuge technology to northern pipeline frost heave design issues and presents a summary of results of centrifuge modeling of frost heave to date, especially with relation to arctic pipelines. An independent opinion of centrifuge technology and its applicability to frost heave is also presented.

Over the past three decades, centrifuge modeling has become a widely accepted tool for the prediction of the behavior of soil-structure systems. Centrifuge modelling because of reduced scale, accelerated timeframe for controlled testing and cost effectiveness provides a unique opportunity for use in the prediction of frost heave and the design development for arctic pipelines. There are many coupled factors controlling the system response, such as geothermal conditions, hydrogeological conditions, confining stress variation, soil stress-strain behaviour, heat transfer, and pore water migration. Most of these factors are reasonably modelled in a centrifuge test. The engineering insight provided by such tests can be extremely valuable, especially with an appreciation of the modeling issues, which could distort the results.

If the scaled responses of two model tests at different scales are similar, then confidence is increased that these physical simulations are representative of full-scale conditions. Such modelling of models of one dimensional frost heave has shown that factors such as frost heave, frost penetration and heave rate do appear to scale correctly in a centrifuge model test. These models also showed good repeatability of results. This modelling of models technique should be used to validate pipe response to frost heave, coupled with tests to demonstrate repeatability of results.

Comparisons made between centrifuge model results and those from full-scale pipeline frost heave testing undertaken at the Calgary test site revealed similar behaviour patterns with respect to heave displacements and time, and a similar thermal response to the prototype conditions was also observed. The substantial reduction of heave rate due to increased pressure on the freezing front as the frost bulb grows was replicated. The circumferential ice lense pattern around the model pipe was consistent with observations from full-scale pipes and laboratory tests.

A semi-empirical design method is emerging, from current centrifuge model tests, which includes a relationship between rate of heave and pressure on the freezing front. The centrifuge model test program should be expanded through a parametric study to include for example consideration of different pipe geometries, burial configurations, soil types, and geothermal and hydro geological conditions. The program can also evaluate heave mitigation strategies and pipe soil interaction through, for example, discontinuous permafrost.

TABLE OF CONTENTS

List of Tables

List of Figures

1 OBJECTIVE

This review summarizes the applicability of centrifuge technology to northern pipeline frost heave design issues and presents a summary of results of centrifuge modeling to date of frost heave, especially with relation to arctic pipelines.

It also evaluates the contribution that centrifuge testing has made to the understanding of frost heave and frozen soil/pipe interaction, its character, mechanisms, rate and probable effects on a variety of soil types. The discussion considers the limitations and advantages of this type of testing along with a comparison of the results of full-scale tests and numerical modelling. There are no operating large diameter chilled pipelines in existence against which to extend this comparison. An assessment and comments on the future applicability of this type of testing for the validation of frost heave theory, prediction of frost heave and the design and operation of buried chilled pipelines, specifically for a Mackenzie Valley Pipeline is included.

An independent opinion of centrifuge technology and its applicability to frost heave was obtained from Dr.Stuart Haigh of Cambridge University as presented in Appendix A.

2 CENTRIFUGE MODELLING

Centrifuge modelling is a useful tool when modelling gravity-dependent phenomena in geotechnical systems, Schofield (1980) & Murff (1996). Centrifugal acceleration is used to simulate increased gravity and allows for correspondence of stress fields between model and full-scale, permitting accurate modelling of geotechnical and other gravity-dependent phenomena. Such modelling has regularly increased general understanding, and permitted calibration and verification of numerical and theoretical models of full-scale situations, Taylor (1995).

Centrifuge modelling has recently been used to replicate the full-scale pipeline frost heave testing undertaken in the 1970s and 80s in support of northern gas pipeline applications, eg. Clark & Phillips (2003). Centrifuge modelling because of reduced scaling, accelerated time frame for testing and cost effectiveness provides a unique opportunity for use in the prediction of frost heave and the development designs for arctic pipelines.

The geotechnical centrifuge modelling technique accounts for the stress-dependent behaviour of soils. Soil models placed at the end of a centrifuge arm are rotated to achieve an inertial radial acceleration field, which replicates Earth's gravity but at a higher level. 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 the associated 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).

2.1 Frost Heave Issues

Frost heave is known to be strongly dependant on the confining stress, e.g. Penner & Ueda (1977). The confining stresses around a buried pipeline will generally increase from near zero at the soil surface nearly linearly with increasing depth. This stress state and that superimposed by the frost action must be properly accounted for in any model, whether physical or numerical, of frost heave of buried pipelines. Centrifuge modelling provides such an account.

There are many different theories to describe frost heave mechanics. Yang (1996) provides an overview of 4 of these theories, namely capillary, secondary heaving, segregation potential and segregation freezing. The segregation potential (SP) theory of Konrad and Morgenstern (1980) is widely used in Canada, although other more recent developments such as Ladanyi and Shen (1993) and Selvaduri and Shinde (1993) have been proposed.

Although the theories are different, there is general consensus on the intrinsic and extrinsic factors that affect development of heave, Yang (1996). These factors include grain size, void ratio, temperature effects, confining stress and permeability. All of these factors can be accommodated in a centrifuge model test.

2.2 Scaling Considerations

The diffusion of pore water pressures and heat are important processes in frost heave problems. Palmer et al (1985) predicted that centrifuge modelling is able to simulate these two diffusion processes correctly. Savidou (1988) proved this prediction for heat transfer involving only conduction and free convection. Frost heave involves more complex heat transfer including phase transformation, but Chen et al (2000) has shown that centrifuge modelling is applicable even for this more complex process.

Miller (1978) presents a mathematical description of his Rigidice frost heave theoretical model, and Miller (1990) conducted a scaling analysis of the governing differential equations of this model. This analysis and the distinct role of gravitational body force in the heaving process led Miller to conclude that scale modelling of frost heave would best be conducted as a body force analog and that a small-scale frost heave test conducted in a centrifuge would be appropriate for this purpose. On the basis of Miller's earlier unpublished discussions on model laws for soil freezing, Black (1985) also presented a set of scaling relationships for frost heave centrifuge modeling and demonstrated that great time savings would be obtained over a full-scale experiment, Ketcham & Black (1995).

The resulting scaling laws relevant to cold regions modelling are given in Table 1. The scaling laws for centrifuge modelling of frost heave have been confirmed by Chen et al (1993a), Ketcham et al (1997) and Yang (1996).

Table 1: Centrifuge Scaling Laws (after Ketcham et al 1997 and Smith 1995)

Physical Quantity	Prototype	Model
Displacement	1	1/N
Area	1	$1/N^2$
Volume	1	$1/N^3$
Acceleration	1	N
Stress	1	1
Force	1	$1/N^2$
Strain	1	1
Temperature	1	1
Time (Diffusion)	1	$1/N^2$
Time (Inertial events)	1	1/N
Time (Viscous flow)	1	1
Interstitial water velocity	1	N
Moisture flux	1	N
Heat flux	1	N

2.3 Limitations

There are obvious potential scaling conflicts from this table, such as the simultaneous modelling of time effects relating to diffusion, inertia and viscous flow. However, such potential conflicts are common in reduced scale physical modelling in engineering. Consider modelling of hydraulic systems where the processes are controlled by such dimensionless groups as Reynolds number, Froude number, Mach number and Weber number. The only way to satisfy all of these conditions simultaneously would be to use a full-scale model, which is generally impractical or too expensive. Instead the modeler chooses only to reproduce those processes in the reduced scale model that are pertinent to their problem, while remaining aware of the possible influence of those processes that were not scaled. The same approach is valid for centrifuge modelling, for example, in frost heave modelling inertial events are unlikely to be of any significance and would not be scaled.

Specific frost heave related considerations include the grain size of ice generated in a centrifuge, frozen fringe thickness and the effects of creep, which are discussed by Smith (1995).

Fine and medium grained soil used in a centrifuge test generally has the same grading as that found in the prototype. Coarser grained soils may give rise to particle size effects. If there are insufficient soil particles in the physical model, then the model behaviour will be significantly constrained by the discrete particulate nature of the model, rather than having the appearance of continuum behaviour. Continuum like behaviour is generally observed when there are more than about 25 soil particles in contact with a structure. For a 25mm diameter model pipe, therefore, the mean soil particle size should not be more than 1mm, that of a coarse sand particle. Palmer et al (2003) show the influence of particle size in pipe uplift model tests in granular soils on the distance to mobilise uplift resistance. This influence is not considered to be significant for centrifuge tests of frost heave of pipelines buried in fine-grained soils such as silt or clayey silt with grain sizes of 0.001 to 0.1mm. This particle size influence on any underlaying or overlaying sand layers or beds in a model should not be significant provided there is no significant shear straining, e.g. rupture band formation, through these areas.

There is evidence from sea ice grown in a centrifuge under an accelerated gravitational field that the ice grains formed are proportionally smaller than those grown in earth's gravity, Barrette et al (1999). Considering the soil grain size ratio is then 1:1 but the ice grain size is not, Smith was concerned that the frozen soil will then not be identical to the prototype and therefore may respond differently. This would affect for example the permeability for water flow through the frozen fringe. Ketcham *et al.* (1997) also raised concern of the scaled down geometry of the ice lens formations. Yang (1996) showed that ice lens seem to be scaled generally in terms of spatial frequency and size.

Ketcham et al. (1997) and Smith (1995) question the time scaling of creep. If creep is a function of temperature and stress which are at a 1:1 scale between model and prototype then the time scale of creep will also be 1:1, which is in conflict with heat diffusion and pore water diffusion that obey a time scale of $1/N^2$. The creep of frozen soil in response to frost heave loading and its conflicting time scale may affect model/prototype similitude. Creep will result in stress relaxation that will become more apparent, the longer the duration of the test. There may be evidence of such relaxation in the constrained footing tests conducted by Ketcham et al (1997).

Ketcham et al (1997) also indicated that the period between initiation of freezing and initiation of uplift loads does not scale to $1/N^2$ as the frost heave process does. This observation is not considered to be correct. Their tests were conducted on a 19 to 29mm thick layer of saturated silt preconsolidated to 35kPa vertical stress. The freezing process was initiated prior to the soil sample being subjected to an increase in centrifuge speed to test acceleration level of 67, 80 or 100g. This self-weight increase causes immediate settlement and primary consolidation movements, which would persist for a period of about half an hour. Any vertical settlement will separate the soil from the suspended constrained footing. There will then be an inevitable delay until the frost heave has compensated for this settlement and forces are measured on the footing. This delay will vary partly because the overconsolidation ratio varied between the 3 tests. In more recent C-CORE frost heave tests, emphasis has been placed on ensuring that primary consolidation is effectively complete before commencing soil freezing. In these tests there has been no evidence of a significant period between the initiation of freezing and the initiation of frost heave.

Despite the limitations stated above, centrifuge modellers to date believe that the tests performed to date support the use of a centrifuge to model the frost heave process.

2.4 Validation

The challenge to all modellers of systems is to demonstrate that their model results are sufficiently valid to permit the model to be used in predicting system response over a wider parametric range. Comparing the model results to actual system measurements best does this validation. However, for geotechnical systems the actual system conditions may be poorly defined and the response of the system to infrequent design events unknown. Alternative means of validation are then required. This may include the comparison of model results with those developed from a second model based on a different set of assumptions. For example, the results of a physical model may be compared to those from a numerical model.

If earthquake engineering is considered, there are data of site response to earthquakes and liquefaction, but very few of these data are associated with well-defined site conditions that existed prior to the earthquake. Centrifuge modelling, developed over the last 20 years, has however gained increased acceptance to provide much needed system response modelling. A report by the Advisory Committee for the National Earthquake Hazard Reduction Program in the USA emphasized the importance of focused research, including centrifuge modelling, to provide results of immediate use to earthquake hazard mitigation. Industry has also accepted centrifuge modelling for this application. The Port of Los Angeles has expanded its facilities through the Pier 400 project. The Port authority required extensive centrifuge model tests to verify and improve the seismic designs of the breakwaters and harbour front structures. Similar centrifuge model tests have been conducted in Cambridge, England of the performance of proposed remediation schemes for the nuclear submarine pens at Devonport in a low-risk earthquake zone. Performance data for such an important facility in a low-risk zone cannot be attained by any other means in a short time frame.

A centrifuge model test is an independent physical event. It may not provide an ideal simulation of the prototype conditions under consideration. However, the engineering insight provided by such tests can be extremely valuable. A centrifuge model test may be viewed as the response of 'the site next door' where conditions are not exactly the same as those of most interest, but are sufficiently close to be of significant interest.

For frost heave of arctic pipelines, there are many coupled processes controlling the system response, such as geothermal conditions, hydrogeological conditions, soil stress-strain behaviour, heat transfer, and pore water migration. The only program of centrifuge modelling of buried pipelines subject to frost heave was initiated by C-CORE 3 years ago. Efforts have been made to simulate the full-scale pipeline frost heave tests conducted at the Calgary test facility, Section 3.1. These simulations have well reproduced the frost heave and heave rates observed from the full-scale tests. There are no publicly available comparisons between numerical models analyses and centrifuge model test data.

An alternative method to validate centrifuge model test data is to conduct 'modelling of models' tests. A 1m diameter pipeline buried at 2m depth could be modeled at $1/10^{th}$ scale using a 0.1m diameter pipe and 0.2m burial or at $1/20^{th}$ scale using a 0.05m diameter pipe and 0.1m burial. If the scaled responses of these two model tests are similar, then confidence is increased that these physical simulations are representative. (Differences in behaviour between the two scales assists in separating the effects of different processes.) Careful consideration is still required however to extrapolate the reduced scale results to a full scale situation. Modelling of models over a wide range of model scales has shown that factors such as frost heave, frost penetration and heave rate do appear to scale correctly in a centrifuge model test, as described in Section 3.

3 CENTRIFUGE MODEL TESTS ON FROZEN SOIL

The first centrifuge model tests using frozen soil were conducted in Russia, Pokrovsky & Fyodorov (1969). The University of Bochum, Germany developed this work through model tests including partly frozen artificial sand islands as possible foundations for exploration platforms in arctic regions, Jessberger et al (1983). None of these early tests examined the phase transformation between frozen and unfrozen soil.

Cambridge University conducted the first centrifuge model tests of thaw settlement and frost heave in the early 1990s. Colin Smith, under the supervision of Professor Andrew Schofield, studied the thaw settlement of pipelines using centrifuge model tests for his doctorate, Smith (1991). X Chen, a visiting professor from Tsinghua University, PRC joined Smith in 1992 to initiate centrifuge model tests of frost heave.

Chen et al (1993a) conducted one-dimensional short column frost heave tests of top down freezing using a small-refrigerated desktop centrifuge. Their tests at both 1/100th and 1/200th scale measured temperatures and surface displacements of the column, Figure 1. The tests clearly showed that the magnitude and rate of frost heave obeyed the expected scaling laws. The success of such modelling of models tests gave confidence to the use of centrifuge testing to examine frost heave issues.

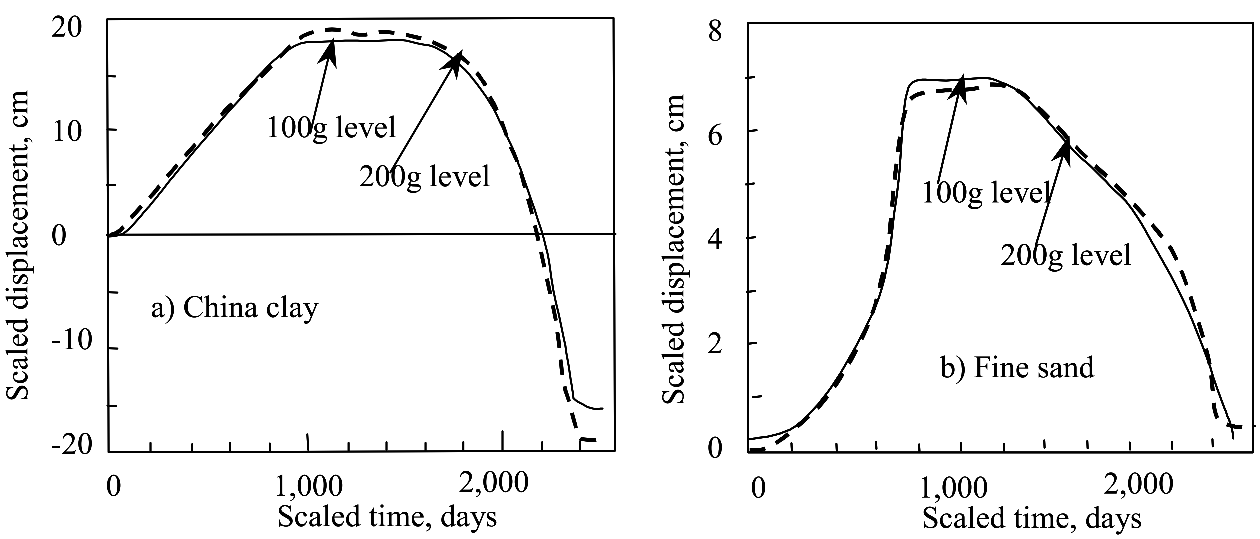

Figure 1: Modelling of models at 100 and 200g, after Chen et al (1993a)

Chen et al (1993b) performed larger size model tests in the 4m-radius Cambridge beam centrifuge of frost heave of buried pipelines. A rigid pipeline section was buried in a vertically partitioned testbed of silt and sand, similar in appearance to one of the full scale tests conducted at the Caen frost heave testing facility, Dallimore and Crawford (1985). Their 1g tests were used to develop the necessary modelling and freezing techniques. The soil model was contained within a passive thermally insulated chamber. Cold gas from a vortex tube was passed through the model pipe at a temperature of about –8 deg C. Only two tests were conducted in the centrifuge at 45g. The effects of continuous pipe freezing and a freeze-thaw cycle on the resulting frost heave were compared. Chen et al (1994) published the results of these first frost heave tests on buried pipeline. There were no modelling of models tests, and no comparison of results to numerical predictions or full-scale measurements. No further frost heave centrifuge model tests of buried pipelines are known of until Phillips et al (2001).

Following Professor Chen’s return to China, he commissioned the centrifuge at Tsinghua University and has continued his frost heave research, Chen et al (1999). Chen et al (2000) considered the effects of freeze thaw cycles on essentially one-dimensional frost heave tests. Modelling of models tests over a narrow range of 1/40th and 1/30th scale confirmed the scaling of heat transfer from the ground surface to a homologous point at 6m depth in silty clay. Chen et al (2002) conducted further tests at 40g on silty clay subject to frost heave and thaw settlement. They showed good repeatability of results, such as freeze and thaw fringe, free frost heave and thaw settlement and soil displacement under different loads.

The US Army Cold Regions Research and Engineering Laboratory (CRREL) has considered the application of centrifuge modelling of frost heave since 1985, Scott and Ting (1985) and Ketcham (1990). The US Army Corp of Engineering have developed a large geotechnical beam centrifuge centre, which anticipated the needs for such cold regions research, Ketcham (1991). Ketcham & Black (1995) made some initial small-scale frost heave experimental observations using a desktop centrifuge. These column experiments were very similar to those conducted by Chen et al (1993a), but did not include any inflight measurements or modelling of model tests.

Ketcham et al (1997) developed the application to measure the frost heave loading from top down freezing on a constrained surface footing using centrifuge modeling at scales of 1/67th, 1/80th and 1/100th in a 0.5m diameter centrifuge. Their 3 scaled models of a 1.27m diameter footing on a 2m deep saturated silt layer were consistent with a narrow range of footing penetration depths, free field frost heave and reasonable agreement in the temporal variation of uplift force, Figure 2. These results indicated that the expected scale factors are correct and centrifuge modelling appropriate for the study of frost heave loading on foundation members. Similarity issues they recognized that may limit the applicability of the technique included stress relaxation, the scaling of ice lens and the delay between initiation of freezing and subsequent uplift force development. These issues are discussed in Section 2.3. The latter issue is misleading as no time was left to allow consolidation of the samples prior to the initiation of freezing.

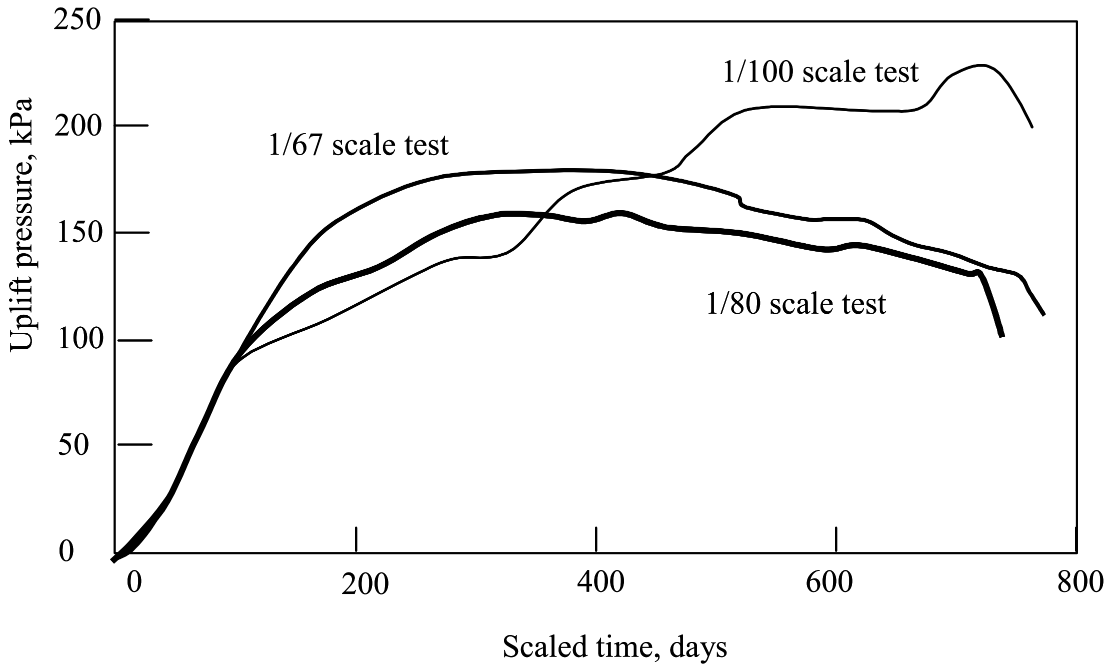

Figure 2: Scaled uplift load response, after Ketcham et al (1997)

Dan Yang, under the supervision of Professor Deborah Goodings at the University of Maryland (UoM) has conducted the most systematic investigation to date of the scaling laws for centrifuge modeling of frost heave in her doctoral thesis, Yang (1996). Six groups of modelling of model tests simulated, using either a pure silt or a naturally occurring silty clay and top down freezing, a one dimensional 3m high soil column at 1/20th, 1/30th and 1/40th scale. For each soil type, two pairs of models were frozen using a step freezing procedure. The first pair had a high water table at 25% of the soil depth, and the second pair with a low water table at 75% of the soil depth. A third pair was tested in silt with a low water table but using a ramped freezing procedure with differing freezing degree-day indices. Thin sections of the frozen samples were examined to obtain ice lens characteristics. The effects of temperature regime, phreatic surface and soil type on soil freezing behaviour were assessed.

The results were compared to short 1g column tests that compared the frost heave dependency on stress level. The modelling of models tests gave strong evidence to support the correctness of the proposed scaling laws: The ultimate heave extrapolated to prototype scale was very close between the 3 scales. Variations within any group were less than 13% from the average value. Frost heave penetration and water content after freezing showed a strong similarity. There was no evidence of adverse scale related effects.

The ice lenses formed at the higher accelerations were clearly smaller in size and closer together than ice lens formed at lower acceleration. Differences were noted in the rate of freezing between ramped and step changes and between soil types. Cumulative freezing degree days were not sufficient to characterize these differences. Results from repeated model tests showed excellent repeatability with coefficients of variation around 6% for ultimate frost heave, frost penetration and water content.

The centrifuge results were used to calculate bounds on the frost heave monitored at a CRREL field test site. The heave and the frost penetration measured in the centrifuge were similar in magnitude to those measured in similar types of soils, in broadly similar ground surface temperatures and moisture environments. This increases confidence in freezing test data obtained from centrifuge models, Yang (1996).

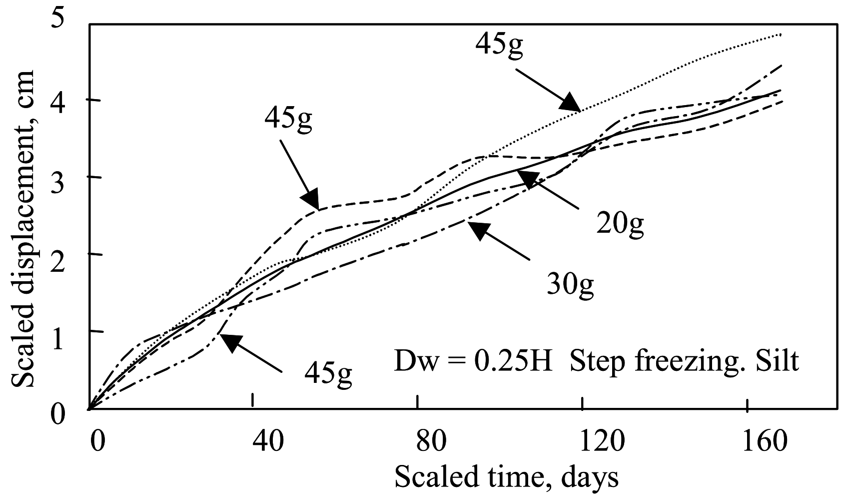

Figure 3: Scaled heave development, after Yang (1996)

The centrifuge measurements in silt were compared to predictions using the CRREL FROST numerical model of Guymon et al (1993). Most input parameters were assessed from laboratory data and accepted data tables. Four parameters were first selected from the CRREL comprehensive documented field site database based on soil type, grain size and heave prediction. This did not provide an acceptable fit to the measurements. These parameters were calibrated using the data from one centrifuge test. Subsequent predictions were excellent compared to the measured heave data. Attempts to calibrate FROST to ultimate heave frost penetration and water content simultaneously were unproductive.

The work of Yang (1996) is summarized in the papers by Yang & Goodings (1998a) and Yang & Goodings (1998b).

UoM has continued working in frost heave looking at boulder jacking through seasonal freezing and thawing, Goodings & Straub (1998) and more recently centrifuge modelling of freezing behaviour of clay, Han & Goodings (2002). They simulated at 35g the freezing behaviour of a 4m deep clay column with a water table 1m below the soil surface. The initial water content had an important role in the development of the freezing response in clay that appeared to be more important than the other mechanical or thermal soil properties. Further developments of this work will be presented in Han & Goodings (forthcoming).

Professors Davies and Harris of the Universities of Dundee and Cardiff respectively have collaborated on a program of centrifuge modelling of permafrost issues related to slope movements and gelifluction, Harris et al (2001), Harris et al (2002), Davies et al (2003) and Harris & Smith (2003).

3.1 Frost Heave of Buried Pipelines

Chen et al (1994) published the results of the first two centrifuge model tests of frost heave effects on a buried pipeline, with a similar set up to one of the full scale tests conducted at the Caen frost heave testing facility, as described above. The only other such centrifuge model tests have been conducted at the C-CORE geotechnical centrifuge centre since 2001 as part of an ongoing research program.

These C-CORE tests are summarized in Table 2. A total of 29 two-dimensional pipeline sections have been tested to date, mainly in clayey silt with burial depths ranging from 0.6 to 2 pipe diameters. The maximum test duration in prototype terms was 14 years, or 2 days in a 1/55th scale model tested at 55g. The results of the first 3 tests are publicly available as described in Phillips et al (2001), Phillips et al (2002) and Clark & Phillips (2003). The results of the fourth test are proprietary to the Geological Survey of Canada, C-CORE (2001).

Table 2: Summary of C-CORE Centrifuge Model Pipelines Tests of Frost Heave

Test ID	Client	Test Date	Soil Type	g Level	Test Duration	Number Pipes	Burial Depth
Calgary Field Demo 1	None	Mar 01	Clayey silt	30	0.5 yrs	1	0.6D
Calgary Field Demo 2	None	May 01	Clayey silt	30	0.6 yrs	1	1.4D
Calgary Field Demo 3	None	Mar 02	Clayey silt	55	2 yrs	1	0.6D
Proprietary tests follow							
GSC Restrained	G.S.C.	Mar 01	Clayey silt	30	0.4 yrs	1	0.6D
Demonstration	Gas Research Institute	May 02	Clayey silt	42	1.6 yrs	1	0.6D
2002 GRI 1 to 5	Gas Research Institute	Nov 02 - Mar 03	Silt and clayey silt	42 to 55	up to 14 yrs	13	0.75 - 2D
2003 GTI 1 to 5	Gas Research Institute	Aug 03 - Feb 04	Clayey silt	55	up to 13 yrs	10	0.75D
Alaskan Simulation	TransCanada	Jul 03	Layered	55	6.3yr	1	0.82D

The other more recent tests for industry are proprietary to third parties. The objective of the test program for Gas Technology Institute (GTI) was to further evaluate centrifuge technology for use as a tool in predicting the effects of frost heave of chilled buried pipelines and to investigate pipeline behaviour under a range of conditions. A range of conditions are being modeled, including :

- Soil type
- Pipe burial depth
- Pipe Temperature
- Seasonal variations in temperature boundary conditions
- Supply of ground-water to the freezing front

Key issues that were identified in designing the test series included the response of a range of frost susceptible soil types, from a fine grained silty clay to coarse grained silt. The effect of pipe burial depth was also considered important, as it is a well known phenomena that increased pressure on the freezing front reduces the rate of frost heave (Carlson 1982, Konrad & Morgenstern 1980). Increases in burial depth may be the most cost effective and flexible method of limiting frost heave to acceptable levels. Another potential measure for reducing frost heave may be to vary the gas temperature to run periodically at above freezing temperatures. In this way, thaw settlement during warm periods could offset frost heave. Initial test results, backed up with frost heave theory, suggest that these methods could be appropriate and provide cost effective mitigation strategies for maintaining pipe movement within acceptable boundaries at critical points along the pipeline.

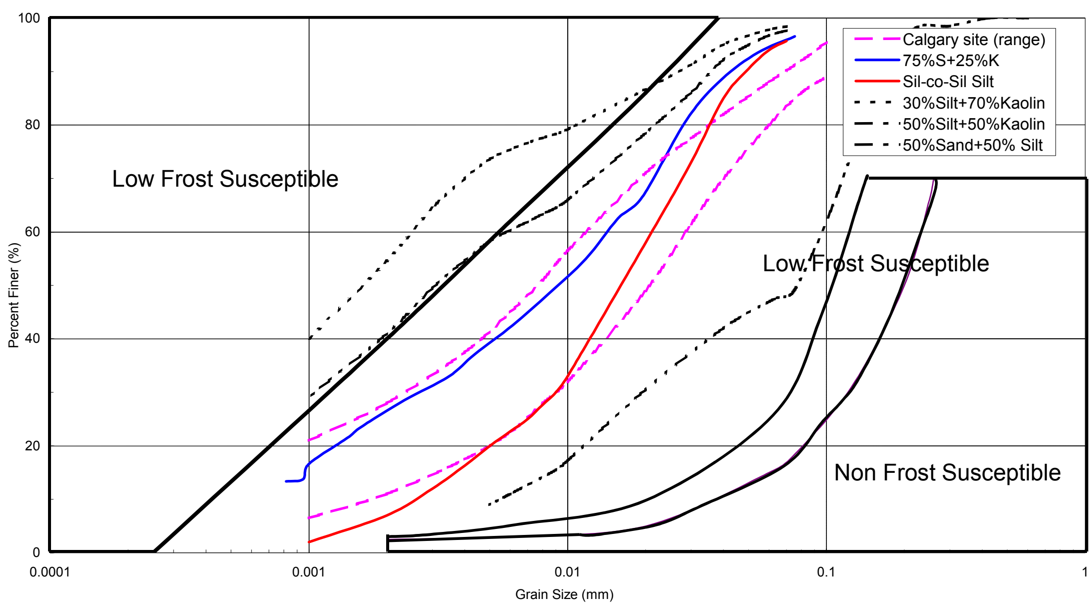

Figure 4: Range of particle size distribution for soils to be used in centrifuge testing

Advances were made in the test set-up to allow multiple pipes to be tested simultaneously within the same package, and a system developed to allow independent temperature control of each pipe during the centrifuge flight. Tests have been performed for a number of soil types and burial depths, and have included the effect of seasonal temperature variation. Figure 4 shows the range of soil gradings that have been tested to date, compared to the range normally considered for frost susceptible soils. The range of soil particle size is prepared by mixing various proportions of kaolin clay and sil-co-sil silt, both materials being easily available to well defined quality standards. No attempt is therefore made to defining the role of mineralogy in frost heave. Burial depths tested are between 0.75 and 2.0 times the pipe diameter. The pipes are generally cooled to -10^{o}C as a base case, although the effect of warmer temperatures and/or seasonal operation at above-zero temperatures has also been integrated into the program, Morgan et al (2004). The test results are not discussed in this review.

Findings from the first four tests and comparisons with large-scale field tests follow. The first three centrifuge tests provided a comparison with full-scale measurements made at the Calgary test site as presented by Slusarchuk et al (1978). The responses from two of the eventual 6 test sections were simulated, namely the control section and the deep burial section as shown in Figure 5. The fourth centrifuge test simulation for GSC simulated a third section where upward movement of the pipe was restrained by a reaction frame.

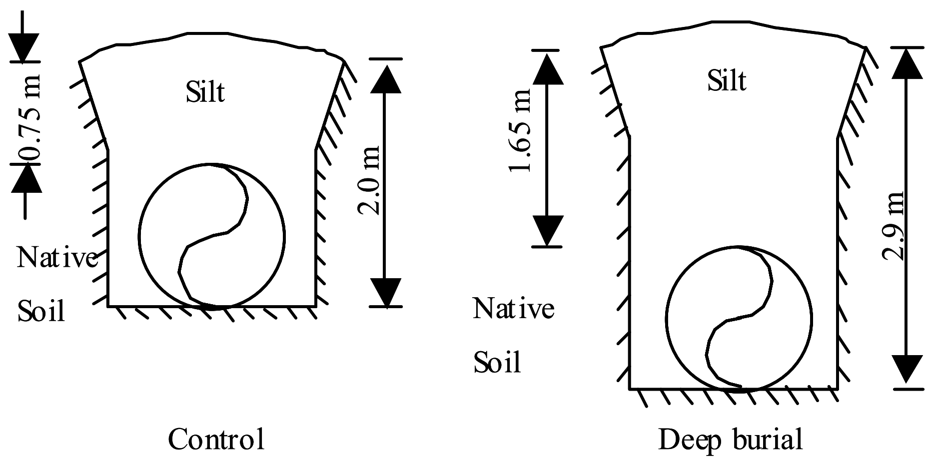

Figure 5: Calgary Ditch Configurations, after Carlson (1982)

Figure 6 shows the range of grain size distributions for the Calgary site and for the samples prepared for centrifuge modeling. The soil used in the modelling study for two tests was a 60%-40% mixture of Sil-Co-Sil silt and Speswhite Fine China kaolin clay. A third test 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 (2002).

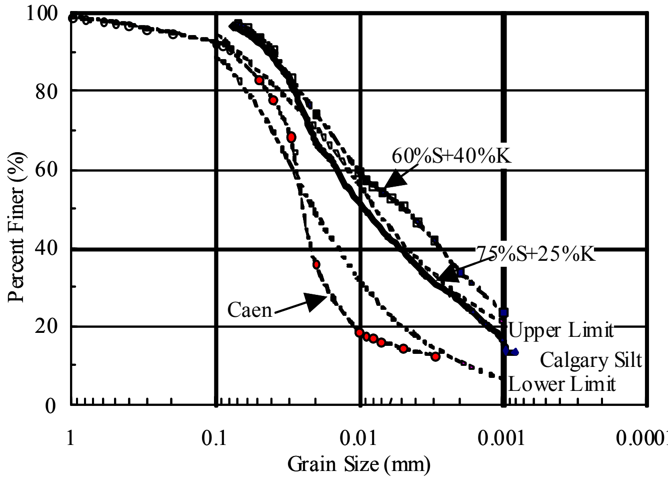

Figure 6: Grain size distributions for Caen, Calgary and model silts

Tests 1 and 3 modelled the control section tested at the Calgary test facility. Test 2 modelled the Calgary deep burial section. A similar thermal response to the prototype conditions was observed. The pipe temperatures are similar between the model and prototype, but the ambient air temperature at the soil surface was an area of model simplification which was modeled as a step change between summer and winter conditions.

Figure 7: Typical post-test pipe cross section Phillips et al (2001)

Figure 7 reveals the typical ice lens formations representative of all three sections. The ice lenses were generated outward from the pipe in a circumferential and radial pattern. The thickness of ice lenses increased with depth below the pipe. Growth of larger ice lenses with increasing distance from the pipe is consistent with the full-scale condition of a chilled pipeline subject to frost heave and that observed in laboratory tests, Konrad (1994). The radial ice formations shown in Figure 7 are thought to be post-test tension cracks that developed from stress relaxation of the soil when centrifuge operation ceased.

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, Figure 8. There is a good comparison between Tests 1 and 3 and the control section, and Test 2 with the deep burial section.

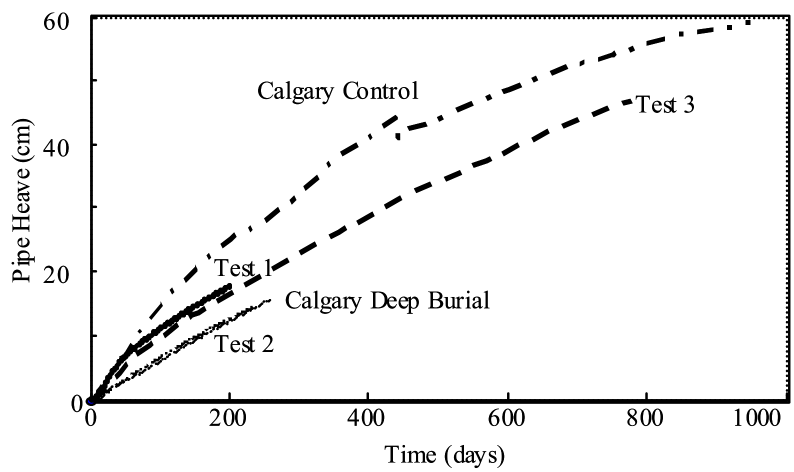

Figure 8: Pipeline heave comparison for Calgary and model tests

Konrad & Morgenstern (1984) show a similarly good comparison between their finite difference segregation potential, SP numerical analysis and the measured performance at the various full-scale test sections. These analyses used the SP value for Calgary silt presented in Figure 9, which also shows the values of SP reported from two different laboratories on samples of kaolin/silt mixes used for centrifuge testing. The SP values for 75%-25% silt-kaolin measured in Laboratory 1 are very similar to those measured at the Calgary test site, but nearly an order of magnitude lower than those measured in the same laboratory for 60%-40% silt-kaolin mixtures. The centrifuge results however do not show a significant sensitivity to these SP readings. SP values of the 75%-25% mixture measured at a second laboratory were significantly lower than those measured at laboratory 1. This suggests that certain difficulties exist in the measurement of SP values in the laboratory, and that the tests are sensitive to preparation procedures and testing techniques.

Figure 10 shows the rate of frost heave plotted against pressure acting on the freezing front for the Calgary test site and for the centrifuge modeling 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^{o} 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.

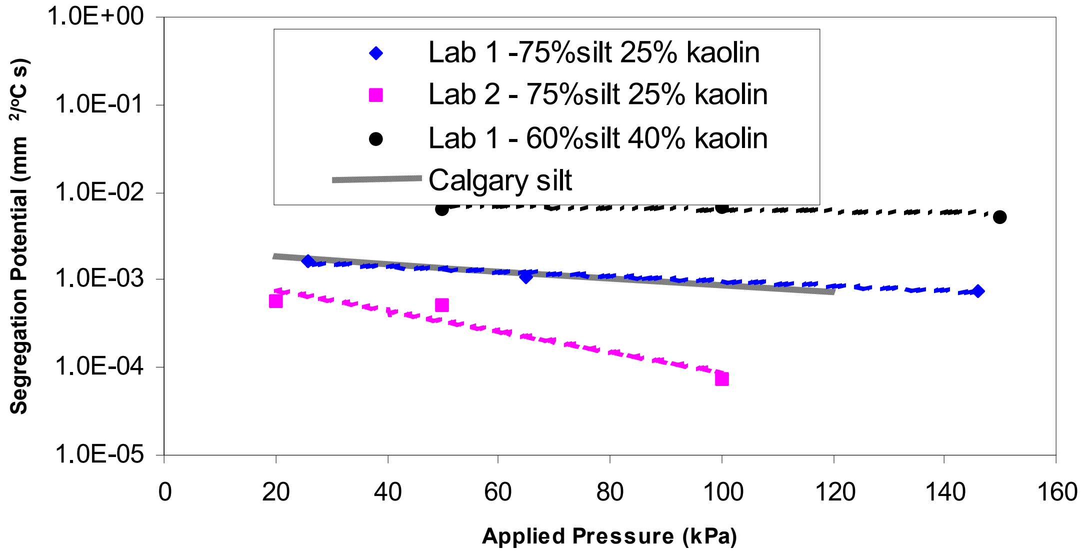

Figure 9: Segregation potential comparison

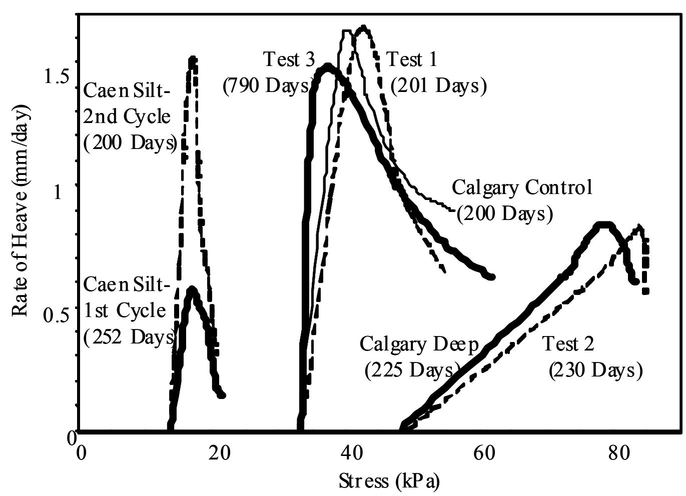

Figure 10: Heave rate with pressure for Caen, Calgary and model tests

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 modeling.

A preliminary centrifuge test of the restrained pipe section at the Calgary Frost Heave Test Facility was presented by C-CORE (2001). The model appeared to have yielded the anticipated thermal and heave behaviour. Comparison of pipe heave displacements and restraint loads between the prototype and the model at full-scale are given in Table 3 for two different time intervals during the test. The thermal and heave response of the model match the prototype. The actual heave measured was very similar for the two pipelines. The magnitude of frost heave forces experienced in the model, at prototype scale, are much greater than the actual prototype. The loads registered at the prototype field-test were under a constant loading restraint and not a zero displacement restraint like the centrifuge model. The constraint on a freezing front has a major influence on the heave force developed. The relative rapidity of the centrifuge test will also have prevented any stress relaxation due to creep.

Table 3: Load and displacement model to prototype comparison

	Freeze time (days)	Pipe heave (cm)	Total load (MN)	Load per unit length (kN/m)
Model	86	5.65	4.4	213
Calgary Prototype	86	4	0.55	45.1
Model	135	7.22	6.0	290.4
Calgary Prototype	135	8	1.81	148.4

4 FUTURE APPLICABILITY TO PIPE FROST HEAVE

Centrifuge modeling linked with simple analytical techniques may be used for efficient design of pipelines for the effects of frost heave.

Emphasis should be placed on demonstrating to the engineering community the repeatability of centrifuge model test data and the validation of these data. This validation should include modelling of models tests of the effects of chilled buried pipes, which have not been conducted to date. Comparisons should also be made to accepted numerical models to further identify the advantage and limitations of both modelling idealizations.

All frost heave pipe centrifuge tests to date have used an effectively rigid pipe section. Centrifuge model tests of flexible pipes have been beneficial in assessing the flexural pipe response to geotechnical loads in other applications, such as differential ground settlement, Hachiya et al (2002). Similar three-dimensional modelling of pipe-soil interaction effects such as across the boundary between frozen and unfrozen soils could be examined. Tests of this nature are planned for later in 2004 at C-CORE.

A semi-empirical design method is emerging, from current centrifuge model tests, that is based on actual heave measurements of pipelines. A range of frost susceptible soils with variable water contents has been tested. A relationship has been developed between rate of heave and pressure on the freezing front. The pressure on the freezing front reflects the initial burial depth and the penetration of the freezing front with time. A predictive semi-empirical model requires a geothermal analysis (several reliable analytical models are available) coupled with a suite of benchmark design curves from the centrifuge test. The centrifuge model test program can be expanded through a parametric study to include, for example, consideration of different pipe geometries, burial configurations, soil types, and geothermal and hydro geological conditions.

A possible design methodology that establishes risk and reliability that could be refined over the next couple of years, is set out below:

- Establish a suite of frost heave design curves for a range of frost susceptible soils relating heave rate to pressure on the freezing front from centrifuge model tests of generic site conditions. These can be obtained from a limited number of centrifuge tests as described above.
- For each terrain unit along the proposed route, estimate the frequency and length of unfrozen soils.
- Establish engineering design criteria for specified limit states through empirical investigations, analytical studies and numerical modeling.
- Assess the system reliability for each limit state. Establish target safety levels for acceptable or tolerable risk. Based on the reliability targets, define failure consequences and conduct the risk analysis that would ensure the established target safety level is achieved.
- Based on the risk-based approach, establish depth of burial for each section, spread or terrain unit.

For critical areas, analyze predicted frost heave at frozen/unfrozen boundaries and frost susceptible/non frost susceptible boundaries and maximum heave in unfrozen sections in relation to established strain criteria. Critical areas along the pipeline route may include the location of changes in terrain, pipe bends, slope areas or approaches to compressor stations. This analysis may include site specific centrifuge model tests. Such tests can also assist in identifying mitigation activities that may include seasonal cyclic operation. Centrifuge testing may also have a role during the operational phase of the pipeline, as unexpected site conditions and pipe response are revealed. Testing may help to identify the cause of this response and provide insight into remediation or mitigative measures.

The combined approach of using centrifuge modeling, numerical analysis and structuiral limit state design methods would provide a cost effective method that could address a range of conditions to define the frost heave behaviour of a pipeline.

5 DESIGN, ENVIRONMENTAL, SAFETY & SECURITY ISSUES

The use of centrifuge testing to date has focused on two areas; (1) establishing that centrifuge testing as a valid technology to use for modeling of ground freezing behaviour, and (2) demonstrating that centrifuge testing can be used to model complex boundary and operating conditions that are not easily analysed using existing tools. The results of centrifuge tests to date suggest that it may be suitable for use as a design tool and also to investigate the effects of various operational strategies.

Following the initial demonstration tests, the use of centrifuge testing to investigate the specific issues relating to pipeline design and operation in northern regions has been performed at C-CORE under contact to PRCI and is therefore proprietary. As such, specific details cannot be discussed, although general comments can be made relating to how these test results could be used for pipeline projects.

A number of tests have been performed that provide insight into the behaviour of pipelines as a result of growth of a frost bulb due to transportation of chilled gas. Some of these observations are not included in current analytical models and highlight the benefits of physical testing. Tests suggest, for example, that certain soils can undergo consolidation as pressure is applied due to frost heave. The pressure generated at the freezing front as ice lenses are generated may induce consolidation of the underlying unfrozen soil, offsetting frost heave displacement and resulting in much reduced pipeline movement.

Similarly, varying the gas temperature between above and below freezing temperatures results in a complicated series of frozen and unfrozen annuli, which may cause numerical instability when analysed. At the very least, an understanding of the complex heat transfer conditions at each of the frozen / unfrozen boundaries is difficult to obtain analytically. The results of centrifuge tests that model this behaviour may be the most flexible method of quantifying such effects.

The analysis of other issues with complex boundary effects would also be suitable for modeling in the centrifuge. Examples could include the effects of soil surface temperature, thawing slope stability, river crossings or effects of surface cover.

In addition to providing direct observation of complex behaviour as described above, the results of centrifuge tests can be used to calibrate numerical analysis, allowing capabilities of these tools to be developed and enhanced. By carefully controlling boundary and test operating conditions, direct comparisons with analytical models can be obtained with minimum extrapolation of results.

Evaluation of environmental, safety or security issues may be better achieved using other methods, although specific geotechnical processes such as contaminant transport have been modeled in the centrifuge. The results of centrifuge tests can be used as input into various risk models when considering safety and security issues.

6 CONCLUSION

Over the past three decades, centrifuge modeling has become a widely accepted tool for the prediction of the behavior of soil-structure systems, as it provides a cost effective and quick method to analyse the behavior of geotechnical systems, especially in areas in which full scale testing is difficult or impossible to achieve. Centrifuge modeling, because of this reduced scaling, accelerated time frame for controlled testing and cost effectiveness provides a unique opportunity for use in the prediction of frost heave and the design development for arctic pipelines

A centrifuge model test is an independent physical event. It will not provide a perfect simulation of the prototype conditions under consideration. However, the engineering insight provided by such tests can be extremely valuable, especially with an appreciation of the modeling issues, which could distort the results. For frost heave of arctic pipelines, there are many coupled factors controlling the system response, such as geothermal conditions, hydrogeological conditions, confining stress variation, soil stress-strain behaviour, heat transfer, and pore water migration. Most of these factors are reasonably modelled in a centrifuge test.

There are frost heave related modelling issues to be considered, including the grain size of ice generated in a centrifuge, the frozen fringe thickness and the effects of creep. These considerations need to be put into perspective through further research.

A method to validate centrifuge model test data is to conduct 'modelling of models' tests. If the scaled responses of the two model tests at different scales are similar, then confidence is increased that these physical simulations are representative (Differences in behaviour between the two scales assist in separating the effects of different processes). Modelling of models of one dimensional frost heave over a wide range of model scales has shown that factors such as frost heave, frost penetration and heave rate do appear to scale correctly in a centrifuge model test. These models also showed good repeatability of results, such as freeze and thaw fringe, free frost heave and thaw settlement and soil displacement under different loads.

This modelling of models technique should be used to validate pipe response to frost heave, coupled with tests to demonstrate repeatability of results.

Comparisons made between centrifuge model results and those from full-scale pipeline frost heave testing undertaken at the Calgary test site, Clark & Phillips (2003), revealed similar behaviour patterns with respect to heave displacements and time. A similar thermal response to the prototype conditions was also observed. The substantial reduction of heave rate due to increased pressure on the freezing front as the frost bulb grows was replicated. The circumferential ice lenses generated outward from the model pipe increased in thickness with increasing distance from the pipe, which is consistent with the full-scale condition of a chilled pipeline subject to frost heave and that observed in laboratory tests.

There are currently no publicly available suitable numerical model results and no operating chilled pipelines in existence against which to extend this comparison. The verification of the results of centrifuge modeling has exactly the same constraints as analytical, empirical or semi-empirical methods. That is it requires full-scale behavior to which it can be compared.

A semi-empirical design method is emerging, from current centrifuge model tests, which includes a relationship between rate of heave and pressure on the freezing front. The centrifuge model test program should be expanded through a parametric study to include, for example, considerations of different pipe geometries, burial configurations, soil types, and geothermal and hydro geological conditions. The program can also evaluate heave mitigation strategies and pipe soil interaction through, for example, discontinuous permafrost.

7 GLOSSARY OF TERMS RELATING TO CENTRIFUGE TESTING

Some of the terminology used in this report relating to centrifuge testing has been included within this glossary to aid readers who may be unfamiliar with this technology:

Geotechnical Centrifuge – Equipment designed for testing scale models of geotechnical processes under enhanced inertial acceleration field. Operated by spinning the test package about an axis such that additional 'gravitational' acceleration acts radially outwards.

Test Package – The module containing soil, structure and instrumentation that undergoes testing in the centrifuge.

Centrifugal Acceleration – acceleration applied to the test package as it spins at the end of the centrifuge arm, as a function of the radius to the package and rotational velocity during operation.

Centrifuge Flight – The process of spinning up, testing and spinning down the centrifuge equipment.

Scaling Laws – laws that describe the scale effects of model testing in the centrifuge. Developed using a combination of dimensional analysis, theory and empirical physical relationships.

Prototype Scale – Consideration at full-scale the behaviour of the structure or process being modeled.

Model Scale - Properties describing the model behaviour without scale factors being applied.

Modeling of Models – the testing of models over a range of scales to establish the scaling laws relating to the process being modeled.

Stress Similitude – The application of identical soil stress states in prototype and homologous points within the model.

In-flight Consolidation – the process of establishing equilibrium of the soil package in the centrifuge prior to performing the test. The application of enhanced gravity and associated stress fields to a fine-grained saturated soil usually results in consolidation, which must be substantially complete prior to starting the testing process.

8 REFERENCES

See BIBLIOGRAPHY for additional references.

Barrette PD, Phillips R, Clark JI, Crocker G & Jones SJ (1999)
Flexural behaviour of model sea ice in a centrifuge. ASCE Jnl Cold Regions Engineering, Vol 13, No 3, pp122-138.

Black, PB (1985)
The RIGIDICE model of frost heave and its input functions. Ph.D. Thesis, Cornell University.

Carlson, E.L., Ellwood, J., Nixon, J. & Slusarchuk, W. (1982) “Field Test Results of Operating a Chilled Buried Pipeline in Unfrozen Ground” Proceedings, 4th Canadian Permafrost Conference, Calgary, pp. 475-480.

Dallimore SR & Crawford H (1985)
Experimental observations of differential heaving and thaw settlement around a chilled pipeline. In Pipelines and Frost Heave, Proc Seminar, Eds Dallimore & Williams.Centre de Geomorphologie, Caen, France April 1984.

Guymon GL, Berg R L & Hromadka TV (1993)
Mathematical model of frost heave and thaw settlement in pavements. CRREL report bno 93-2. Cold Regions Research and Engineering Laboratory, Hanover, NH, USA.

Hachiya M, Inoue Y, Tohda J, Takatsuka Y & Takagi R (2002)
Response of buried pipelines to differential ground movement. pp. 911-916 In Physical Modelling in Geotechnics: ICPMG ’02. Eds. Phillips, Guo & Popescu.

Konrad JM (1994)
Frost heave in soil: concepts and engineering. 16th Canadian Geotechnical Colloquium. Canadian Geotechnical Journal, Vol 31, pp223-245.

Konrad JM & Morgenstern NR (1980)
A mechanistic theory of ice lens formation in fine grained soils. Canadian Geotechnical Journal, Vol 17, pp473-486.

Konrad JM & Morgenstern NR (1984)
Frost prediction of chilled pipelines buried in unfrozen soils. Canadian Geotechnical Journal, Vol 21, p100-115.

Ladanyi B and Shen M (1993)
Freezing pressure development on a buried chilled pipeline. Proc 2nd Int Symp on Frost in Geotechnical Engineering, Anchorage, USA, pp23-33.

Murff, JD (1996).

The geotechnical centrifuge in offshore engineering. OTRC Honors Lecturer, Proc. Offshore Technology Conference, Houston, Texas.

Palmer AC, White DJ, Baumgard AJ, Bolton MD, Barefoot AJ, Finch M, Powell T, Faranski AS & Baldry JAS (2003)
Uplift resistance of buried submarine pipelines: comparison between centrifuge modelling and full scale tests. Géotechnique 53 10:887-893.

Penner E & Ueda T (1977)
The dependence of frost heaving on load application. Int Symp on Frost Action in Soils. Lulea, Sweden, Vol 1, pp92-101.

Savidou C (1988)
Centrifuge modeling of heat transfer in soil. Centrifuge '88, pp 583-591.

Schofield AN (1980).
Cambridge geotechnical centrifuge operations. Geotechnique 20, p227-268.

Selvaduri APS & Shinde SB (1993)
Frost heave mechanics of buried pipelines. ASCE Jnl of Geotechnical Engineering, 119, pp1929-1951.

Slusarchuk, W, Clark, JI, Nixon, J, Morgenstern, N & Gaskin, P (1978)
Field Test Results of a Chilled Pipeline Buried in Unfrozen Ground. Proceedings 3rd Canadian Permafrost Conference, Edmonton, pp. 877-883.

Taylor, RN (Ed) (1995)
Geotechnical Centrifuge Technology. Blackie Academic & Professional.

9 BIBLIOGRAPHY
– Centrifuge modelling of frost heave & frozen soil

C-CORE (2001)
Centrifuge Modelling of Frost Heave on a Restrained Pipe- Final Report. 01-C11. Prepared in confidence for Geological Survey of Canada, May 2001.

Chen X, Pu J & Luo X (1999)
Centrifuge modeling tests of soil freezing heave. J of China Coal Society Vol 24, No 6. pp. 615-619 (in Chinese).

Chen X, Luo X , Pu J & Yin K(2000)
Centrifuge modeling of foundation frost heave and thaw settlement. Ground Freezing 2000 pp. 115-118.

Chen X, Pu J & Yin K (2002)
Validity of heat transfer in centrifugal modeling tests of soil foundation. pp. 309-312 In Physical Modelling in Geotechnics: ICPMG '02. Eds. Phillips, Guo & Popescu.

Chen X, Schofield AN & Smith CC (1993a)
Preliminary tests of heave and settlement of soils undergoing one cycle of freeze-thaw in a close system on a small centrifuge. Proc 6th Int Conf Permafrost Vol 2. pp. 1070-1072.

Chen, XS, Schofield, AN & Smith, CC (1994)
Centrifuge modelling of frost heave of pipelines. pp.91-96, International Symposium on Ground Freezing, 7th, Nancy, France, Oct. 24-28, 1994. Proceedings. Ground Freezing 94. Edited by M. Frémond: Rotterdam, A.A. Balkema, 1994; 10 refs.

Chen X, Schofield AN & Smith CC (1993b)
Frost heave of pipelines: Centrifuge tests and 1G tests. CUED Report D-soils/TR262.

Clark JI & Phillips R (2003)
Centrifuge modelling of frost heave of arctic gas pipelines. In Permafrost, ICOP 2003, Eds. Phillips, Springman & Arenson. Proc .8th Intl Permafrost Conference, Vol 1, p151-156.

Davies MCR, Hamza O & Harris C (2003)
Physical modelling of permafrost warming in rock slopes. In Permafrost, ICOP 2003, Eds. Phillips, Springman & Arenson. Proc .8th Intl Permafrost Conference, Vol 1, p169-174.

Goodings DJ & Straub N (1998)
Boulder jacking through seasonal freezing and thawing. Centrifuge 98, Tokyo, Japan , Vol 1 pp. 869-874 Editor : Kimura T. Balkema, Rotterdam, Netherlands .

Han SJ & Goodings D J (2002)
Centrifuge Modeling of freezing behaviour of clay. pp. 291-296 In Physical Modelling in Geotechnics: ICPMG '02. Eds. Phillips, Guo & Popescu.

Han SJ, & DJ Goodings (forthcoming)
A Simple Model for Prediction of Frost Heave in Clay. Submitted to ASCE Geotechnical Journal.

Harris C & Smith JS (2003)
Modelling gelifluction: the significance of frost heave and slope gradient. In Permafrost, ICOP 2003, Eds. Phillips, Springman & Arenson. Proc .8th Intl Permafrost Conference, Vol 1, p355-360.

Harris C, Davies MCR & Rea B (2002)

Centrifuge modelling of slope processes in thawing ice rich soils. pp297-302 In Physical Modelling in Geotechnics: ICPMG '02. Eds. Phillips, Guo & Popescu.

Harris C, Rea B, & Davies MCR (2001)
Scaled physical modelling of mass movement processes on thawing slopes. Permafrost and Periglacial Processes, Vol 12, 1, pp. 125-135, John Wiley & Sons Ltd, Chichester, United Kingdom.

Jessberger HL, Diekmann N, Jordan P, Makowski E, Guttler U, Ebel W, Bassler KH (1983)
Partly Frozen Artificial Sand Islands As Foundation For Exploration Platforms In Artic Seas. VIII European Conference on Soil Mechanics & Foundation Engineering, Helsinki, Finland, Vol 2 pp. 913-922.

Ketcham SA (1990)
Applications of centrifuge testing to cold regions geotechnical studies. US CRREL Report.

Ketcham S.A (1991).
Centrifuge applications in cold regions research. Large centrifuge: a critical army capability for the future Part III Miscellaneous paper GL 91-12 Rh Ledbetter, ed. US Army Corp of Engineerins Waterways Experiment Station, Vicksburg, Miss. 34-35.

Ketcham SA & Black PB (1995)
Initial results from small-scale frost heave experiments in a centrifuge. US CRREL Report 95-9.

Ketcham S, Black P & Pettro R (1997)
Frost heave loading of constrained footing by centrifuge modeling. J of Geotech Engineering ASCE 123(2) pp. 874-881.

Miller, RD (1978)
Frost heaving in non-colloidal soils. Proceedings of the Third International Conference on Permafrost, vol. 1, p. 708–713.

Miller, RD (1990)
Scaling of freezing phenomena in soils. In Chapter 1, Scaling in Soil Physics: Principles and Applications (D. Hillel and D.E. Elrick, Ed.). Madison, Wisconsin: Soil Science Society of America.

Morgan V, Clark JI, Hawlader B & Zhou J (2004)
Prediction of long-term frost heave of chilled gas pipelines by centrifuge modeling. Paper IPC04-0139 submitted to Proceedings of IPC 2004 International Pipeline Conference, October 4 - 8, 2004, Calgary, Alberta, Canada.

Palmer AC, Schofield AN & Vinson TS (1985)
Centrifuge modeling of underwater permafrost and sea ice. Proc 4th Int OMAE Vol 2, pp 65-69.

Phillips R, Clark JI & Hanke R (2001)
Centrifuge modeling of pipeline frost heave. Proc 54th Can Geotech Conf, Calgary.

Phillips R, Clark JI & Hanke R (2002)
Pipeline Frost Heave Modeling. pp. 313-318 In Physical Modelling in Geotechnics: ICPMG '02. Eds. Phillips, Guo & Popescu.

Pokrovsky, GI & Fyodorov IS (1969)
Centrifuge Model Testing in the Construction Industry. English translation from Russian by Building Research Establishment Library Translation Service.

Scott RF & Ting JM (1985)
Centrifuge modelling of frost heave phenomena: A feasibility study. Report submitted to the US Army Cold Regions Research and Engineering Laboratory.

Smith CC (1995)
Cold Regions Engineering in Geotechnical Centrifuge Technology. Taylor R N (ed) Glasgow, Chapman & Hall.

Smith CC (1991)
Thaw induced settlement of pipelines in centrifuge model tests. PhD Thesis, Cambridge University.

Yang D (1996)
Investigation of the Scaling law for centrifuge modeling of frost heave. PhD Thesis, University of Maryland.

Yang D & Goodings DJ (1998a)
Climatic Soil Freezing Modelled in a Centrifuge. ASCE Journal of Geotechnical Engineering, Volume 124, No. 12, December, pp1186-1194.

Yang D & Goodings DJ (1998b)
Predicting Frost Heave Using the FROST Numerical Model with Centrifuge Physical Models. ASCE Journal of Cold Regions Engineering, Volume 12, No. 2, June, pp. 64-83.

APPENDIX A – REVIEW OF CENTRIFUGE MODELLING OF FROST HEAVE

Dr Stuart Haigh
Cambridge University Engineering Dept
Trumpington St, Cambridge, CB2 1PZ, United Kingdom
skh20@eng.cam.ac.uk

1. Introduction

Geotechnical centrifuge modeling is a tool that has developed over the past seventy years for the investigation of the behavior of geotechnical structures. Although first proposed by Edouard Phillips in 1869, the first centrifuge tests were carried out in the former USSR by Pokrovskii & Fiodorov [1] in 1931. Over the past three decades, centrifuge modeling has become a widely accepted tool for the prediction of the behavior of soil-structure systems, as it provides a relatively cheap and quick method to analyse the behavior of geotechnical systems.

2. Principles

Small scale modeling of geotechnical processes is highly desirable, as it provides a cheaper, quicker and more controllable route to an understanding of geotechnical system behavior than full-scale testing. In order, however, for this small scale modeling to be worthwhile, the scaling of behavior from large to small scales needs to be understood.

Small-scale modeling in general interprets the behavior of a small, highly instrumented model to imply the behavior of a large prototype system under homologous circumstances.

As soil is a highly non-linear material, whose strength and stiffness are functions of stress level, it is almost impossible to scale the behavior of a model to that of the prototype unless the stress states at homologous points in the model and prototype are identical. As in a geotechnical structure such as a dam, all (or almost all) of the stresses acting on any soil element within the structure come from the self-weight of other soil or water elements, it is impossible at 1-g to replicate the stress field within the prototype in the model structure. If, however, a 1:N scale model constructed of the same materials as the prototype is tested at Ng within the enhanced gravity field of a geotechnical centrifuge it can be shown that the stresses and strains within the model are identical to those at homologous points within the prototype.

3. Scaling Laws

We have seen in the previous section that the stresses and strains in a 1:N scale model tested at Ng are the same in model and prototype structures. However, in order to extend the interpretation of centrifuge test data, scaling laws need to be derived for other parameters. Many of these scaling laws can be derived either from dimensional analysis or by evaluation of known relationships between parameters for which scaling laws have been derived. For example:

Suppose we want to calculate the scaling law for force for a 1:N scale model tested at Ng.

a) By dimensional analysis:

Force has dimensions of MLT^{-2}
Length has dimensions of L, and scales as 1/N
Acceleration has dimensions of LT^{-2} and scales as N
Density has dimensions of ML^{-3} and scales as 1
Thus from length and acceleration we can imply that time scales as 1/N
From length and density we can imply that mass scales as $1/N^3$
Therefore, force scales as $1/N^2$

b) From a known relationship

Weight = Density x Volume x Gravity
$1/N^2 = 1 \times 1/N^3 \times N$

By following this example, we can determine scaling laws for a wide variety of quantities, as summarized in Table 1. These scaling laws have been divided into those with scales chosen by the modeler, those with scales forced on us by our decision to use the same materials in the model as are present in the prototype and those which can be derived from combinations of other scaling laws.

Table 1: Scaling laws in centrifuge modeling (after Schofield [2])

	Quantity	Dimensions	Model / Prototype
Chosen scales	Length	L	1/N
	Acceleration	LT^{-2}	N
	Stress	$ML^{-1}T^{-2}$	1
	Strain	Dimensionless	1
Material scales	Density	ML^{-3}	1
	Permeability	LT^{-1}	1
	Particle size	L	1
Derived scales	Dynamic Velocity	LT^{-1}	1
	Seepage Velocity	LT^{-1}	N
	Dynamic Time	T	1/N
	Seepage Time	T	$1/N^2$
	Force	MLT^{-2}	$1/N^2$

It can be seen from the above table that inconsistencies occur between the scaling laws for quantities which are dimensionally similar such as the times taken for dynamic and seepage events to occur. These inconsistencies occur owing to the non-scaling of particle size and permeability from prototype to model. This can have important implications for models in which inertial loading is significant, as will be discussed in Section 4.4.

4. Similarity

In order for the prototype behavior to be properly scaled in the model, the features that must be achieved in the centrifuge tests are:

a) Geometric similarity
b) Water flow similarity
c) Thermal similarity
d) Dynamic similarity
e) Identical constitutive behavior

These will be dealt with in turn for a general centrifuge model.

4.1 Geometric similarity

Geometric similarity between model and prototype is always assumed in centrifuge modeling at the macro-scale. This implies that all components of the model, (e.g. soil depth and extent and foundation sizes), are scaled down by a factor N from prototype to model, as shown in Table 1. This similarity, however, does not exist at the micro-scale, as particle sizes are not usually scaled down from prototype to model. Scaling down of particles would significantly alter the constitutive behavior of the soil and is hence undesirable. Keeping identical particle sizes in model and prototype can, however, cause problems when either the size of items interacting with the soil, (such as pipes), becomes close to the size of soil grains, or when shear bands whose thicknesses are a function of particle size are present.

Both of these length scale conflicts have been quantified in the literature. Authors such as Ovesen [3] have studied the effect of the ratio of particle size to component size in boundary value problems such as bearing capacity and penetration resistance. In general it has been recommended that the ratio of component size to particle size should not fall below a value of 30 in order to avoid excessive errors.

Palmer *et al.* [4] carried out both full-scale 1-g tests and centrifuge tests looking at the uplift resistance of buried pipelines in order to quantity scale effects on shear band formation. They found that the displacement required to mobilize the full uplift resistance in a sand with D_{50} of 0.27 mm was approximately 2.5mm both at 1-g and at 10-g (unscaled). From this they surmised that localized shear zones are not properly scaled in the centrifuge, owing to non-scaling of particle size, and that this can have a significant impact on mobilization distances. While macro-scale constitutive relationships scale properly in the centrifuge, any localization of strains into shear bands will be governed by the scaling of particle size, rather than global dimensions, and hence may not scale properly in the centrifuge.

4.2 Water Flow Similarity

In order for similarity of behavior to be observed between model and prototype, the correct pore-fluid flow regime must exist within the model. This implies that the fluid pressure at homologous points in space and time must be identical.

Fluid flow in soils is governed by d'Arcy's Law:

$$v = -k\nabla h$$

In which v is the fluid velocity, k is the permeability of the soil and h is the pore-pressure head. It can be shown that in a geometrically similar model of 1:N scale at Ng, stresses and hence pore-pressures at homologous points are identical and thus, as the distances in the model are N times smaller than in the prototype, the gradients of pore-pressure head scale as N. Thus, as permeability is identical in model and prototype, flow velocity scales as N.

The time taken for the water to flow a certain distance in the model thus scales as $1/N^2$, as the velocity is N times higher in the model, and the distance traveled is N times lower.

Consolidation time also scales as $1/N^2$, as it is a seepage driven process. This can be shown by considering Terzaghi's 1-D consolidation equation:

$$\frac{\partial u}{\partial t} = \frac{k}{m_v \gamma_w} \frac{\partial^2 u}{\partial z^2}$$

where k is permeability, u is excess pore pressure, m_v is the coefficient of volume compressibility and γ_w is the unit weight of water. It can be seen that in the centrifuge model, k, m_v and γ_w are identical as they are material properties. It can also be seen that the excess pore-pressures must be the same in model and prototype for stress similarity to exist. As the dimension z is N times smaller in the model than in the prototype, $\partial^2 u/\partial z^2$ must be N^2 times larger in the model. The rate of change of pore pressure must hence also be N^2 times larger, so the time for consolidation to occur scales as $1/N^2$.

This scaling law holds provided that the soil is identical (not scaled) on a micro-scale between model and prototype, and hence that permeability is identical between model and prototype.

The scaling law on time of $1/N^2$ is one of the major advantages of centrifuge modeling over 1-g full-scale testing, as it means that the long-term behavior of geotechnical systems can be investigated in a reasonable timescale. For example, a model clay embankment tested at 100-g for 24 hours would simulate 30 years of prototype time.

The validity of these scaling laws for fluid flow have been demonstrated under certain sets of circumstances by Arulanandan *et al*. [5] and Celorie *et al*. [6].

4.3 Thermal Similarity

Thermal similarity implies that temperatures at homologous points in the model and prototype at equivalent times are identical. It is obviously simple to maintain the thermal boundary conditions of the model to be identical to those of the desired prototype, however the heat flow equations must be studied in order to check that there is no inconsistency between the time scaling laws for thermal and other processes. Heat conduction can be described by the equation:

$$C\frac{\partial\theta}{\partial t} = K\nabla^2\theta$$

in which C is specific heat capacity, K is the thermal conductivity and θ is the temperature.

For a geometrically similar model comprising the same soil as the prototype, C and K are identical in model and prototype. As the temperatures are identical at homologous points but the length scales as 1/N, the temperature gradients scale as N and $\nabla^2\theta$ scales as N^2. The rate of change of temperature thus scales as N^2, implying a time scale factor of $1/N^2$. It can be seen from the previous section that this time scale factor is identical to that for seepage processes and hence no inconsistency occurs in the simultaneous modeling of thermal and fluid flow processes. It can also be shown that heat flux (energy flow per unit area) will be N times greater in the model than in the prototype.

Thermal processes coupled with fluid flow in centrifuge models have been investigated by Savvidou [7 & 8] and by Booker & Savvidou [9].

4.4 Dynamic Similarity

Dynamic similarity implies that the scaling of forces is identical, regardless of the origin of these forces. Ketcham and Black [10] derived the following force scaling laws:

1) Self-weight force scales as $1/N^2$
2) Seepage force scales as $1/N^2$
3) Inertia force scales as 1 (if time is scaled as $1/N^2$)
4) Viscous force scales as 1 (if time is scaled as $1/N^2$)

Thus it can be seen that dynamic similarity is only achieved with a time scaling factor of $1/N^2$ if inertial and viscous forces are not important in the situation modeled. This implies that accelerations and fluid velocities within the model should be small.

If accelerations within the model are not small, as is the case in the modeling of earthquake effects, the inertial force conflict can be overcome by using a pore-fluid such as silicone oil of viscosity N times higher than that of water, (as in Haigh *et al.* [11]). This drops the permeability of the soil to the pore fluid by a factor N and hence drops seepage velocity. A time scale factor of 1/N can then be used with self-weight, seepage and inertial forces all scaling as $1/N^2$. The disadvantages of this approach are that consolidation now takes N times longer than when using water as a pore-fluid, lessening one of the advantages of centrifuge modeling, and that heat transfer processes are not slowed down and hence are incorrectly scaled.

4.5 Identical Constitutive Behavior

Identical constitutive behavior between model and prototype is usually assured by using the same soil in the model as is present in the prototype. This holds provided that there is no dependence of the constitutive behavior on either sample scale or strain rate.

Sample scale is important either where localization of strain occurs forming shear bands whose thickness is a function of particle size, as discussed in Section 4.1 or for brittle materials such as ceramics in which strength varies with the size of sample chosen owing to the presence of cracks within the material.

Rate effects on constitutive behavior include creep, in which strains accumulate over time allowing stress relaxation. This behavior will not necessarily be accelerated by the same factor N^2 as the model time and hence may not be correctly modeled.

5. Modeling of Models

If a case arises where the equations governing the model behavior are not well understood, the applicable scaling laws can be derived or checked using the technique of "modeling of models". This technique involves the testing of two or more models of the same prototype at differing g-levels and then using the relationship between the results of the two tests to determine the applicable scaling laws.

For example, suppose we wished to investigate the bearing capacity of a 10m diameter shallow foundation. This foundation could be modeled either as a 10cm diameter foundation tested at 100g or as a 20cm diameter foundation at 50g.

Once these two tests had been carried out, suppose that model A exhibited a foundation settlement of 1mm under a load of 20N, whereas model B showed a settlement of 2mm with a load of 80N. We know from our initial scaling laws on length that these two model settlements both correspond to 10cm of settlement at prototype scale, and hence both forces must also correspond to the same force at prototype scale. Thus if we assume that our scaling law is a power law:

$$F_{prototype} = F_A \times N_A^x = F_B \times N_B^x \Rightarrow x = \frac{\log(\frac{F_A}{F_B})}{\log(\frac{N_B}{N_A})}$$

Therefore in our example, the power x is log(20/80) / log(50/100) = 2. So the force scales as $1/N^2$. This technique can also allow us to verify that the scaling we have derived by other means is valid, as the results from two tests of identical prototypes at different scales should be identical within the experimental error when plotted at prototype scale.

6. Known Modeling Issues

There are several sources of error implicit in centrifuge modeling whose impact should be quantified when carrying out a centrifuge modeling program. These include:

g-field curvature:	As the g-field in a centrifuge is radial, the equipotentials at the model are not straight but curved, resulting in distortion of the stress field. This error is small when the model width is small relative to the centrifuge radius.
Variation of g with radius:	As centripetal acceleration is proportional to radius, the g-level in a model becomes progressively greater with depth through a soil layer. This error is small when the model is shallow relative to the centrifuge radius.
Particle size scaling:	As mentioned in Section 4.1, as particle sizes are not scaled down by N between prototype and model, any model in which shear bands are created may exhibit incorrect scaling of mobilization distances.
Time scaling laws:	If significant inertial or viscous forces are present in the model, the differing time scaling laws of inertial, viscous and seepage forces need to be considered.
Creep:	The scaling law on creep may be inconsistent with other scaling laws in the model.
Boundary effects:	Boundaries should be designed to minimize their effects on the model. They should be stiff enough to maintain K_0 stresses and smooth, in order to minimize their effects on the vertical stress state within the model. Boundaries should also be kept sufficiently far away from regions of interest to minimize their influence on failure mechanisms.

7. Frost Heave Theory

When ground surface temperatures or the temperatures of pipes passing through soils fall to below the freezing point of water, they will cause the soil at the interface to begin to freeze. As water expands by 9% on freezing, a certain amount of ground heave would be expected, however, migration of water into the freezing areas causes this problem to be much more severe.
In freezing soils, the pore water is in equilibrium with ice crystals forming within the soil pores. As the ice crystals grow they impart a stress on the soil skeleton surrounding the pore. When this stress becomes equal to the total stress acting on the soil at this location, (i.e. effective stress falls to zero) the soil skeleton is fractured and an ice lens is initiated. As the ice lens grows, water is removed from the pores to form ice, reducing the fluid pressure surrounding the lens. This causes further water to be drawn towards the lens due to the pore-pressure gradient set up. If the rate of

freezing of water at the ice lens, (governed by the outflow of heat), is matched by the inflow of water due to the pressure gradient, the ice lens will continue to grow. If the inflow of water is insufficient to match the rate of freezing, water within the soil pores surrounding the ice lens will begin to freeze in what is known as the “frozen fringe”, further reducing the soil permeability. If at any point within this frozen fringe effective stress falls to zero, a new ice lens will be initiated. As water is drawn into these ice lenses from elsewhere in the soil bed, a volumetric expansion takes place, resulting in frost heave. This heave can cause distortions of the ground surface if freezing is progressing downwards from the ground surface, or heaving of pipes if they are causing the soil surrounding them to freeze.

In order to determine how this problem will scale in the centrifuge, we must consider each of the principles of similarity discussed in Section 4. Geometric, thermal and fluid flow similarity can easily be satisfied for the initial soil configuration. Dynamic similarity will also be achieved with a time scale of $1/N^2$, as the fluid velocities and solid accelerations within the model are small. The constitutive behavior of the initial unfrozen soil can also be assumed to be identical to that of the prototype, as no significant strain localization has occurred prior to freezing.

As freezing progresses some issues begin to become relevant to the scaling. These issues can be divided into three areas:

1. Ice crystal formation
2. Ice creep & fracture
3. Uplift resistance mobilization

9.1 Ice Crystal Formation

As was mentioned in Section 4.1, two distinct scaling laws for length exist within the model, macro-scale lengths and displacements being scaled by 1/N, whereas micro-scale lengths, such as particle sizes, are unscaled. This may cause problems as ice crystals grow within the soil, as crystals may exist both as macro-scale ice lenses and at micro-scale within pores. It is also uncertain what the scaling law is for ice-crystal growth under increased gravity.

Experiments conducted by Langhorne & Robinson [12] and Lovell & Schofield [13] in the 1980s suggested that the grain size of sea ice is scaled as 1/N in the centrifuge, consistent with the macro length scale. Consideration of the Laplace surface tension equation:

$$p_1 - p_2 = 2\frac{\gamma_{12}}{r_{12}}$$

where p_1 and p_2 are the pressures of the two phases (ice and water), γ_{12} is the surface tension on the interface between phases and r_{12} is the mean radius of curvature of the interface, however, suggests that as the phase pressures and surface tension are equal in the model and prototype, that the mean radius of curvature should also scale as 1, i.e. in the same way as particle size.

For prototype behavior to be exhibited by the model, it is vital that the size of the ice lenses scales as 1/N as otherwise a non-realistic pattern of lenses will be observed. If one considers the behavior of the soil of the freezing fringe, however, any ice crystals within the pores of the soil in this zone will block pores and hence drop the permeability of the soil, limiting the flow of water into the lenses, and hence the extent of their growth. If the size of these crystals scales as 1/N, the crystals will be much smaller in relation to the pores than those in the prototype structure and hence one might expect the model to show larger than expected permeability through the frozen fringe and hence larger lens size. If, however, the ice crystals within the pores of the frozen fringe scale as 1, similarity on the micro-scale will be assured and hence permeability will be identical between model and prototype, consistent with the behavior in the rest of the model.

Little information is available on the scaling and importance of the size and rate of growth of ice crystals within voids and hence this is an aspect of the model behavior that should be quantified by modeling of models.

9.2 Ice Creep & Fracture

Ice is known to be susceptible to creep deformations under sustained loading. Van Steenis *et al.* [14] report the results of experiments on the creep of floating ice and derive a best-fit material law of:

$$\frac{d\varepsilon}{dt} = 2 \times 10^{-25} \sigma^{3.25}$$

where σ is the applied stress in Pascals and dε/dt is the creep rate per second. This would imply that as the stresses in the model and prototype are identical, the strain rates are also identical and hence the time should be identical in model and prototype. This is obviously in contradiction to the scaling factor on time of $1/N^2$ used for seepage and thermal behavior within the model.

Creep will be important in redistributing the stresses around the ice lens and will lessen the heave due to lens formation. Nixon [15] performed some numerical studies including the effects of frozen soil creep on the bending moments induced in a pipeline passing from stable to heaving soil. It was found that increasing the creep coefficient from zero to 6×10^{-9} kPa^{-3} yr^{-1} dropped the induced bending moments in the pipe at the interface between stable and heaving soil by approximately 25%.

Ice is also a brittle material, whose strength is primarily characterized by a fracture toughness, rather than by a yield stress. It was demonstrated by Palmer [16] that the scaling law for the behavior of materials that deform by fracture rather than yield depends on the ratio of the crack size present in the model to that in the prototype. If the crack size is identical in model and prototype, behavior is correctly modeled in a standard centrifuge test, however, if the crack size also decreases from prototype to model, the apparent strength of the material will be greater in the model by the square root of the crack size ratio. Palmer suggests that for brittle materials, 1:N scale models should be tested at $N^{3/2}$ to achieve identical constitutive behavior.

This is obviously impossible for tests such as those under consideration here where non-brittle materials are also present, but this relationship should be borne in mind when analyzing test results.

9.3 Uplift Resistance Mobilization

As discussed in Section 4.1, work carried out by Palmer *et al.* [4] investigated the effect of model scale on the uplift resistance of buried pipelines. Whilst this work did not include freezing ground, the results are still worthy of consideration here. Localized uplift of freezing ground will be governed by equilibrium of the uplift forces due to the formation of ice lenses and the resisting forces due to the self-weight and strength of the overlying soil. Palmer *et al.* showed that whilst the resistance provided against uplift of a pipeline in the centrifuge at 10-g was similar to that found at 1-g, the response in the centrifuge was less stiff, with a similar amount of un-scaled displacement being required to mobilize the full resistance at 10-g as at 1-g.

This result may influence localized frost heave, but as the particle size of frost-heave susceptible soils is in general small, the movements required in order to mobilize full resistance are likely to be small in relation to the soil heave. This should minimize the influence of this error on the results.

8. Previous work on Frost Heave

Previous centrifuge studies have been carried out on frost heave, some of which involved modeling of models in order to clarify the applicable scaling laws.

8.1 Yang & Goodings [17]

Yang & Goodings [17] carried out a series of 11 centrifuge tests on level beds of silt and silty clay, chilled on the surface with cold air from a vortex tube. The models were tested at three g-levels, 20, 30 & 45-g, with a scale factor of $1/N^2$ being used for time. It was shown that for models of identical prototypes tested at different g-levels, the ultimate heave deviated by a maximum of 13% from the mean and the depth of frost penetration by a maximum of 9%. Repeatability tests were also carried out and showed a coefficient of variation of around 10% for identical models tested at the same g-level, similar to that found from the modeling of models tests. No pattern of heave with g-level was observed, leading to the conclusion that the scatter was due to experimental error and was not a function of g-level.

Post-test, the models were sectioned in order to investigate the size of ice lenses formed in the tests. It was found that the lenses formed showed a trend of decreasing size and decreasing spacing with increasing g-level. Insufficient data is presented to allow confirmation of the scaling law on ice lens size from this paper.

This work leads to the conclusion that uniform 1-D frost heave can be scaled in the centrifuge.

8.2 Ketcham at al. [18]

Ketcham *et al*. [18] performed three centrifuge tests at 67, 80 and 100-g in order to investigate the uplift forces on a constrained footing on freezing silt. The test data shows reasonable agreement on the depth of frost penetration, free-field heave and peak uplift force. The time taken to achieve uplift from the beginning of freezing and the shape of the uplift force-time curves, however, show some marked differences. The time to achieve uplift appears to correlate more closely with model time than with the prototype time, (scaled as $1/N^2$), and the uplift force shows considerably more post-peak softening in lower g-level models than in the 100-g model. This suggests that the frozen soil is creeping allowing stress relaxation. If the creep is occurring with a time scale factor of 1, as suggested in Section 7.2, this fits with the data presented, as the lower g centrifuge tests occur over a longer model time, allowing more creep to occur.

It should be noted that the temperatures of the top and bottom interfaces of the soil layer were not logged during the experiment, the temperatures plotted being the values that the temperature controllers were attempting to achieve. It is not hence known how well the desired temperature profiles were followed and whether this varied with g-level due to the increased heat flux in higher g models.

It should also be noted that as the same reaction frame system was used for the three tests, the prototype vertical stiffness of the foundation system was greater at 100g than at the lower g-levels. This may have influenced the results.

Sections were taken of the models post-test in order to examine the size and distribution of ice lenses. It was concluded that the ice lens pattern in the samples was not geometrically similar in the three tests. In the 100g test, a 3mm thick zone of vertically biased lenses was observed which was progressively less thick in the lower g models. Above this zone horizontally biased lenses were present in the lower g models, which were not visible in the 100-g test.

The results of this work lead to some skepticism of the scaling behavior of frost heave, though the sparseness of instrumentation and the lack of repeated tests makes it impossible to draw robust conclusions about the fundamental scaling behavior of frost heave in the centrifuge.

8.3 Phillips et al. *[19]*

Phillips *et al*. [19] present the results of two preliminary demonstration centrifuge tests on frost-heave of buried chilled pipelines and compare the scaled results of these tests with those observed at full-scale in tests conducted by the University of Calgary in 1973-74 (Slusarchuk *et al*. [20]). The scaled results for the first 200 days of prototype operation show good comparison between 30-g and 1-g tests, with a maximum variation of about 20% between centrifuge and 1-g models. Ice lenses were observed by post-test excavation and were seen both circumferentially and radially. It is surmised by the authors that the radial lenses are the result of post-test stress relaxation, whereas the circumferential lenses were formed during the test and caused the uplift of the pipe. The ice lenses were seen to become larger with increasing distance from the pipe, consistent with the work of Konrad [21] who suggests that as the freezing front propagates outwards from the pipe, its rate of growth falls, allowing more water to be drawn in to the developing lenses which hence achieve a greater size.

This work suggests that results representative of those of full-scale experiments can be achieved when modeling frost heave in the centrifuge. Further experiments including modeling of models and repeated tests would give greater confidence in the reliability of these procedures.

9. Conclusions

Centrifuge modeling is a valuable tool for the prediction of the behavior of geotechnical structures, especially in areas in which full scale testing is difficult or impossible to achieve. The technique allows the prototype behavior of geotechnical systems to be implied from the behavior of models in which the stress state is made identical by the enhanced gravity field of a centrifuge. Scaling laws for many geotechnical parameters have been derived and discussed, the most important of which is the $1/N^2$ scaling law for time, which implies that the short-term behavior of a model can predict the long-term behavior of the prototype system.

It has been shown over the last thirty years that when carried out with care and an appreciation of the modeling issues which could distort the results, centrifuge modeling can accurately predict the behavior of full-scale geotechnical systems and can give an important input into the design process.

The theory and previous work conducted on the centrifuge modeling of frost-heave suggest that this is an area with considerable promise, good correlation having been seen between full-scale and centrifuge experiments, (Phillips *et al.* [19]). The scaling of this phenomenon is however not completely understood, with several complex issues including creep and ice crystal growth being not fully resolved. The results of centrifuge tests on the frost-heave of pipelines could give a very valuable insight into this behavior and be developed into a useful design tool, but in order to achieve confidence in the results a validation exercise involving modeling of models and repeated tests should be carried out.

10. References

1. Pokrovskii G.I. & Fiodorov I.S. (1936) *Studies of soil pressures and deformations by means of a centrifuge.* Proc. 1st Int. Conf. Soil Mech. & Foundation Eng., Vol.1, p.70

2. Schofield A.N. (1980) *Cambridge geotechnical centrifuge operation.* Géotechnique **30** 3:227-268

3. Ovesen N.K. (1979) *The scaling law relationship - Panel Discussion*. Proc. 7th European Conference on Soil Mechanics and Foundation Engineering Vol. 4 319-323

4. Palmer A.C., White D.J., Baumgard A.J., Bolton M.D., Barefoot A.J., Finch M., Powell T., Faranski A.S. & Baldry J.A.S. (2003) *Uplift resistance of buried submarine pipelines: comparison between centrifuge modelling and full scale tests.* Géotechnique **53** 10:887-893

5. Arulanandan K., Thompson P.Y., Kutter B.L., Meegods, N.J., Muraleetharan, K.K. & Yogachandran C. (1988) *Centrifuge modeling of transport processes for pollutants in soils.* ASCE Journal of Geotechnical Engineering **114** 2:185-205

6. Celorie J.A., Vinson T.S., Woods S.L. & Istok J.D. (1989) *Modeling solute transport by centrifugation.* ASCE Journal of Environmental Engineering **115** 3:73-84

7. Savvidou C. (1984) *Heat transfer and consolidation in saturated soils.* PhD thesis, Cambridge University, UK.

8. Savvidou C. (1988) *Centrifuge modeling of heat transfer in soil.* Proc. Int. Conference Geotechnical Centrifuge Modeling, 583-591

9. Booker J.R. & Savvidou C. (1985) *Consolidation around a point heat source.* Int. Journal Numerical and Analytical Methods in Geomechanics **9** 173-184

10. Ketcham S.A. & Black P.B. (1995) *Initial results from small-scale frost heave experiments in a centrifuge.* US Army Cold Regions Research and Engineering Lab Report 95-9

11. Haigh S.K., Madabhushi S.P.G., Soga K., Taji Y. & Shamoto Y. (2000) *Lateral spreading during centrifuge model earthquakes*. Proc. International Conference GeoEng2000

12. Langhorne & Robinson (1983) *Effects of acceleration on sea ice growth*. Nature **305** 695-698

13. Lovell & Schofield *Centrifugal modeling of sea ice*. Proc. 1st Int. Conf. Ice Technology. 105-113

14. Van Steenis K., Hicks F.E., Hrudey T.M. & Beltaos S. (2002) *Modeling creep deformation in floating ice.* Canadian Journal of Civil Engineering **30** 28-41

15. Nixon J.F. (1994) *Role of heave pressure dependency and soil creep in stress analysis for pipeline frost heave.* Proc. 7th Int. Cold Regions Engineering Specialty Conference. 397-412

16. Palmer A.C. (1991) *Centrifuge modeling of ice and brittle materials.* Canadian Geotechnical Journal **28** 896-898

17. Yang D. & Goodings, D.J. (1998) *Climatic soil freezing modeled in centrifuge.* ASCE Journal of Geotechnical and Geoenvironmental Engineering **124** 12:1186-1194

18. Ketcham S.A., Black, P.B. & Pretto R (1997) *Frost heave loading of constrained footing by centrifuge modeling.* ASCE Journal of Geotechnical and Geoenvironmental Engineering **123** 9:874-880

19. Phillips R., Clark, J.I. & Hanke, R. (2002) *Pipeline frost heave modeling.* Proc. Int. Conf. On Physical Modeling in Geotechnics, St John's, NL. 313-318

20. Slusarchuk, W., Clark, J.I., Nixon, J., Morganstern, N. & Gaskin, P. (1978) *Field test results of a chilled pipeline buried in unfrozen ground.* Proc. 3rd Canadian Permafrost Conf., Edmonton. 877-883

21. Konrad, J-M (1994) *16th Canadian Geotechnical Colloquium: Frost heave in soils: Concepts and Engineering.* Canadian Geotechnical Journal **31** 2:223-245