A Study of Frost Heave-related Exposure Risk to Abandoned Transmission Pipelines in Cropland Areas of Southern Canada
Stage 1 (Literature Search and Numerical Modeling)
Volume 1 (Technical Report)

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Sign-off Sheet

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A STUDY OF FROST HEAVE-RELATED EXPOSURE RISK TO ABANDONED TRANSMISSION PIPELINES IN CROPLAND AREAS OF SOUTHERN CANADA
STAGE 1 (LITERATURE SEARCH AND NUMERICAL MODELING)
VOLUME 1 (TECHNICAL REPORT)

Forward to the Report by PARSC

Abstract

Pipeline abandonment refers to the permanent removal from service of a pipeline. It is not a frequent occurrence in Canada, but it is a subject that requires research to fully understand life cycle implications. Frost heave is a mechanism that could cause exposure of abandoned pipelines. This study was commissioned by PARSC (see PARSC background below) to understand the mechanism that could cause heaving of abandoned transmission pipelines with a focus on agricultural lands across Canada. This report presents the results of Stage 1 - Literature Search and Numerical Modeling.

A total of six literature searches were carried out, and over 450 different references were cited. The core literature search was a review and critical analysis of existing models/concepts of frost heaving in soils. The other searches were carried out on issues pertinent to this study and required to support numerical model development: frost penetration depth in soils, pipeline depth, soil structure and strength of frozen soils, water and wind erosion within transmission pipeline rights-of-way, and an update of the literature review on frost heaving conducted by Det Norske Veritas (DNV) in 2010. The literature searches confirmed that the conclusion drawn by DNV in 2010 remains true (i.e., there is no published information on the risk of abandoned pipeline exposure attributable to frost heave). A review of the broader literature on the frost heave process does, however, suggest that frost heave could pose an exposure risk to abandoned pipelines under certain geoclimatic conditions.

With respect to numerical modelling, the study team operationalized an existing Konrad model for frost heave in soils in the Python programming language and assembled and/or created a number of predictive functions necessary to run the same model. The overall outcome was a 3-tiered approach to estimate the risk of frost heave in soils. Tier 1 (broadest level) uses a simple 'climate only' modeling approach to estimate the maximum depth of frost penetration in soils. Tier 2 (intermediate level) uses a more process-based 'climate and soil' modeling approach to simulate heat and water flux in soils during the winter season. Tier 3 (detailed level) uses an even more complex 'climate and soil' approach (i.e., the Konrad model) to estimate the frost heave risk and heave rate in soils. This multi-tiered approach produced a practical method for readily identifying soil conditions with high frost heave risk.

Pipeline Abandonment Research Steering Committee (PARSC)

The Canadian Energy Pipelines Association (CEPA), the National Energy Board (NEB), the Alberta Energy Regulator and the Canadian Association of Petroleum Producers have collaborated on technical and environmental issues associated with pipeline abandonment. In 1996, the NEB published a review document titled "Pipeline Abandonment – A Discussion Paper on Technical and Environmental Issues". In 2007, CEPA published a report titled "Pipeline Abandonment Assumptions" which discussed technical and environmental considerations for development of pipeline abandonment strategies. A comprehensive review was undertaken by the NEB as part of the Land Matters Consultation Initiative (LMCI) which involved four discussion papers on the different topic areas, 45 meetings and workshops in 25 communities across Canada, and written submissions from 13 parties. The final LMCI report, published in 2009 recommended that knowledge gaps on the physical issues of pipeline abandonment be addressed. Thus, DNV was commissioned to i) conduct a literature review regarding the current understanding worldwide with respect to the physical and technical issues associated with onshore pipeline abandonment, ii) use the results of the literature review to critically analyze and identify gaps in current knowledge, and iii) make recommendations as to potential future research projects that could help to fill those gaps. DNV published this Scoping Study in November 2010.

CEPA and PTAC have established the Pipeline Abandonment Research Steering Committee (PARSC) as a framework for collaboration to guide and direct innovation and applied research, technology development, demonstration, and deployment in order to address knowledge gaps summarized in the DNV Scoping Study. Research findings from the PARSC projects will be shared on a broad scale throughout the pipeline industry, the oil and gas industry, as well as with regulators, government agencies, and other stakeholders.

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Introduction

Landowners in southern Canada with transmission pipeline ROWs traversing their properties are understandably concerned about the long-term positional stability of abandoned pipelines. Mechanisms that could cause transmission (hydrocarbon) pipeline exposure include frost heave, pipeline upheaval buckling, buoyancy, as well as water and/or wind erosion of soil. In response to these landowner concerns, PARSC has embarked on ‘Stage 1’ (Project: PARSC - 003) of a multi-stage study to investigate the potential of one of these mechanisms (frost heave) to cause transmission pipeline exposure in cold climate regions, particularly once these pipelines have been abandoned.

Stage 1: Literature search and numerical modeling (Project: PARSC - 003)

Study Goal: to understand the mechanism of frost heaving of abandoned transmission pipelines

Study Objectives (Stage 1):

Research Obj. #1:	to carry out a thorough literature review and critical analysis of existing published numerical models of frost heaving in soils
Research Obj. #2:	to assemble all existing pedotransfer functions (PTFs), and create any new PTFs, that are needed to satisfy the information requirements of the Konrad (1999; 2005) approach to allow SP parameter estimation for the major soil types found in cropland areas of southern Canada
Research Obj. #3:	to operationalize a computer-based frost heave model utilizing elements from both the Konrad (1999; 2005) and Groenevelt & Grant (2013) approaches, and develop a user interface/manual

Main Findings

A total of six literature searches were carried out, and over 450 different references were cited throughout Volumes 1 and 2. The most important of these was a review and critical analysis of existing models/concepts of frost heaving in soils, which satisfied Research Obj. #1. It was also important, however, to conduct literature reviews on several other ancillary issues pertinent to this study and required to support numerical model development. Research Obj. #2 was achieved by assembling and/or creating a number of PTFs required by the Konrad (1999; 2005) model for frost heave in soils. Research Obj. #3 was met by operationalizing the Konrad (1999;

2005) model concepts in the Python programming language, known as the *Konrad_SP1.0* model.

A 3-tiered approach was used to estimate the risk of frost heave in soils. Tier 1 (broadest level) uses a simple 'climate only' modeling approach (i.e., the 'freezing index' method) to estimate the maximum depth of frost penetration in soils. Tier 2 (intermediate level) uses a more process-based 'climate and soil' modeling approach (i.e., the SHAW 1D model) to simulate heat and water flux in soils during the winter season. Tier 3 (detailed level) uses an even more complex 'climate and soil' approach (i.e., the *Konrad_SP1.0* model) to estimate the frost heave risk and heave rate in soils.

Two geoclimatic issues (macro-climate and soils) set the 'Prairie Ecozone' region of western Canada apart from the rest of southern Canada, and required a duplication of effort in formulating some of the PTFs needed to run the *Konrad_SP1.0* model. For example, two sets of PTFs were needed for i) the soil consistency (Atterberg) limits, and ii) specific surface area of soil.

To our knowledge, this study is the first of its kind where the Konrad (1999; 2005) approach to estimation of the 'segregation potential' (SP) parameter has been coupled with a wide array of PTFs (either already published, or newly developed in this study) for the purpose of estimating the frost susceptibility of soils in Canada. This multi-faceted approach to the PARSC - 003 project produced a practical method for readily identifying soil conditions with high frost heave risk. The involvement of PTFs could also facilitate the use of existing soil inventories in Canada in linear facilities planning, such as the Soil Landscapes of Canada (v3.2).

Conclusions

This study confirmed that the conclusion drawn in a 2010 scoping study remains true (i.e., there is no published information on the risk of abandoned pipeline exposure attributable to frost heave). A review of the broader literature on the frost heave process does, however, suggest that frost heave could pose an exposure risk to abandoned pipelines under certain geoclimatic conditions.

There are at least four factors that may cause preferential formation of ice lenses around an abandoned pipeline, and particularly immediately below that pipeline, as follows:

i. the steel in the pipeline wall is a much stronger thermal conductor than the surrounding moist soil. It is known that the two most essential driving forces leading to heave and heaving pressures in soils are the water intake rate (or the upward Darcy flux), and the heat extraction rate at the soil surface

ii. if the pipeline is positioned above the local groundwater table, there will be more 'free water' available at the bottom of the pipeline for ice lens formation than at positions closer to the soil surface, and the unsaturated hydraulic conductivity will be higher. The Darcy (water) flux, driven by the temperature gradient, is the major contributor to ice lens formation and frost heave in soils

iii. ice segregation in a frozen soil matrix (including ice lens formation) preferentially occurs in soil zones where overburden pressures are lower. The overburden pressure directly beneath an abandoned pipeline (i.e., air- or N_2-filled [ambient]) is significantly lower than in adjacent soil areas beyond the pipeline trench (i.e., at the same depth). The mass of an empty pipeline segment is significantly lower than the wet bulk density of the soil that it displaces, particularly for larger diameter pipelines

iv. if ice lenses form incidentally a short distance away from the pipeline, they may relocate to the area beneath the pipeline (where overburden pressures are lower) through the process of 'regelation'

Abundant ice lens growth directly beneath the pipeline could potentially jack the abandoned pipeline toward the surface over time.

Recommendations

Four recommendations were made in this report, as follows:

Recommendation #1:

It is recommended that PARSC/PTAC should bypass the proposed 'Stage 2' (Laboratory soil column freezing tests) of this multi-stage investigation of frost heave risk to abandoned pipelines, and proceed directly to 'Stage 3' (Field measurements and observations).

Recommendation #2:

It is recommended that PARSC/PTAC put resources into fully developing the *Groenevelt_HI1.0* model (largely conceptual at present), which is based on sound thermodynamic principles and has little dependency on PTFs (i.e., would likely only require a PTF to estimate saturated and unsaturated hydraulic conductivity), unlike the *Konrad_SP1.0* model.

Recommendation #3:

It is recommended that efforts be continued to either i) locate a non-Fortran version of the SHAW 1D model (by contacting researchers who have published on SHAW 1D in the last decade, including its creator Dr. Flerchinger), or ii) initiate a new attempt to re-write the Fortran program code into the Python programming language.

Recommendation #4:

It is recommended that a more in-depth study be carried out on the pipeline segment (diameter and length) matter from a 'pipeline design engineer' perspective.

ACKNOWLEDGMENTS

Stantec Consulting Ltd. would like to thank Petroleum Technology Alliance Canada (PTAC) for providing funding for this study, as well as the Pipeline Abandonment Research Steering Committee (PARSC) for their guidance during the study and in the preparation of this report.

Abbreviations

The entries in each of the following six abbreviation lists are arranged in alphabetical order

1. Terms / phrases / acronyms

AEI	agri-environmental indicator
AEIs	agri-environmental indicators
A/G	above-ground
CESI	Canadian Environmental Sustainability Indicators
CLI	Canada Land Inventory
CMP	component tables
CPESC	Certified Professional in Erosion and Sediment Control
DBMS	data base management system
DOC	depth of (soil) cover
EDP	excavation damage prevention
ELC	Ecological Land Classification
FDD	freezing degree-day
FDDs	freezing degree-days
FI	freezing index
GDD	growing degree-day
GDDs	growing degree-days
GIS	geographic information system
GPS	global positioning system
GWT	groundwater table
HI	heave index
n	number of observations
NAHARP	National Agri-Environmental Health Analysis and Reporting Program
PAT	polygon attribute tables
PTF	pedotransfer function
PTFs	pedotransfer functions
r (or R)	coefficient of simple (or multiple) correlation
r^2 (or R^2)	coefficient of simple (or multiple) determination
RMSE	root mean square error
ROW	right-of-way
ROWs	rights-of-way
s.e.e.	standard error of estimate
SLT	soil layer tables
SNT	soil name tables
SP	segregation potential
TDD	thawing degree-day
TDDs	thawing degree-days
U/G	under-ground
1D	one-dimensional
2D	two-dimensional

2. Soil property (and other) variables

BET	Brunauer, Emmett and Telier
C_c	compression index
d_{50}(FF)	average size of the fines fraction
D_b	dry bulk density
D_p	particle density
EGME	ethylene glycol monomethyl ether
L	length (when expressing dimensions)
K	hydraulic conductivity of soil
MDD	maximum dry density
NCL	normal consolidation line
OWC	optimum water content
P	maximum depth of frost penetration
PI	plasticity index
SOC	soil organic carbon content
SOM	soil organic matter content
SSA	specific surface area
t	time (when expressing dimensions)
T	temperature (when expressing dimensions)
w	gravimetric soil water content
w_{wp}	gravimetric soil water content at the permanent wilting point
w_L	liquid limit
w_P	plastic limit
σ_c'	preconsolidation stress

3. Computer-based systems

CanSIS	Canada Soil Information System
CSV	‘comma- (or character-) separated values’ file type
Groenevelt_HI1.0	Groenevelt & Grant (2013) Heave Index model (version 1.0)
HYDRUS 2D	soil heat and water flux model (two-dimensional)
Konrad_SP1.0	Konrad (1999; 2005) Segregation Potential model (version 1.0)
RUSLE	Revised Universal Soil Loss Equation
RUSLE2	Revised Universal Soil Loss Equation (version 2)
SHAW 1D	Simultaneous Heat and Water model (one-dimensional)
SLC	Soil Landscapes of Canada
SLC1.0	Soil Landscapes of Canada (version 1.0)
SLC3.2	Soil Landscapes of Canada (version 3.2)
SOIL	Soil water and heat model
USLE	Universal Soil Loss Equation
WEPS	Wind Erosion Prediction System

4. Reference list abbreviations

AAFC	Agriculture and Agri-Food Canada
ALA	American Lifelines Alliance
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CEPA	Canadian Energy Pipeline Association
DNV	Det Norske Veritas
IRWA	International Right of Way Association
MOT	Ontario Ministry of Transportation
MTC	Ontario Ministry of Transportation and Communications
NEB	National Energy Board
OCSRE	Ontario Centre for Soil Resource Evaluation
OEB	Ontario Energy Board
OIP	Ontario Institute of Pedology
OMAF	Ontario Ministry of Agriculture and Food
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
PARSC	Pipeline Abandonment Research Steering Committee
PASC	Pipeline Abandonment Steering Committee
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture - Agricultural Research Services

5. Canadian provinces and territories

AB	Alberta
BC	British Columbia
MB	Manitoba
NB	New Brunswick
NL	Newfoundland/Labrador
NS	Nova Scotia
NT	Northwest Territories
NU	Nunavut
ON	Ontario
PE	Prince Edward Island
QC	Quebec
SK	Saskatchewan
YT	Yukon Territories

6. U.S. states

AL	Alabama	MT	Montana
AK	Alaska	NE	Nebraska
AZ	Arizona	NV	Nevada
AR	Arkansas	NH	New Hampshire
CA	California	NJ	New Jersey
CO	Colorado	NM	New Mexico
CT	Connecticut	NY	New York
DE	Delaware	NC	North Carolina
FL	Florida	ND	North Dakota
GA	Georgia	OH	Ohio
HI	Hawaii	OK	Oklahoma
ID	Idaho	OR	Oregon
IL	Illinois	PA	Pennsylvania
IN	Indiana	RI	Rhode Island
IA	Iowa	SC	South Carolina
KS	Kansas	SD	South Dakota
KY	Kentucky	TN	Tennessee
LA	Louisiana	TX	Texas
ME	Maine	UT	Utah
MD	Maryland	VT	Vermont
MA	Massachusetts	VA	Virginia
MI	Michigan	WA	Washington
MN	Minnesota	WV	West Virginia
MS	Mississippi	WI	Wisconsin
MO	Missouri	WY	Wyoming

1.0 INTRODUCTION

Conventional field crop production in southern Canada typically involves i) tillage operations using soil-engaging equipment, and ii) sub-surface tile drain installation. Hence, farm landowners with transmission pipeline rights-of way (ROWs) traversing their properties are understandably concerned about the long-term positional stability of abandoned pipelines (NEB, 2010). Mechanisms that could cause transmission (hydrocarbon) pipeline exposure include frost heave, pipeline upheaval buckling, buoyancy, as well as water and/or wind erosion of soil. In response to these landowner concerns, PARSC has embarked on Stage 1 of a multi-stage study (Project PARSC - 003) to investigate the potential of one of these mechanisms (frost heave) to cause transmission pipeline exposure in cold climate regions, particularly once these pipelines have been abandoned (NEB, 2013).

A recent scoping study on pipeline abandonment (DNV, 2010) found that there was no published information available on this cold region geohazard (frost heave), and that this gap in knowledge needed to be addressed with mission-oriented research. It was recommended in the DNV (2010) report that laboratory soil column freezing tests should be used as a basis for the development and calibration of a numerical model for estimating frost heave risk and rates, and that modeled results should be validated with field measurements and observations. The terms of reference for Project PARSC - 003 follow the DNV (2010) recommendations.

The overall study on frost heave proposed by PARSC is comprised of three sequential stages, as follows:

Stage 1: Literature search and numerical modeling (Project PARSC - 003)
Stage 2: Laboratory testing
Stage 3: Field measurements

Collectively, it is expected that Stages 1 - 3 would require 5 years to complete if carried out sequentially. Project PARSC - 003 pertains to Stage 1 only (1 year in duration), since PARSC will only determine the need for Stage 2 and/or Stage 3 after reviewing the results from this current Stage 1 study.

1.1 REFERENCES (SECTION 1)

Det Norske Veritas (DNV). 2010. Pipeline abandonment scoping study. A report prepared for the National Energy Board (NEB). 85 pp. Available at: http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnbndnmnt/pplnbndnmntscpngstd.pdf (verified Oct. 6, 2014)

National Energy Board (NEB). 2010. Pipeline Regulation in Canada: A Guide for Landowners and the Public. Revised September 2010. NEB Publications Office, Calgary, AB. 56 pp. Available at: http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnrgltncnd/pplnrgltncnd_ndx-eng.html (verified Oct. 6, 2014)

National Energy Board (NEB). 2013. Funding requirements for pipeline abandonment to be the focus of upcoming NEB hearing. NEB News Release, April 19, 2013 (Hearing Order MH-001-3013 - Set-Aside and Collection Mechanisms). Available at: http://www.neb-one.gc.ca/clf-nsi/rthnb/nws/nwsrls/2013/nwsrls11-eng.html (verified Oct. 6, 2014)

2.0 BACKGROUND

2.1 POTENTIAL GEOTECHNICAL CAUSES OF PIPELINE EXPOSURE

It is important to examine the known potential 'geotechnical' causes of pipeline exposure (i.e., soil- or slope-related) that are of concern during the operating lifespan of a transmission hydrocarbon pipeline (DNV, 2010). Palmer & Williams (2003) discuss two of these phenomena: 'pipeline upheaval buckling' and 'frost heaving'. Upheaval buckling (i.e., large upward movements of a buried pipeline) 'is caused by the interaction between the longitudinal compressive force present during operation and overbend irregularities in the profile' (Palmer & Williams, 2003, p. 1033). This phenomenon is more common in offshore pipelines, but can occur in onshore pipelines as well (Fig. 6.5) where frost heave is acknowledged to be one of several mechanisms that can contribute to pipeline upheaval buckling (Nixon & Burgess, 1999; Palmer & Williams, 2003).

Currently, frost heaving of operating hydrocarbon pipelines is a geohazard that is primarily of concern in permafrost environments, and hence is outside the scope of this study (i.e., abandoned pipelines in southern Canada). To illustrate this geohazard in general terms, however, Figure 7.2 shows soil columns that have been subjected to controlled laboratory freeze testing (Konrad, 1993). The formation of horizontal ice lenses (ice segregation features) and upward vertical soil displacement are clearly discernable.

These two phenomena (i.e., upheaval buckling and frost heave) can be visually simulated in the laboratory, with the inclusion of 'scaled pipelines' in the test set-up providing useful information for pipeline design engineers. Figure 2.1a shows the end point of a routine pipe uplift resistance test conducted in a mini-drum centrifuge (0.8m diam.), with a 22-mm 'pipeline' embedded in layered and saturated silica sand as the test soil matrix (White *et al*., 2001). Figure 2.1b shows a frost heave test in progress, with a rigid-walled object (i.e., a red-coloured rock) embedded in a saturated, medium-textured soil and a downward advancing freezing front (USACE, 1992). In this test set-up, the rock was heaved upward by about 75 mm once the freezing front had reached the bottom of the soil-filled test chamber. In both the uplift resistance and frost heave tests illustrated here, the cavity that formed beneath the rigid-walled object was filled by slumping of the surrounding soil, which reinforces the upward movement of rigid-walled objects.

In southern Canada, pipelines are used to transport a variety of liquid hydrocarbon products which can create seasonally variable thermal conditions in the vicinity of the pipe. It is likely that these pipelines are significantly less susceptible to frost heave during their operational lifetime, compared to their abandoned condition, because of heat released into the surrounding soil from the warm product during transmission (DNV, 2010). Most metals are strong thermal conductors (e.g., iron = 80 Wm^{-1}K^{-1}; steel = 43 Wm^{-1}K^{-1}), allowing rapid heat extraction from the warm product through the pipeline walls and into the surrounding soil. Modeling of soil heat flux has been used to estimate soil temperature isotherms in the vicinity of warm transmission pipelines (TransCanada Corp., 2009).

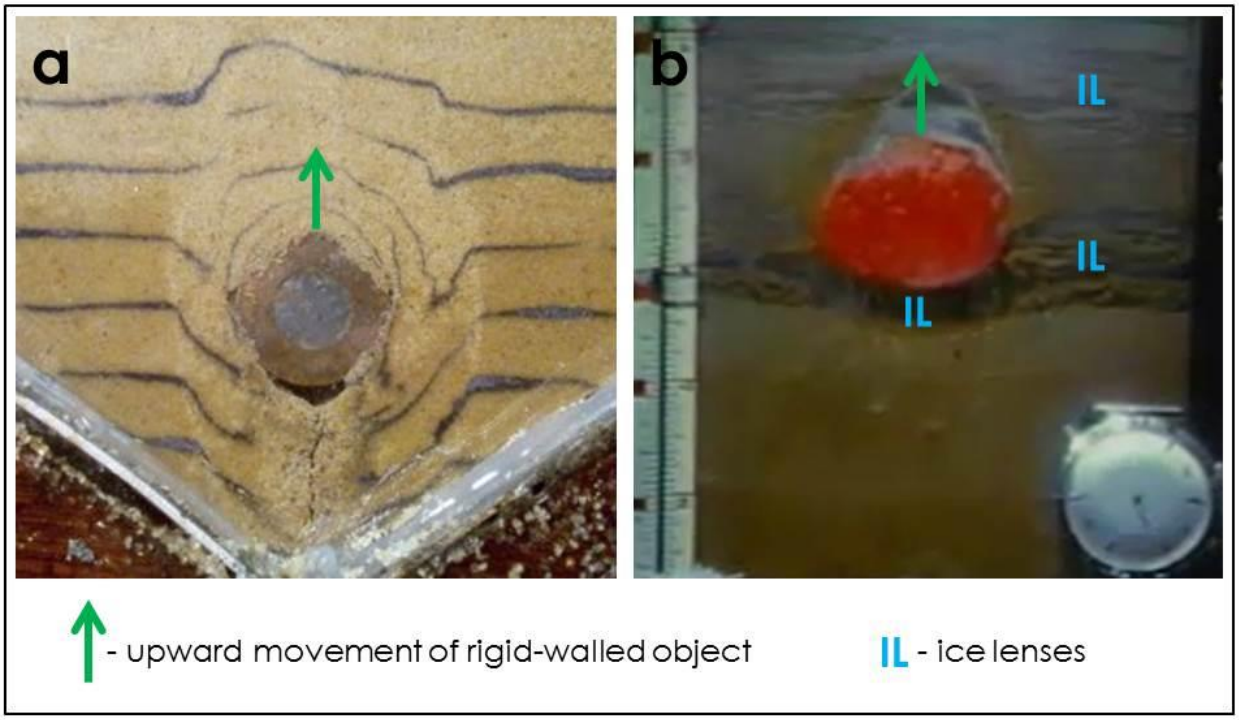


Figure 2.1: Potential geotechnical causes of pipeline exposure during the operating lifespan of a transmission hydrocarbon pipeline include a) pipeline upheaval buckling (after White *et al.*, 2001), and b) frost heave (after USACE, 1992).

Similar elevated pipeline temperatures are common within natural gas pipeline ROWs. With the increase in pressure of natural gas at compressor stations, there is a corresponding increase in gas temperature for a significant distance downstream. Figure 2.2 shows a natural gas pipeline ROW during a 'January thaw' period near the town of Bright in southern Ontario. The trajectory of four parallel pipelines within this ROW is evident, where the soil was partially thawed in mid-winter. Fig. 2.2 illustrates very well the phenomenon of heat extraction from a warm product, and the heat flux through a metal pipeline wall, into the surrounding cold soil and ultimately into even colder air. The heat extraction rate in winter will depend on the overall temperature gradient, the soil thermal properties, the surface conditions (snow and/or plant residue cover), etc.

Figure 2.2: **Soil heating downstream from a natural gas compressor station in January near Bright, ON (photo: R.A. McBride).**

Another potential cause of pipeline exposure is 'buoyancy' (DNV, 2010; Zhou *et al.*, 2013), which can occur in very wet or saturated soil conditions (e.g., wetlands, floodplains of watercourses, stream crossings). This is illustrated in Fig. 2.3, where contractors installed a natural gas transmission pipeline across a tributary within the Grand River watershed in southern Ontario. The conventional means of avoiding buoyancy problems in a stream crossing situation is by weighing the pipe down with concrete pipe weights.

Figure 2.3: **Installation of a natural gas pipeline a) across the Nith River near Ayr, ON, with b) concrete pipe weights reducing exposure risk from buoyancy (photos: R.A. McBride).**

The remaining potential geotechnical causes of pipeline exposure are all directly soil-related; soil erosion within the ROW by wind and/or water (Gavassoni & Garcia, 2010), including soil mass movement. Figure 2.4a shows an exposed transmission pipeline on steeply sloping terrain. Here, the soil cover is likely to have been stripped moreso by mass movement of soil than by conventional rill or gully erosion. Figure 2.4b shows three parallel pipelines exposed in a dryland area due to severe localized wind erosion within the pipeline ROW.

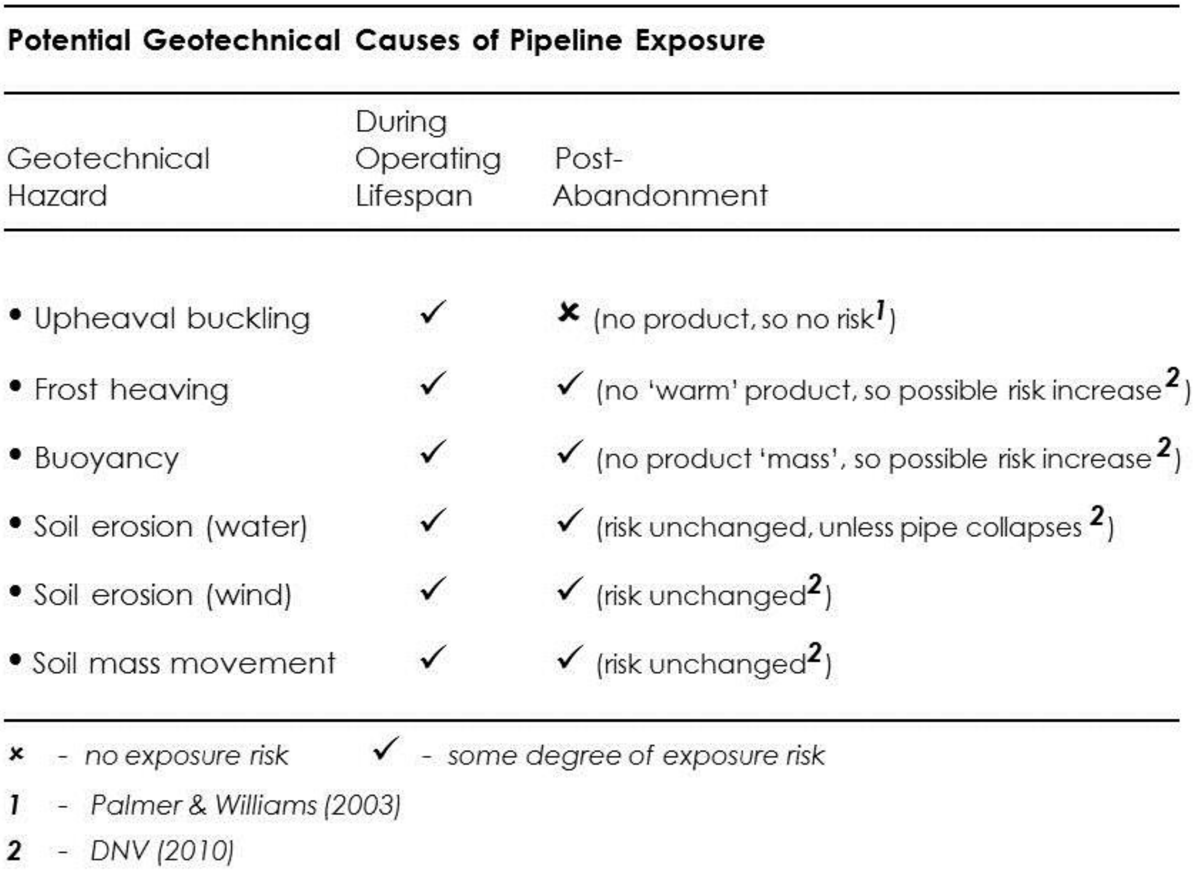
http://geosyntheticsmagazine.com/articles/1012_f2_landfill_recycle.html

http://repository.unm.edu/bitstream/handle/1928/23207/Knutt%20Peterson%20Thesis%20Final%2012_12_2012.pdf?sequence=1

Figure 2.4: Soil degradation processes of a) water erosion or mass movement, and b) wind erosion, which have the potential to expose buried pipelines.

For the purposes of this study (PARSC - 003), it is particularly important to identify potential geotechnical causes of pipeline exposure that are operative once a transmission pipeline is abandoned. Table 2.1 shows that only one of the phenomena discussed above is eliminated with pipeline abandonment (i.e., pipeline upheaval buckling), since the absence of product pumping would eliminate the 'longitudinal compressive force' needed to cause buckling and exposure. The risk of exposure by frost heave and/or buoyancy is potentially higher post-abandonment than it was during the operating lifespan (DNV, 2010), assuming the abandoned pipe is simply air-filled (or filled with nitrogen gas to inhibit corrosion), as opposed to being filled with grout where the increased overburden pressure might moderate the risk of frost heave and/or buoyancy. It is not believed that the rates of soil erosion by water (including mass movement) or wind would be significantly affected by abandonment in the absence of pipe collapse (DNV, 2010).

Table 2.1: Potential geotechnical causes of pipeline exposure during its operating lifespan, and after it has been abandoned.



Potential Geotechnical Causes of Pipeline Exposure

Geotechnical Hazard	During Operating Lifespan	Post-Abandonment
• Upheaval buckling	✓	✗ (no product, so no risk[1])
• Frost heaving	✓	✓ (no 'warm' product, so possible risk increase[2])
• Buoyancy	✓	✓ (no product 'mass', so possible risk increase[2])
• Soil erosion (water)	✓	✓ (risk unchanged, unless pipe collapses [2])
• Soil erosion (wind)	✓	✓ (risk unchanged[2])
• Soil mass movement	✓	✓ (risk unchanged[2])

✗ - *no exposure risk* ✓ - *some degree of exposure risk*

1 - Palmer & Williams (2003)

2 - DNV (2010)

2.2 SIMULATION OF FROST LINE CONFIGURATIONS AROUND BURIED OBJECTS

Modeling of soil heat flux has been used to estimate soil temperature isotherms in the vicinity of transmission pipelines carrying warm, cold or ambient temperature hydrocarbon products, but there is a dearth of such analysis for abandoned pipelines (see Appendix H). Figure 2.5 shows the results of soil heat flux modeling around a warm pipeline in early January at Glasgow, MT (TransCanada Corp., 2009). As noted earlier, most metals are strong thermal conductors, allowing rapid heat extraction from the warm product through the pipeline walls and into the surrounding soil. Even with surface soil temperatures < 0°C in early January, Fig. 2.5 shows a clear 'bump' in the soil temperature isotherms above the warm pipe.

Another illustration of this type of simulation comes from a 2D transient finite element model, which was used by Modisette & Modisette (2014) to solve the heat conduction equation in soil. Three buried object scenarios were considered (i.e., warm pipe [60°F, or 15.5°C], cold pipe [20°F, or -6.7°C], and buried granite rock [ambient]), and the simulations were run over a 5-year (260-week) period. Figures 2.6 - 2.8 provide 'snapshots' of selected finite element simulations.

Figure 2.6 shows how the frost line gradually envelopes the warm pipe (e.g., heated crude oil) during the winter season as the regional 0°C isotherm descends deeper into the soil profile. In Fig. 2.6c, the initial frost line has completely enveloped the warm pipe, and a second frost line (somewhat horizontal) has been established well below the pipe position.

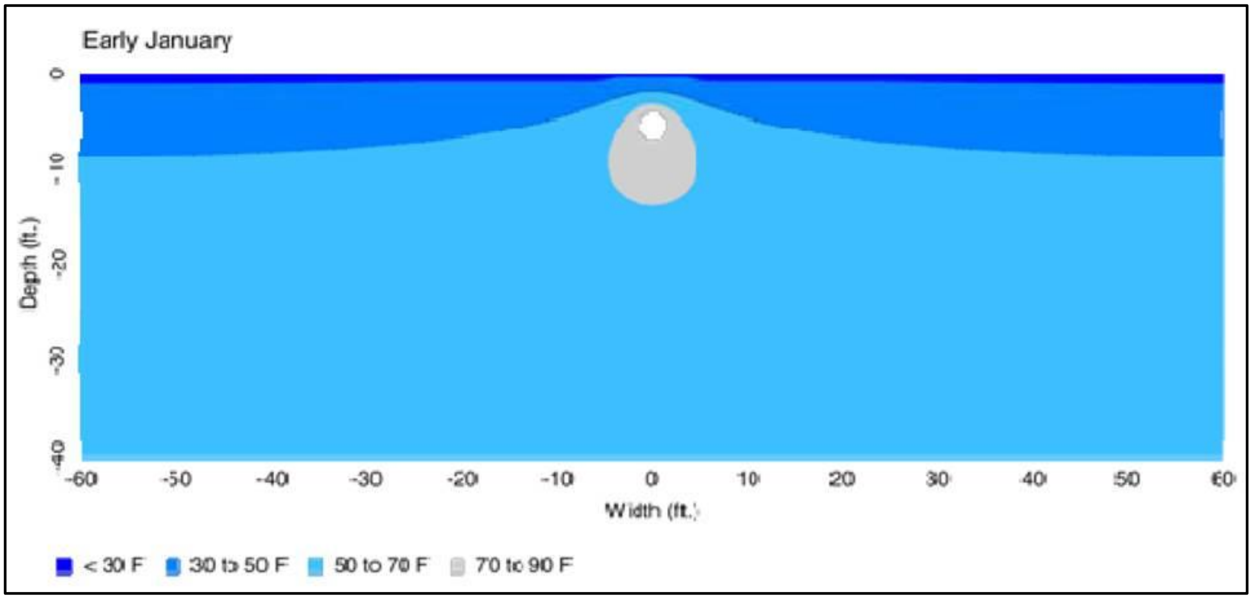


Figure 2.5: **Results of soil heat flux modeling around a warm pipeline in early January at Glasgow, MT. (after TransCanada Corp., 2009).**

Figure 2.7a shows the frost line completely enveloping the cold pipe (e.g., chilled natural gas) during the summer season. By early winter, the frost line that enveloped the cold pipe has merged with the regional frost line that is descending deeper into the soil profile (Fig. 2.7b). By late winter, the frost line has moved well below the pipe position (Fig. 2.7c).

Figure 2.8 (buried granite rock) represents the closest heat flux simulation to an abandoned pipeline scenario that was found in the published literature. Figure 2.8a shows the frost line in winter as it approaches the buried rock. The ‘bump’ in the frost line above the rock reflects the higher thermal conductivity of granite (about 4 $Wm^{-1}K^{-1}$) in relation to the surrounding soil (about 1 $Wm^{-1}K^{-1}$), but it is still much lower than that of pipe steel (43 $Wm^{-1}K^{-1}$). A week later, the frost line has largely moved through the solid rock (Fig. 2.8b), and two weeks later it is positioned just below the rock (Fig. 2.8c). The ‘dip’ in the frost line below the rock again reflects the comparatively higher thermal conductivity of the granite and the depletion of heat within and below the rock (Fig. 2.8c).

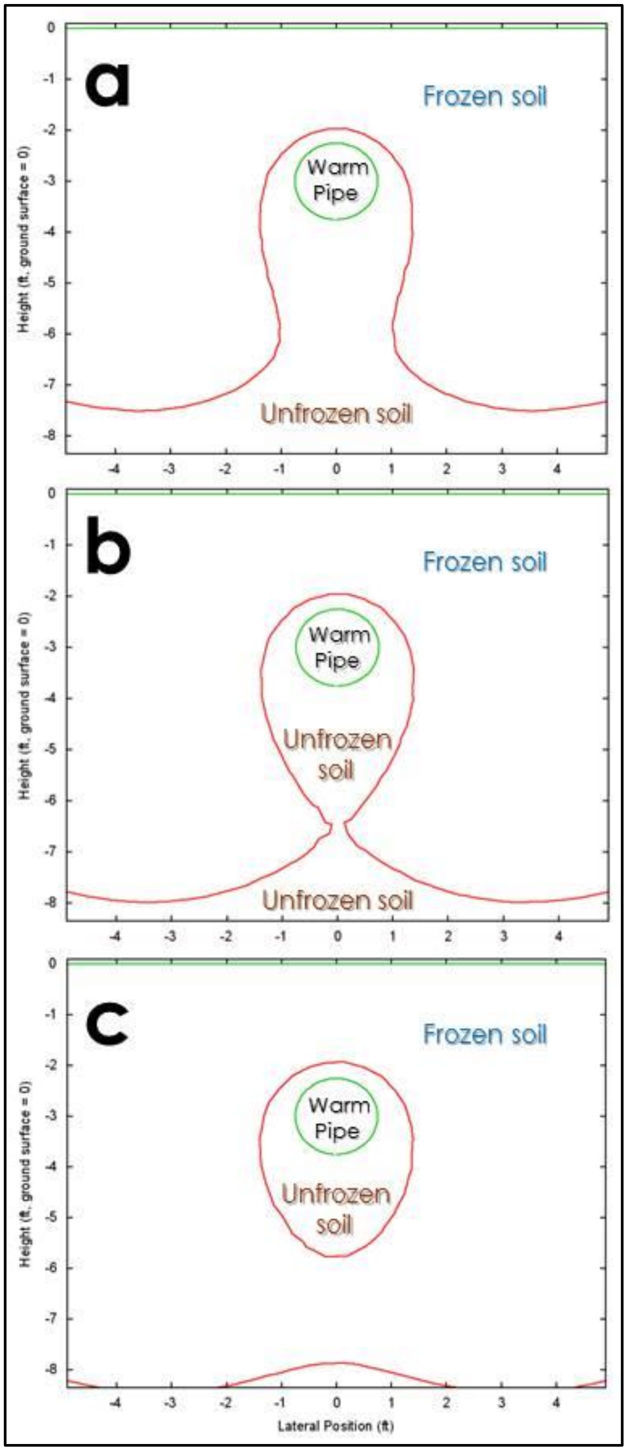


Figure 2.6: Warm pipe frost line simulation results for three consecutive weeks in winter (a - week 145; b - week 146; c - week 147). Frost line denoted in red. (after Modisette & Modisette, 2014).

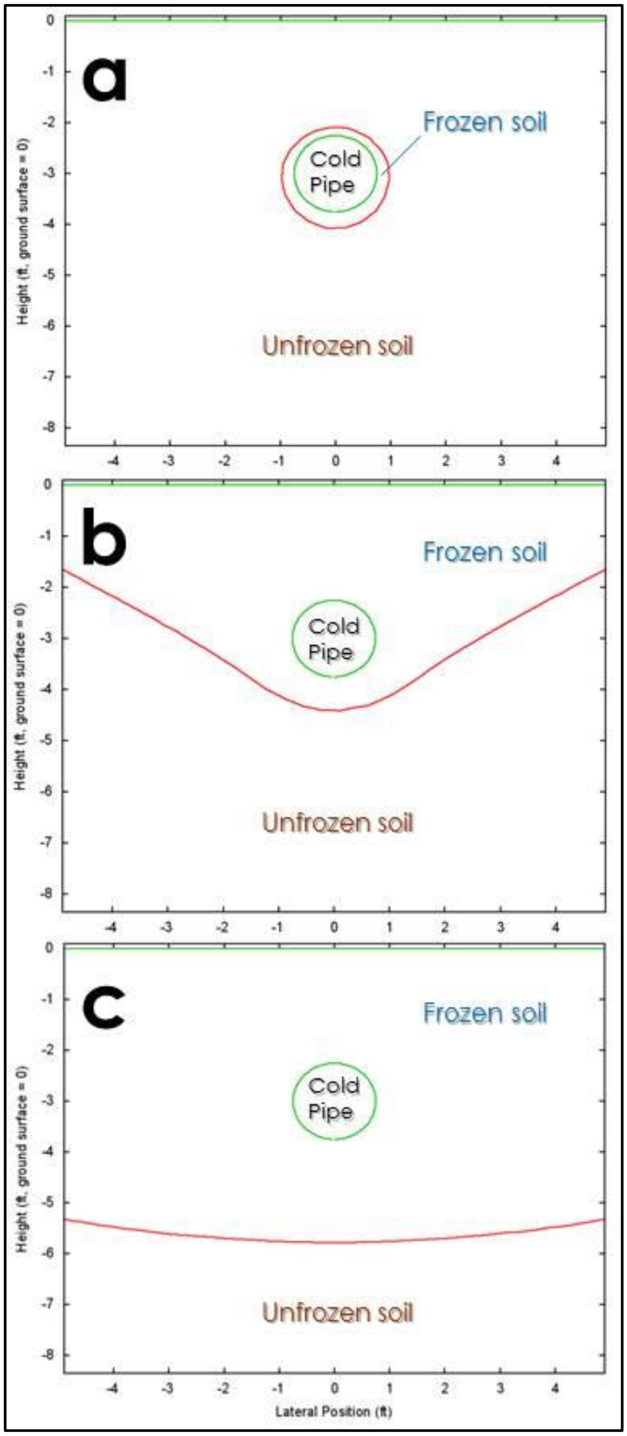


Figure 2.7: Cold pipe frost line simulation results for a) summer, b) early winter, and c) late winter. Frost line denoted in red. (after Modisette & Modisette, 2014).

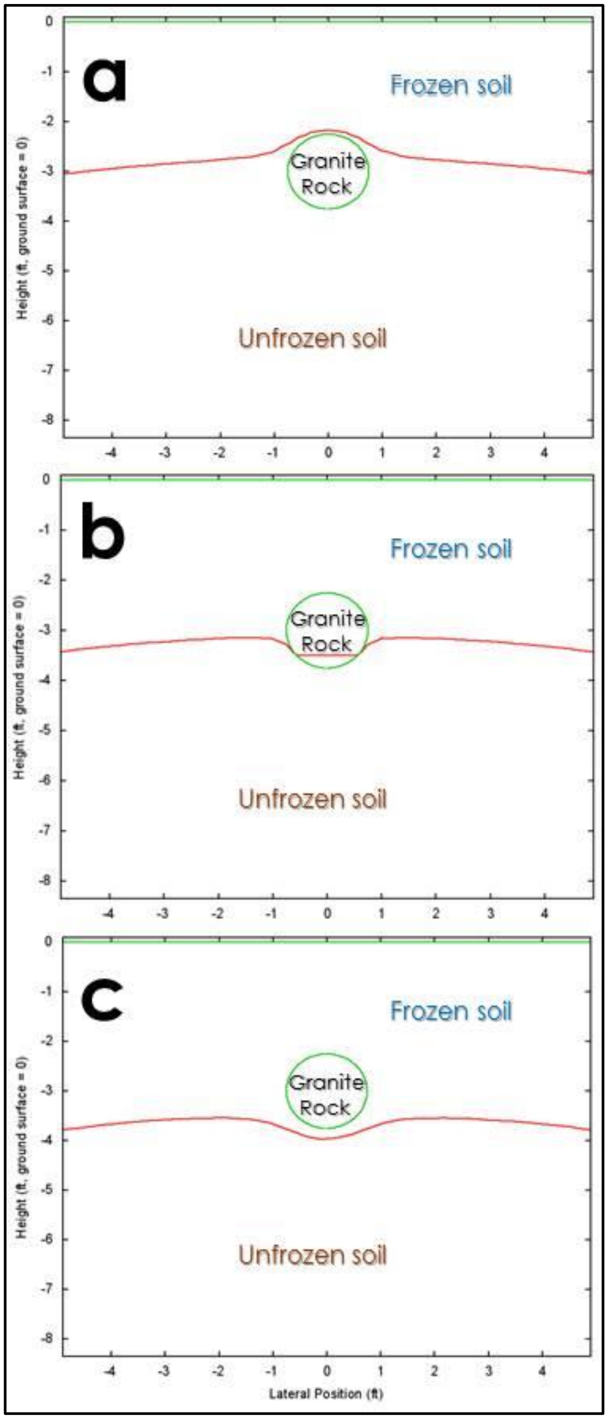


Figure 2.8: Frost line simulation results for three consecutive weeks in winter (a - week 192; b - week 193; c - week 194) for a buried granite rock. Frost line denoted in red. (after Modisette & Modisette, 2014).

2.3 PIPELINE ABANDONMENT AND LANDOWNERS

It is important to examine the issue of abandoned transmission pipelines from the standpoint of landowners in southern Canada with pipeline ROWs traversing their property. The agricultural community (in particular) would have land holdings located primarily within the green map units in Fig. 2.9.

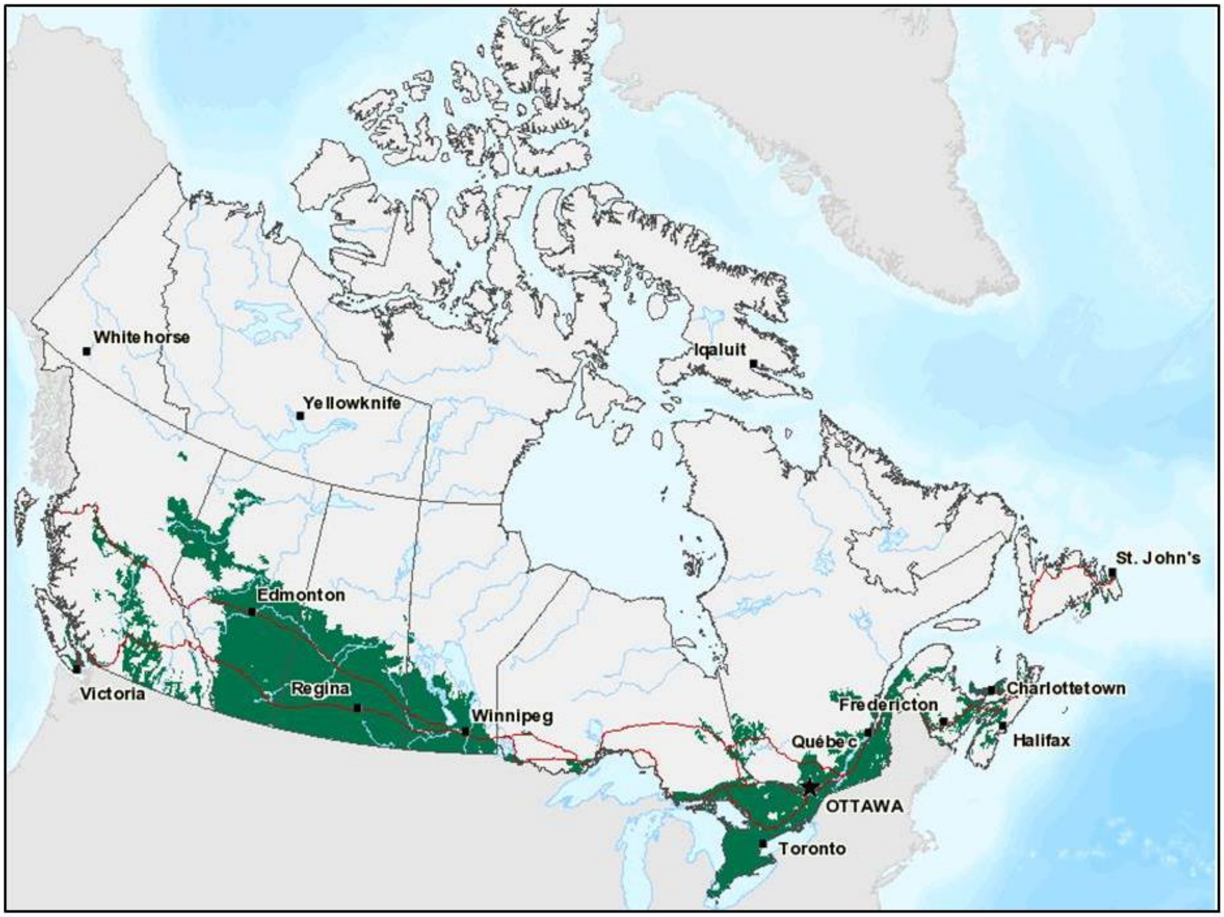


Figure 2.9: Map of potential cropland in Canada (green map units), based on a computer analysis and scale reduction of 200 Canada Land Inventory (CLI) agricultural capability maps. CLI classes 1-3 are included for all provinces except BC and NL, where classes 1-4 are shown (Source: AAFC, 2013).

As noted in Section 1, conventional field crop production in Canada typically involves tillage operations using soil-engaging equipment. Sub-soiling or deep-ripping operations, used to relieve compacted soil conditions, can extend to as much as 1 m below the surface (Fig. 2.10a).

The installation of sub-surface tile drains, however, can extend well below a 1 m depth (Fig. 2.10b). As a result, landowners are understandably concerned about the long-term positional stability of pipelines (whether they are operational or abandoned).

http://www.classic-combines.com/blenchsingle.html

http://www.grainews.ca/2014/04/29/do-it-yourself-tile-drainage/

Figure 2.10: **Typical farm practices in southern Canada often include a) sub-soiling and deep-ripping operations, and b) sub-surface tile drain installation.**

2.4 OVERVIEW OF PAST FROST HEAVE MODELING EFFORTS

Over the last century, efforts to explain the frost heave phenomenon in soils and develop theoretical models have followed two divergent pathways (Peppin & Style, 2013):

i) the 'capillary' (or 'primary' frost heave) model concept
ii) the 'frozen fringe' (or 'secondary' frost heave) model concept

Since the 1970's, however, the 'frozen fringe' model type has been predominant, with two distinct 'schools' of investigation leading the way (Groenevelt & Grant, 2013). The 'Miller school' tended to focus on the fundamental 'science of energy (thermodynamics)', while the 'Anderson school' adopted a more 'geotechnical engineering' approach (see Appendix B). Each of these 'schools' has yielded at least one practical 'heave index' that would be suited for pipeline applications in this PARSC - 003 study:

i) the 'segregation potential' (SP) of Konrad & Morgenstern (1983) - 'Anderson school'
ii) the 'heave index' (HI) of Groenevelt & Grant (2013) - 'Miller school'

It is noteworthy that the SP and HI parameters were arrived at independently from very different perspectives on the frost heave process, but both parameters have essentially the same physical meaning (i.e., the absolute value of the ratio of the Darcy [water] flux and the temperature gradient).

In the field of frost heave estimation, the SP parameter is 'time-tested and proven', while the much newer HI parameter is derived from sound thermodynamic principles but is largely conceptual and untested at this point in time (Appendix A). It is for these reasons that this study attempts to make use of elements of both the Konrad (1999; 2005) and Groenevelt & Grant (2013) approaches in achieving the overall study goal and research objectives #2 and #3 (Section 3).

2.5 REFERENCES (SECTION 2)

Agriculture and Agri-Food Canada (AAFC). 2013. Soil Landscapes of Canada (version 3.2). Available at: http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html (verified Oct. 6, 2014)

Det Norske Veritas (DNV). 2010. Pipeline abandonment scoping study. A report prepared for the National Energy Board (NEB). 85 pp. Available at: http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnbndnmnt/pplnbndnmntscpngstd.pdf (verified Oct. 6, 2014)

Gavassoni, E. and C.B. Garcia. 2010. Prediction of exposure risk for buried pipelines due to surface erosion. p. 192-201. *In* S.E. Burns, S.K. Bhatia, C.M.C. Avila and B.E. Hunt (eds.) Proc. 5th Int'l. Conf. on Scour and Erosion (ICSE-5). ASCE, Geotechnical Special Publ. no. 210. Nov. 7-10, 2010, San Francisco, CA.

Groenevelt, P.H. and C.D. Grant. 2013. Heave and heaving pressure in freezing soils: A unifying theory. Vadose Zone J. 12(1). 11 pp.

Konrad, J.-M. 1993. Frost heave potential. p. 797-806. *In* M.R. Carter (ed.) Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. CRC Press, Lewis Publishers, Boca Raton, FL.

Konrad, J.-M. 1999. Frost susceptibility related to soil index properties. Can. Geotech. J. 36:403-417.

Konrad, J.-M. and N.R. Morgenstern. 1983. Frost susceptibility of soils in terms of their segregation potential. p. 660-665. *In* Proc. 4th Int'l. Conf. on Permafrost, Fairbanks, AK. National Academy Press, Washington, DC.

Modisette, J.P. and J.L. Modisette. 2014. Pipe line frost heave (or the lack thereof). Paper PSIG 1421. Pipeline Simulation Interest Group (PSIG) Annual Meeting, Baltimore, MD. May 6-9, 2014. 8 pp.

Nixon, J.F. and M. Burgess. 1999. Norman Wells pipeline settlement and uplift movements. Can. Geotech. J. 36:119-135.

Palmer, A.C. and P.J. Williams. 2003. Frost heave and pipeline upheaval buckling. Can. Geotech. J. 40:1033-1038.

Peppin, S.S.L. and R.W. Style. 2013. The physics of frost heave and ice-lens growth. Vadose Zone J. 12(1). 12 pp.

TransCanada Corp. 2009. Pipeline temperature effects study (Appendix S). Available at:http://keystonepipeline-xl.state.gov/documents/organization/205567.pdf (verified Oct. 6, 2014)

U.S. Army Corps of Engineers (USACE). 1992. Frost action in soils (video). Produced in 1960s, published in 1992, digitized in 2013. Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH.

White, D.J., A.J. Barefoot and M.D. Bolton. 2001. Centrifuge modelling of upheaval buckling in sand. Int'l. J. Physical Modelling in Geotechnics 2:19-28.

Zhou, X., J. Wang and X. Wang. 2013. Study on anti-buoyancy design and engineering measures for gas pipeline in cross-river shield tunnel. p. 1683-1692. *In* B. Ma, M. Najafi, G. Jiang and L. Slavin (eds.) Proc. Int'l. Conf. on Pipelines and Trenchless Technology. ASCE. Oct. 19-22, 2012, Wuhan, China.

3.0 STUDY GOAL AND OBJECTIVES

Study Goal: to understand the mechanism of frost heaving of abandoned transmission pipelines

The above study goal (and its wording) originated directly from recommendations contained in the DNV (2010) scoping study, and was re-iterated in the PARSC (2013) 'Request for Proposals' document. It should be noted that the engineering and scientific communities view frost heave in soils somewhat differently: the former largely as a phenomenon to be explained 'mechanistically', and the latter more as a 'thermodynamic process' to be explained theoretically. This study has adopted the latter approach wherever possible.

Study Objectives (Stage 1):

Research Obj. #1: to carry out a thorough literature review and critical analysis of existing published numerical models of frost heaving in soils

Research Obj. #2: to assemble all existing pedotransfer functions (PTFs), and create any new PTFs, that are needed to satisfy the information requirements of the Konrad (1999; 2005) approach to allow SP parameter estimation for the major soil types found in cropland areas of southern Canada

Research Obj. #3: to operationalize a computer-based frost heave model utilizing elements from both the Konrad (1999; 2005) and Groenevelt & Grant (2013) approaches, and develop a user interface/manual

3.1 REFERENCES (SECTION 3)

Det Norske Veritas (DNV). 2010. Pipeline abandonment scoping study. A report prepared for the National Energy Board (NEB). 85 pp. Available at: http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnbndnmnt/pplnbndnmntscpngstd.pdf (verified Oct. 6, 2014)

Groenevelt, P.H. and C.D. Grant. 2013. Heave and heaving pressure in freezing soils: A unifying theory. Vadose Zone J. 12(1). 11 pp.

Konrad, J.-M. 1999. Frost susceptibility related to soil index properties. Can. Geotech. J. 36:403-417.

Konrad, J.-M. 2005. Estimation of the segregation potential of fine-grained soils using the frost heave response of two reference soils. Can. Geotech. J. 42:38-50.

Pipeline Abandonment Research Steering Committee (PARSC). 2013. Request for proposals: PARSC 003 - Frost Heave Effects on Pipeline Exposure Rates. Petroleum Technology Alliance Canada (PTAC), Calgary, AB. August, 2013. 6 pp.

4.0 STUDY METHODOLOGY

4.1 PREFACE

The study methodology closely followed the overall study goal and three research objectives as stated in Section 3. A total of six literature searches were carried out. The most important of these was a review and critical analysis of existing models/concepts of frost heaving in soils (Section 4.2), which satisfied Research Objective #1. It was also important, however, to conduct literature reviews on several other ancillary issues pertinent to this study and required to support numerical model development (Section 4.3). Research Objective #2 was achieved by assembling and/or creating a number of PTFs required by the Konrad (1999; 2005) model for frost heave in soils (Section 4.5). Research Objective #3 was met by operationalizing the Konrad (1999; 2005) model concepts in the Python programming language, which is referred to as the *Konrad_SP1.0* model (Section 4.4).

4.2 CORE LITERATURE SEARCH (NUMERICAL MODELS OF FROST HEAVING IN SOILS [LitRev1])

A vast amount of literature has been published on the subject of frozen soils and frost heave over the last several decades. For example, the bibliography of Mullins (2003) listed approximately 14,000 published articles/reports spanning a 25-year period (1978-2003), although a good number of these publications pertained to permafrost terrain which is outside the scope of this study. The task of assembling the most pertinent literature for this study was made manageable by i) concentrating on the frost heave phenomenon in soils in temperate climate zones only, and ii) categorizing the research papers that deal with frost heave models/concepts according to their relevance to frost heave of pipelines (i.e., Category I or II).

'Category I' included research papers that were relevant to frost heave of pipelines, whereas 'Category II' included those that were not overly relevant to the current study but still contained useful information. Because of the dearth of publications dealing with frost heave of pipelines outside of permafrost landscapes, 'Category I' publications could also include those dealing with underground utilities and other buried structures (e.g., culverts).

A comparative critical analysis or critique was carried out on the frost heave models/concepts put forth in these publications, and the findings were compiled into two different formats:

Annotated bibliography: Firstly, the sourced references were compiled into an 'annotated bibliography' made up of research sources for each of Categories I and II, with a concise summary of each source (i.e., the published abstract) and a critical assessment of its value or relevance to this study. Where possible, the critical analysis addressed several key questions for the model/concept revealed in each source, including the following:

- Does the model/concept advance the thinking on frost heave thermodynamics in soils?
- Does the model/concept belong to the 'capillary' or 'frozen fringe' theoretical category?
- Does the model/concept originate from the 'Anderson school', the 'Miller school' or other less established 'schools of thought'?
- Has the model/concept been adequately calibrated/validated in the lab and/or field?
- What are the information/data requirements of the model/concept?
- What is the capability of the model/concept to deal with the issue of frost heave risk for pipeline segments abandoned-in-place (i.e., variable diameter and length)?

Narrative-style paper: Secondly, the information on models/concepts contained in some of the key sourced references was synthesized into a comprehensive 'narrative-style paper' on the topic of frost heave in soils.

4.3 SECONDARY LITERATURE SEARCHES

4.3.1 Frost penetration depth in soils (LitRev2)

It was important in this study to review all methods that are in common usage for estimating or simulating the depth of frost penetration in soils, since this information is key to determining regions of southern Canada where the 0°C isotherm may reach the depth of transmission pipelines. An example of a simple estimation technique for frost penetration depth in soils is the 'freezing index' (FI) method, which involves tracking 'freezing degree-days' (FDDs) based on winter air temperatures alone. The FI method suggests that the maximum depth of frost penetration (long-term average) under bare-soil conditions is expected to be about 234 cm in Peace River AB, 150 cm in Calgary AB, and 79 cm in Sarnia ON (Chisholm & Phang, 1981).

Figure 4.1 shows a hypothetical 100-cm diameter pipeline at a depth of 120 cm in Lethbridge, AB, where the FI method predicts a maximum frost penetration depth of 125 cm. It can be hypothesized that, once the 0°C isotherm reaches the top of the steel pipeline, the temperature of the full circumference of the pipe is likely to fall rapidly to ≤ 0°C, since most metals are strong thermal conductors (e.g., iron = 80 $Wm^{-1}K^{-1}$; steel = 43 $Wm^{-1}K^{-1}$). Heat would be quickly conducted from the steel pipe to the advancing 'freezing front'. This could potentially allow ice lenses to begin to form anywhere around the pipe circumference, but particularly at the bottom of the pipe where there is likely to be more availability of 'free water' in the soil (i.e., a perched or shallow groundwater table). Hence, ice lenses could form beneath the pipe long before the regional freezing front ever reached that depth (Fig. 4.1).

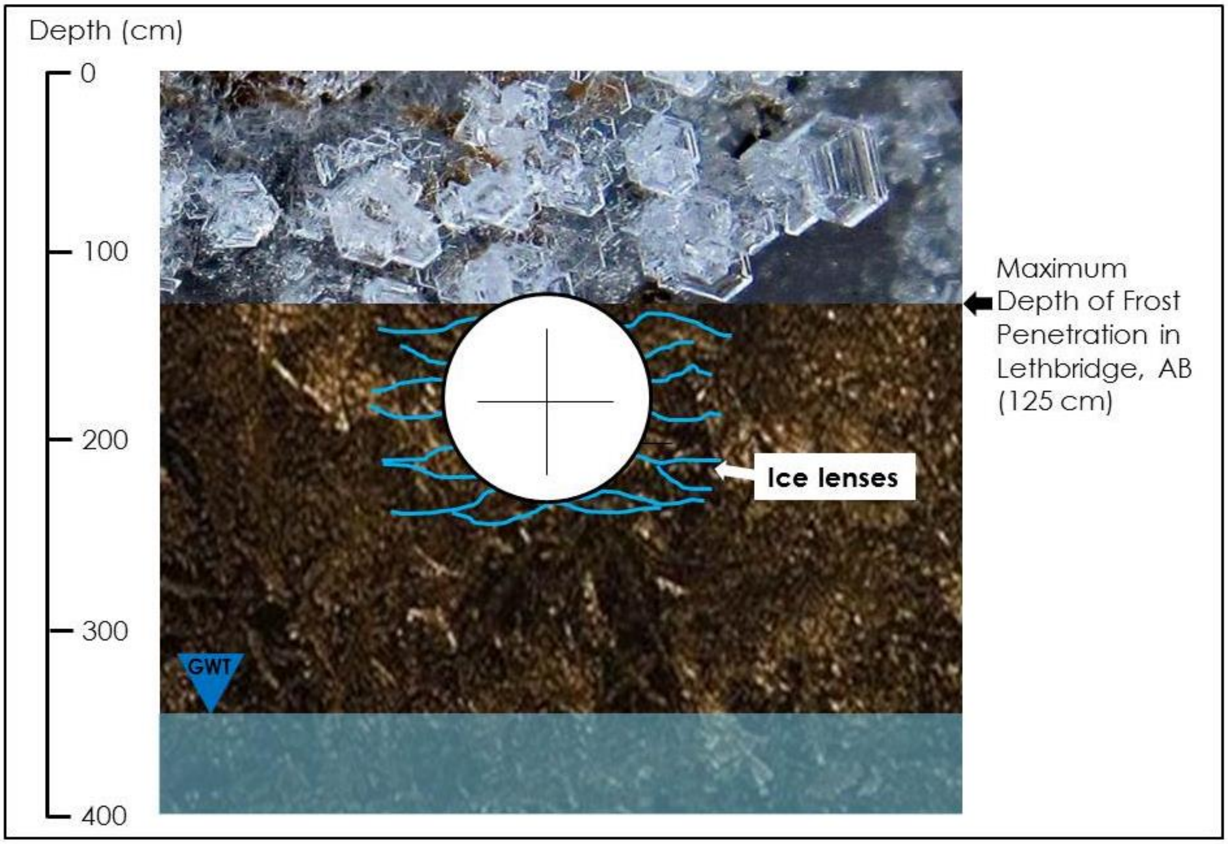


Figure 4.1: **The 'freezing index' (FI) method estimates a maximum frost penetration depth of 125 cm for Lethbridge, AB. Once the 0°C isotherm reaches the depth of the top of the pipeline (at 120 cm in this diagram), there would be rapid heat extraction from the steel pipe, and a significant risk of ice lenses forming around the pipe. 'GWT' denotes 'groundwater table'.**

An example of a more process-based simulation method is the SHAW 1D (Simultaneous Heat and Water, one dimensional) finite difference model of Flerchinger & Saxton (1989), which has been successfully used to predict the depth of frost penetration in Canada, U.S. and internationally.

4.3.2 Pipeline depth (LitRev3)

According to the National Energy Board, transmission pipelines are typically buried between 1 and 3 m below the surface in Canada (NEB, 2010, p. 36). Figure 4.2 illustrates this depth range for a hypothetical pipeline with a diameter of 100 cm. Transmission pipeline diameters can range up to 122 cm o.d. (or 48" o.d.). Figure 4.2 also shows a groundwater table at depth, which is critical to establishing the frost heave risk (i.e., source of 'free water' to an advancing freezing front). It should be noted that PARSC has recommended that a pipeline depth range of 90 to 120 cm (to the top of the pipeline) be used in any frost heave simulations in this study.

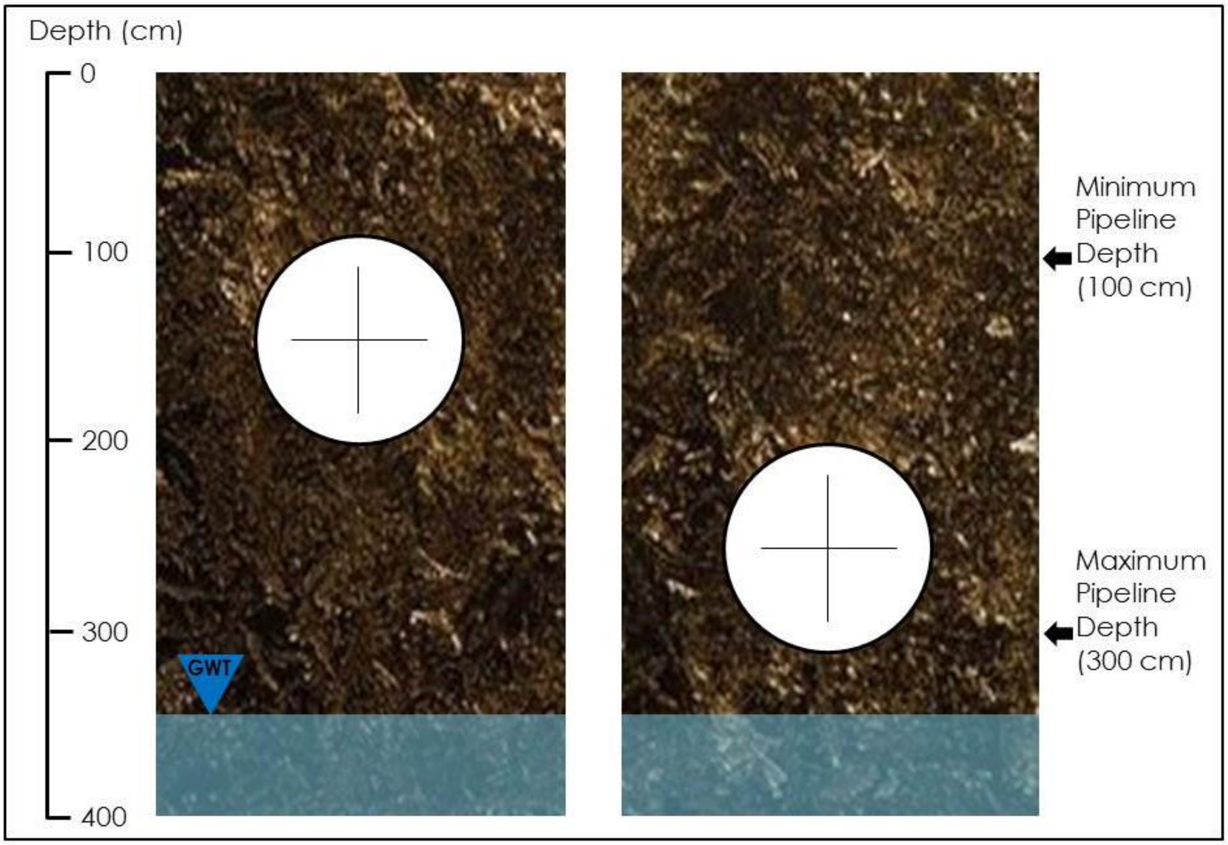


Figure 4.2: **Transmission pipelines are typically buried between 1 and 3 m below the surface in Canada (NEB, 2010). 'GWT' denotes 'groundwater table'.**

It was important in this study to review all available methods of measuring pipeline depth in soils. Pipeline companies require this information to allow monitoring of the effect of surface soil erosion and/or pipeline upheaval on altering the position of the pipe relative to the soil surface, potentially leading to exposure. Finally, incidental soil compaction that may arise from normal farm operations within pipeline ROWs is not considered to be a geohazard that could directly lead to pipeline exposure, but it can lead to a reduction in the depth of soil cover over pipelines (NEB, 2010, p. 31).

4.3.3 Soil structure and strength of frozen soils (LitRev4)

The changes in soil structural form and stability attributable to the freeze-thaw process (i.e., annual resiliency of soil structure) remain topics of considerable debate in the field of soil science. It was important to review the published research literature with respect to these structural changes, by way of the main processes operative in the soil during winter conditions. Pipelines are installed in trenches backfilled with structurally-disturbed soil (i.e., cementing agent bonds and age-hardening effects are disrupted), so the soil strength is likely to be different in the backfilled trench than in the natural field soil outside of the ROW (Ivey & McBride, 1999). This is important in assessing if the backfilled soil will be able to resist pipeline upheaval as the soil water and temperature regimes shift seasonally.

4.3.4 Water and wind erosion within transmission pipeline ROWs (LitRev5)

It was noted in Section 2 that water and/or wind erosion of soil are mechanisms that could cause transmission (hydrocarbon) pipeline exposure. It is important to review the published information on soil erosion within pipeline ROWs, and the potential for pipeline exposure caused by these soil degrading processes.

4.3.5 Update DNV (2010) report literature review on frost heaving (LitRev6)

Sufficient time (4 yrs) has elapsed since the release of the DNV (2010) scoping study that it would be important to re-confirm that report's conclusion that there are no known publications related specifically to frost heaving of abandoned pipelines.

The DNV (2010) study used two search engines for its literature review (Engineering Village; Science Direct), with a view to focusing primarily on engineering literature. The PARSC - 003 study, however, required a broader search of available literature on a much wider range of subject matter and experience. The fields of study encompassed in PARSC - 003 include pipeline engineering, soil science, agronomy, data base management systems (DBMS) for soils and climate, geographic information systems (GIS), etc. In addition to peer-reviewed literature, other sources needed to be accessed for the PARSC - 003 study, including:

- industry-specific magazines (e.g., Right of Way magazine) and non-academic/pseudo-scientific journals (e.g., Pipeline and Gas Journal)
- private-sector businesses that support the pipeline industry (e.g., conduct pipeline integrity surveys)
- dissertations
- government documents
- popular press

Consequently, the 'Google' and 'Google Scholar' search engines were used for all of the literature reviews conducted for the PARSC - 003 study, including geotechnical hazards and exposure of abandoned pipelines for *LitRev6*. For example, Google Scholar accesses most peer-reviewed online journals of the largest scholarly publishers in North America, Europe and elsewhere, in addition to scholarly books, other non-peer reviewed journals, etc.

The DNV (2010) report did not reveal the 'keywords' that were used to seek literature on the topic of frost heaving of abandoned pipelines, so it was not possible to emulate/update the original literature review systematically. The following are the keyword clusters used here in the publication search for *LitRev6*:

Keyword clusters:

abandoned pipeline frost heave
abandoned pipeline cold climate
abandoned pipeline geotechnical hazard
frost heave pipe
frost heave culvert

4.4 NUMERICAL MODELING (NumMod)

4.4.1 Preface

As noted in Section 2.4, the modeling approach anticipated at the outset of this study was the determination of a 'heave index' ($mm^2\ s^{-1}\ {}^{o}C^{-1}$, or $m^2\ s^{-1}\ K^{-1}$), with the SP parameter of Konrad (1999; 2005) and the HI parameter of Groenevelt & Grant (2013) being the strongest candidates. However, this modeling effort was not necessarily going to be to the exclusion of all other models investigated in the literature review of numerical models of frost heaving of soil (Section 4.2). If a more robust (yet practical) simulation model were to be identified in the literature review that warranted the same level of effort as the SP and HI parameter approach, the capability of this additional model would also be thoroughly investigated. Ultimately, the modeling approach adopted would need to be applicable to the major soil types found within the potential cropland regions of southern Canada (Fig. 2.9). Classes 1-3 in the Canada Land Inventory (Agriculture) capability system represent the 'prime' or 'quality' lands best suited for common field crop production in Canada.

4.4.2 Segregation Potential (Konrad, 1999; 2005)

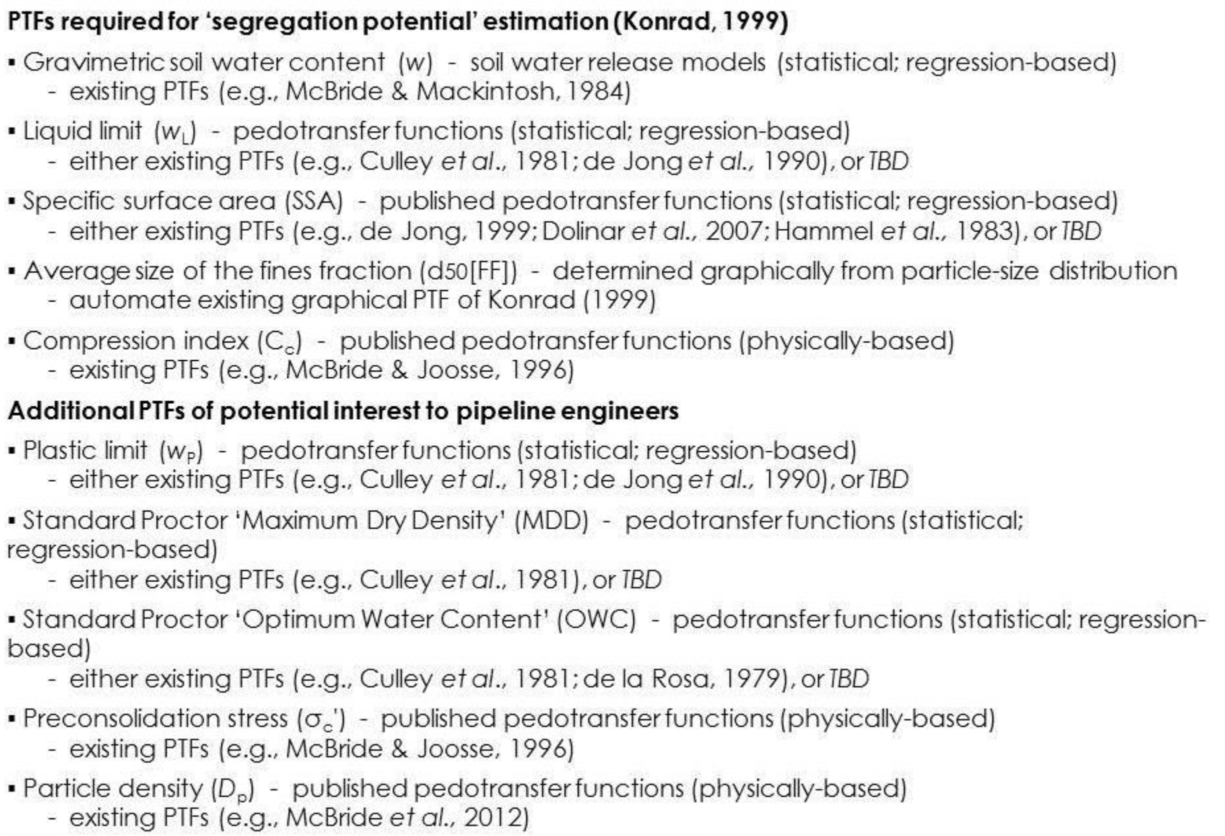
It was anticipated that the 'segregation potential' (SP) parameter would become part of the modeling effort in this study (Appendix A). Hence, a significant amount of background work was needed to operationalize the Konrad (1999; 2005) approach for cropland soils in southern Canada.

Konrad (1999) suggested that the ratio w/w_L is one of three parameters that define the relative frost heaving susceptibility of soils (Fig. A-1, Appendix A). A second key parameter is specific surface area (Aylmore, 2002), which is also closely correlated with the liquid limit (w_L). It is well known that clay content, soil organic carbon content and clay mineralogy strongly influence the soil consistency limits (McBride, 2007), largely by way of their influence on the specific surface area (Dolinar *et al.*, 2007; Hammel *et al.*, 1983). In order to easily relate estimates or measurements of w to the test index w_L (i.e., the ratio w/w_L) for soils in southern Canada, predictive equations would need to be developed allowing reliable estimation of w_L in different geographical regions of the country where the clay mineralogy may be different (Kodama, 1979).

Pedotransfer functions (PTFs) are predictive equations for certain soil properties that have been developed using data from existing published soil inventories (Wosten, 2002). As such, PTFs 'translate the data that we have into the information that we need'. PTFs add value to these basic data (e.g., soil constituent properties such as particle-size distribution, soil organic carbon content) by translating these data into estimates of other more laboriously- and expensively-determined soil properties that may be required for a particular physically-based model or soil/land quality assessment (e.g., geotechnical soil test indices).

A comprehensive literature review was carried out in this study to identify existing published PTFs for the required geotechnical soil test indices (e.g., liquid limit, specific surface area). Table 4.1 outlines the soil parameters that would need to be reliably estimated for the major soil types found on croplands in southern Canada, plus a few other soil physical/engineering properties that are likely to be of interest to pipeline engineers. For example, the liquid limit of soils in southern Saskatchewan could be estimated using the PTFs published by de Jong *et al.* (1990). Where required PTFs do not exist (e.g., soil consistency [Atterberg] limits of Ontario soils), geotechnical test data would need to be assembled from published soil inventories in order to develop the needed predictive equations.

Table 4.1: Soil parameters to be estimated using pedotransfer functions (TBD = 'PTFs to be developed')



PTFs required for 'segregation potential' estimation (Konrad, 1999)

- Gravimetric soil water content (w) - soil water release models (statistical; regression-based)
  - existing PTFs (e.g., McBride & Mackintosh, 1984)
- Liquid limit (w_L) - pedotransfer functions (statistical; regression-based)
  - either existing PTFs (e.g., Culley *et al*., 1981; de Jong *et al.*, 1990), or *TBD*
- Specific surface area (SSA) - published pedotransfer functions (statistical; regression-based)
  - either existing PTFs (e.g., de Jong, 1999; Dolinar *et al.*, 2007; Hammel *et al.*, 1983), or *TBD*
- Average size of the fines fraction (d50[FF]) - determined graphically from particle-size distribution
  - automate existing graphical PTF of Konrad (1999)
- Compression index (C_c) - published pedotransfer functions (physically-based)
  - existing PTFs (e.g., McBride & Joosse, 1996)

Additional PTFs of potential interest to pipeline engineers

- Plastic limit (w_P) - pedotransfer functions (statistical; regression-based)
  - either existing PTFs (e.g., Culley *et al*., 1981; de Jong *et al.*, 1990), or *TBD*
- Standard Proctor 'Maximum Dry Density' (MDD) - pedotransfer functions (statistical; regression-based)
  - either existing PTFs (e.g., Culley *et al*., 1981), or *TBD*
- Standard Proctor 'Optimum Water Content' (OWC) - pedotransfer functions (statistical; regression-based)
  - either existing PTFs (e.g., Culley *et al*., 1981; de la Rosa, 1979), or *TBD*
- Preconsolidation stress (σ_c') - published pedotransfer functions (physically-based)
  - existing PTFs (e.g., McBride & Joosse, 1996)
- Particle density (D_p) - published pedotransfer functions (physically-based)
  - existing PTFs (e.g., McBride *et al.*, 2012)

To our knowledge, this study would be the first of its kind where the Konrad (1999: 2005) approach to SP parameter estimation would be coupled with a wide array of PTFs (either already published, or to be developed in this study) for the purpose of estimating the frost heave susceptibility of soils in Canada. This approach to the PARSC - 003 project would produce a practical method for readily identifying soil conditions with high frost heave potential. This approach could also facilitate the use of existing soil inventories in Canada in linear facilities planning. Maps showing the spatial distribution of different degrees of soil susceptibility to frost heave could be created through application of established principles of soil survey interpretation.

4.4.3 Heave Index (Groenevelt & Grant, 2013)

It was anticipated that the 'heave index' (HI) parameter would become part of the modeling effort in this study (Appendix A). Hence, existing public domain or commercial models that simulate soil heat and water flux would be used to provide the soil water and temperature regime data needed to calculate HI in soil around an abandoned pipeline.

To illustrate, the SHAW 1D model (Section 4.3.1) would be used to estimate the maximum depth of frost penetration at a given location in southern Canada. Weather data sets could be assembled with a 'climate generator' for that geographic location. SHAW model simulations could be carried out for several different groundwater table positions, and several different winter weather conditions (30-yr climatic norm conditions; abnormally cold winter conditions; abnormally mild winter conditions). This could establish whether or not there is a potential problem with frost heave at that location. For example, if the 0°C isotherm does not reach the top of the pipeline (at a depth of perhaps 120 cm), there is essentially no risk of frost heave (Fig. 4.1).

However, if it is determined that there is a significant risk, the HYDRUS 2D 'soil heat and water flux' model might be used to provide the soil water and temperature regime data (in two dimensional space) needed to calculate the HI parameter and the risk of ice lens formation around the abandoned pipe.

4.5 PEDOTRANSFER FUNCTION DEVELOPMENT (PTFDev)

4.5.1 Preface

A brief background on PTF development was given in Section 4.4.2 in the context of soil information needs for the Konrad (1999; 2005) frost heave modeling approach (Fig. A-1, Appendix A), with emphasis on the 'liquid limit' (w_L), 'specific surface area' (SSA), and 'compression index' (C_c) soil parameters. The Konrad (1999; 2005) model also requires estimates of i) the 'average size of the fines fraction' (d_{50}[FF]), and ii) the soil water regime ('gravimetric soil water content' [w]), but the latter will not require new PTF development because of the large number of such PTFs available in the literature to choose from.

4.5.2 Estimation of soil consistency limits (Linear regression model calibration and validation)

Available data on soil physical and engineering properties were assembled for a large number of soil horizons characterized by the Ontario Centre for Soil Resource Evaluation, or OSCRE (formerly the Ontario Institute of Pedology, or OIP), for soil series mapped during the course of five municipal-level soil inventory upgrades in southern Ontario published over a decade (1984 -

1994). This calibration data set represented a wide range of the more important agricultural soil series in this part of the province, and were compiled from published soil inventory reports for the Regional Municipality of Haldimand-Norfolk (Presant & Acton, 1984), the Regional Municipality of Niagara (Kingston & Presant, 1989), Middlesex County (Hagerty & Kingston, 1992), Elgin County (Schut, 1992) and Kent County (Wilson, 1994). Together, this group of five municipalities encompassed a large contiguous geographic region (about 12,000 km^2) along the northern shore of Lake Erie underlain by sedimentary Paleozoic parent rock of Silurian and Devonian ages (Fig. 4.3).

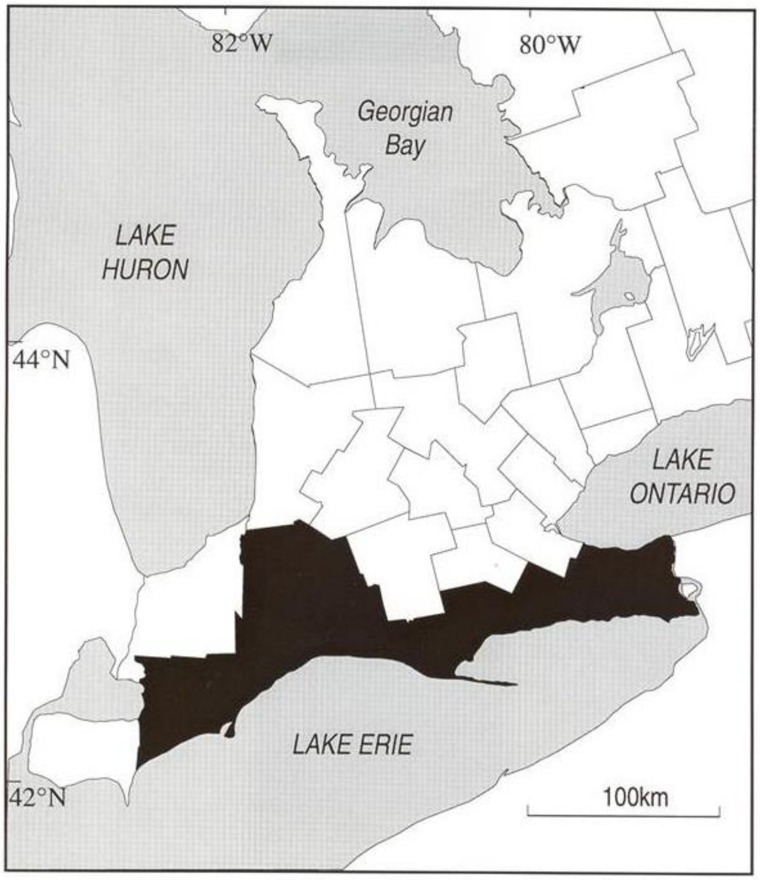


Figure 4.3: The five municipalities in southern Ontario (shown in black) from where soil data were assembled for pedotransfer function development.

A total of 203 soil horizons from 71 soil profiles were identified that had measured data on particle-size distribution, soil organic carbon (SOC) content, dry bulk density (D_b), the soil consistency (Atterberg) limits, and the Standard Proctor Density test indices. The SOC content was measured by wet oxidation, using ortho-phenanthroline-ferrous sulfate as an indicator (McGill, 1978). Particle-size analysis was carried out by the pipette method after pretreatment with hydrogen peroxide and calgon (Green, 1978a), and D_b was determined by the structurally-intact core method (Green, 1978b). All soil properties had been measured from bulk soil samples taken from exposed soil pit walls, except for D_b which was reported as means of up to nine (but no less than three) individual structurally-intact cores per horizon (5.0 cm long x 4.7 cm diameter).

The soil consistency limit data originated from the accredited Soils and Aggregates Section laboratory, Highway Engineering Division, Ontario Ministry of Transportation and Communications, Toronto, ON. The plastic limit (w_P) (ASTM D424-71) and liquid limit (w_L) (ASTM D423-72) tests were carried out in accordance with standard ASTM procedures (ASTM, 1981). The particle-size distribution and SOC content data originated from a soil analytical laboratory accredited by OMAFRA (Ontario Ministry of Agriculture, Food and Rural Affairs). The D_b data originated from a soil test laboratory at the University of Guelph operated by OSCRE/OIP.

Pearson's correlations and multiple regressions were performed with the PROC CORR and PROC REG procedures, respectively, in SAS/STAT (SAS Institute Inc., 2002).

An existing published data set (Joosse & McBride, 2003) was utilized as an independent validation data set. Physical and chemical properties were reported for 36 soil horizons sampled from 12 soil profiles at 4 different locations in southern Ontario (Table 1 in Joosse & McBride [2003]). The measured properties included w_P, w_L, particle-size distribution, SOC content, $CaCO_3$ content and pH. Details on the laboratory methods used can be found in Joosse & McBride (2003). Simple linear regressions were performed with the PROC REG procedure in SAS/STAT (SAS Institute Inc., 2002).

4.5.3 Estimation of specific surface area

A literature review was carried out on existing published PTFs that permit the reliable estimation of the specific surface area (SSA) of soils. Because there are very little published data available for this soil parameter in Canada, there was no opportunity to engage in PTF development of the sort outlined in Sections 4.5.2 and 4.5.5 (i.e., 'data mining'). Hence, the best available existing PTF was selected from the literature review and used in this study.

4.5.4 Estimation of the compression index of cohesive soils

The influence of overburden pressure on frost heave and the 'segregation potential' (SP) can be accounted for by an empirical relationship involving the compression index (C_c) of the soil (Konrad, 1999). The best available existing PTF for soil compressibility estimation was selected from a review of available literature, and was used in this study to reliably estimate C_c for cohesive soils in southern Ontario.

4.5.5 Estimation of Standard Proctor density test indices (Linear regression model calibration)

Data on the Standard Proctor Density test indices (‘Maximum Dry Density’ [MDD] and ‘Optimum Water Content’ [OWC]) were available in the same data set described in Section 4.5.2 above (i.e., 203 soil horizons from 71 soil profiles in southern Ontario). The Standard Proctor test index data originated from the accredited Soils and Aggregates Section laboratory, Highway Engineering Division, Ontario Ministry of Transportation and Communications, Toronto, ON. The MDD and OWC (ASTM D698) tests were carried out in accordance with standard ASTM procedures (ASTM, 1981).

These test indices are useful measures of soil strength or degree of soil overconsolidation in order to contrast soil strength within a pipeline trench area to that outside the ROW (Ivey & McBride, 1999) during different soil water and temperature regime conditions. This information can help to assess the susceptibility of pipelines to exposure caused by frost heave (i.e., overburden pressure). PTFs were developed for these two parameters using the same statistical procedures described in Section 4.5.2 above.

4.5.6 Estimation of average size of the fines fraction

Konrad (1999) reports a graphical technique that can be used to estimate the ‘average size of the fines fraction’ (d_{50}[FF]) of soils from particle-size distribution data. An effort was made to ‘automate’ that manual procedure in order to facilitate use of the d_{50}(FF) parameter in model computations.

4.6 REFERENCES (SECTION 4)

ASTM. 1981. Annual Book of ASTM Standards, Part 19. American Society for Testing and Materials. West Conshohocken, PA.

Aylmore, L.A.G. 2002. Specific surface area. p. 1289-1292. *In* R. Lal (ed.). Encyclopedia of Soil Science. 1st edition. Marcel Dekker, Inc., New York, NY.

Chisholm, R.A. and W.A. Phang. 1981. Aspects of prolonged exposure of pavements to sub-zero temperatures. Part 1 - Measurement and prediction of frost penetration in highways. Policy Planning and Research Division, Ontario Ministry of Transportation and Communications, Downsview, ON. 75 pp.

Culley, J.L.B., B.K. Dow, E.W. Presant and A.J. MacLean. 1981. Impacts of installation of an oil pipeline on the productivity of Ontario cropland. Research Branch, Agriculture Canada. LRRI Contribution No. 66. 88 pp.

de Jong, E. 1999. Comparison of three methods of measuring surface area of soils. Can. J. Soil Sci. 79:345-351.

de Jong, E., D.F. Acton and H.B. Stonehouse. 1990. Estimating the Atterberg limits of southern Saskatchewan soils from texture and carbon contents. Can. J. Soil Sci. 70:543-554.

de la Rosa, D. 1979. Relation of several pedological characteristics to engineering qualities of soil. J. Soil Sci. 30:793-799.

Det Norske Veritas (DNV). 2010. Pipeline abandonment scoping study. A report prepared for the National Energy Board (NEB). 85 pp. Available at: http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnbndnmnt/pplnbndnmntscpngstd.pdf (verified Oct. 6, 2014)

Dolinar, B, M. Misic and L. Trauner. 2007. Correlation between surface area and Atterberg limits of fine-grained soils. Clays Clay Miner. 55:519-523.

Flerchinger, G. N. and K. E. Saxton. 1989. Simultaneous heat and water model of a freezing snow-residue-soil system I. Theory and development. Trans. ASAE 32:565-571.

Green, A.J. 1978a. Particle-size analysis. p. 4-29. *In* J.A. McKeague (ed.). Manual on soil sampling and methods of analysis. 2nd edition. Canada Soil Survey Committee, Canadian Society of Soil Science.

Green, A.J. 1978b. Bulk density and particle density. p. 29-37. *In* J.A. McKeague (ed.). Manual on soil sampling and methods of analysis. 2nd edition. Canada Soil Survey Committee, Canadian Society of Soil Science.

Groenevelt, P.H. and C.D. Grant. 2013. Heave and heaving pressure in freezing soils: A unifying theory. Vadose Zone J. 12(1). 11 pp.

Hagerty, T.P., and M.S. Kingston. 1992. The soils of Middlesex County. Report No. 56 of the Ontario Centre for Soil Resource Evaluation. Queen's Printer for Ontario, Toronto, ON.

Hammel, J.E., M.E. Sumner and J. Burema. 1983. Atterberg limits as indices of external surface areas of soils. Soil Sci. Soc. Am. J. 47:1054-1056.

Ivey, J.L. and R.A. McBride. 1999. Delineating the zone of topsoil disturbance around buried utilities on agricultural land. Land Degradation and Development 10:531-544.

Joosse, P.J., and R.A. McBride. 2003. Assessing physical soil quality of plastic soils of differing mineralogy and pre-stress history using mechanical parameters: I. Saturated compression tests. Can. J. Soil Sci. 83:45-63.

Kingston, M.S., and E.W. Presant. 1989. The soils of the regional municipality on Niagara. Report No. 60 of the Ontario Institute of Pedology. Queen's Printer for Ontario, Toronto, ON.

Kodama, H. 1979. Clay minerals in Canadian soils: their origin, distribution and alteration. Can. J. Soil Sci. 59:37-58.

Konrad, J.-M. 1999. Frost susceptibility related to soil index properties. Can. Geotech. J. 36:403-417.

Konrad, J.-M. 2005. Estimation of the segregation potential of fine-grained soils using the frost heave response of two reference soils. Can. Geotech. J. 42:38-50.

McBride, R.A. 2007. Soil consistency: upper and lower plastic limits. p. 761-769. *In* M.R. Carter and E.G. Gregorich (eds.) Soil sampling and methods of analysis. Canadian Society of Soil Science. CRC Press, Taylor & Francis Group, Boca Raton, FL.

McBride, R.A. and P.J. Joosse. 1996. Overconsolidation in agricultural soils: II. Pedotransfer functions for estimating preconsolidation stress. Soil Sci. Soc. Am. J. 60:373-380.

McBride, R.A. and E.E. Mackintosh. 1984. Soil survey interpretations from water retention data: I. Development and validation of a water retention model. Soil Sci. Soc. Am. J. 48:1338-1343.

McBride, R.A., R.L. Slessor and P.J. Joosse. 2012. Estimating the particle density of clay-rich soils with diverse mineralogy. Soil Sci. Soc. Am. J. 76(2):569-574.

McGill, W.B. 1978. Organic carbon by wet oxidation (modified Walkley-Black method). p. 115-117. *In* J.A. McKeague (ed.). Manual on soil sampling and methods of analysis. 2nd edition. Canada Soil Survey Committee, Canadian Society of Soil Science.

Mullins, T. 2003. Permafrost and Frozen Ground Bibliography (1978 - 2003). Glaciological Data (Report GD-31). National Snow and Ice Data Centre, World Data Center for Glaciology, Boulder, CO. 1150 pp.

National Energy Board (NEB). 2010. Pipeline Regulation in Canada: A Guide for Landowners and the Public. Revised September 2010. NEB Publications Office, Calgary, AB. 56 pp. Available at: http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnrgltncnd/pplnrgltncnd_ndx-eng.html (verified Oct. 6, 2014)

Presant, E.W., and C.J. Acton. 1984. The soils of the regional municipality on Haldimand-Norfolk. Report No. 57 of the Ontario Institute of Pedology. Queen's Printer for Ontario, Toronto, ON.

SAS Institute Inc. 2002. SAS/STAT software user's guide. Version 9.1.3, SAS Institute Inc., Cary, NC.

Schut, L.W. 1992. The soils of Elgin County. Report No. 63 of the Ontario Centre for Soil Resource Evaluation. Queen's Printer for Ontario, Toronto, ON.

Wilson, E.A. 1994. The soils of Kent County. Preliminary maps no. 38, 39 and 40, scale 1:50,000. Ontario Centre for Soil Resource Evaluation. Queen's Printer for Ontario, Toronto, ON.

Wosten, J.H.M. 2002. Pedotransfer functions. p. 967-971. *In* R. Lal (ed.). Encyclopedia of Soil Science. 1st edition. Marcel Dekker, Inc., New York, NY.

5.0 STUDY RESULTS

5.1 PREFACE

The full details on the study findings/results are compiled in a series of Appendices in Volume 2 of the PARSC - 003 report. The ensuing Sections 5.2 - 5.5 are comprised of overview summaries of the content of the relevant Appendices, as follows:

<u>Core Literature Search (Section 5.2 - *Research Objective #1*):</u>

- Appendix B (Narrative Paper on Frost Heave Models)
- Appendix C (Annotated Bibliography on Frost Heave Models)

<u>Secondary Literature Searches (Section 5.3):</u>

- Appendix D (Frost Penetration Depth in Soils)
- Appendix E (Pipeline Depth)
- Appendix F (Soil Structure and Strength of Frozen Soils)
- Appendix G (Water and Wind Erosion within Transmission Pipeline ROWs)
- Appendix H (Update DNV [2010] Report Literature Review on Frost Heaving)

<u>Numerical Modeling (Section 5.4 - *Research Objective #3*):</u>

- Appendix A ('Segregation Potential' and 'Heave Index' Concepts)
- Appendix I (Programming Code for the *Konrad_SP1.0* Frost Heave Model [Mathcad version])
- Appendix J (Example Output from the *Konrad_SP1.0* Frost Heave Model)
- Appendix Q (Relationships between Internal Soil Drainage Class and Seasonal Groundwater Table Depth)
- Appendix R (Soil Landscapes of Canada [SLC3.2])
- Appendix S (Variation of Regional Geoclimatic Conditions across Southern Canada)
- Appendix T (Pipeline Segments Abandoned-in-Place [Variable Diameter & Length])

<u>Pedotransfer Function Development (Section 5.5 - *Research Objective #2*):</u>

- Appendix K (Estimation of the Consistency [Atterberg] Limits of Southern Ontario Soils)

- Appendix L (Estimation of the Specific Surface Area of Soils)
- Appendix M (Estimation of the Compression Index of Southern Ontario Soils)
- Appendix N (Estimation of the Standard Proctor Density Test Indices of Southern Ontario Soils)
- Appendix O (Five Municipality Soil Data Set for Southern Ontario)
- Appendix P (d_{50}[FF]soil particle-size distribution parameter)

5.2 CORE LITERATURE SEARCH (NUMERICAL MODELS OF FROST HEAVING IN SOILS [LitRev1])

5.2.1 Annotated bibliography

A total of 31 papers underwent a rigorous review in this annotated bibliography. The most important group of research publications to this study belonged to Category I, since they are most relevant to frost heave of pipelines. Category I is dominated by researchers from the ‘Anderson School’ (most notably Dr. J.-M. Konrad), although the ‘Miller School’ is represented (Groenevelt & Grant, 2013).

5.2.2 Narrative-style paper

This narrative paper examines in great detail the findings from two publications, each representing one of the two ‘schools of thought’ on frost heave in soils. Out of the ‘Anderson School’ (CRREL) came the concept of the ‘segregation potential’ (SP). Out of the ‘Miller School’ (Cornell University) came the model for the frost heave rate. Critical examination of the two papers leads to the formulation of a unifying theory for the thermodynamic process of heave in freezing soils. Ideas from both ‘Schools’ are put on a fundamental thermodynamic footing leading to the formulation of a ‘Heave Index’ (HI). Both ‘Schools’ use, as the driving force for heave, the temperature gradient in the frozen fringe. It is argued and demonstrated that this choice leads to erratic results. The driving force should be the temperature gradient over the entire layer of soil that is at sub-zero temperatures (i.e., the combined frozen zone plus the frozen fringe). The value of HI is completely dominated by the hydraulic conductivity function (saturated or unsaturated) of both of i) the unfrozen soil below the frozen fringe, and ii) the soil layer at sub-zero temperatures.

5.3 SECONDARY LITERATURE SEARCHES

5.3.1 Frost penetration depth in soils (LitRev2)

A review of available literature was carried out on the subject of frost penetration depth in soils, which included mostly relevant research (peer-reviewed journal articles), but also some government and university technical reports, and unrefereed scientific conference proceedings. The full literature review can be found in Appendix D (i.e., 31 references), and the main highlights are listed below in point-form.

Key Findings:

- the main factors controlling the downward movement of a ‘freezing front’ (or ‘0°C isotherm’) into the ground are climate, geographic position, soil type, soil water content, and surface cover (vegetation, snow)
- the main methods of tracking the depth/thickness of frozen soil in the field include i) direct physical probing, ii) field installation of ‘frost tubes’, iii) field measurement of soil temperature profiles using instrument nests, and iv) the use of empirical or analytical/numerical models
- good examples of empirical and analytical/numerical model types are i) the ‘freezing index’ (FI), and ii) the SHAW 1D finite difference model, respectively
- much of the research on frost penetration depth has been carried out by highway engineers working with asphalt/concrete or aggregate surfaces that are free of snow and ice in winter
- bare soils represent the ‘worst case scenario’ in terms of the maximum depth of the freezing front, because there is no insulating cover of snow or vegetation
- many researchers have noted a strong curvilinear relationship when the maximum depth of frost penetration is plotted against FI
- results from the FI method suggest that, in the three prairie provinces (AB, SK, MB) and QC, abandoned pipelines would have to be positioned deeper than 120 cm below the soil surface in order to avoid coming into contact with frozen soils during an average winter season
- at least one study showed that a function directly relating measured frost heave in roadways to FI was linear (i.e., strong positive correlation), and that shallow groundwater tables induced greater frost heave
- a simple ‘climate-only’ model (i.e., requiring only air temperature data) was required to estimate the maximum depth of frost penetration for the reconnaissance ‘Tier 1’ frost heave modeling effort (PARSC - 003 study). Based on the literature review findings, the FI method is recommended
- a more complex ‘climate and soil’ model was required to estimate the depth of frost penetration for the ‘Tiers 2 and 3’ frost heave modeling effort (PARSC - 003 study). Based on the literature review findings, the SHAW 1D finite difference model is recommended

5.3.2 Pipeline depth (LitRev3)

A review of available literature was carried out on the subject of pipeline depth, which included relevant research (peer-reviewed journal articles), the regulatory environment (government documents and legislation), and general information from practitioners on pipeline integrity surveys (private-sector websites). The full literature review can be found in Appendix E (i.e., 24 references), and the main highlights are listed below in point-form.

Key Findings:

- the 'depth of soil cover' (DOC) issue is self-regulated within the Canadian pipeline industry by way of the 'Excavation Damage Prevention Toolbox', which is 'a collection of damage prevention shared learnings and practices for onshore, hazardous liquid transmission pipeline operation'. The EDP Toolbox specifies that the minimum DOC should be 80 cm in Alberta and 60 cm in the rest of Canada
- in cropland areas in Ontario, pipeline companies generally try to ensure that pipelines are placed deeper than existing or proposed sub-surface tile drain systems (up to 120 cm deep) or municipal drains
- internationally, numerous private-sector companies carry out a wide range of 'pipeline integrity' investigations, including DOC surveys (onshore and offshore)
- DOC surveys are conducted using a wide array of non-contacting geophysical instruments (from the surface), 'smart pigs' (from within the pipeline itself), and other methods
- incidental soil compaction from normal farm operations occurring within pipeline ROWs is not a direct potential geotechnical cause of pipeline exposure, but it can lead to a reduction in the depth of soil cover over pipelines
- soil compaction is a significant form of land degradation in all agricultural areas of Canada, except the semi-arid Prairie Ecozone

5.3.3 Soil structure and strength of frozen soils (LitRev4)

As noted in Section 4.3.3, the changes in soil structural form and stability/strength attributable to the freeze-thaw process remain topics of considerable debate in the soil science field. A comprehensive review of the published research literature was carried out, with a view to summarizing any established or emerging consensus on these soil structural changes in cold climate regions, and the main processes responsible. The full unabridged literature review can be found in Appendix F (i.e., 170 references, spanning research from almost the last 100 years), and the main highlights are listed below in point-form. Overall, the published research literature on this topic area reveals a great deal of contradictory results, so it is difficult to derive broad, general conclusions that are widely supported by reproducible research findings.

Key Findings:

- the freezing of soil pore water can result in the formation of different types of ice, such as granular, honeycomb or stalactite frost
- the formation of pore ice is viewed primarily as a destructive force in terms of soil structural integrity, although a few studies note improved soil aggregation. Structurally-destructive pore ice is the result of rapid freezing rates at high water contents close to the soil surface. The growth of intra-aggregate ice crystals may shatter aggregates, or expanding inter-aggregate ice may either crush aggregates or compress them into a more stable configuration
- segregational ice involves the formation of ice lenses under slower rates of freezing at greater depths in the soil profile. The upward water migration towards the growing ice lens leads to desiccation and consolidation of both the underlying soil and the inter-lens layers. At the same time, structural discontinuities are formed in the soil at the ice lens locations
- the approximate 9% volumetric expansion resulting from ice formation has been observed to rupture existing aggregates and increase the proportion of fine material
- many small crystals associated with pore ice have been observed to destroy the soil micro-structure by disrupting the micro-pore fraction, rather than the aggregates themselves, and to increase aggregation through compression
- at low soil water contents, the pore system may be sufficiently empty to largely accommodate the volumetric expansion associated with pore water freezing. However, as water contents rise, the pore system is less able to accommodate this expansion, and structural deterioration may result
- at soil water contents below approximately 65% saturation, freezing-induced desiccation of the soil surrounding the growing pore ice can lead to volumetric shrinkage in the soil
- ice crystal growth has the effect of compressing the soil aggregates and increasing the size of inter-aggregate pores
- constructive macro-pore freezing occurs at temperatures only slightly below freezing, while destructive micro-pore freezing occurs at colder temperatures
- increases in the length of time a soil experiences near freezing temperatures is more destructive (i.e., freeze-thaw cycles reduce aggregation, while continuously frozen conditions has the opposite effect)
- greater structural stability of aggregates occurs at greater depth, where the ultimate freezing temperatures are less cold
- in addition to pore ice, segregation ice may also have an overall destructive influence on soil structure

- aggregate stability is generally inversely related to the number of freeze-thaw cycles
- a 50% reduction in soil shear strength has been observed after the first freeze-thaw cycle, but little change occurs with additional cycles
- there is some evidence that soil water redistribution continues within a frozen soil
- as continuously frozen conditions allow greater development of ice lenses, the consolidation and desiccation of the soil may be much more extensive, resulting in an increase in structural stability over that resulting from freeze-thaw cycles
- increased aggregation is observed with freeze-thaw in clay-rich soils. It is thought that the presence of clay aids in the formation of bridges between soil particles, thus increasing aggregation
- the presence of polyvalent cations is generally assumed to contribute to greater structural stability through stronger interlayer bonding
- lower sub-zero temperatures reduce the thickness of the adsorbed layers resulting in desiccation and consolidation of the clay
- organic matter is often viewed as a soil constituent responsible for good structural form and stability. Any beneficial effects due to elevated organic matter levels may not be sustained throughout the winter if numerous freeze-thaw cycles occur
- a bare soil surface will both freeze and thaw more rapidly than one with an insulative cover of mulch or crop residue
- soils with higher initial water contents have generally been found to experience a greater degree of water re-distribution and greater structural modification upon freezing
- the presence of an insulative snow cover may be beneficial in terms of reducing the magnitude and frequency of freeze-thaw events, or destructive freeze-drying events
- on flat soil surfaces, the freezing front penetrates uniformly into the soil *ceteris paribus*, and one-dimensional freezing results. An irregular, cloddy surface causes a variable advancement of the freezing front, with freezing being more three-dimensional in nature
- while frozen soil can exhibit shear strengths over an order of magnitude higher than in their pre-frozen state, post-thaw strengths can be over an order of magnitude lower, depending largely on the water content at the time of freezing
- immediately following thaw, large decreases in shear strength are typically observed as the locations of former ice lenses become failure planes within the soil. However, an increase in strength to near pre-freeze levels is often noted following ‘thaw consolidation’. Thaw consolidation is a loss in soil volume and a decrease in pore size resulting from the de-watering of a thawing soil

- there is evidence that, without thaw consolidation, the soil would possess a poor structural state in the spring
- initially loose samples typically show greater increases in strength with freezing than do initially consolidated samples, likely due to the consolidation resulting from the freezing process
- most researchers have noted an increase in macro-porosity, particularly in fine-textured soils, as a result of freeze-thaw processes
- some researchers have found that thawed soil permeability is isotropic, resulting from the formation of both vertical and horizontal fissures as a result of freezing. Others maintain that only the horizontal permeability is dramatically increased as a result of the discontinuities remaining in sites of former ice lenses
- the most rapid freezing occurs at the soil surface, resulting in the likely formation of more structurally-damaging pore ice
- as thawing proceeds from the surface downwards, the existence of underlying soil that is still frozen may inhibit drainage. This wetting could lead to rapid aggregate breakdown through slaking or differential swelling. 'Cryo-slaking' is a process where air expulsion during thaw induces structural collapse
- when frozen soil is freeze-dried, ice sublimates from the pore system in the vapour phase, without melting. Such conditions are particularly likely in the late winter over bare soil surfaces during periods of low atmospheric humidity and high wind speeds
- pressures due to segregational frost heaving have been estimated to be in excess of 100 kPa
- desiccation-induced shrinkage may alone be responsible for the increased aggregation and structural stability noted immediately after freezing

5.3.4 Water and wind erosion within transmission pipeline ROWs (LitRev5)

A review of available literature was carried out on the subject of wind and water erosion (including mass movement of soil) within transmission pipeline ROWs, which included relevant research (peer-reviewed journal articles), pseudo-scientific articles, case studies, dissertations, and general information from practitioners in the field of erosion control and site stabilization within pipeline ROWs (private-sector websites). The full literature review can be found in Appendix G (i.e., 30 references), and the main highlights are listed below in point-form.

Key Findings:

- wind and/or water erosion (including mass movement of soil) are i) significant forms of land degradation in all agricultural areas of Canada, and ii) geotechnical hazards that can potentially reduce the 'depth of soil cover' (DOC), cause pipeline exposure, or even pipeline failure

- the 'Universal Soil Loss Equation' (USLE) has been the tool of choice internationally for soil conservation planning (water erosion) for the last 30+ years, and is used extensively by pipeline engineers to determine i) the appropriate spacing of diversion berms on pipeline ROWs, and ii) pipeline exposure risk
- geotechnical engineers proactively design and build a number of water erosion control features within pipeline ROWs where the terrain conditions warrant it, including subdrains, 'ditch plugs' ('sack breaker' or 'sand-bentonite' types), and 'diversion berms' ('waterways')
- internationally, numerous private-sector companies provide a wide range of services pertaining to erosion control and site stabilization on pipeline ROWs
- for pipelines abandoned-in-place, ground subsidence due to corrosion and structural failure of the pipelines is not believed to be an imminent problem (particularly for smaller diameter pipelines), nor a significant source of near-term water erosion risk within pipeline ROWs
- wind erosion is the dominant process responsible for the decline in agricultural soil quality in the Prairie Ecozone
- the Wind Erosion Prediction System (WEPS) has been the tool of choice internationally for soil conservation planning (wind erosion) for the last 20 years
- many different types of wind barriers have been used with varying degrees of success on pipeline ROWs to reduce wind erosion damage, including 'wood-strand erosion control mulch', agricultural straw, native hay mulch, brush mulch, net structures, and snow fencing

5.3.5 Update DNV (2010) report literature review on frost heaving (LitRev6)

A review of available literature was carried out on the subject of frost heaving of abandoned pipelines. No articles were found that were specific to this topic area, but there was some pertinent proxy information on frost heave of culvert pipes. A list of eight references (with abstracts) is provided in Appendix H.

5.4 NUMERICAL MODELING (NumMod)

5.4.1 Preface

The methodology used in the numerical modeling component of this study is outlined in Section 4.4, and examples of the programming code and tabulated output of the *Konrad_SP1.0* model are provided in Appendices I and J, respectively.

5.4.2 Three-tiered approach to modeling frost heave in soils

5.4.2.1 Tier 1

At the Tier 1 (broadest) level, a modeling approach was required where the main applications would be:

i. to carry out generalized risk assessments (for frost heave in soils) at a regional scale, or broader reconnaissance levels

ii. to pre-screen a specific geographic area or pipeline ROW for frost heave risk, and 'red flag' areas that may require a Tier 2 (and possibly Tier 3) analysis (Fig. 5.1)

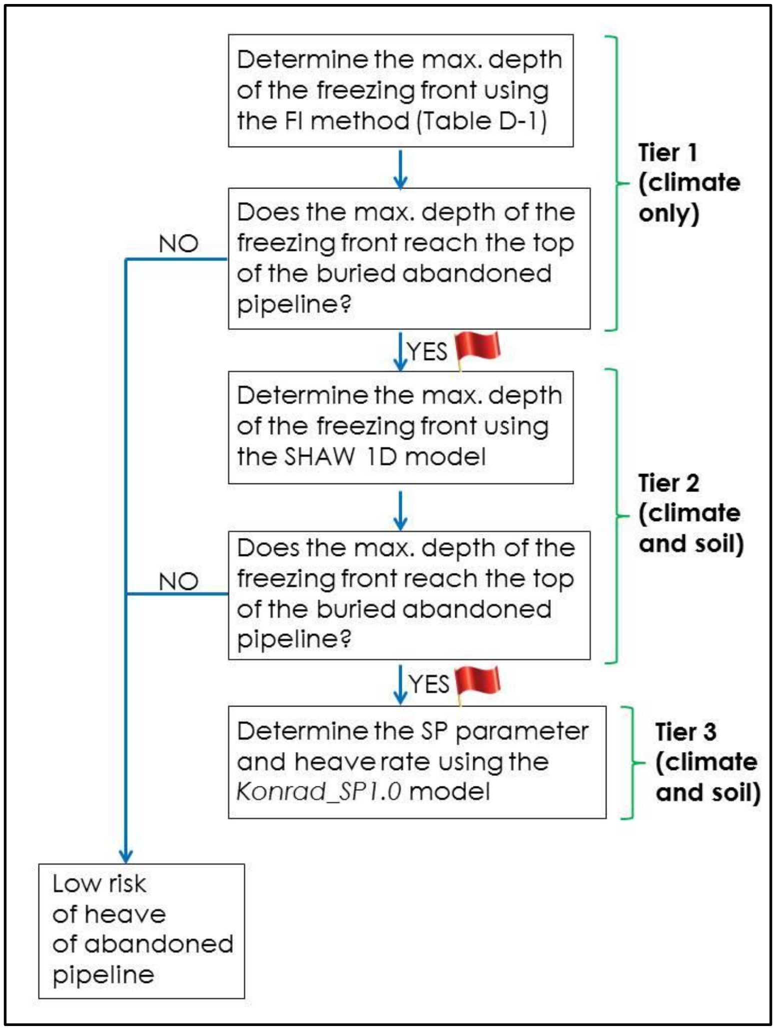


Figure 5.1: Flowchart of the 3-tiered decision support system for determining the risk of heave of abandoned pipelines.

At this broad reconnaissance level, the input data requirements had to be kept to a minimum. The literature review conducted on 'frost penetration depth in soils' (see Appendix D) clearly indicated that the 'freezing index' (FI) approach (with possible refinements for daylength and sun angle) was the method of choice for Tier 1. The FI approach to estimating the maximum depth of the freezing front in soil requires only air temperature data (i.e., a 'climate-only' modeling approach). Any geographic location in southern Canada can be evaluated, under a 'worst case scenario' set of site conditions (i.e., bare soil; no vegetative cover; no snow pack). If long-term mean depths of frost penetration are required, 30-year climatic normal data for mean daily air temperature are required.

Table D-1 (Appendix D) provides i) the freezing index (^{o}C·day), and ii) the estimated maximum depth of the freezing front, for 177 locations across Canada based on 30-year climatic normal data for mean daily air temperature. Only if the 0^{o}C isotherm reaches the depth of the top of an abandoned pipeline (i.e., at a depth of perhaps 90 - 120 cm) would there be any risk of frost heave of the pipe.

Figure D-5 (Appendix D) shows a map of isotherms of 'annual total freezing degree-days below 0^{o}C' for Canada. It may be possible to develop a more useful nation-wide map of frost penetration depth for southern Canada using 'kriging' software.

5.4.2.2 Tier 2

At the Tier 2 level, a modeling approach was required where the main application would be:

i. to conduct a more detailed analysis of a specific geographic area or pipeline ROW for frost heave risk (after being 'red flagged' in Tier 1 [Fig. 5.1])

A more complex 'climate and soil' model was required to estimate the depth of frost penetration for the Tiers 2 and 3 frost heave modeling effort. At this more detailed site-specific scale, it would be necessary to use a one-dimensional (1D) modeling approach that would i) require both soil and climate data, and ii) simulate a more realistic set of site conditions than in Tier 1 (i.e., soil has a vegetative cover and/or a snow pack). In this study, the soil data would originate from SLC3.2 (see Appendix R). As for the climatic analysis, it was concluded from the literature review in Appendix D that the SHAW 1D model is the recommended method of choice for the PARSC - 003 study (i.e., for heat and water flux simulation modeling). Most researchers with an interest in estimating the depth of frost penetration in cold climate regions regard the SHAW 1D model as i) 'time-tested and proven', and ii) the 'state-of-the-art' model of choice for most freezing soil applications. As with Tier 1, only if the 0^{o}C isotherm reaches the depth of the top of an abandoned pipeline (i.e., at a depth of perhaps 90 - 120 cm) would there be any risk of frost heave of the pipe.

It was decided that all new computer programming that would be required to operationalize models under Tiers 2 and 3 would use the open source 'Python' programming language (Python Software, 2014). The SHAW 1D model is freely available to download from a USDA-ARS website (USDA-ARS, 2008). The most current release of SHAW 1D is version 2.3.6 (made available in November 2004), but it is written in an early version of the Fortran programming language which is becoming progressively less compatible with newer PC operating systems. As a result, our Stantec research group made an attempt to translate the Fortran program code (over 200 pages) into the Python programming language, but this attempt was unsuccessful. Hence, for the time being, SHAW 1D will have to be run exogenously to the main *Konrad_SP1.0* model (see Tier 3 discussion below), which is compiled in the Python programming language.

At the time of writing, our Stantec research group had initiated an online search for one or more researchers who have experienced the same operational difficulties with SHAW v2.3.6, and may have successfully translated the Fortran program code to a more PC-friendly programming language (see Section 7.4). The following is the introductory passage being used in those initial email contacts:

"Our research group at the University of Guelph has been using the SHAW model for more than fifteen years in various geoclimatic projects. We have been very satisfied with both the implementation and the modeled results. With the continued development of PC-based operating systems, however, we have encountered significant compatibility issues which are restricting our ability to use the model. With this in mind, we would like to enquire if you are aware of any updated versions of SHAW that would be more compatible with newer PC operating systems, without resorting to emulators. We have checked the USDA-ARS webpage for updates, but have found that version 2.3.6 (2004) which we are currently using is the only download available."

In the meantime, SHAW 1D will have to be run exogenously to the main *Konrad_SP1.0* model, which is compiled in the Python programming language

5.4.2.3 Tier 3

5.4.2.3.1 Preface

At the Tier 3 level, a more complex modeling approach was required where the main application would be:

i. to conduct a thorough thermodynamic analysis of a specific geographic area or pipeline ROW for frost heave risk (after being 'red flagged' in Tiers 1 and 2 [Fig. 5.1])

As with Tier 2, both climate and soil data would be required. A thorough review of the literature on frost heave in soils was completed (see Appendices B and C), and this confirmed our view (i.e., at the time of writing the proposal for this study in late 2013) that there were only two strong options to be considered for modeling frost heave in soils for Tier 3:

- the Konrad (1999; 2005) 'segregation potential' (SP) approach
- the Groenevelt & Grant (2013) 'heave index' (HI) approach

As noted above, it was decided that all new computer programming that would be required to operationalize models under Tiers 2 and 3 would use the open source Python programming language.

Section 3 outlines the goal and research objectives of the PARSC - 003 study. Research Objective 3 was 'to operationalize a computer-based frost heave model utilizing elements from both the Konrad (1999; 2005) and Groenevelt & Grant (2013) approaches, and develop a user interface/manual'. After much closer examination of these two models, however, it became clear that there existed several fundamental differences between them that needed to be reconciled (e.g., the location in the soil profile where the thermal gradient and the Darcy flux should be measured or estimated). This reconciliation would require more investigation time than available in the PARSC - 003 project. It is for this reason that there did not appear to be any opportunity of blending elements from both models in formulating the final model to be used in this study. Hence, the modeling effort in this study concentrated on the Konrad model (*Konrad_SP1.0*), with a large supporting effort put into formulating PTFs as input data to *Konrad_SP1.0* (see Section 5.5).

5.4.2.3.2 An overview of results from the *Konrad_SP1.0* model

Figures 5.2 - 5.5 are histograms of estimated frost heave rates generated by the *Konrad_SP1.0* model for all of the 'useable' soil polygons in SLC3.2 across southern Canada. The model was used to estimate heave rates under saturated soil conditions with i) freezing front depths ranging from 50 cm to 350 cm below the soil surface, and ii) an assumed thermal gradient in the soil (between the soil surface and the freezing front) of 20°C m^{-1}. It was important to examine the heave rates over a wide range of freezing front depths (50 - 350 cm) in order to firmly establish trends, which will be discussed below. It should be noted, however, that the FI method (bare soil) only predicts one location in the southern 10 provinces of Canada where the depth of frost penetration exceeds 300 cm (i.e., 321 cm in Churchill, MB) (see Table D-1 [Appendix D]). Figures 5.2 and 5.3 show the model output for the algorithms published in Konrad (1999) only, which is denoted as 'heave' in *Konrad_SP1.0*. Figures 5.4 and 5.5 show the model output for the algorithms published in both Konrad (1999) and Konrad (2005), which is denoted as 'heave2' in *Konrad_SP1.0*.

The estimated heave rates in Figs. 5.2 - 5.5 pertain to the upward vertical displacement (per unit time) occurring in the soil at the depth of maximum frost penetration (i.e., the frozen fringe and vicinity where ice lenses form). It is presumed that the upward vertical displacement at these sub-soil levels will translate into similar upward vertical displacements at the soil surface. Overall, the magnitude of the heave rates (mm day^{-1}) seem plausible for both the 'heave' and 'heave2' model outputs, as does the shift in the skewed distribution with depth. It is evident that with increasing frost depth in the soil profile, however, there is i) a narrowing of the skewed distribution of heave rates, and ii) a modest lowering of the mean heave rates due to increased overburden pressure and other effects. The narrowing of the skewed distributions reflects the 'control section' concept in pedology (i.e., soil surveys), which is defined as 'the vertical section upon which the taxonomic classification of soil is based (usually the 0 - 100 cm depth range in mineral soils)' (AAFC, 2013a). In setting up the SLC3.2 soil database for use by the *Konrad_SP1.0* model, it was assumed that the soil properties are uniform below the 'control section' (i.e., below a depth of 100cm). In many cases, the soil properties within the 'control section' are more variable and more vulnerable to frost heave (e.g., lower dry bulk density and higher field-saturated hydraulic conductivity) than in the deep subsoil (>100 cm depth).

To put the values shown in Figs. 5.2 - 5.5 into the context of the PARSC - 003 study (i.e., agricultural soils in southern Canada), Kay *et al.* (1985) reported measured maximum surface displacements of 62 mm (i.e., frost heave) during winter in a tilled agricultural field site at Elora, ON (near Guelph, ON). The soils at the Elora field site were silt loam to clay loam in texture. The measured depth of the 0°C isotherm at the site was generally about 30 cm from mid-January to mid-March (2 months), although it deepened to about 60 cm for less than a week in February. This 0°C isotherm level is comparable to the 50 cm freezing front depth of the Fig. 5.2a ('heave') and 5.4a ('heave2') histograms. It is worth noting that the maximum depth of frost penetration estimated by the FI method (Table D-1 [Appendix D]) for this locality is about 108 cm for bare soil conditions (i.e., Guelph, ON). Kay *et al.* (1985) reported measured snow depths of 20 - 35 cm through that same 2-month mid-winter period, which would account for the lesser measured frost penetration depth of 30 - 60 cm.

The *Konrad_SP1.0* frost heave model was run for these soil/site and weather conditions at the Elora field site. Using an assumed temperature gradient of 10°C m^{-1} and a freezing front depth of 30 cm, the model estimated a daily heave rate ('heave') of 1.98 mm day^{-1} for the clay loam soil and 2.72 mm day^{-1} for the silt loam soil. For a freezing front depth of 60 cm, the model estimated a daily heave rate ('heave') of 1.87 mm day^{-1} for the clay loam soil and 2.53 mm day^{-1} for the silt loam soil. If these heave rate values are compared to values on the corresponding histogram (Fig. 5.2a) created for all agricultural soils across Canada from the SLC3.2 data base, the frost susceptibility of the Elora soils is somewhat below the mean value of the nation-wide (skewed) distribution.

Assuming that the 0°C isotherm persisted at a depth of 30 cm from mid-January to mid-March (about 60 days), the *Konrad_SP1.0* model would estimate a seasonal surface displacement of 119 to 163 mm which is higher than was actually observed at the Elora field site. Kay *et al.* (1985)

reported that this site was imperfectly drained and the soil was unsaturated (i.e., *Konrad_SP1.0* assumes saturated soil conditions). In fact, the measured groundwater table depth at the Elora field site was reported to be quite deep and actually increased during the freezing period (which is atypical for southern Ontario), but never exceeded150 cm below the soil surface. The field site was also artificially drained. These soil/site factors that would limit the Darcy (water) flux to the frozen fringe could account for the over-estimate of the heave rate by the *Konrad_SP1.0* model in this instance.

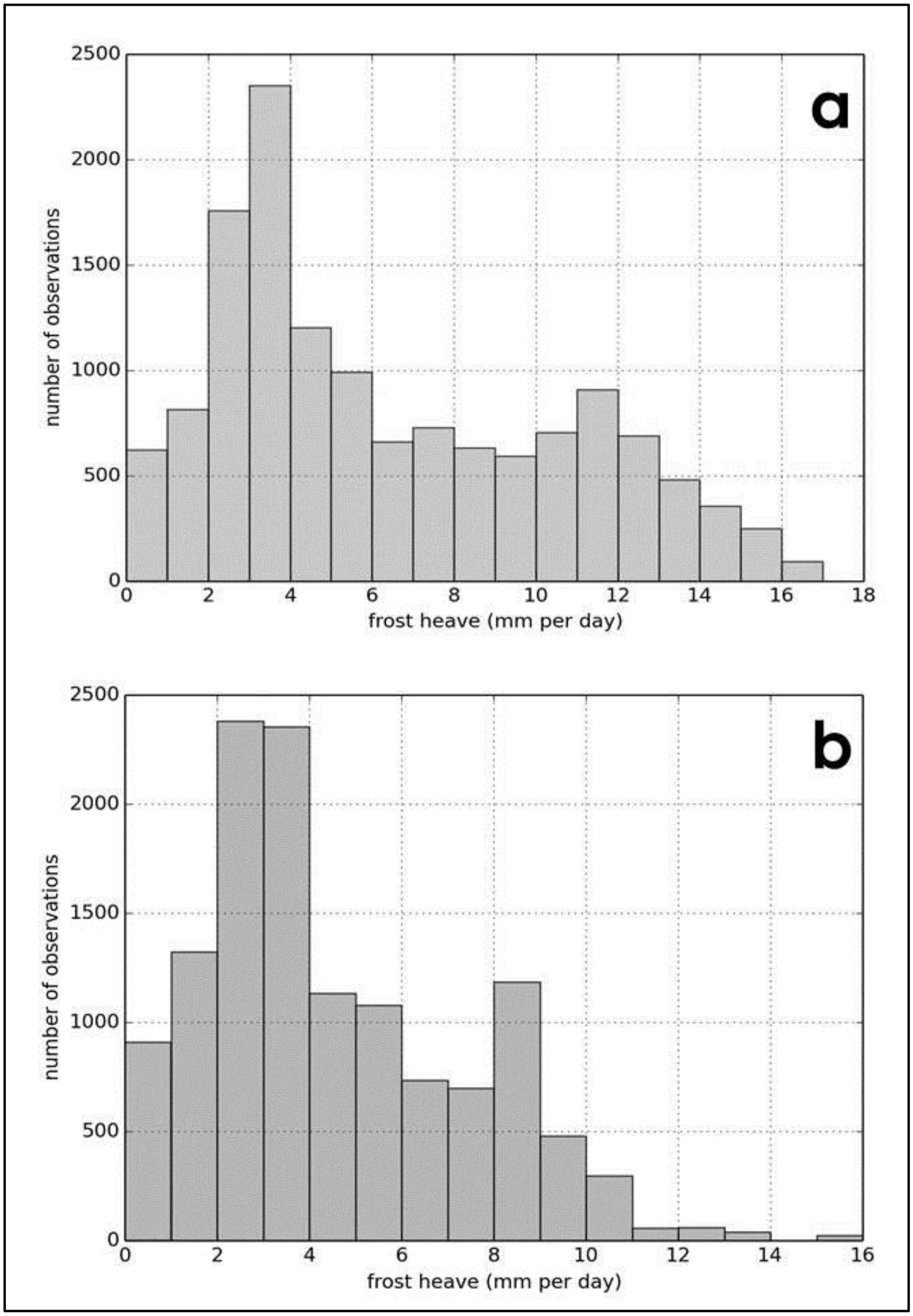


Figure 5.2: **Histograms showing heave rate estimates from *Konrad_SP1.0* ('heave') for freezing front depths of a) 50 cm, and b) 150 cm below the soil surface.**

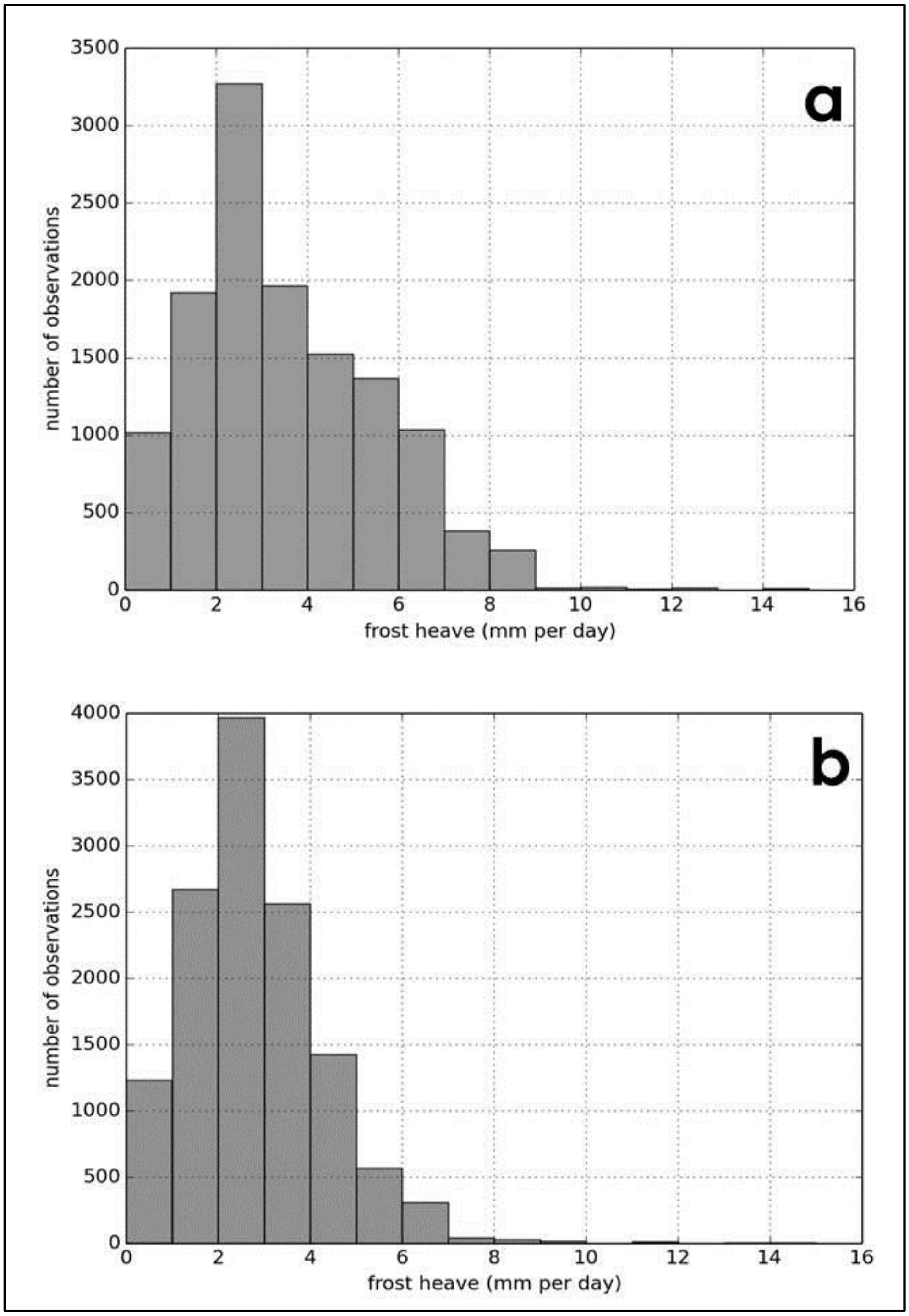


Figure 5.3: **Histograms showing heave rate estimates from *Konrad_SP1.0* ('heave') for freezing front depths of a) 250 cm, and b) 350 cm below the soil surface.**

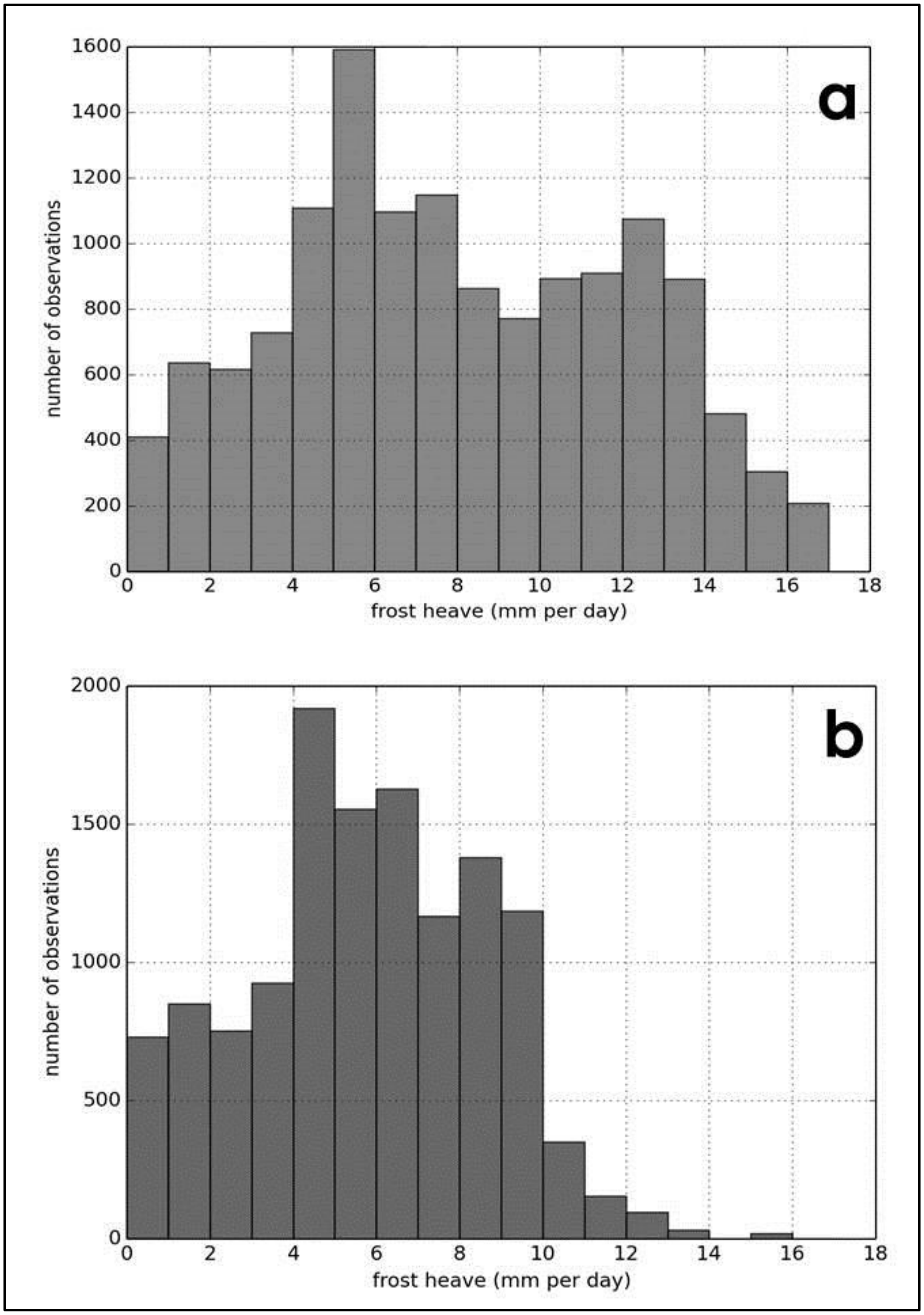


Figure 5.4: Histograms showing heave rate estimates from *Konrad_SP1.0* ('heave2') for freezing front depths of a) 50 cm, and b) 150 cm below the soil surface.

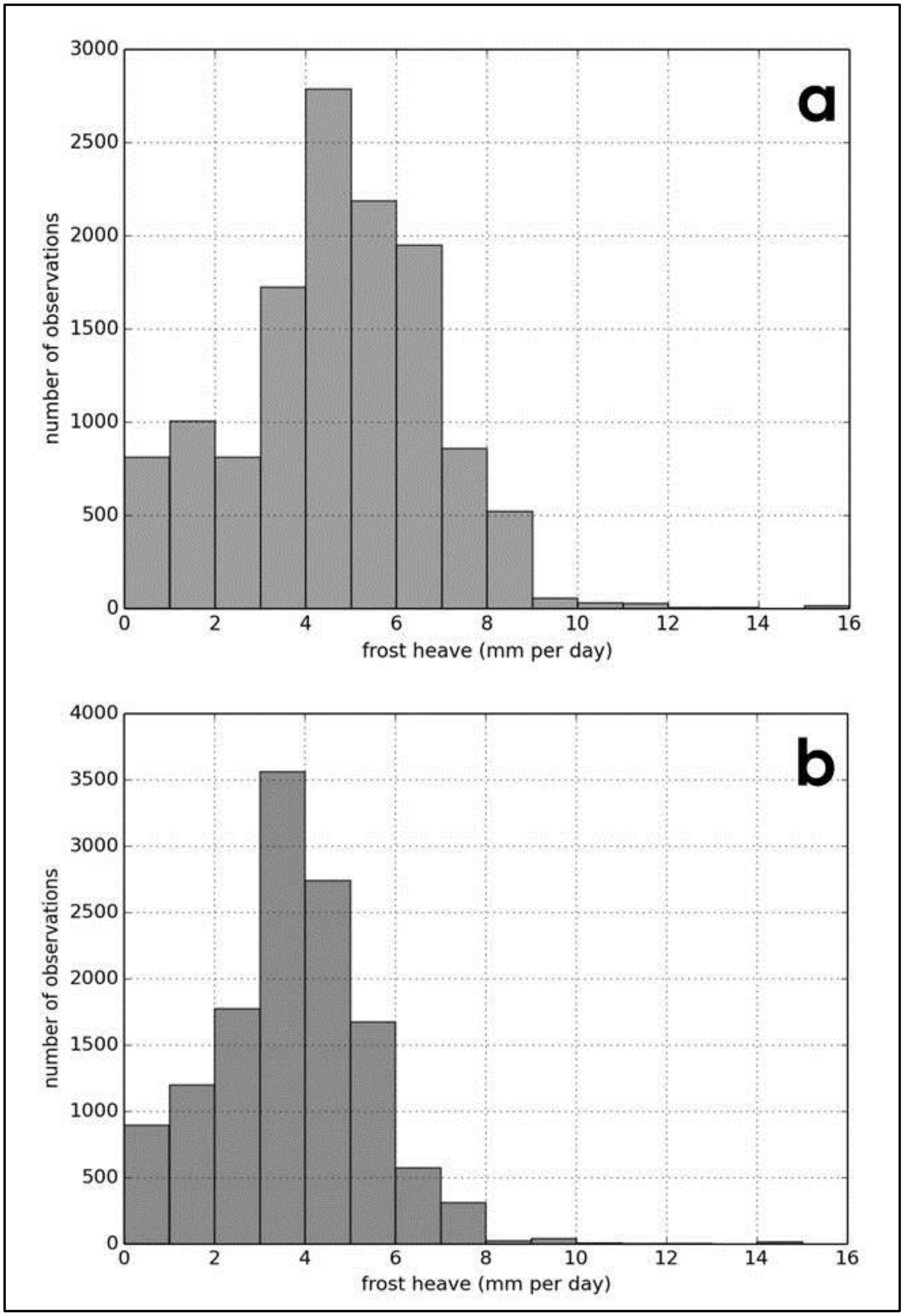


Figure 5.5: **Histograms showing heave rate estimates from *Konrad_SP1.0* ('heave2') for freezing front depths of a) 250 cm, and b) 350 cm below the soil surface.**

5.5 PEDOTRANSFER FUNCTION DEVELOPMENT (PTFDev)

5.5.1 Preface

As noted in Appendix S, many soil physical and engineering properties are sensitive to the nature of the clay minerals present. In Canada, soil clay fractions with a significant component of expanding clay minerals (i.e., smectites) are found primarily in the Prairie Ecozone, whereas soils characterized by non-expanding clay minerals (i.e., clay mica [illite], chlorite) are found in the remainder of the country (Appendix S). Where necessary (and possible), existing PTFs are described in this section, or new PTFs developed, that make this distinction. Figure 5.6 shows this distinction geographically, with 'smectitic PTFs' being assigned to the Prairie Ecozone and 'micaceous PTFs' being assigned to the remainder of southern Canada.

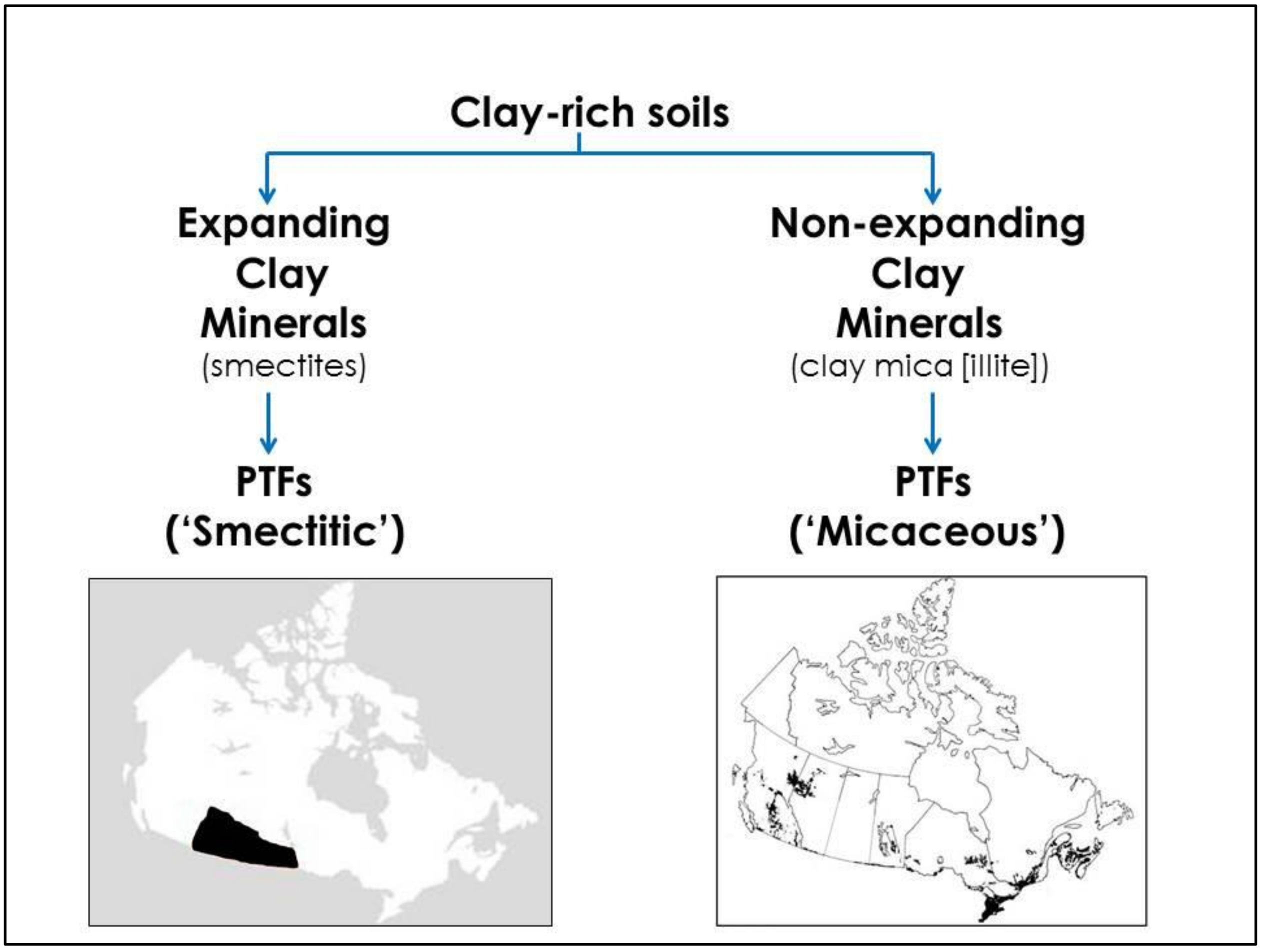


Figure 5.6: **Flowchart showing the geographic distinction in clay mineral types across southern Canada that can influence pedotransfer function development.**

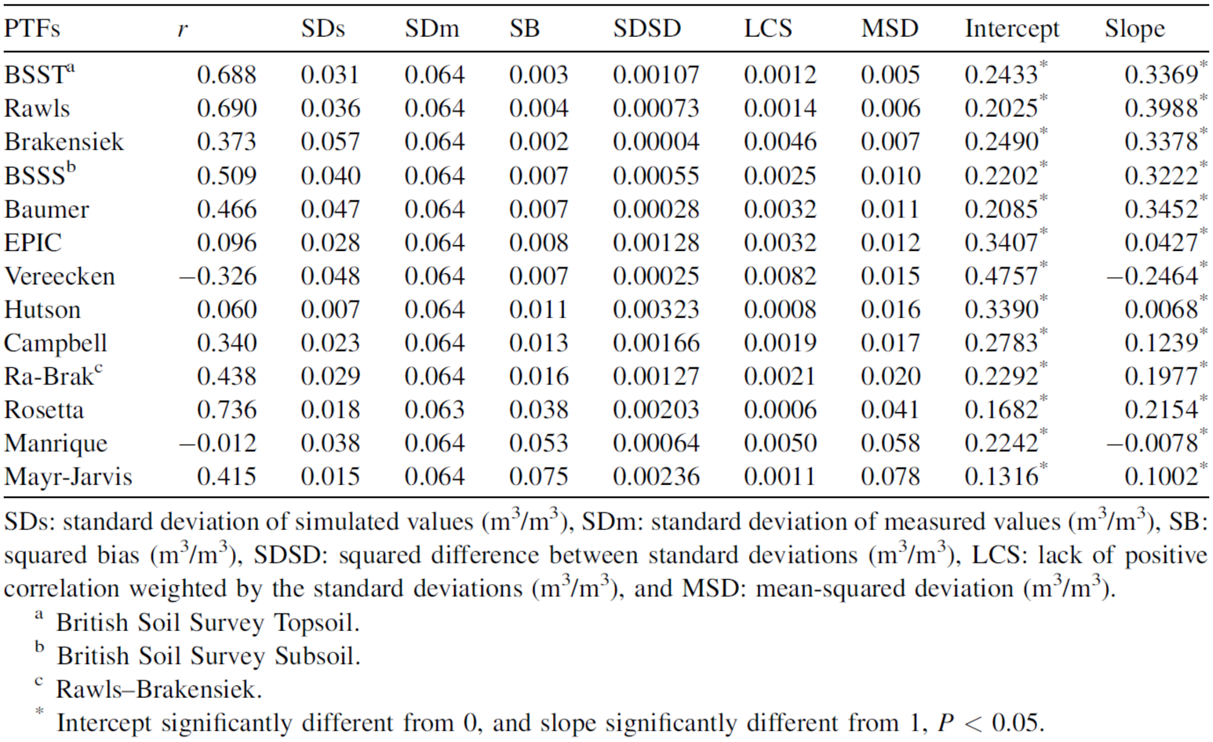
5.5.2 Estimation of the gravimetric soil water content

5.5.2.1 Preface

Konrad (1999) suggested that the ratio w/w_L is one of several parameters that define the relative frost heaving susceptibility of soils, through the estimation of the 'segregation potential' (SP) (see Appendix A). Hence, one or more existing PTFs that estimate the gravimetric soil water content (*w*) had to be identified for use in this study.

The best method available for estimating *w* is to use PTFs that estimate the entire soil water retention curve to at least pF 4.18 (i.e., water pressure potential of -1.5 MPa). Givi *et al.* (2004) applied 13 PTFs, that are widely used globally by the research community, to estimate the soil 'field capacity' and 'permanent wilting point' (Tables 5.1 and 5.2, respectively). However, many of these PTFs performed poorly, and the highest reported correlation coefficient (*r*-value) was only 0.736 for field capacity estimation (Table 5.1), and only 0.774 for permanent wilting point estimation (Table 5.2).

Table 5.1: Evaluation of thirteen PTFs for estimating the field capacity of Iranian soils. (after Givi *et al.*, 2004).



PTFs	r	SDs	SDm	SB	SDSD	LCS	MSD	Intercept	Slope
BSST[a]	0.688	0.031	0.064	0.003	0.00107	0.0012	0.005	0.2433*	0.3369*
Rawls	0.690	0.036	0.064	0.004	0.00073	0.0014	0.006	0.2025*	0.3988*
Brakensiek	0.373	0.057	0.064	0.002	0.00004	0.0046	0.007	0.2490*	0.3378*
BSSS[b]	0.509	0.040	0.064	0.007	0.00055	0.0025	0.010	0.2202*	0.3222*
Baumer	0.466	0.047	0.064	0.007	0.00028	0.0032	0.011	0.2085*	0.3452*
EPIC	0.096	0.028	0.064	0.008	0.00128	0.0032	0.012	0.3407*	0.0427*
Vereecken	−0.326	0.048	0.064	0.007	0.00025	0.0082	0.015	0.4757*	−0.2464*
Hutson	0.060	0.007	0.064	0.011	0.00323	0.0008	0.016	0.3390*	0.0068*
Campbell	0.340	0.023	0.064	0.013	0.00166	0.0019	0.017	0.2783*	0.1239*
Ra-Brak[c]	0.438	0.029	0.064	0.016	0.00127	0.0021	0.020	0.2292*	0.1977*
Rosetta	0.736	0.018	0.063	0.038	0.00203	0.0006	0.041	0.1682*	0.2154*
Manrique	−0.012	0.038	0.064	0.053	0.00064	0.0050	0.058	0.2242*	−0.0078*
Mayr-Jarvis	0.415	0.015	0.064	0.075	0.00236	0.0011	0.078	0.1316*	0.1002*

SDs: standard deviation of simulated values (m^3/m^3), SDm: standard deviation of measured values (m^3/m^3), SB: squared bias (m^3/m^3), SDSD: squared difference between standard deviations (m^3/m^3), LCS: lack of positive correlation weighted by the standard deviations (m^3/m^3), and MSD: mean-squared deviation (m^3/m^3).

[a] British Soil Survey Topsoil.

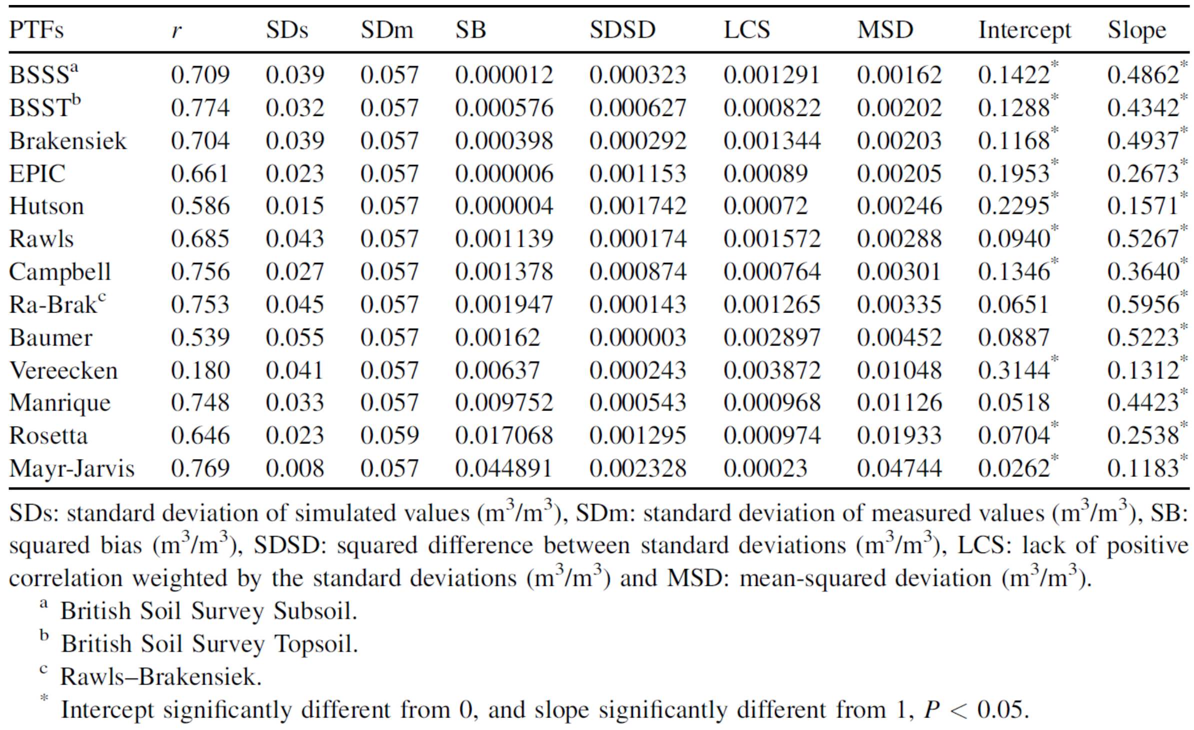
[b] British Soil Survey Subsoil.

[c] Rawls–Brakensiek.

* Intercept significantly different from 0, and slope significantly different from 1, $P < 0.05$.

In the Canadian context, the soil water retention model of McBride & Mackintosh (1984) has gained wide acceptance within the national soil science community. For example, this PTF is used in SLC3.2 to generate estimates of *w* for water pressure potentials of 0 (saturation), -10, - 33 and -1500 kPa (AAFC, 2013b). Past studies have examined the comparative predictive capability of the PTF of McBride & Mackintosh (1984), which was developed for use on Ontario soils, against other PTF alternatives. de Jong & McKeague (1987) showed that its predictive capability compared very favourably to the PTF of de Jong & Loebel (1982). Fallow (2009) drew the same conclusion in comparing its predictive capability to that of the more globally accepted 'Saxton' (Saxton & Rawls, 2006) and 'Rosetta' (Schaap *et al.*, 2001) PTFs. For these reasons, the soil water retention model of McBride & Mackintosh (1984) was used to estimate *w* in this study for soils with micaceous clay mineralogy.

Table 5.2: Evaluation of thirteen PTFs for estimating the permanent wilting point of Iranian soils. (after Givi *et al.*, 2004).



PTFs	*r*	SDs	SDm	SB	SDSD	LCS	MSD	Intercept	Slope
BSSS[a]	0.709	0.039	0.057	0.000012	0.000323	0.001291	0.00162	0.1422*	0.4862*
BSST[b]	0.774	0.032	0.057	0.000576	0.000627	0.000822	0.00202	0.1288*	0.4342*
Brakensiek	0.704	0.039	0.057	0.000398	0.000292	0.001344	0.00203	0.1168*	0.4937*
EPIC	0.661	0.023	0.057	0.000006	0.001153	0.00089	0.00205	0.1953*	0.2673*
Hutson	0.586	0.015	0.057	0.000004	0.001742	0.00072	0.00246	0.2295*	0.1571*
Rawls	0.685	0.043	0.057	0.001139	0.000174	0.001572	0.00288	0.0940*	0.5267*
Campbell	0.756	0.027	0.057	0.001378	0.000874	0.000764	0.00301	0.1346*	0.3640*
Ra-Brak[c]	0.753	0.045	0.057	0.001947	0.000143	0.001265	0.00335	0.0651	0.5956*
Baumer	0.539	0.055	0.057	0.00162	0.000003	0.002897	0.00452	0.0887	0.5223*
Vereecken	0.180	0.041	0.057	0.00637	0.000243	0.003872	0.01048	0.3144*	0.1312*
Manrique	0.748	0.033	0.057	0.009752	0.000543	0.000968	0.01126	0.0518	0.4423*
Rosetta	0.646	0.023	0.059	0.017068	0.001295	0.000974	0.01933	0.0704*	0.2538*
Mayr-Jarvis	0.769	0.008	0.057	0.044891	0.002328	0.00023	0.04744	0.0262*	0.1183*

SDs: standard deviation of simulated values (m^3/m^3), SDm: standard deviation of measured values (m^3/m^3), SB: squared bias (m^3/m^3), SDSD: squared difference between standard deviations (m^3/m^3), LCS: lack of positive correlation weighted by the standard deviations (m^3/m^3) and MSD: mean-squared deviation (m^3/m^3).

[a] British Soil Survey Subsoil.

[b] British Soil Survey Topsoil.

[c] Rawls–Brakensiek.

* Intercept significantly different from 0, and slope significantly different from 1, $P < 0.05$.

5.5.3 Estimation of the liquid limit

5.5.3.1 Preface

As noted in Section 5.5.2.1 (above), Konrad (1999) suggested that the ratio w/w_L is one of several parameters that define the relative frost heaving susceptibility of soils, through the estimation of the 'segregation potential' (SP) (see Appendix A). Hence, a minimum of two PTFs that estimate the liquid limit (w_L) of soils had to be identified for use in this study (i.e., one for soils with micaceous clay mineralogy, and one for soils with smectitic clay mineralogy).

5.5.3.2 Estimation of the liquid limit for soils with micaceous clay mineralogy

It is proposed for the PARSC - 003 study that the liquid limit of Canadian soils with micaceous clay mineralogy be estimated using the function relating w_L to soil organic carbon and clay contents for southern Ontario soils (Eqn. 5.1). The equation ($R^2 = 0.809$) is as follows:

$$w_L = 15.95 + 0.57(\text{clay}) + 3.05(\text{SOC}) \qquad \text{Eqn. 5.1}$$

where: w_L = liquid limit (%kg kg^{-1})

clay = soil clay content (%kg kg^{-1})

SOC = soil organic carbon content (%kg kg^{-1})

Eqn. 5.1 should not be used to estimate w_L for soils with >77% kg kg^{-1} clay content, or with >4% kg kg^{-1} soil organic carbon content. Details on the derivation of Eqn. 5.1 can be found in Appendix K.

5.5.3.3 Estimation of the liquid limit for soils with smectitic clay mineralogy

It is proposed for the PARSC - 003 study that the liquid limit of Canadian soils with smectitic (montmorillonitic) clay mineralogy be estimated using the function relating w_L to soil organic carbon and clay contents, as published by de Jong *et al.* (1990) for southern Saskatchewan soils (Eqn. 5.2). The equation ($R^2 = 0.86$) is as follows:

$$w_L = 13.75 + 0.637(\text{clay}) + 2.937(\text{SOC}) \qquad \text{Eqn. 5.2}$$

where: w_L = liquid limit (%kg kg^{-1})

clay = soil clay content (%kg kg^{-1})

SOC = soil organic carbon content (%kg kg^{-1})

Eqn. 5.2 should not be used to estimate w_L for soils with >87% kg kg^{-1} clay content, or with >6.4% kg kg^{-1} soil organic carbon content. A comparison of the regression coefficients in Eqns. 5.1 and 5.2 shows that they are numerically quite similar, suggesting that variations in the clay mineralogy of Canadian soils have surprisingly little influence on the liquid limit. This observation is in sharp contrast to the findings in Section 5.5.4 (below) for the specific surface area (SAA), where SSA values for smectitic soils are shown to be several fold higher than for micaceous soils.

5.5.4 Estimation of the specific surface area

5.5.4.1 Preface

One of the soil parameters required for estimation of the 'segregation potential' (SP), in accordance with Konrad (1999), is the specific surface area (SSA) (see Appendix A). Konrad (1999) argued that methods that determine the area per unit mass of both the external and internal surfaces of mineral particles (e.g., ethylene glycol [EGME] method) are preferred for SP estimation and analysis. It is the SSA and d_{50}(FF) parameters that are the two most important by far in the Konrad (1999) model, in terms of their effect on the SP values.

5.5.4.2 Estimation of SSA for soils with micaceous clay mineralogy (water sorption method)

The SSA of a soil can be estimated if the thickness of the adsorbed water film is known for a particular water pressure potential greater than about pF 3.0. It is proposed for the PARSC - 003 study that the SSA of Canadian soils with micaceous clay mineralogy be estimated using the water sorption method based on the water film thickness on mineral surfaces at pF 4.18, as per Eqn. 5.3:

$$SSA = 386\,(w_{wp}) \qquad \text{Eqn. 5.3}$$

where: SSA = specific surface area ($m^2\,g^{-1}$)

w_{wp} = gravimetric soil water content at the permanent wilting point, or pF 4.18 (kg kg^{-1})

The independent variable (w_{wp}) in Eqn. 5.3 will be estimated using the following regression equation from McBride & Mackintosh (1984):

$$w_{wp} = 1.338\,(\text{clay})^{0.7} \qquad \text{Eqn. 5.4}$$

where: clay = soil clay content (%kg kg^{-1})

w_{wp} = gravimetric soil water content at the permanent wilting point, or pF 4.18 (%kg kg^{-1})

Details on the derivation of Eqn. 5.3 can be found in Appendix L, including a validation step using measured SSA data (EGME method) published in Ross (1978).

5.5.4.3 Estimation of SSA for soils with smectitic clay mineralogy

It is proposed for the PARSC - 003 study that the SSA of Canadian soils with smectitic (montmorillonitic) clay mineralogy be estimated using the function relating SSA (EGME method) to clay content, as published by de Jong (1999) for Chernozemic soils in southern Saskatchewan (Fig. 5.7). The equation ($r^2 = 0.86$) is as follows:

$$SSA = 86 + 4.0\,(\text{clay}) \qquad \text{Eqn. 5.5}$$

where: SSA = specific surface area using the EGME method ($m^2\ g^{-1}$)

clay = soil clay content (%kg kg^{-1})

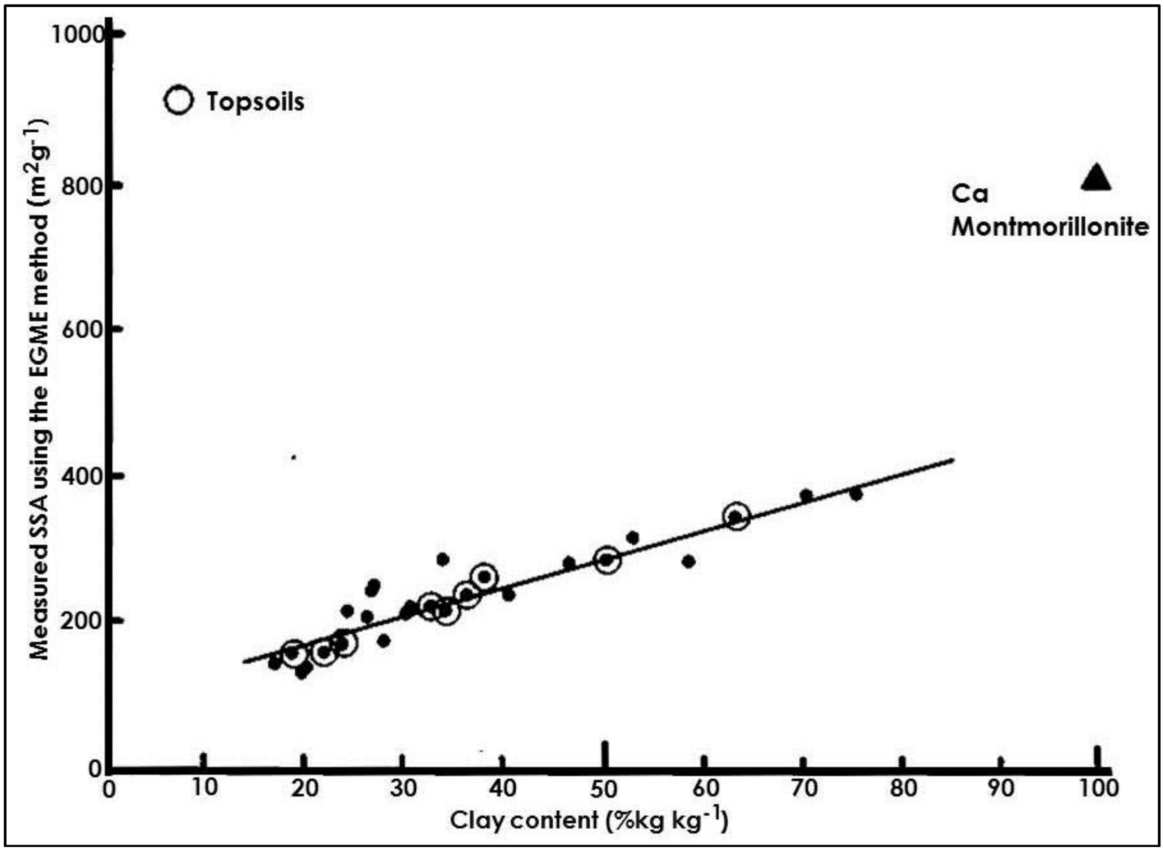


Figure 5.7: Dependence of specific surface area measured by EGME sorption on clay content of 27 Chernozemic soil horizon samples from southern Saskatchewan. Topsoil horizons are denoted with open circles (O). A Ca montmorillonite clay sample (SSA = 800 $m^2\ g^{-1}$) was used as a reference. (after de Jong, 1999).

5.5.5 Estimation of the compression index

5.5.5.1 Preface

According to Konrad (1999), the influence of overburden pressure on the 'segregation potential' (SP) and frost heave can be accounted for by an empirical relationship involving the compression index (C_c) of the soil.

5.5.5.2 Estimation of the compression index for soils with micaceous clay mineralogy

A series of equations is provided in Appendix M that allows the estimation of the slope of the 'normal consolidation line' (NCL), or C_c*, for southern Ontario soils. The series of calculations culminates in the following equation:

$$C_c^* = \frac{e_{w_L} - e_{w_P}}{\log\left(\frac{\sigma'_{w_P}}{\sigma'_{w_L}}\right)} \qquad \text{Eqn. 5.6}$$

where: C_c^* = slope of the 'normal consolidation line' (NCL)

e_{wL} = liquid limit expressed as a void ratio

e_{wP} = plastic limit expressed as a void ratio

σ'_{wL} = effective stress at the liquid limit (kPa)

σ'_{wP} = effective stress at the plastic limit (kPa)

Details on the derivation of Eqn. 5.6 can be found in Appendix M.

Clearly, the use of Eqn. 5.6 will require the estimation of both of the soil consistency (Atterberg) limits (see Appendix K). As noted in Section 5.5.3.3 above, the liquid limit of Canadian soils with micaceous clay mineralogy can be estimated using the PTF relating w_L to soil organic carbon and clay contents for southern Ontario soils (Eqn. 5.7). The equation ($R^2 = 0.809$) is as follows:

$$w_L = 15.95 + 0.57(\text{clay}) + 3.05(\text{SOC}) \qquad \text{Eqn. 5.7}$$

where: w_L = liquid limit (%kg kg^{-1})

clay = soil clay content (%kg kg^{-1})

SOC = soil organic carbon content (%kg kg^{-1})

Similarly, the plastic limit of Canadian soils with micaceous clay mineralogy can be estimated using the PTF relating w_P to soil organic carbon and clay contents for southern Ontario soils (Eqn. 5.8). The equation ($R^2 = 0.604$) is as follows:

$$w_P = 14.28 + 0.12(\text{clay}) + 3.05(\text{SOC}) \qquad \text{Eqn. 5.8}$$

where: w_P = plastic limit (%kg kg^{-1})

clay = soil clay content (%kg kg^{-1})

SOC = soil organic carbon content (%kg kg^{-1})

Eqns. 5.7 and 5.8 should not be used to estimate the consistency limits for soils with >77% kg kg^{-1} clay content, or with >4% kg kg^{-1} soil organic carbon content. Details on the derivation of Eqns. 5.7 and 5.8 can be found in Appendix K.

5.5.5.3 Estimation of the compression index for soils with smectitic clay mineralogy

A review of the literature did not reveal any existing PTFs capable of estimating C_c for soils with smectitic clay mineralogy. It is not known if Eqn. 5.6 can be used with any reliability for this purpose.

5.5.6 Estimation of the Standard Proctor Density test indices

5.5.6.1 Preface

The Standard Proctor Density test indices are useful measures of soil strength or degree of soil overconsolidation in order to contrast soil strength within a pipeline trench area to that outside the ROW (Ivey & McBride, 1999) during different soil water and temperature regime conditions. This information can help to assess the susceptibility of pipelines to exposure caused by frost heave (i.e., overburden pressure).

5.5.6.2 Estimation of the MDD and OWC for soils with micaceous clay mineralogy

PTFs were developed for the 'Maximum Dry Density' (MDD) and 'Optimum Water Content' (OWC) parameters using the calibration data set in Appendix O (see Appendix N). It is proposed for the PARSC - 003 study that the MDD and OWC of Canadian soils with micaceous clay mineralogy be estimated using the functions relating MDD and OWC to soil organic carbon and particle-size distribution for southern Ontario soils (Eqns. 5.9 and 5.10). The equations for MDD and OWC (R^2 = 0.770 and 0.795, respectively) are as follows:

$$MDD = 2.055 - 0.00228(silt) - 0.00561(clay) - 0.0813(SOC) \qquad \text{Eqn. 5.9}$$

where: MDD = Standard Proctor Maximum Dry Density (Mg m^{-3})

silt = soil silt content (%kg kg^{-1})

clay = soil clay content (%kg kg^{-1})

SOC = soil organic carbon content (%kg kg^{-1})

$$OWC = 15.070 - 0.082(sand) + 0.125(clay) + 1.992(SOC) \qquad \text{Eqn. 5.10}$$

where: OWC = Standard Proctor Optimum Water Content (%kg kg^{-1})

sand = soil sand content (%kg kg^{-1})

clay = soil clay content (%kg kg^{-1})

SOC = soil organic carbon content (%kg kg^{-1})

Eqns. 5.9 and 5.10 should not be used to estimate MDD or OWC for soils with >77% kg kg^{-1} clay content, >84% kg kg^{-1} silt content, >67% kg kg^{-1} sand content, or >4% kg kg^{-1} soil organic carbon content. Details on the derivation of Eqns. 5.9 and 5.10 can be found in Appendix N.

5.5.6.3 Estimation of the MDD and OWC for soils with smectitic clay mineralogy

A review of the literature did not reveal any existing PTFs capable of estimating the MDD and OWC test indices for soils with smectitic clay mineralogy. It is not known if Eqns. 5.9 and 5.10 can be used with any reliability for this purpose.

5.5.7 d_{50}(FF) soil particle-size distribution parameter

Konrad (1999) suggested that the particle-size distribution of the 'fines fraction' (d < 0.075 mm) is one of several parameters that define the relative frost heaving susceptibility of soils. A parameter was devised by Konrad (1999) for use in estimating the SP parameter, referred to as d_{50}(FF), which can be determined graphically (see Appendix P). In Appendix P, we have further devised new sub-routines which automate the determination of this parameter using curve-fitting techniques. Figure 5.8 shows an example of such a plot using SLC3.2 data for an Alberta soil. It is the d_{50}(FF) and SSA parameters that are the two most important by far in the Konrad (1999) model, in terms of their effect on the SP values.

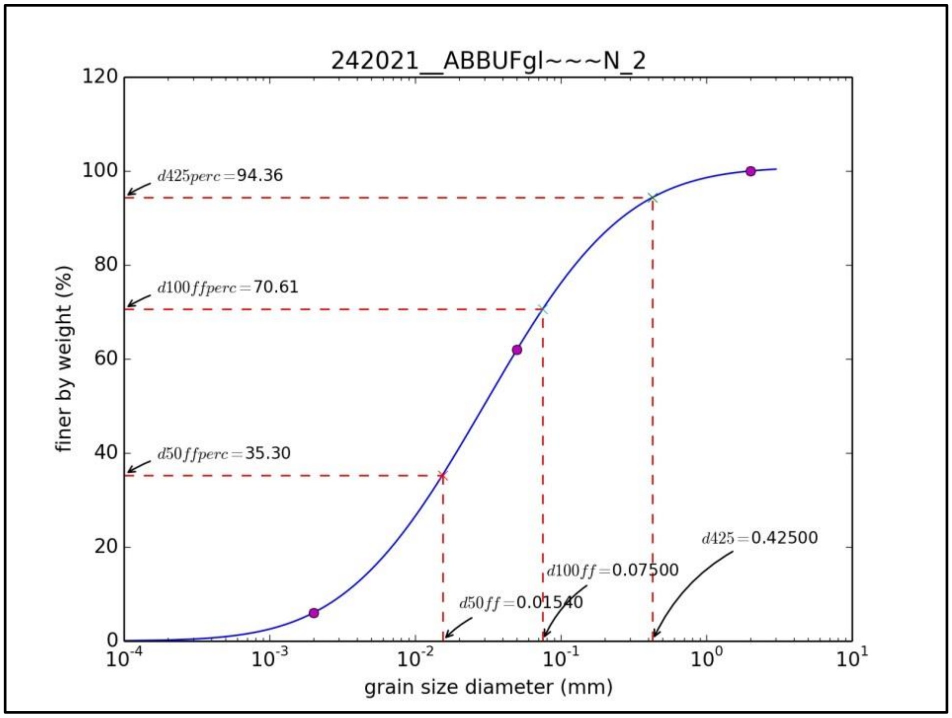


Figure 5.8: **Example output for an Alberta soil (SLC3.2) from the automated curve-fitting PTF that determines the d_{50}(FF) parameter from silt and clay contents.**

5.6 REFERENCES (SECTION 5)

Agriculture and Agri-Food Canada (AAFC). 2013a. Glossary of terms in soil science. Available at: http://sis.agr.gc.ca/cansis/glossary/ (verified Oct. 6, 2014)

Agriculture and Agri-Food Canada (AAFC). 2013b. Soil Landscapes of Canada (version 3.2). Available at: http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html (verified Oct. 6, 2014)

Anderson, D. 2010. Vertisolic soils of the prairie region. Prairie Soils and Crops Journal 3(5):29-36. Available at: http://www.prairiesoilsandcrops.ca/articles/volume-3-5-screen.pdf (verified Oct. 6, 2014)

de Jong, E. 1999. Comparison of three methods of measuring surface area of soils. Can. J. Soil Sci. 79:345-351.

de Jong, E., D.F. Acton and H.B. Stonehouse. 1990. Estimating the Atterberg limits of southern Saskatchewan soils from texture and carbon contents. Can. J. Soil Sci. 70:543-554.

de Jong, R. and K. Loebel. 1982. Empirical relations between soil components and water retention at 1/3 and 15 atmospheres. Can. J. Soil Sci. 62:343-350.

de Jong, R. and J.A. McKeague. 1987. A comparison of measured and modelled soil water retention data. Can. J. Soil Sci. 67:607-703.

Fallow, D. 2009. Assembling measurements and estimates of soil hydraulic conductivity data for soil water budget modeling. A report prepared by the Dep't. of Land Resource Science, University of Guelph for the OMAFRA research program (Project 26589). May, 2009. 30 pp.

Givi, J., S.O. Prasher and R.M. Patel. 2004. Evaluation of pedotransfer functions in predicting the soil water contents at field capacity and wilting point. Agricultural Water Management 70:83-96.

Groenevelt, P.H. and C.D. Grant. 2013. Heave and heaving pressure in freezing soils: A unifying theory. Vadose Zone J. 12(1). 11 pp.

Ivey, J.L. and R.A. McBride. 1999. Delineating the zone of topsoil disturbance around buried utilities on agricultural land. Land Degradation and Development 10:531-544.

Kay, B.D., C.D. Grant and P.H. Groenevelt. 1985. Significance of ground freezing on soil bulk density under zero tillage. Soil Sci. Soc. Am. J. 49(4):973-978.

Kodama, H. 1979. Clay minerals in Canadian soils: their origin, distribution and alteration. Can. J. Soil Sci. 59:37-58.

Konrad, J.-M. 1993. Frost Heave Potential (Chapter 74). p. 797-806. *In* M.R. Carter (ed.). Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Lewis Publishers. Boca Raton, FL.

Konrad, J.-M. 1999. Frost susceptibility related to soil index properties. Can. Geotech. J. 36:403-417.

Konrad, J.-M. 2005. Estimation of the segregation potential of fine-grained soils using the frost heave response of two reference soils. Can. Geotech. J. 42:38-50.

McBride, R.A. and E.E. Mackintosh. 1984. Soil survey interpretations from water retention data: I. Development and validation of a water retention model. Soil Sci. Soc. Am. J. 48:1338-1343.

Python Software. 2014. Python 3.4.1 programming language. Available at: https://www.python.org/ (verified Oct. 6, 2014)

Ross, G.J. 1978. Relationships of specific surface area and clay content to shrink-swell potential of soils having different clay mineralogical compositions. Can. J. Soil Sci. 58:159-166.

Saxton, K.F and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70(5):1569-1578.

Schaap, M.G., F.J. Leij and M. Th. Van Genuchten. 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrology 251:163-176.

United States Department of Agriculture - Agricultural Research Service (USDA-ARS). 2008. SHAW model. Northwest Watershed Management Research, Pacific West Area, Boise, ID. Available at: http://www.ars.usda.gov/Research/docs.htm?docid=16931 (verified Oct. 6, 2014)

Van Loon, W.K.P. 1991. Heat and Mass Transfer in Frozen Porous Media. Ph.D. Thesis. University of Wageningen, The Netherlands.

6.0 SUMMARY AND CONCLUSIONS

This 'Summary and Conclusions' section has been assembled by reproducing excerpts of key phrases contained in the PARSC (2013) 'Request for Proposals' document (reproduced in italics), followed by commentary (in unitalicized text) on i) the way in which the specific issue has been addressed in the PARSC - 003 study/report, and ii) the conclusions drawn.

6.1 OVERALL STUDY GOAL

'The objective of this project is to understand and validate the mechanism of heaving of abandoned pipelines.' (PARSC, 2013, p. 1).

Even though the above excerpt uses the term 'objective', our research group regards the excerpt as more of an overall study 'goal' statement within which we have identified three specific research objectives for the PARSC - 003 project (see Section 3). The above study goal (and its wording) originated directly from recommendations contained in the DNV (2010) scoping study, and was re-iterated in PARSC (2013). The directive 'to understand' pertains to 'Stage 1' of this investigation on frost heave risk to abandoned pipelines, and so involves extensive literature reviews and numerical modeling of the frost heave process. The directive 'to validate', however, pertains to 'Stages 2 and 3' where both laboratory testing and field measurements / observations are envisaged after Stage 1 is completed.

It should be noted that the engineering and scientific communities view frost heave in soils somewhat differently: the former largely as a phenomenon to be explained 'mechanistically', and the latter largely as a 'thermodynamic process' to be explained theoretically (Fig. 6.1). The PARSC - 003 study adopted the latter 'school of thought' wherever possible. This fundamental schism dividing the two established 'schools of thought' is discussed at length in Appendices B and C. Despite these core differences, however, the heave indices originating from the respective 'schools of thought' (i.e., the SP and HI parameters) both support the view that the Darcy flux, driven by the temperature gradient, is the major contributor to ice lens formation and frost heave in soils (Fig. 6.2).

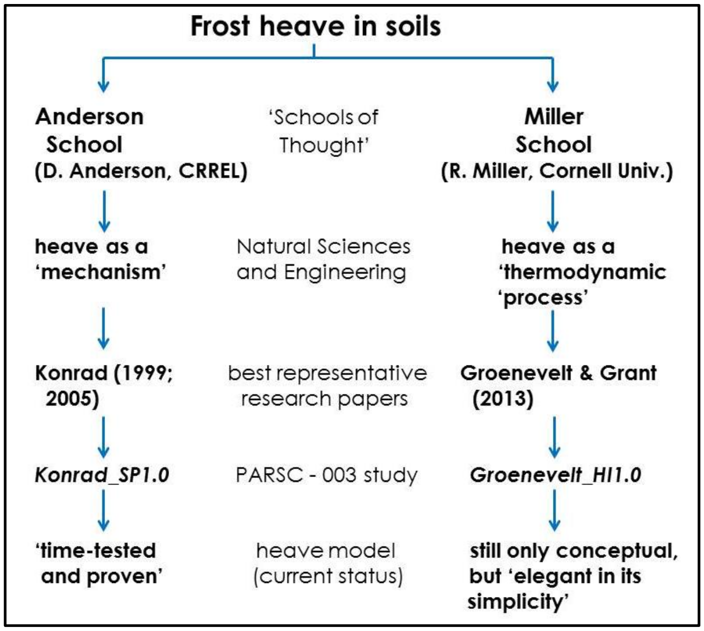


Figure 6.1: Flowchart summarizing some of the main trends in frost heave research found in the review of literature (see Appendices B and C).

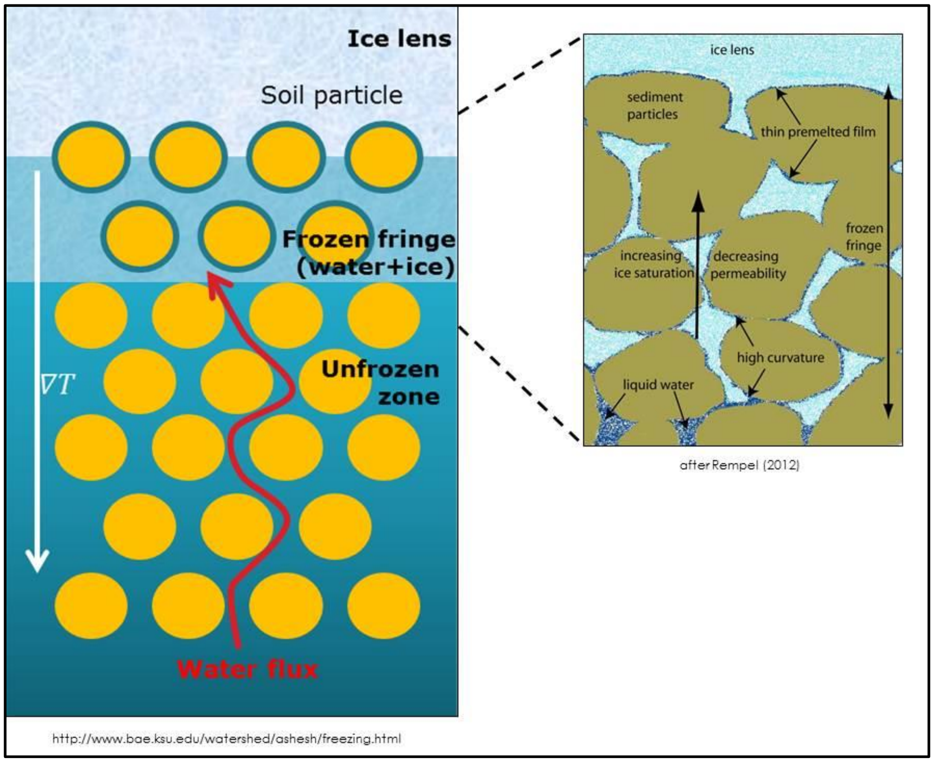


Figure 6.2: Schematic diagrams showing the Darcy (water) flux, driven by the temperature gradient (∇T), as the major contributor to ice lens formation and frost heave in soils.

It should be noted that the annotated bibliography carried out for this study (see Appendix C) suggests that there is a basic lack of understanding concerning the thermodynamics of the frost heave process among a surprisingly large proportion of researchers working in this field.

6.2 FROST PENETRATION DEPTH IN SOILS

'The identification of information sources or records of frost penetration depth in Canadian agricultural soils would be a benefit.' (PARSC, 2013, p. 3).

At a broad reconnaissance level in southern Canada (Tier 1), a literature review (see Appendix D) clearly indicated that the 'freezing index' (FI) approach was the method of choice for estimating the maximum depth of the freezing front in soil, since it uses only air temperature data (i.e., a 'climate-only' modeling approach). At a more detailed site-specific scale (Tier 2), a one-dimensional (1D) modeling approach requiring both soil and climate data was needed, and the literature search showed that the SHAW 1D model was the clear method of choice (see Appendix D).

A 'red flag' at Tier 1 (i.e., the freezing front reaches the depth of the top of the pipeline) would prompt a more in-depth Tier 2 analysis using the SHAW 1D model, and a 'red flag' at Tier 2 would prompt a Tier 3 analysis of estimated heave and heave rate using the *Konrad_SP1.0* model (see Appendices I and J). Figure 5.1 illustrates this 3-tiered decision support system in the form of a flowchart.

6.3 MAJOR SOIL TYPES ACROSS CANADA

'The focus will be on agricultural land…and will exclude permafrost (PARSC, 2013, p. 1).
'…all major types of soils in all major regions crossed by transmission pipelines should be studied.

Permafrost soils are excluded from [the] project scope.' (PARSC, 2013, p. 2).

'Numerical modeling results should cover major soil types…' (PARSC, 2013, p. 3).

The nation-wide scope of the PARSC - 003 project clearly indicated the need to access the Soil Landscapes of Canada database (SLC3.2), which includes a series of GIS coverages that show the major characteristics of land and soil for all of Canada at a uniform scale of 1:1M (see Appendix R). Our research group has been somewhat disappointed in some aspects of the SLC3.2 database (i.e., missing data, unusable soil layers and polygons), particularly in much of the Atlantic provinces. Overall, however, SLC3.2 contains about 40,000 'usable' soil layers (out of a total of about 60,000 soil layers, or 'records') and about 4,000 'usable' polygons nation-wide (out of a total of about 12,000 polygons). Only about 3,600 polygons could actually be used in the *Konrad_SP1.0* model (out of a total of about 4,000 otherwise 'usable' polygons). A significant number of soil layers could not be used because the soil properties (e.g. soil organic carbon content, clay content) were outside of the permissible range allowed by certain of the pedotransfer functions (PTFs) used in this study (see Section 5.5).

6.4 PIPELINE SEGMENTS ABANDONED-IN-PLACE (VARIABLE DIAMETER AND LENGTH)

'Pipelines may be segmented during abandonment and left in place as short or long segments. After pipeline abandonment, frost heave has the potential to result in pipeline exposure. Once the warm product is removed, heave of the pipeline could begin to occur especially if it is a short piece of pipe. However, lengthy sections of pipeline may be anchored in place. The rate and importance of this mechanism is thought to depend on soil type, available moisture and wind erosion. No information appears to be available in the literature pertaining to this geohazard and its ability to expose a pipeline once abandoned.' (PARSC, 2013, p. 1).

Pipelines may be abandoned in short [or] long sections. Both cases should be studied….The project is concerned with medium diameter (>12" - 24") and large diameter (>24") pipelines and both cases should be studied. (PARSC, 2013, p. 2).

6.4.1 Overview

Heat extraction at the soil surface and its rate dictate the processes of soil freezing, water migration, regelation and the Darcy flux in the surrounding unfrozen soil (Groenevelt & Grant, 2013). Hence, 'soil type' and 'available moisture' (see excerpts above) can loosely be considered as factors influencing frost heave insofar as they influence the soil hydraulic conductivity (saturated or unsaturated) and the Darcy flux. Soil erosion (by wind or water), on the other hand, has no direct influence on frost heave, but it is a geotechnical hazard in its own right (see Appendix G).

As for the pipeline segment issue, information contained in Appendix T suggests that the 'virtual anchor length' (*La*) concept may be useful in guiding recommendations on minimum lengths of abandoned pipe segments in order to improve long-term positional stability and diminish the risk of frost heave. Further, the *La* parameter is sensitive to pipe diameter, so minimum length recommendations could vary for 'medium' and 'large' diameters. Unfortunately, the three established computational methods used by pipeline design engineers do show significant inconsistency in estimating i) soil restraint force (per unit length) vs. pipe displacement relationships, and ii) the virtual anchor length (*La*) parameter in low strength/low bulk density soils. This suggests that these computations represent an 'inexact science', and require further investigation so that a preferred computational method with acceptable reliability can be identified for this abandoned pipeline application.

As for the issue of frost heave of abandoned pipelines in general, a literature review (Appendix H) confirmed the findings of the DNV (2010) scoping report. The search yielded very little relevant literature, and no articles directly pertaining to frost heave of abandoned pipelines for either the period up to 2010 (DNV, 2010) or since.

6.4.2 Overburden pressure and regelation

Ice segregation in a frozen soil matrix (including ice lens formation) preferentially occurs in soil zones where overburden pressures are low (Fig. 6.3). Similarly, ice that has recently formed in a frozen soil matrix tends to move away from being under significant overburden pressures (Groenevelt & Grant, 2013). If there is an opportunity for recently formed ice to relocate itself to a more favourable position (e.g., in a large soil pore or air-filled crack), it will do so by the process of regelation. 'Regelation' is the movement of the ice phase with respect to the frozen soil matrix which occurs as a result of locally melting ice, movement of liquid water, and subsequent refreezing (Groenevelt & Grant, 2013). Regelation can also cause ice lenses in frozen soil to relocate themselves, or to grow or shrink.

http://en.wikipedia.org/wiki/Frost_heaving

Figure 6.3: **Ice lens formation (and upward vertical displacement) at the soil surface where overburden pressures are negligible.**

With respect to overburden pressures beneath pipelines, let us consider the mass of soil displaced by two contrasting abandoned (empty) pipeline segments. One is a 'large' diameter pipeline segment (121.9 cm o.d. [48"]), and the other is a 'medium' diameter pipeline segment (45.7 cm o.d. [18"]). Both pipeline segments have the same length (10 m) and the same wall thickness (12.7 mm [0.50"]). The larger diameter pipeline segment would have a mass of 3.78 Mg, and would displace a soil volume of 11.67 m^3. Assuming a wet bulk density of soil of 1.8 Mg m^{-3} (i.e., dry bulk density of 1.3 Mg m^{-3}, and a volumetric soil water content of 0.50 m^3 m^{-3}), the displaced soil would have a mass of 21.01 Mg. Hence, the ratio of the mass of displaced soil to that of the empty pipeline segment is 5.6 (i.e., 21.01 Mg / 3.78 Mg). In contrast, the smaller diameter pipeline segment would have a mass of 1.39 Mg, and would displace a soil volume of 1.64 m^3. Again assuming a wet bulk density of soil of 1.8 Mg m^{-3}, the displaced soil would have a mass of 2.96 Mg. Hence, the ratio of the mass of displaced soil to that of the empty pipeline segment is only 2.1 (i.e., 2.96 Mg / 1.39 Mg).

Figure 6.4 shows a hypothetical situation with two parallel abandoned pipeline segments of different diameters (as described above) within the same ROW, and with the same depth of soil cover (i.e., 120 cm). The ROW is located near Lethbridge, AB, where the FI method (Tier 1) predicts a maximum frost penetration depth of 125 cm (see Table D-1). It can be hypothesized that, once the $0^{o}C$ isotherm reaches the top of the two steel pipelines, the temperature of the full circumference of the pipes is likely to fall rapidly to $\leq 0^{o}C$, since most metals are strong thermal conductors (e.g., iron = 80 $Wm^{-1}K^{-1}$; steel = 43 $Wm^{-1}K^{-1}$). Heat would be quickly conducted from the steel pipe to the advancing freezing front. This could potentially allow ice lenses to begin to form anywhere around the pipe circumference, but particularly at the bottom of the pipe where there is likely to be more availability of 'free water' in the soil (i.e., a perched or shallow groundwater table). Hence, ice lenses could form beneath the pipeline segments long before the regional freezing front ever reached that depth (Fig. 6.4).

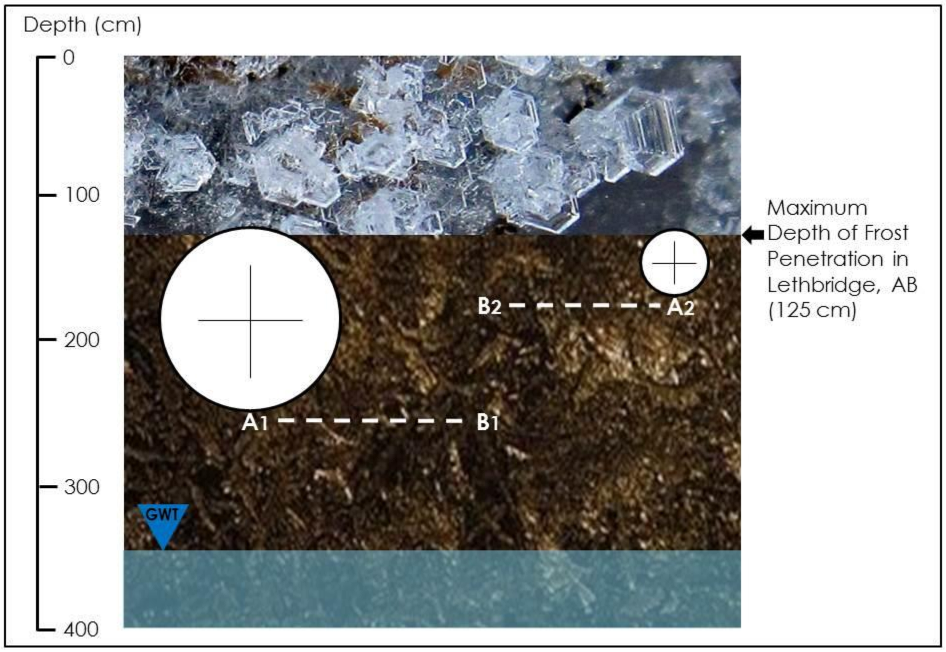


Figure 6.4: **The ‘freezing index’ (FI) method estimates a maximum frost penetration depth of 125 cm for Lethbridge, AB. Any ice lenses that may form at locations B1 and B2 could migrate to locations at A1 and A2, respectively, beneath the abandoned pipelines by the process of regelation.**

As the freezing front continues to advance through the winter season, any ice lenses that may form at locations B1 and B2 could migrate to locations at A1 and A2, respectively, beneath the abandoned pipeline segments by the process of regelation (Fig. 6.4). The overburden pressure at location B1 is much higher than that at location A1, since the ratio of the mass of displaced soil to that of the empty 48” pipeline segment is 5.6. Conversely, the overburden pressure at location B2 is only marginally higher than that at location A2, since the ratio of the mass of displaced soil to that of the empty 18” pipeline segment is only 2.1. If regelation is indeed an actively occurring process in frozen soils, then this simple analysis suggests that abandoned pipeline segments of ‘large’ diameter may be at a higher risk for heave than abandoned pipeline segments of ‘medium’ diameter (Fig. 6.4).

6.4.3 Heaving pressures

Groenevelt & Grant (2013) defined heaving pressure as ‘the minimum, downward, vertical force per unit horizontal area required to prevent upward movement’ (p. 5 of 11), but further noted that i) heave can also occur in non-vertical directions, and ii) there may be confounding regelation effects if the ‘horizontal area’ is too small. They further cited research sources indicating that growing ice crystals can develop heaving pressures in the 1.4 to 1.5 MPa range (i.e., enough to lift a large building). The ability of ice crystals to grow under even higher pressures is limited only by the tensile strength of the water that is being supplied to the frozen fringe. The enormously large values of the potential heaving pressures are clearly and unambiguously predicted by the Clapeyron equation.

It is known that onshore pipelines moving product can be jacked upward out of the ground (Fig. 6.5) by longitudinal compressive forces interacting with pipeline overbend irregularities, or 'upheaval buckling' (see Section 2.1). Clearly, the vertical soil restraint force (per unit length) has been exceeded where upheaval buckling occurs. There is no reason to believe that ice crystal growth in frozen soil is any less capable of generating pressures that would also exceed the vertical soil restraint force (per unit length) of many soils, causing upward vertical displacement of abandoned pipelines in a fashion similar to Fig. 6.5.

Figure 6.5: Upheaval buckling of onshore pipelines in Canada (after Nixon & Burgess, 1999).

6.5 MODELED RISK AND RATE OF FROST HEAVE

'The purpose of the project is to answer questions about the rate of frost heave for transmission pipelines that may be abandoned in Canada.' (PARSC, 2013, p. 2).

'During Stage 1, the potential and rate of frost heave will be predicted using scientific information in the public domain…' (PARSC, 2013, p. 2).

'Numerical modeling may utilize a model already in the possession of the applicant, adaptation of an existing model or the complete development of a new one.' (PARSC, 2013, p. 3).

The *Konrad_SP1.0* model, a key product of the PARSC - 003 study, is an adaptation of an existing 'test index' model as published by Konrad (1999; 2005). The SP parameter, which is a useful indicator of the risk of frost heave, also permits the estimation of the heave rate (see Appendix A and Section 5.4.2.3.3). A key portion of the programming code (Mathcad version) is provided in Appendix I, and some example output from *Konrad_SP1.0* can be found in Appendix J.

There is no disputing that the introduction of the 'segregation potential' (SP) parameter by Konrad & Morgenstern (1981; 1983) over 30 years ago has had a major 'citation impact' on the published literature on frost heave in soils since that time. Nevertheless, the SP parameter must either be i) measured by laboratory soil column freeze testing (Konrad, 1993), which is subject to test artefact problems (see Section 7.1), or ii) estimated using the test index approach (Konrad, 1999; 2005) which would require a heavy dependence on PTFs in the absence of available measured test indices.

Indeed, Konrad argues that 'for linear projects such as pipeline routes and highways, the method using SP values determined from laboratory freezing tests may not be economically justified' (Konrad, 1999, p. 404). It could further be argued that the measurement of test indices (e.g., liquid limit, specific surface area) may be almost as laborious and costly as laboratory soil column freezing tests. In this regard, the development of PTFs may be the most cost-effective avenue, especially when working in large geographic areas (i.e., nation-wide scale of the PARSC - 003 study).

Konrad (1999) calculates a preliminary SP_o parameter, and then applies a series of 'adjustments' to SP_o until the final SP parameter is derived. The adjustments are related to i) the fines fraction (i.e., particle-size distribution), ii) soil fabric, iii) clay mineralogy, and iv) overburden pressure. This SP parameter adjustment process continues in the follow-up paper published six years later (Konrad, 2005). The sequence of adjustments can be seen in Tables J-4 and J-5, and is simplified as follows:

Extracted from Table J-4:
SPoSs → SPo → SPo_f → SPo_w → SP_o → 'heave' (Konrad, 1999)

Extracted from Table J-5:
Ss_ref → SPo_ref → SPo_2 → SPo_f2 → SPo_w2 → SP_o2 → 'heave2' (Konrad, 2005)

In effect, the information on test indices (e.g., liquid limit, particle-size distribution of the fines fraction, specific surface area) is used as a surrogate for a direct measure or estimate of the soil hydraulic conductivity. Konrad routinely assumes in his publications that freezing soils are in a saturated state, hence it is K_{fs} (field-saturated hydraulic conductivity) that is the pertinent measure. Soil saturation (at the depth that pipelines are normally placed) may be a reasonable assumption during the winter season in areas of southern Canada outside of the Prairie Ecozone, but not within the Prairies Ecozone itself (see Appendices Q and S). It is known that the two most essential driving forces leading to heave and heaving pressures in soils are i) the water intake rate, or the upward Darcy flux, and ii) the heat extraction rate at the soil surface (Fig. 6.2) (Groenevelt & Grant, 2013). More research is needed to determine which one of these two driving forces governs the heaving process.

In addition to the development of the *Konrad_SP1.0* model, it was the intent of the research group to also operationalize the concepts contained in Groenevelt & Grant (2013) and create a completely new model for frost heave of soils based on thermodynamic principles (*Groenevelt_HI1.0*) (Fig. 6.1). To do this, however, it was necessary to first 'reconcile' some of the fundamental differences between the two main 'schools of thought' on frost heave in soils (i.e., 'mechanism' vs. 'thermodynamic process'). At the time of writing, our research group is continuing with this research activity. Figure 6.1 summarizes some of the main points made in the above discussion.

6.6 FUTURE STAGE 3 FIELD PROGRAM (MEASUREMENTS AND OBSERVATIONS)

'It appears that it could be very challenging to determine the historical rate of heave in an abandoned pipeline that would have been constructed 50 years ago given that records of burial depth may not be available with the needed precision.' (PARSC, 2013, p. 3).

Figure 7.3 provides a summary of a published case study of an abandoned natural gas pipeline in southern Alberta (Swanson *et al*., 2010), the only such case study found in the numerous literature reviews contained in the PARSC - 003 report. This case study underscores the concerns raised in the excerpt above, since the pipeline was constructed in 1925 and very few records exist on pipeline depth or other terms of reference that might be used to infer the geotechnical hazards that might have been operative over a 90-year period.

6.7 REFERENCES (SECTION 6)

Det Norske Veritas (DNV). 2010. Pipeline abandonment scoping study. A report prepared for the National Energy Board (NEB). 85 pp. Available at:http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnbndnmnt/pplnbndnmntscpngstd.pdf (verified Oct. 6, 2014)

Groenevelt, P.H. and C.D. Grant. 2013. Heave and heaving pressure in freezing soils: A unifying theory. Vadose Zone J. 12(1). 11 pp.

Konrad, J.-M. 1993. Frost Heave Potential (Chapter 74). p. 797-806. *In* M.R. Carter (ed.). Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Lewis Publishers. Boca Raton, FL.

Konrad, J.-M. 1999. Frost susceptibility related to soil index properties. Can. Geotech. J. 36:403-417.

Konrad, J.-M. 2005. Estimation of the segregation potential of fine-grained soils using the frost heave response of two reference soils. Can. Geotech. J. 42:38-50.

Konrad, J.-M. and N.R. Morgenstern. 1981. The segregation potential of a freezing soil. Can. Geotech. J. 18:482-491.

Konrad, J.-M. and N.R. Morgenstern. 1983. Frost susceptibility of soils in terms of their segregation potential. p. 660-665. *In* Proceedings of the 4th International Conference on Permafrost, Fairbanks, Alaska. National Academy Press, Washington, D.C.

Nixon, J.F. and M. Burgess. 1999. Norman Wells pipeline settlement and uplift movements. Can. Geotech. J. 36:119-135.

Pipeline Abandonment Research Steering Committee (PARSC). 2013. Request for proposals: PARSC 003 - Frost Heave Effects on Pipeline Exposure Rates. Petroleum Technology Alliance Canada (PTAC), Calgary, AB. August, 2013. 6 pp.

Rempel, A.W. 2012. Hydromechanical processes in freezing soils. Vadose Zone J. 11(4). 10 pp.

Swanson, J.M., T. Kunicky and P. Poohkay. 2010. Environmental considerations for pipeline abandonment: a case study from abandonment of a southern Alberta pipeline. Proceedings 8th Intl. Pipeline Conference (IPC2010 - ASME), Calgary, AB. Sept. 27-Oct. 1, 2010. 7 pp.

7.0 AREAS FOR FUTURE RESEARCH

7.1 LABORATORY SOIL COLUMN FREEZING TESTS

7.1.1 Background

As noted in Section 1 of this report, the DNV (2010) scoping report found that there was no known published information available on the risk of exposure of abandoned pipelines attributable to frost heave, and that this gap in knowledge needed to be addressed with mission-oriented research. It was recommended in DNV (2010) that laboratory soil column freezing tests should be used as a basis for the development and calibration of a numerical model for estimating frost heave risk and rates, and that modeled results should be validated with field measurements and observations. The terms of reference for Project PARSC - 003 (PARSC, 2013) generally followed the DNV scoping report recommendations. PARSC proposed that the overall study on frost heave could potentially be comprised of three sequential stages, as follows:

Stage 1: Literature search and numerical modeling (Project PARSC - 003)
Stage 2: Laboratory testing
Stage 3: Field measurements

PARSC would only determine the need for Stage 2 and/or Stage 3 after reviewing the results from this current Stage 1 study (PARSC, 2013).

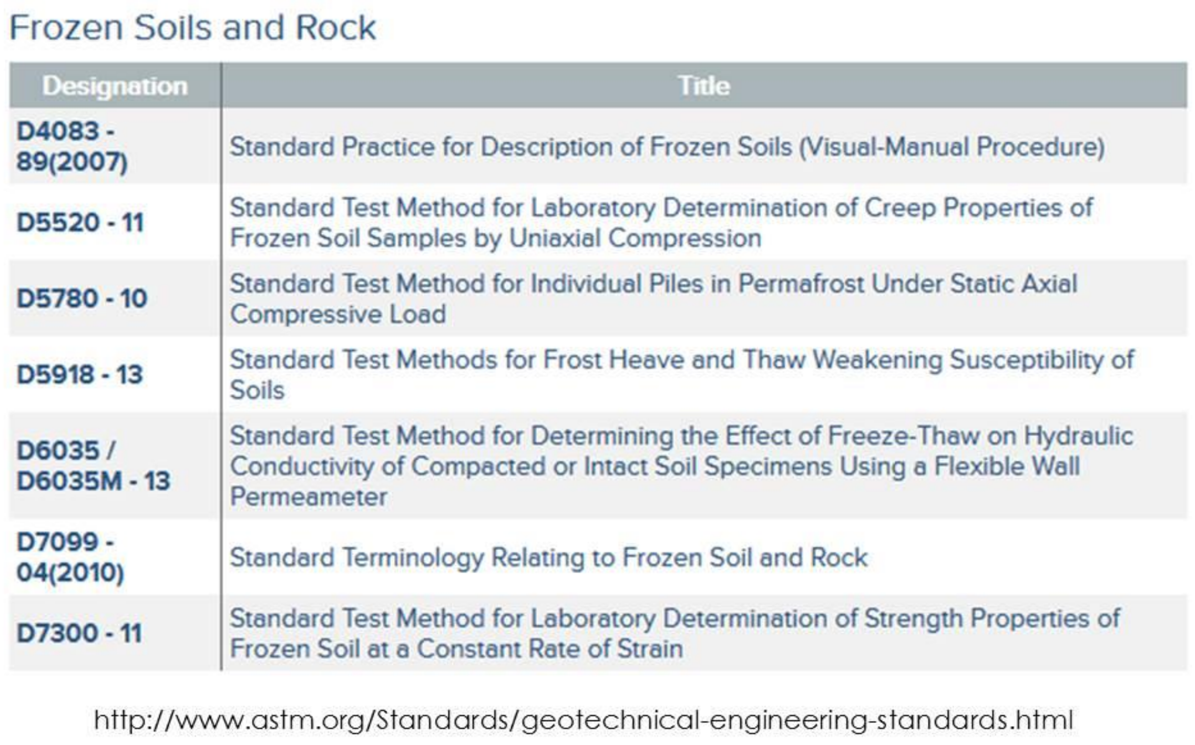
7.1.2 Soil column freezing test standards and procedures

The *Konrad_SP1.0* frost heave model developed in this study (see Section 5.4 and Appendices I and J) is based on the 'segregation potential' (SP). The SP parameter can be determined directly from laboratory 'step-freezing' tests on soil cores/columns (Konrad, 1993), or it can be estimated from soil index properties (Konrad, 1999; 2005), as has been done in the PARSC - 003 study. With the 'step-freezing' method, boundary temperatures are fixed for the duration of the soil column freezing test. An alternative protocol is the 'ramp-freezing' method, where the boundary temperatures are varied with time to simulate seasonal cooling and warming.

Alternatives to the Konrad (1993) test methods can be found in methods manuals published by several international standards organizations. Examples include the methods and apparatus outlined in ASTM Standard D5918 (see Table 7.1), and in the Swiss Standard SN 670 321a (2001). The latter test method employs the Schleibinger 'Soil Freeze/Thaw Chamber' (Fig. 7.1) which provides very accurate measures of maximum soil expansion during freezing, as well as the loss of soil strength after thawing (i.e., CBR-F test). Figure 7.2 shows horizontal ice lenses and vertical soil displacement in frozen soil columns after this type of testing.

It is worth noting that the 1st Edition of the Canadian Society of Soil Science (CSSS) 'Methods Manual' (Carter, 1993) contained a discrete section with five chapters entitled 'Analysis of Frozen Soils', which included the entry (Chapter 74) by Dr. J.-M. Konrad on laboratory soil column freezing tests (Konrad, 1993). The 2nd Edition of the CSSS 'Methods Manual' published 14 years later (Carter & Gregorich, 2007), however, did not include a single chapter (let alone an entire section) on the analysis of frozen soils in the laboratory or in the field. The reason for this worrisome omission is not known.

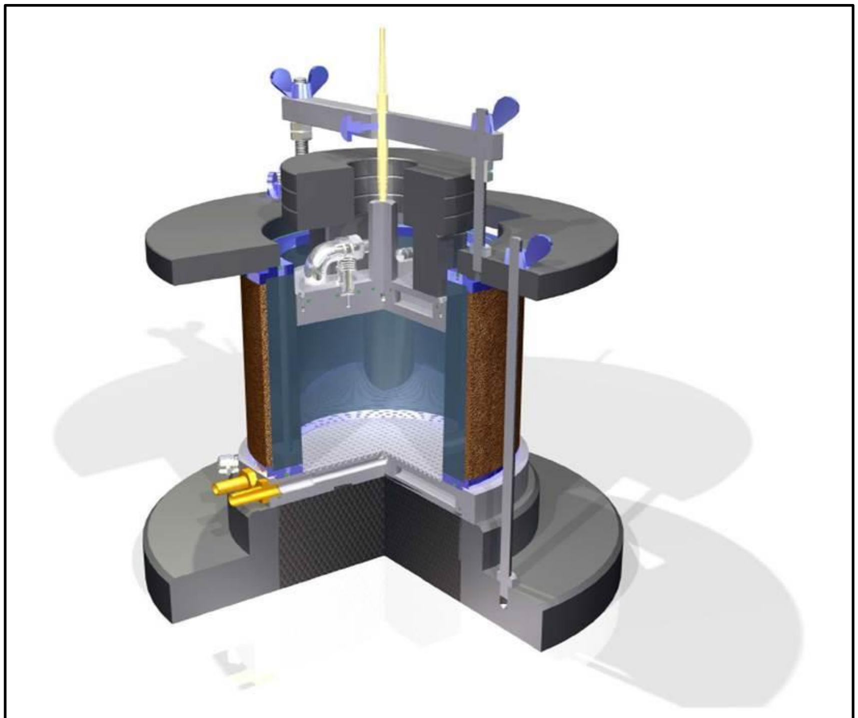
Table 7.1: Current ASTM Standards involving frozen soils and rock.



Frozen Soils and Rock

Designation	Title
D4083 - 89(2007)	Standard Practice for Description of Frozen Soils (Visual-Manual Procedure)
D5520 - 11	Standard Test Method for Laboratory Determination of Creep Properties of Frozen Soil Samples by Uniaxial Compression
D5780 - 10	Standard Test Method for Individual Piles in Permafrost Under Static Axial Compressive Load
D5918 - 13	Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils
D6035 / D6035M - 13	Standard Test Method for Determining the Effect of Freeze-Thaw on Hydraulic Conductivity of Compacted or Intact Soil Specimens Using a Flexible Wall Permeameter
D7099 - 04(2010)	Standard Terminology Relating to Frozen Soil and Rock
D7300 - 11	Standard Test Method for Laboratory Determination of Strength Properties of Frozen Soil at a Constant Rate of Strain

http://www.astm.org/Standards/geotechnical-engineering-standards.html



http://www.schleibinger.com/cmsimple/en/?Durability:Soil_Freeze-Thaw_Chamber

Figure 7.1: **Schematic of the Schleibinger 'Soil Freeze/Thaw Chamber'.**

http://bigthink.com/devil-in-the-data/the-stone-age-was-not-stone-age http://lms.epfl.ch/research/exp-facilities/standard-geotechnical-laboratory-tests

Figure 7.2: **Soil columns after laboratory freezing tests, showing wall-to-wall ice lens continuity in soils that are a) well aggregated, and b) structureless (single grain).**

7.1.3 Concerns with soil column freezing tests

It has been recognized for some time that laboratory soil column freezing tests often do not simulate field conditions well (Groenevelt & Grant, 2013; Kay *et al*., 1977; Smith & Onysko, 1990). For example, Groenevelt & Grant (2013) argued that ice lenses typically form wall-to-wall in freeze-thaw chambers (Fig. 7.2), thus obstructing the movement of liquid water within the soil column. This does not occur under field conditions, however, where pore water can migrate around ice lenses and thus provide greater opportunity for 'regelation'. In short, the 'boundary conditions' in the field are not the same as those for a soil column in the laboratory. More specific issues are as follows:

i. in a laboratory soil column freeze test, the warmest (deepest) ice lens blocks all upward flow of liquid water. This causes the temperature gradient in the 'frozen fringe' to become the dominant driving force for the upward movement of liquid water. In the field, however, ice lenses are finite in all directions, so that liquid water can flow around them. Hence, in the field, it is the 'overall temperature gradient' (i.e., from the soil surface to the depth of the 0°C isotherm) which is the driving force for the upward movement of liquid water.

ii. Konrad & Duquennoi (1993) wrote: "The present model considers that the soil specimen can be separated into a 'passive zone' defined as the frozen soil between the top surface and the base of the warmest ice lens, and an 'active zone' composed of the frozen fringe and the unfrozen soil." (p. 3112).

Commentary: This statement demonstrates that a laboratory soil column freeze test creates a test artefact that does not occur in the field. Since the soil column has a finite diameter, ice lenses typically grow wall-to-wall (Fig. 7.2). Such ice lenses then block all upward movement of liquid water. In the field, there is no such obstruction and there is no 'passive zone'**.** The whole soil profile, whether frozen or unfrozen, is an 'active zone'**.** That makes the concept of a 'frozen fringe' layer or zone within the soil profile rather frivolous. The entire soil profile (i.e., from the soil surface to the depth of the 0°C isotherm) is a 'frozen fringe', with ice lenses of all sizes and shapes, crystals, needles and other ice fragments distributed in abundance.

iii. Konrad & Duquennoi (1993) wrote: "....since the ice lens carries the full overburden pressure." (p. 3114).

Commentary: This is another test artefact created by the finite diameter of the soil column with ice lenses stretching from wall-to-wall. In the field, ice lenses maneuver themselves (partly during their formation, and partly by regelation) into a position whereby they are carrying the least possible amount of overburden pressure.

iv. Kay *et al.* (1977) found that the upward movement of water into the upper soil layer under field conditions was far greater than their frost heave model predicted. This is to be expected, because in the field each separate ice lens can pull in liquid water on both sides (i.e., the bottom [warm side] and the top [cold side]). In a soil column experiment, with wall-to-wall ice lenses, the top of a continuous ice lens is made inactive (or 'passive') because the liquid water cannot bypass it from below. In addition, the whole soil layer above a continuous ice lens becomes inactive (or 'passive'). So, if the frost heave model of Kay *et al.* (1977) predicted well under laboratory freeze test conditions, it is unlikely that it would do so under winter field conditions.

v. Kay *et al.* (1977) wrote: "The model predicted only about half the heave that was recorded by the heavograph." (p. 37).

Commentary: The observed heave in the field (measured with a 'heavograph') was much greater (about 2-fold) than their frost heave model predicted. This is to be expected, because in the field ice lenses can grow on both sides, whereas in a soil column the ice lenses can grow only on the bottom (warm) side. If the authors had set the boundary conditions in their laboratory soil column freeze tests such that the ice lenses were allowed to grow on both the warm and the cold side, the model may well have predicted twice the amount of heave that it did, which would have corresponded well to the values recorded by the heavograph in the field.

vi. Smith & Onysko (1990) wrote: "….if the water phase is continuous right into the frozen ground…., then it is probable that some formation of ice lenses occurs within the frozen ground." (p. 76).

Commentary: This statement supports the argument that i) the amount of heave observed in laboratory soil column freeze tests, and ii) the concept of a 'frozen fringe', are not useful for field applications.

vii. Smith & Onysko (1990) wrote: "The vertical displacement of the soil associated with this is resisted by friction between the soil and the sidewall of the column". (p. 78).

Commentary: This statement again supports the assertion that the amount of heave observed in laboratory soil column freeze tests is not transferable to field conditions. Further, when frost heave is measured in laboratory soil columns, there is a chance that the warmest ice lens "bites" itself into the wall of the column and fails to respond properly.

Recommendation #1:

It is recommended that PARSC/PTAC should bypass the proposed 'Stage 2' (Laboratory soil column freezing tests) of this multi-stage investigation of frost heave risk to abandoned pipelines, and proceed directly to 'Stage 3' (Field measurements and observations).

7.2 FIELD MEASUREMENT PROGRAM ('STAGE 3')

7.2.1 Suggested field research strategy

Pursuant to Recommendation #1 above, the following outlines (in general terms) a proposed strategy for a field measurement research program (3-year duration).

Figure E-1 (Appendix E) shows the transmission pipeline network for hydrocarbon products across the U.S. and Canada. The geographic coincidence of this network with the potential cropland areas in southern Canada (Fig. 2.9) suggests that the main focus on field site selection should be in southern Alberta, southern Saskatchewan, southern Ontario, and the St. Lawrence lowlands of southern Quebec. This geographic distribution would capture many of the major soil and clay mineral types across southern Canada (see Fig. 5.6, as well as Appendices R and S).

It is suggested that at least twelve monitoring stations should be established at several locations across southern Canada where abandoned transmission (hydrocarbon) pipelines are known to exist, but these are believed to be very few at present. Assistance would be required from PTAC and its member companies in identifying these potential field sites. The target soil characteristics should be medium- to fine-textured soils with high water-holding capacity and moderate to high water transmissibility properties. Soil thermal properties (i.e., thermal conductivity/resistivity, thermal diffusivity, specific heat capacity) should also be measured to assist in final site selection.

Datalogged thermistor nests should be installed in order to continuously monitor soil temperature profiles in the vicinity of the abandoned pipeline test sites. Biodegradable erosion control (grass seed) blankets should be established over the monitoring stations in order to eliminate any confounding effects attributable to i) variable land cover/surface conditions, or ii) wind or water erosion. Any changes in 'depth of soil cover' over the 3-yr period (attributable to frost heave) should be monitored by direct physical probing to the top of the pipeline.

Table 7.2 lists the soil parameters at each monitoring station that should be measured in the laboratory and/or field, or estimated with PTFs. Several measures of soil strength or degree of soil overconsolidation are included in Table 4.1 (i.e., Standard Proctor test indices, preconsolidation stress) and Table 7.2 (i.e., void ratio, cone penetration resistance, field-saturated hydraulic conductivity) in order to contrast soil strength in the pipeline trench area with that outside of the ROW (Ivey & McBride, 1999) during different soil water and temperature regime conditions (see Appendix T).

7.2.2 Availability of field sites with abandoned pipelines

It was noted in PARSC (2013) that "it appears that it could be very challenging to determine the historical rate of heave in an abandoned pipeline that would have been constructed 50 years ago given that records of burial depth may not be available with the needed precision" (pg. 3). Figure 7.3 typifies the issue that PARSC raised about a possible Stage 3 field program.

Figure 7.3 provides a summary of a published case study of an abandoned natural gas pipeline in southern Alberta (Swanson *et al*., 2010), the only such case study found in the literature review contained in the PARSC - 003 report. It has been segregated from the rest of the report, and presented here as a case study 'vignette', because it is intentionally/necessarily rife with speculation and conjecture.

At the time of writing, Stantec (Guelph) had made some initial enquiries involving pipeline companies operating in Ontario, and there do appear to be some abandoned pipeline segments in existence in the southern part of the province that might be suitable for this field program.

Table 7.2: **Soil parameters that should be measured in the lab and/or field (including methods/ instruments).**

- Depth of soil cover (cm) over abandoned pipeline
  - *direct physical probing*
- Soil particle-size distribution
  - *sieve method (sand fractions) and pipette method*
- Soil organic carbon content (SOC)
  - *LECO induction furnace method*
- Volumetric soil water content (Θv)
  - *frequency domain reflectometry method (Delta-T thetaprobe)*
- Gravimetric soil water content (*w*)
  - *gravimetric method (bulk soil sampling and processing)*
- Void ratio (*e*) or dry bulk density (*Db*)
  - *structurally-intact soil core sampling and processing*
- Field-saturated hydraulic conductivity (Kfs)
  - *Decagon mini-disk infiltrometer, or Guelph pressure infiltrometer*
- Soil water retention curve (Ψ[Θ])
  - *pressure plate apparatus*
- Cone penetration resistance
  - *Rimik recording cone penetrometer*
- Soil thermal properties (thermal conductivity/resistivity, thermal diffusivity, specific heat capacity)
  - *Decagon KD2 Pro Thermal Properties Analyzer*
- Surface soil temperature (°C at 10-cm depth [mid-plow layer])
  - *datalogged thermistors (Spectrum Watchdog)*
- Soil temperature profiles (°C in 25-cm depth increments to FDD-estimated depth of frost penetration
  - *datalogged thermistor nests (Onset Hobo)*

CASE STUDY 'VIGNETTE'

(on a possible instance of frost heave of an abandoned pipeline in Canada)

There have been very few documented cases of pipeline abandonment published in the literature (peer-reviewed or otherwise). Indeed, the only article encountered while reviewing literature for the PARSC-003 study is one from Alberta (Swanson *et al.*, 2010), and the authors do not cite any other cases in their reference list.

Swanson *et al.* (2010) reported on a case study in southern Alberta where an approx. 90-year old natural gas pipeline (constructed 1925) was decommissioned by removing problematic segments amounting to 1/3 of its 33 km length, and leaving the remainder abandoned-in-place. The pipeline trench was hand-dug in the 1920's, and so was likely comparatively shallow (in today's terms). However, Fig. 1 shows that the trench seems to be sufficiently wide for a person to stand at its base while digging, which would allow a greater depth to be achieved. Figure 1 also shows sizeable hand-dug spoil piles next to the trench. Using the 27.3 cm (10.75'') o.d. pipe as a visual scale reference, the spoil piles appear to be about 75 to 90 cm high, which might suggest that the trench was about 60 cm deep in open field areas. This would put the top of the 27.3 cm diameter pipe at about 33 cm below the surface. Figure 2 shows that the top of the pipeline may have been considerably deeper (perhaps about 100 cm) at road crossings.

The abandonment process began in 2005 and required a few years to complete, but it is unclear if product was still being transported up to that date. Interestingly, Fig. 3 shows that the pipeline was exposed through a heavily-treed woodlot area. While it appears that the exposed pipe may be lying in a shallow erosion gully, the geohazard involved in exposing the pipeline could also have been frost heave. It is possible that once the pipe was 'jacked' to the surface by frost heave, this may have altered surface runoff flow patterns in the woodlot and caused some rill and/or shallow gully erosion on either side of the pipe. The apparent young age of the woodlot does not suggest that it was 80-years old in 2007 when the Fig. 3 photo was taken, but it may have undergone natural regeneration or have been in the midst of transitioning to a climax forest type. If the Fig. 3 site has been wooded since 1925, it is unlikely that water erosion of soil caused the pipeline exposure.

The authors state the following about the depth of soil cover (DOC) observed in 2007:
The pipeline 'was generally located within the soil A horizon, and the depth of cover ranged from at the surface to approximately 6" into the soil B horizon'. This could be interpreted to mean that the top of the pipeline (for the most part) was between 0 and 20 cm of the surface in 2007 (i.e., most Ap horizons are about 20 cm thick in Canada). If it was originally emplaced in a 60-cm deep trench (i.e., top of pipe at about 33 cm below the surface), it may have been 'jacked' upward by frost heave by up to 33 cm over a 80 year period. It is highly unlikely that surficial water erosion of soil was a major geohazard contributor to this apparent 'pipeline exposure' situation.

This southern Alberta case could be one to be investigated in Stage 3 of the PARSC-003 study. There is still 2/3 of the pipeline currently abandoned-in-place (22 km).

Reference

Swanson, J.M., T. Kunicky and P. Poohkay. 2010. Environmental considerations for pipeline abandonment: a case study from abandonment of a southern Alberta pipeline. Proceedings 8th Intl. Pipeline Conference (IPC2010 - ASME), Calgary, AB. Sept. 27-Oct. 1, 2010. 7 pp.

Fig. 1 **Fig. 2** **Fig. 3**

Figure 7.3: A case study 'vignette' on a possible instance of frost heave of an abandoned pipeline in Canada. (after Swanson *et al.*, 2010).

7.3 RECONCILIATION OF THE MILLER AND ANDERSON ‘SCHOOLS’

As noted in Appendix B, there have been two attempts made in the literature to reconcile the two ‘schools of thought’ on frost heave modeling in soils. Van Loon (1991) and Groenevelt & Grant (2013) introduced a ‘B’ parameter and a ‘heave index’ (HI), respectively, that had the same dimensions ($L^2 t^{-1} T^{-1}$) and units ($m^2 s^{-1} K^{-1}$) as the ‘SP’ parameter of Konrad (1999; 2005) (see Appendix A). There is no disputing that the introduction of the ‘SP’ parameter by Konrad & Morgenstern (1983) over 30 years ago has had a major ‘citation impact’ on the published literature on frost heave in soils since that time, and right up to the present day. Nevertheless, the SP parameter must either be i) measured by laboratory soil column freeze testing (Konrad, 1993), which is subject to test artefact problems, or ii) estimated using the test index approach (Konrad, 1999; 2005) which would require a heavy dependence on PTFs in the absence of available measured test indices.

Recommendation #2:

It is recommended that PARSC/PTAC put resources into fully developing the *Groenevelt_HI1.0* model (largely conceptual at present), which is based on sound thermodynamic principles and has little dependency on PTFs (i.e., would likely only require a PTF to estimate saturated and unsaturated hydraulic conductivity), unlike the *Konrad_SP1.0* model.

7.4 UPDATING THE SHAW 1D MODEL

As noted in Section 5.4, an attempt was made in the PARSC - 003 study to re-write the Fortran program code of the SHAW 1D model into the Python programming language, but the attempt was unsuccessful.

Recommendation #3:

It is recommended that efforts be continued to either i) locate a non-Fortran version of the SHAW 1D model (by contacting researchers who have published on SHAW 1D in the last decade, including its creator Dr. Flerchinger), or ii) initiate a new attempt to re-write the Fortran program code into the Python programming language.

7.5 PIPELINE SEGMENTS ABANDONED-IN-PLACE (VARIABLE DIAMETER AND LENGTH)

Information assembled in Appendix T suggests that soil restraint properties and the ’virtual anchor length’ concept seem to be an avenue worth pursuing on the matter of frost heave risk to abandoned pipeline segments. Resolution of this matter will likely require a ‘pipeline design engineer’ perspective. For example, the study of Tian (2011) could be replicated to verify or refute that the three established computational methods produce very different results, but do so in a Canadian context (using measured soil mechanics parameter data from Canadian soils).

Recommendation #4:

It is recommended that a more in-depth study be carried out on the pipeline segment (diameter and length) matter from a 'pipeline design engineer' perspective.

7.6 REFERENCES (SECTION 7)

Carter, M.R. (ed.). 1993. Soil Sampling and Methods of Analysis (1st edition). Canadian Society of Soil Science. Lewis Publishers. Boca Raton, FL. 823 pp.

Carter, M.R. and E.G. Gregorich (eds.). 2007. Soil Sampling and Methods of Analysis (2nd edition). Canadian Society of Soil Science. CRC Press, Taylor & Francis Group, Boca Raton, FL.

Det Norske Veritas (DNV). 2010. Pipeline abandonment scoping study. A report prepared for the National Energy Board (NEB). 85 pp. Available at:http://www.neb-one.gc.ca/clf-nsi/rthnb/pblcprtcptn/pplnbndnmnt/pplnbndnmntscpngstd.pdf (verified Oct. 6, 2014)

Groenevelt, P.H. and C.D. Grant. 2013. Heave and heaving pressure in freezing soils: A unifying theory. Vadose Zone J. 12(1). 11 pp.

Ivey, J.L. and R.A. McBride. 1999. Delineating the zone of topsoil disturbance around buried utilities on agricultural land. Land Degradation and Development 10:531-544.

Kay, B.D., M.I. Sheppard and J.P.G. Loch. 1977. A preliminary comparison of simulated and observed water redistribution in soils freezing under laboratory and field conditions. In: p. 29-41, Proc. Int'l. Symp. Frost Action in Soils, Vol. 1, Lulea, Sweden.

Konrad, J.-M. 1993. Frost Heave Potential (Chapter 74). p. 797-806. *In* M.R. Carter (ed.). Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Lewis Publishers. Boca Raton, FL.

Konrad, J.-M. 1999. Frost susceptibility related to soil index properties. Can. Geotech. J. 36:403-417.

Konrad, J.-M. 2005. Estimation of the segregation potential of fine-grained soils using the frost heave response of two reference soils. Can. Geotech. J. 42:38-50.

Konrad. J.-M. and C. Duquennoi. 1993. A model for water transport and ice lensing in freezing soils. Water Resources Research 29(9):3109-3124.

Konrad, J.-M. and N.R. Morgenstern. 1983. Frost susceptibility of soils in terms of their segregation potential. p. 660-665. *In* Proc. 4th Int'l. Conf. on Permafrost, Fairbanks, AK. National Academy Press, Washington, DC.

Pipeline Abandonment Research Steering Committee (PARSC). 2013. Request for proposals: PARSC 003 - Frost Heave Effects on Pipeline Exposure Rates. Petroleum Technology Alliance Canada (PTAC), Calgary, AB. August, 2013. 6 pp.

Smith, M.W. and D. Onysko. 1990. Observations and significance of internal pressures in freezing soil. p. 75 - 81. *In* Proc. 5th Canadian Permafrost Conference, Universite Laval, Collection Nordicana 54.

Swanson, J.M., T. Kunicky and P. Poohkay. 2010. Environmental considerations for pipeline abandonment: a case study from abandonment of a southern Alberta pipeline. Proceedings 8th Intl. Pipeline Conference (IPC2010 - ASME), Calgary, AB. Sept. 27-Oct. 1, 2010. 7 pp.

Swiss Association for Standardization. 2001. Frosthebungsversuch und CBR-Versuch nach dem Auftauen / Essai de gonflement au gel et essai CBR après degel. SN 670 321a (2001).

Tian, D. 2011. Determination of soil restraint properties and calculation of virtual anchor lengths in buried pipelines. KBR. Inc. Gas Speak Colloquium 2011. Sept. 12-14, 2011, Canberra, Australia.

Van Loon, W.K.P. 1991. Heat and Mass Transfer in Frozen Porous Media. Ph.D. Thesis. University of Wageningen, The Netherlands.

8.0 REFERENCES

A main focus in the PARSC - 003 study was the review of literature relevant to the process of frost heave in soils as well as a wide range of ancillary topics, and over 450 different references were examined. As a result, an overall reference list covering the entire report (Volumes 1 and 2) was not compiled for 'Section 8 - REFERENCES'. Instead, shorter reference lists are distributed throughout both volumes.

In Volume 1, reference lists are compiled at the end of the main sections (first order headings), so that the reader can quickly locate the details on cited sources. Each of Sections 1 through 7 has a dedicated reference list. In Volume 2, all but 2 of the 20 appendices also have dedicated reference lists. As a result, the various reference lists distributed through both volumes of the report are not mutually-exclusive, and there is some repetition of specific publications among lists.