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Svein-Erik Sveen

Artificial Thawing of Seasonally Frozen Ground

Performance Characteristics of Hydronic Based Thawing

Doctoral thesis

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Thesis for the Degree of
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Preface and acknowledgements

This thesis is submitted in partial fulfilment of the requirements for the Philosophiae Doctor degree (PhD) at the Norwegian University of Science and Technology (NTNU). The work has been carried out at formerly Narvik University College (NUC), now part of UiT–Norwegian Arctic University. The Norwegian Ministry of Education and Research, the ColdTech project (administered by Norut Narvik[1]), Nordland County council, and Heatwork AS have supported the research financially, for which I am greatly appreciative.

January 1st 2016, NUC merged with UiT. Since then, I have been working full-time as an Assistant professor at UiT–Narvik, Institute of Building, Energy and Material Technology, while finishing the PhD-work.

As part of my initial work during 2009–2010, I was charged with relocating and upgrading the frost in ground laboratory (FiG-lab), first established in 2007. Ideas for improvements came while attending courses and doing field-work at the University Centre in Svalbard (UNIS), January–June 2009, and during my visit to the Northern (Arctic) Federal University in Arkhangelsk (NArFU), Russia, in 2010. I thank the Arctic Technology Department at UNIS for providing office accommodation during my stay, and NArFU for the opportunity to test our data logging systems at their wooden house laboratory.

I am much obliged to former rector at NUC, Arne Erik Holdø, and Professor Per-Arne Sundsbø, for initiating this work and for recommending me for the position. I am also appreciative of my colleagues at the institute in Narvik, Professors Rajnish K. Calay and Mohamad Mustafa, for taking time to read the thesis and amend its English.

I am very grateful and forever indebted to my supervisors Professor Bjørn Reidar Sørensen and Associate professor Hung Thanh Nguyen at UiT–Narvik, and Professor Trygve M. Eikevik at NTNU. Without their guidance and contributions, this work would have been futile.

I also thank our highly skilled laboratory personnel, Øyvind Søraas (initial project manager), Kjell Ellingsen, Ståle Herving, Jørn Bergvill and Boy-Arne Buyle (project manager), for their assistance in relocating the FiG-lab, thus ensuring that UiT has an enduring, state-of-the-art lab-facility for continued research within frost in ground.

Finally, I thank my wife Marianne for her support and patience, and my two sons, Elias and Simon, for enduring my absence for long periods throughout these years.

Narvik, March 2017
Svein-Erik Sveen

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Abstract

Frozen ground engineering has developed rapidly in the past several decades under the pressure of necessity. With an increased focus on exploration and extraction of oil and gas reserves in the Arctic, the topic has gained actuality and received more attention in recent years. In addition, the United Nations' Intergovernmental Panel on Climate Change (IPCC) has published several assessment reports since 1990, on climate change and the implications of increased global temperatures on permafrost and seasonally frozen ground in cold regions.

To facilitate excavation and foundation work in seasonally freezing or permafrost regions, the frozen soil must be thawed, either by natural (solar) thawing, or by artificial thawing, where an auxiliary heat source is utilized to accelerate the process. As frozen soils related problems have broadened in scope, the inadequacy of traditional thawing methods have become increasingly apparent.

In this study, the process of rapid thawing of frozen ground subjected to hydronic heating was studied, utilizing full-scale experiments. The method is based on known principles, but modified to accommodate effective, in situ thawing of frozen ground. The main objectives of the study were to describe the novel application of the method and working principles, assess its performance characteristics when used for artificial thawing, and provide input on system optimization of hydronic based defrosting systems.

The methodology used is a case study, supported by full-scale thawing experiments performed on various types of homogenous, initially frozen soils. The results from two identical experiments, carried out during the winters 2011 and 2012, are compared and held up against results from an initial thawing experiment from 2007. The corresponding soil temperature increase, phase change and variation in moisture content for each type of soil are presented. Furthermore, the outdoors laboratory facilities used for the experimental work in 2011 and 2012 are described.

The operating principles of the method are described in detail and the thaw efficiency is compared with traditional thawing techniques. Numerical simulations of time-dependent heat transfer in fully saturated sand are performed to get an idea of the relative influence on soil temperature, resulting from variations in fundamental parameters (sensitivity analysis) such as distance between pipes, inlet temperature and fluid flow rate.

In addition to an introductory part, the thesis contains a review covering some of the relevant literature, a synthesis of the work done, a summary of the simulation results from a working paper, and a conclusion. The thesis' main contributions are the four papers enclosed in the appendices (1-4). Summarized, the study has provided a scientific description of hydronic heating utilized for thawing frozen ground and an assessment of the method's performance characteristics. The work has provided increased insight into the complicated heat and mass

transfer occurring during artificial thawing through full-scale experiments, and shown what thaw rates to expect in various soils. The simulations have helped visualize the dynamics and shown to what extent variations in central parameters influence the process. Finally, the work has resulted in the establishment of new outdoors laboratory facilities for continued research on frozen ground.

Due to the limited scope of the field-work, additional experiments are recommended, following the same methodology and procedures as previously. In order to determine differences in initial ice and water content or ice-water ratio between the various soils prior to thawing, it is recommended to collect frozen core samples prior to any new experiments. As an alternative to repeated experiments, frozen core samples could be collected from the various soil bins during winter. It would provide both additional information about the initial conditions prior to thawing, as well as an opportunity for determining additional properties such as frozen and thawed (unfrozen) thermal conductivities of the soils used.

Additionally, continued modelling efforts of the artificial thawing process are recommended, properly accounting for the effects of phase change and heat losses from the surface. Unique for this study is the simultaneous monitoring of soil temperatures and moisture variations. These data records should be used to address some of the research questions considered, but not treated in this study, as well as for further system optimization.

Nomenclature

A	area	m^2
A, B	factors related to Darcy friction factor	-
A_s	amplitude of surface temperature oscillation	^oC
A_z	amplitude of subsurface temperature oscillation	^oC
c	specific heat	kJ/(kg·K)
C	volumetric heat capacity (ρc)	kJ/(m^3K)
$^oC{\cdot}days$	Celsius degree days	^{o}C·days
CS	capacitance sensor	-
d, d_h	diameter; hydraulic diameter	m; m
D_{10}	effective diameter (soil gradation parameter)	mm
f_D	Darcy friction factor	-
$^oF{\cdot}days$	Fahrenheit degree days	^{o}F·days
e	surface roughness	m
h	convection heat transfer coefficient	W/(m^2K)
I	surface or air temperature index	^{o}C·days
I_f	local frost index	^{o}C·days
I_t	local thaw index	^{o}C·days
k	thermal conductivity	W/(m·K)
l	latent heat of fusion (soil water)	J/kg
L	volumetric latent heat of fusion (ρl)	J/m^3
L	unit	liter
$\dot{m}$	mass (fluid) flow rate	L/s
n	surface N-factor	-
Nu	Nusselt number	-
p	pressure	N/m^2
Pr	Prandtl number	-
Q	amount of energy transfer by heat	J
$\dot{Q}, \dot{W}$	heat transfer rate	W
Re	Reynolds number	-
t	time	s
T	temperature	K
TC	thermocouple	-
TS	thermistor string	-
u	fluid velocity	m/s
x, y, z	Cartesian coordinates	-
X	phase change interface depth	m
Z	depth; pipe perimeter	m; m

Greek letters

α	thermal diffusivity; Modified Berggren parameter	m^2/s; -
γ	Neumann phase change parameter	-
θ	air temperature	ºC
λ	Modified Berggren correction factor	-
μ	dynamic viscosity; Modified Berggren parameter	kg/(m·s); -
v	kinetic viscosity	m^2/s
ρ	density	kg/m^3

Subscripts

0	initial state
2	solid or soil
30d	30-day mean
a	air
ext, int	external; internal
f	fusion or frozen
i	initial
max	maximum
min	minimum
p	at constant pressure
s	surface; soil or solid
t	thaw
u	unfrozen
wall	pipe wall
z	depth

Contents

1. Introduction

The chapter aims to give a brief background of this research and to highlight the importance of studying artificial thawing of seasonally frozen ground. This is followed by the objectives, limitations, methodology and the contributions of this research. A section outlining the remainder of this thesis, together with a list of included publications, are given at the end of this chapter.

1.1 Background

Narvik University College (NUC) first became involved with hydronic based thawing back in 2004, when a local landscape gardener sought our assistance in improving a new type of defrosting system adapted for thawing of frozen ground. NUC, which is now a faculty within the UiT–Norwegian Arctic University, started a collaboration with what later became a major supplier of defrosting systems to the commercial markets in Europe and northwest Russia. During the process, a frost in ground laboratory (FiG-lab) for full-scale experiments was established.

Early on, it became clear that the defrosting system in question did not exactly represent an entirely new approach, but rather a novel way of utilizing a previously known method in order to thaw frozen ground effectively. However, this particular way of utilizing hydronic heating for thawing purposes was deemed sufficiently original to be granted several U.S. patents (Bruckelmyer 1996; 1998). Our preliminary experiments gave indications of the method being practical, flexible and apparently efficient compared with traditional techniques. Moreover, the potential of this technique to offer a long sought-after tool for extending the construction season was unmistakeable. This is important to commercial and industrial construction companies, utilities, municipalities and residential contractors operating in cold regions, because it allows for excavations, ditching and other ground work to take place all year round.

1.2 Artificial thawing

One of the first to use the term ‘artificial thawing’ within the field of frozen ground engineering was Jumikis (1979). He referred to two kinds of vertical, cylindrical defreeze-pipe systems, one single-pipe with open lower-end jets, and another double-walled, closed lower-end with forced fluid circulation. The latter was used as either a cold-water or a hot-water thawing system, depending on the availability of electricity for heating water.

The principle of operation of the hot-water variant is essentially the same as the hydronic based thawing method referred to in this thesis. Both utilize a hot, circulating fluid to raise the surface temperature of the pipes to a degree sufficient to thaw the surrounding soil. The main difference is that the former required the drilling of several vertical holes prior to installing the pipes, thus being more resource demanding and thawing smaller areas than the latter. The advantage of vertically installed pipes (radial thawing) is that almost all the generated heat is conducted to the ground, resulting in highly efficient thawing of the soil near the pipe mantle.

The hydronic based thawing method, which is the subject matter of this thesis, involves distributing the flexible pipes horizontally across the ground surface (top-down thawing), and do not require pre-drilling. This result in an altered thaw pattern and different thaw rates compared with vertically installed pipes. To reduce heat losses during operation, the pipes are covered with combined vapour and insulation blankets. This approach allows comparatively larger areas to be thawed, makes it easier to move to adjacent areas for continued operation, and is less demanding in terms of labour and equipment.

Jumikis (1979) suggested that using a coolant, radial thawing might be good also for extracting heat from the soil. In fact, that is exactly how the method he described is being used today (Yuan and Yang 2016; Balossi Restelli et al. 2016). In the literature, this is termed ‘artificial ground freezing’ or just AGF, and has been commonly used for several decades in Scandinavia, Germany, UK, France and North America to strengthen the soil and as a groundwater barrier during construction (Zhou and Tang 2015). In comparison, artificial thawing has not received the same attention. Besides isolated experiments in the period after the mechanizations of mine workings in the early 1900s, the research on this topic is lacking. Furthermore, there is a shortage of full-scale thawing experiments reported in the literature. Another persuasive argument for further investigations are developments over the last two decades, where the applicability and efficiency of hydronic based thawing have seen considerable improvements, promoting widespread use in Scandinavia, eastern Europe and northwest Russia (Heatwork 2016; Wacker Neuson 2016).

1.3 Objectives

1.3.1 Problem setting

From the onset, it was decided that the study should focus on thawing experiments, taking advantage of the possibilities represented by the original frost in ground laboratory. The prospect of additional experiments encouraged discussions about which issues to pursue. The preliminary experiments had left unresolved questions concerning factors influencing hydronic based thawing, such as extent and significance of phase change (latent heat). Early in situ tests on various soils gave indications of ice and water content having strong influence on thaw progression. For example, it was found that soils with moderate fines, sand and water (ice) content retained more water during thawing, and thawed faster than coarse-grained soils.

To address some of these issues and assess the thaw efficiency of hydronic based thawing, further experiments were necessary. The scope was somewhat scaled down when it became clear that relocating the frost in ground laboratory would be part of the work. Back then, this was an unexpected development. Fortunately, it coincided in time with the start-up of another research project (ColdTech[2]). This resulted in additional funding for the relocation project and gave an opportunity to choose a more suitable location, a wider range of sensors, and prepare the site for general-purpose frost in ground experiments.

The main objectives of the study were to describe the novel application of hydronic based thawing, working principles, and assess the method's performance characteristics when utilized for artificial thawing of frozen ground. The work has included the following activities:

- Designing and building of appropriate laboratory facilities suitable for full-scale experiments on frozen ground, including instrumentation necessary for monitoring of spatial and temporal variations of soil temperature and soil moisture.
- Monitoring of thermal (heat transfer) and hydrodynamic responses (mass transfer) through thawing experiments on various, homogenous soils to obtain data necessary to assess the thaw efficiency of the method.
- The use of numerical modelling software (in this case COMSOL Multiphysics[3]) to perform a sensitivity analysis as basis for input on optimization of hydronic based defrosting systems.

1.3.2 Revisions

During the work, adjustments were made to supervision, schedule, direction, and scope that should be noted. The first major revision came after several meetings during September 2014, when Associate professor Hung Thanh Nguyen entered the project as co-supervisor. He assisted in structuring the remaining work into clearly set out tasks, focusing on completing the analysis of the results from the experiments and preparing them for publication.

The second revision was made during October 2015 and was more comprehensive than the first. It occurred at the time when the first key article (paper III) was being prepared for submission, promoting decisions on topics and number of additional articles. It was decided to aim for two more journal articles, one covering the remaining results (soil moisture variations), and one about the influence of phase change and water content on the thawing process (numerical simulations). Owing to problems implementing phase change into the numerical model, the latter was instead changed to a sensitivity analysis. The model was then used in a number of parametric sweeps, altering fundamental operating and design parameters one at a time, such as the distance between pipes, inlet temperature and fluid flow rate, to get an idea of their relative influence on the thawing process.

The last revision was made during April 2016. Acknowledging that completing a numerical model adequately incorporating phase change would require considerably more work, it was decided to define such efforts as further work and instead focus on one final, comprehensive

[2] ColdTech – Sustainable Cold Climate Technology (http://www.forskningsradet.no/prognett-nordsatsing/ColdTech_Sustainable_Cold_Climate_Technology/1253958563223).
[3] COMSOL AB, Tegnérgatan 23, SE-111 40 Stockholm, Sweden.

article (paper IV). This move ensured sufficient time for a proper analysis of the soil moisture records from the experiments, i.e., the remaining, not published results. As a substitute, and partial fulfilment of the objective related to numerical modelling, the results of the sensitivity analysis are summarized in Chapter 4 in this thesis.

1.4 Limitations

The primary focus in this work is on hydronic heating utilized for artificial thawing of seasonally frozen ground. Emphasis is on spatial and temporal variations in soil temperatures, bound and unbound water content (phase changes), and associated thaw rates. While there are references to initial experiments in 2007, the main part of the work is based on two full-scale thawing experiments (2011 and 2012) performed on three types of homogenous soils: silty sand, gravelly sand, and uniform gravel.

The soils have been exposed to varying weather conditions in the time leading up to the experiments. There have been no changes to the preparations made prior to, or the procedures followed during the experiments. Furthermore, they are limited to the use of one particular type of defrosting system for providing the heat necessary for thawing.

Although the hydronic thawing method is relevant also for perennially frozen ground (permafrost), such application of the method is outside the scope of this study. The same applies to consequences of frost heave and thaw settlements seen from an engineering point of view. For the same reasons, conceptual models of the thawing process (macro scale), or chemical and physical driving forces are not treated in this work.

As the numerical simulations (Chapter 4) do not account for phase change, the model is therefore only used for assessing the relative influence of variations of certain parameters.

1.5 Methodology

Besides a literature review to obtain insight to some of the progress made and remaining challenges in this field of research, the methodology used in this work is a quantitatively oriented case study. Full-scale experiments are performed as means to quantify certain characteristics of a specific artificial thawing method.

The size of the defrosting system itself does not prevent normal scale investigations of certain features in a standard laboratory environment. However, monitoring the effects from simultaneous thawing of large volumes of initially frozen soils would be difficult under such circumstances. Space limitations can often be a challenge, but even if that was not an issue, downscaled experiments bring the risk of introducing scaling errors and related uncertainties. An added benefit of a full-scale approach is that the laboratory facilities established during the course of the work can be used for further investigations in the future.

1.6 Contributions of the thesis

This work has extended the knowledge within the field of frozen ground engineering in general, and about artificial thawing of frozen ground in particular.

It is demonstrated that conduction-based thawing is an efficient and flexible approach compared with some traditional techniques reliant on other heat transfer mechanisms. Preliminary performance tests based on soil temperature monitoring gave indications of the thaw rates being nonlinear and varying with soil type (paper I and II).

The initial findings are corroborated by additional experiments. It is shown that thaw rates decrease nonlinearly with increasing depth or distance to the heat source, that this is a very rapid process compared with natural thawing, and that water content, fines content (frost susceptibility) and porosity of the soils are influential factors (paper III).

It is shown that hydronic based thawing applied to confined areas results in silty and gravelly sand becoming fully saturated. Compared with coarser and more porous soils such as uniform gravel, the former soils experience higher thaw rates. It is shown that water redistribution and migration are more prominent in the uppermost soil layer, and that the amount of water changing phase has a major impact on the thawing process and what thaw rates to expect in various soils (paper IV). It is shown that thaw rates calculated from soil moisture records correspond well with similar rates calculated from soil temperature records.

Finally, the work has provided insight to the heat and mass transfer occurring in various soils during artificial thawing, how those interconnected phenomena interact in practice (paper III and IV), and resulted in some general recommendations on optimization of hydronic based defrosting systems (Chapter 4).

1.7 Thesis outline

Chapter 1 briefly describes the background of the work, and includes the objectives, limitations, methodology, and contributions from the thesis. A list of the resultant publications is presented in a separate section at the end of the chapter.

Chapter 2 presents a review of some of the notable early efforts and later progress made in this field of research, including both theoretical and experimental work.

Chapter 3 contains a summary of the work presented in the four papers listed in section 1.8.

Chapter 4 presents the preliminary modelling efforts and the main results of a sensitivity analysis.

Chapter 5 brings together the conclusions of this work and presents recommendations for further work.

Paper I–IV are enclosed in the appendices.

1.8 List of publications

1.8.1 Included papers

The following list contains the publications developed during the work referred to in this doctoral thesis, including a recently submitted manuscript. The collection of papers are the main contribution of the thesis.

At the EUCOPIII conference in 2010, both an abstract and an associated, full-length paper (paper I) were submitted. While only abstracts were included in the conference proceedings, both are included in the thesis. The subsequent papers (paper II and III) have been peer reviewed and are published in two different international journals. The final paper (paper IV) has been submitted and is currently being reviewed.

I Sveen, S. E., and Sørensen, B. R. (2010). "Effective thawing of frozen ground– performance testing of a new thawing method based on hydronic heat (conduction)." *Proc., 3rd European Conf. on Permafrost (EUCOPIII)*, Univ. Centre in Svalbard, Svalbard, Norway.

II Sveen, S. E., and Sørensen, B. R. (2013). "Establishment and instrumentation of a full scale laboratory for thermal and hygroscopic investigations of soil behavior in cold climates." *J. Appl. Mech. Mater.*, 239, 827–835.

III Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017a). "Thaw penetration in frozen ground subjected to hydronic heating." *J. Cold Reg. Eng.*, 10.1061/(ASCE)CR.1943-5495.0000117:31(1).

IV Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017b). "Soil moisture variations in frozen ground subjected to hydronic heating." *J. Cold Reg. Eng.* (submitted).

1.8.2 Additional papers

The following conference papers are not part of the thesis, but are relevant to the approach and instrumentation chosen for the experiments. The decision was based on assessments of the measurement systems and sensors used in the project mentioned below, in Archangel, Russia.

Varfolomeev, A., Sveen, S. E., Sørensen, B. R. (2011). "Monitoring of temperatures of a research wooden module house built in Archangel", *Proc., 24th Int. Congress on Condition Monitoring and Diagnostics Engineering Management (COMADEM2011)*, COMADEM International, ISBN 0-9541307-2-3, 1466–1474.

Varfolomeev, A., Sveen, S. E. (2011). "Analysis of thermal investigations at experimental module house built in Archangel", *Proc., Workshop on Sustainable Energy Solutions for Buildings in the High North*, The Research council of Norway, Narvik University College, – Archangel: KIRA, ISBN 978-5-98450-182-8, 29–35.

2. Frost in ground

Considering the large land areas of the globe experiencing frozen ground conditions during the coldest period of the year and the implications on daily life, it is not surprising to find an abundance of literature on the topic. This chapter recounts some of the early research efforts and progress made in the field in general, and within artificial thawing in particular. It refers to theoretical and experimental work most relevant to this study. In addition, references to sources defining the cold regions of the Northern hemisphere and the Arctic are mentioned since they are relevant to the types of frozen ground conditions found in this geographic region.

2.1 A historical perspective

Right from the early days, people living and working in the cold regions of the North had to learn to cope with seasonal frost and frozen ground conditions. Some adaptations were made out of necessity to sustain life under harsh conditions, while others were driven by an anticipation of economic gains, illustrated by Fig. 2.1.

Figure 2.1. A small, hydraulic gold mining operation in what was then Oregon Territory, from 1885, at the northwestern coast of today's U.S.A. (http://www.miningartifacts.org/).

Phenomena such as frost weathering of mountainsides and rocks, upheave of stones and pillars, frost heaving and thaw settlements during spring thaw are typical for regions experiencing cold winters. Being one prominent cold region in the north, Scandinavia, unsurprisingly, has contributed to research and development on frost in ground. A final report from a comprehensive study (1970–76) on the topic (Sætersdal 1976), refers to early research in Sweden and Norway. As early as 1914, experimenting on freezing soils, S. Johansson (Sweden) discovered that water migrating to the frost front accumulated as layers of ice. He believed that to be the main cause of frost heave in some soils (Black and Hardenberg 1991). Up until then it had been assumed that frost heave was caused by the volume expansion resulting from freezing pore water. Another pioneer was G. Beskow (Swedish Road Institute), who during 1930–35 wrote several publications about fundamental problems arising from freezing of fine-grained soils. Based on conceptual ideas, backed by extensive laboratory experiments as well as contemporary work by Taber (1929; 1930) and Casagrande (1931), he produced his classical monograph on the mechanics of frost heaving (Beskow 1935).

Noteworthy contributions from Norway are K. Heie (Norwegian Road Administration), who in 1932 wrote several reports on frost heave on roads. Another was A. Watzinger, who during 1938–1941 investigated the thermal conductivity of soils and developed methods for calculating frost penetration (Watzinger et al. 1938; 1941). During the years from 1944 to 1971, Skaven-Haug developed practical methods for reducing frost penetration beneath roadbeds and railways based on the work of Beskow and Watzinger. Besides his contributions, the national research efforts on frost in ground were very limited during this period. It was not until 1968, when the Research Council of Norway established a special committee to identify areas for future research on the topic that the situation changed. This resulted in the Frost Action in Soils Program (1970–76), which built on previous work and lead to a number of publications as well as national guidelines for preventing of frost damage (Sætersdal 1976). The Frost in Ground Committee, established in 2005, has since issued several publications referring to recent research efforts in Norway (Myhre 2005; 2007; 2009; 2010). The committee is still active and represents the ‘Norwegian Adhering Body’ in the International Permafrost Association (IPA).

Black and Hardenberg (1991), at the Cold Regions Research & Engineering Laboratory (CRREL), gave historical perspectives in frost heave research conducted in North America and Europe since the early 1900s. It is both an interesting and comprehensive overview of early research attempting to understand the principles underlying moisture movement in freezing soils.

There are several excellent books about frozen ground engineering in general, which, in part, deal with artificial thawing or freezing. One is Andersland and Ladanyi (2004), which have been frequently consulted during this work. In their introduction, they state that as practical problems involving frozen ground have broadened in scope, the methods for dealing with them have evolved. For example, they point to significant advances in artificial ground freezing (AGF) technology, used for temporary earth support and groundwater control in difficult soil or rock strata. One full chapter is dedicated to thaw behaviour of frozen ground, with focus on thaw settlement, consolidation, and associated stresses.

Another is a monograph by Esch (2004a) which deals with artificial thawing methods in a detailed and systematic way. Examples of various techniques tried over the years, based on different approaches with the mechanizations of mine workings in the early 1930s, are outlined. The various methods are classified by the direction of heat flow, i.e., one-dimensional (surficial) and two-dimensional (radial) thawing. Another way of grouping them is according to the method and heat source used:

- *Steam thawing* was mainly used as an open lower-end jet system for radial thawing. It was efficient, but more expensive compared to other methods. An added benefit was that it could be used year round. A modified version of this method has been used for the past two decades, for example in Norway, where it has been used to thaw sub-drains beneath roads during winter (Reitan 2013).
- *Hot and cold water thawing* are basically alike, with the exception of a heat exchanger or boiler used for hot-water thawing, making it more expensive to use. Similar to steam thawing, both approaches were mainly used for radial thawing (Jumikis 1979), and in some cases for removing fines by flushing (surficial thawing). The highest thaw efficiencies were achieved when the primary water flow path was along the contact area between thawed and frozen soil. Although cold-water thawing relied on large amounts of water and summertime conditions, it was commonly used for dredging operations during the 1930s and 1940s in Fairbanks and Nome, in Alaska.
- *Electric thawing* involved inserting electrical resistance elements into boreholes (radial thawing), imposing an alternating current between the electrodes and using the soil's resistance to generate a Joule-heating effect. This approach was considered most suited for silt and clay soils (Jumikis 1985), but apparently rarely used. Another approach based on electrically heated blankets, reportedly extensively used in Russia, was tried experimentally during construction of the Trans-Alaskan Pipeline (1974–1977).
- *Solar thawing* was included although it is normally considered a natural or passive thawing method. Nonetheless, by various modifications to the surface, such as stripping away all surface cover and shade-causing vegetation (active solar thawing), net energy flow into the ground can be increased and vertical (surficial) thawing intensified. Even though this method initially involves machinery, labour and is a slow process compared with artificial thawing, it may be considered as a preconstruction preparation, especially for large areas or in permafrost regions (Esch 1982; 1984).

As mentioned in the introduction (section 1.2), the principle of operation of hot-water thawing, referred to by Jumikis (1979), is similar to the hydronic based thawing method referred to in this thesis. The main difference is that the traditional technique required drilling several vertical holes prior to installing the pipes. Thus, the method was very efficient for thawing small areas. However, it was considerably more costly compared with how it is being utilized today.

Laboratory and full-scale experiments, where some of the mentioned methods (and others) are used, are referred to in section 2.4.

2.2 Geographic area and types of frozen ground

2.2.1 Cold regions

With the exception of the Antarctic continent and extreme southern tip of South America, both largely uninhabited, the cold regions of the Southern hemisphere are oceanic. As such, addressing the various challenges people face living under harsh winter conditions are therefore more relevant for the cold regions of the Northern hemisphere.

Bates and Bilello (1966) defined the southern limit of the cold regions of the Northern hemisphere by the isotherm for 0ºC mean temperature during the coldest month of the year. With minor exceptions, the 40th parallel approximates this boundary, as shown in Fig. 2.2. The southernmost areas within the boundary experience seasonal frost penetration, whereas permafrost dominates north of the Arctic Circle (66º32′N). The definition is still in common use today (Andersland and Ladanyi 2004).

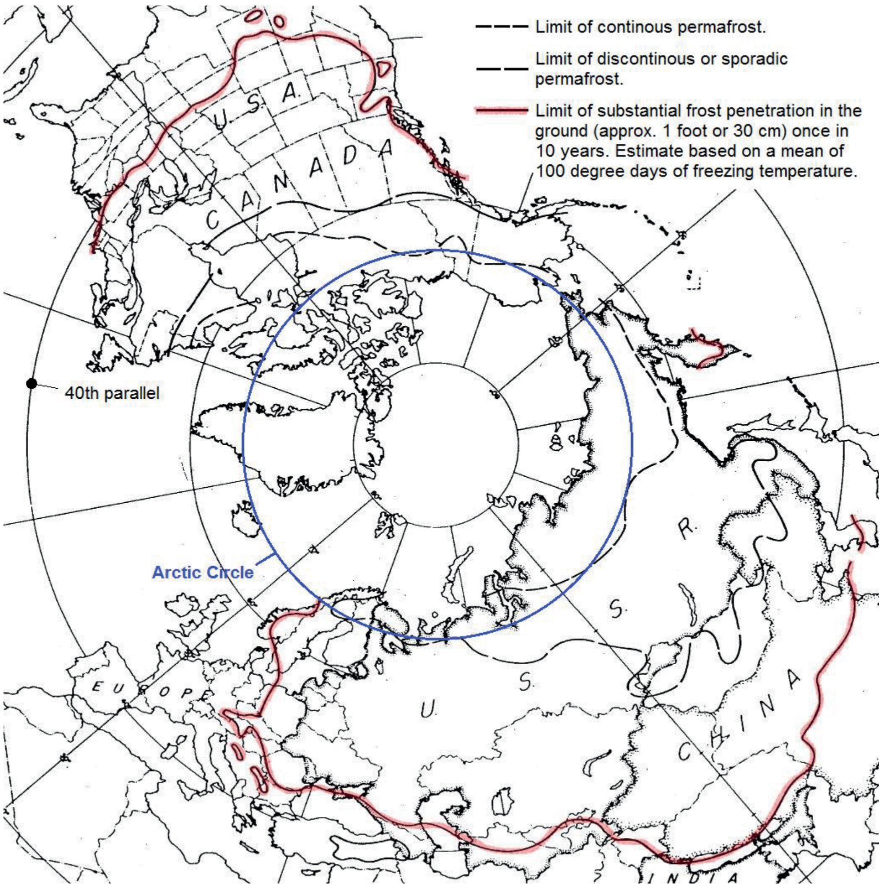

Figure 2.2. Boundary defining the southern limit of the cold regions of the Northern hemisphere, after Bates and Bilello (1966). Note that a frost index of 100ºF·days is equal to 55ºC·days.

Cold regions are characterized by long and cold winters with low air temperatures, snow, ice, frozen ground, ice fog and whiteout. Nearly half a century ago, Gerdel (1969) divided cold regions into three temperature-defined climatic zones:

- *Cold winter*, where the mean temperature during the coldest month of the year (θ_{30d}) is between –17.8ºC and 0ºC.
- *Very cold winter*, where –31.7ºC < θ_{30d} < –17.8ºC.
- *Extremely cold winter*, extending northward from the –31.7ºC isotherm, where temperatures of –62.2ºC or less might be expected.

He asserted that stresses imposed by a cold regions environment influence engineering design, facilities maintenance and operations, transportation, and human performance. Adapting to the environment becomes a necessity under such circumstances, and has become second nature to the people living in these regions. Taking into account a certain growth has occurred among the non-indigenous population in the years since the survey by the Arctic Monitoring and Assessment Programme (AMAP 1998), it is observed that large parts of cold regions of the Northern hemisphere are sparsely populated, illustrated by Fig. 2.3.

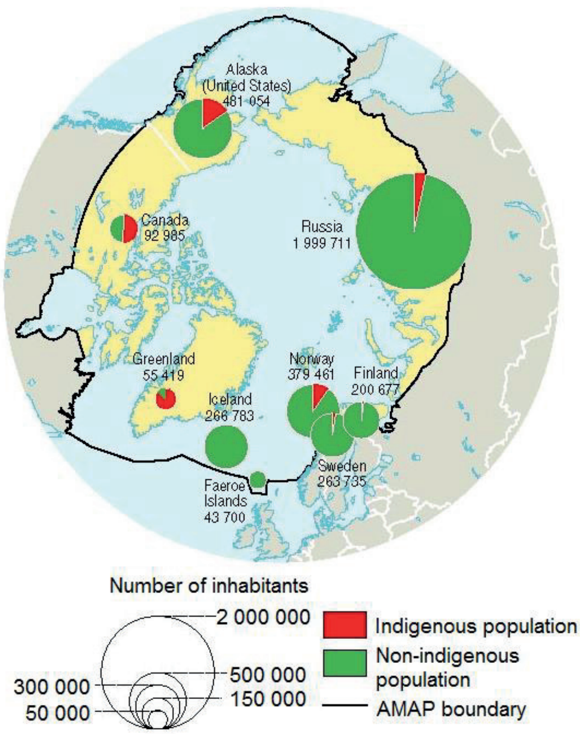

Figure 2.3. Number of inhabitants (per 1990–1995) living within the boundary set by AMAP (1998); Russia 1,999,711; Norway 379,461; Finland 200,677; Sweden 263,735; Iceland 266,783; Faroe Islands 43,700; Greenland 55,419; Canada 92,985 and Alaska 481,054.

This is probably one of the reasons why the particular challenges of living in such an environment and the ingenious ways of dealing with them are not extensively reported in the literature. Artificial or accelerated thawing of frozen ground is just one of many examples of techniques developed and refined by people living in this region.

2.2.2 The Arctic

The Arctic is part of the cold regions of the Northern hemisphere. AMAP (1998) presents several definitions of the Arctic boundary. One is by the Arctic Circle (66º32′N), another is the area north of the 10ºC July isotherm, i.e., north of the region which has a mean July air temperature of 10ºC, as shown in Fig. 2.4a. A third, but even finer gradation is based on the treeline and floristic boundaries, which introduced additional terms such as 'high' and 'low' arctic, as well as 'subarctic' (Fig 2.4b).

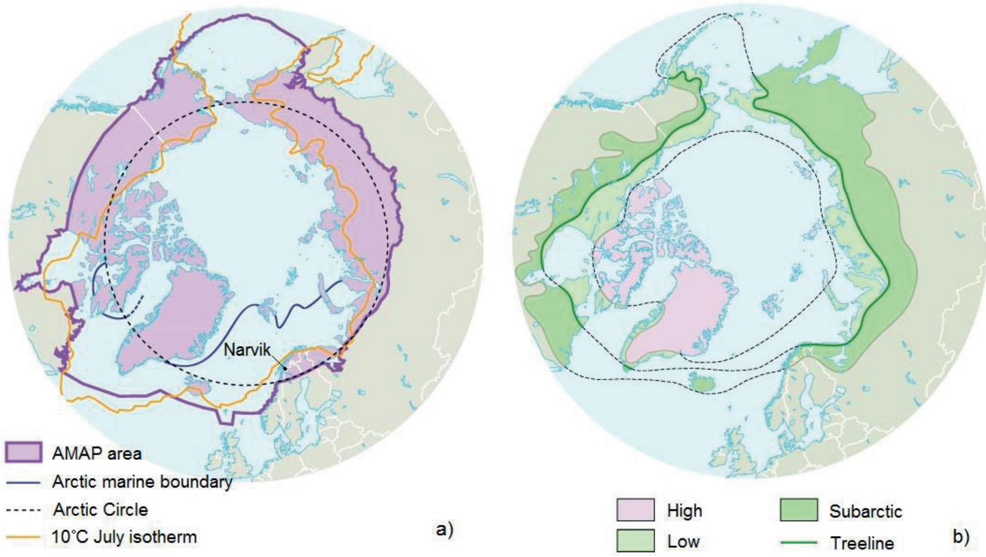

Figure 2.4. a) The Arctic defined by the 10ºC July isotherm; b) high, low and subarctic floristic boundaries, according to AMAP (1998).

As indicated in Fig. 2.4a, Narvik is located in Northern Norway, north of the Arctic Circle, just within the subarctic border (Fig. 2.4b). As most coastal cities situated along the west coast of Norway it benefits from a temperate climate. The Gulf Stream brings with it relatively warm, moist air masses from the Atlantic Ocean, which push the polar front northwards and let westerly winds dominate. This results in higher mean annual air temperatures than what is common at similar latitudes elsewhere. Consequently, seasonal frozen ground conditions dominates during winter, as opposed to continuous permafrost in other areas at the same latitudes (French 2008).

2.2.3 Permafrost versus seasonal frost

Andersland and Ladanyi (2004) refer to a method for conceptualizing how variations in air temperatures affect the thermal regime in the ground. By assuming that soil surface temperatures undergo the same approximate periodic fluctuations, they can be reasonably estimated by a sinusoidal function fitted to monthly mean air temperatures for a given location. Replacing the initial sinus term with one accounting for phase lag, and reducing the amplitude, the soil temperature pattern is attenuated with depth as shown in Fig. 2.5 and 2.6.

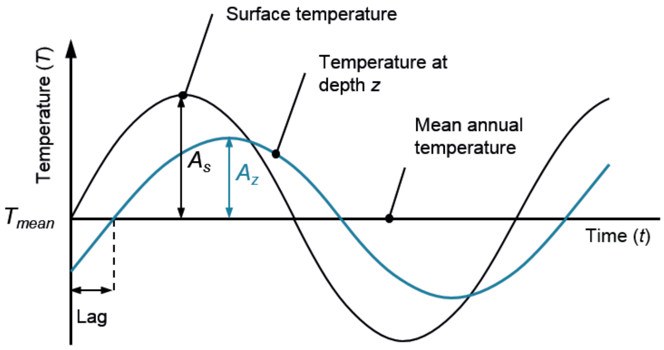

Figure 2.5. Surface and ground temperatures fluctuating around the mean annual air temperature (T_{mean}). The subsurface thermal response is dampened with increasing depth, resulting in a reduced amplitude (A_z) and an increased time lag compared with the surface (A_s).

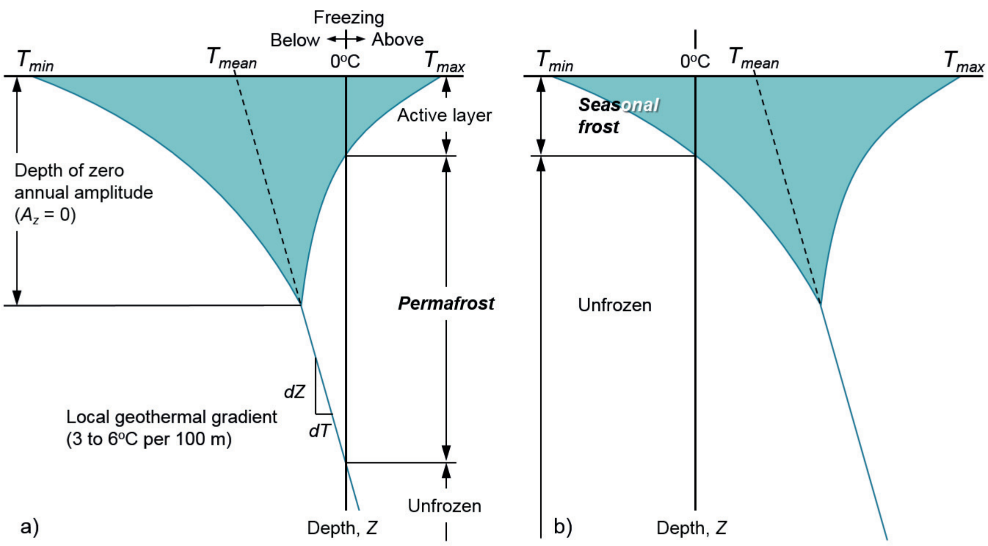

Figure 2.6. Typical ground thermal regime indicating the range of annual ground temperature variations (coloured area), mean annual temperature (T_{mean}), and the geothermal gradient; a) permafrost has an active (seasonally thawing) layer above the permanently frozen layer; b) whereas in seasonally frozen ground, only the topmost soil layer freezes during winter.

In French (2008) permafrost, or perennially frozen ground, is defined as ground (i.e. soil, bedrock or organic matter) that remains at or below 0ºC for at least two consecutive years. Permafrost distribution in the Arctic is categorized as continuous, discontinuous or sporadic. However, the soil is not necessarily 'permanently frozen' since areas outside the polar cap normally have an active top layer which thaws during the warmest period of the year, as shown in Fig. 2.6a. Furthermore, the freezing point of soil water may be depressed several degrees below 0ºC if it contains salts.

2.3 Theoretical work

As illustrated by Figs. 2.5 and 2.6, the change in the soil thermal regime is controlled by the energy fluxes at its boundaries. The temperature of the soil in contact with a fluid (air) is governed by the energy exchange between the soil and the fluid, and the heat propagation within the soil. In this study, an artificial heat source is used to increase the heat load at the surface boundary, thus replacing the source that normally controls the energy flux. Therefore, it is mainly the heat and mass transfer occurring within the soil column that are of interest.

Natural processes sometimes occur at such a slow rate (or without phase changes) that they can be analysed on a steady-state basis with adequate accuracy. That is not the case with artificial thawing of frozen soils. From a mathematical viewpoint, phase changes transform the basic problem from linear to nonlinear form. Fig. 2.7 illustrate a theoretical problem of transient, one-dimensional heat transfer in initially frozen soil with a moving boundary (thaw-freeze interface). Those kinds of problems are commonly referred to as 'Stefan problems' after Josef

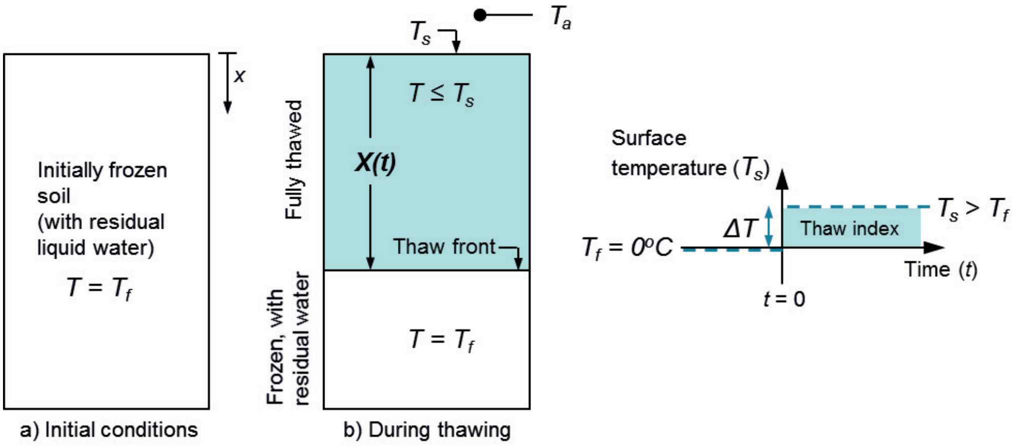

Figure 2.7. a) An initially frozen, thermally uniform, semi-infinite soil column at temperature $T = T_f$ is exposed to a sudden (step) increase in the temperature at the surface (T_s) at time = 0; b) The resulting position of the thaw front $X(t)$ after a period of thawing (thaw index = $T_s \cdot t$ or $T_a \cdot t$, where T_a is air temperature). Note the difference by x (distance below surface for any arbitrary point) and X (distance below surface to the thaw-freeze interface). X increases with time.

Stefan (1835–1893). He did research on sea ice formation and melting in the Polar oceans, and was one of the first to study this problem (Kurylyk et al. 2014; Paynter 1999). Various forms of the Stefan solution have been proposed in the literature (Mitchell and Myers 2010). This section briefly describes the most commonly referred to solutions for calculating the position of the thawing or freezing front, illustrated by Fig. 2.7.

Heat exchange is considered occurring only due to conduction and pore water phase change. Assuming soil thawing taking place over an infinitesimal temperature range, the soil is considered either frozen or thawed at any point in space and time, although trace amounts of unfrozen (bound or residual) water may remain within the frozen zone. The temperature dynamics within the thawed zone is governed by transient, one-dimensional conduction:

$$k\frac{\partial^2 T}{\partial x^2} = c\rho\frac{\partial T}{\partial t} \quad for\ 0 \leq x \leq X \tag{1}$$

where k is the bulk thermal conductivity for the thawed zone [W/(mºC)], c is the specific heat of the thawed soil water matrix [J/(kgºC)], ρ is the density of the thawed zone (kg/m^3), and x is the distance below surface for any arbitrary point (m). T is the temperature distribution within the thawed zone (ºC), t is the time (s), and X the distance between the surface and the thaw front (m), as shown in Fig. 2.7b.

For the classical Stefan solution, the initial and boundary conditions are as follows:

Initial conditions: $T(x, t = 0) = T_f$

Surface boundary condition: $T(x = 0, t) = T_s$

Interface boundary condition: $T(x = X, t) = T_f$

where T_f is temperature at which all soil freezing or thawing occurs (taken as 0ºC), T_s is the prescribed soil surface temperature boundary condition (>0ºC). As indicated by the initial condition, the soil being exactly at freezing temperature (T_f = 0ºC), any increase in temperature will result in fully thawed soil. This also implies that the temperature within the frozen zone, when $x > X$ at any point in time, is uniform and equal to the freezing temperature. Because the solution assumes no thermal gradient in the frozen zone, it only has to consider the thermal dynamics in the thawed zone.

Adhering to the noted initial and boundary conditions, assuming constant surface temperature (T_s = constant), a linear temperature distribution in the thawed zone, and neglecting latent heat adsorption (phase change) at the thaw interface, an approximate solution to the Stefan problem (commonly referred to as the 'Stefan solution') can be written as follows (Nixon and McRoberts 1973):

$$X = \alpha\sqrt{t} \quad where \quad \alpha = \sqrt{\frac{2k_u T_s}{L}} \tag{2}$$

where X is the thaw penetration depth (m), t is the time (s), k_u is the bulk thermal conductivity for the thawed (unfrozen) soil [W/(mºC)], L is the soil volumetric latent heat (kJ/m^3), and T_s the (constant) surface temperature. Because the Stefan solution does not account for the heat energy absorbed during phase change, it tends to overestimate thaw depths.

During the 1860s, Carl G. Neumann (1832–1925) presented an exact solution for the freezing of bulk water that predates the Stefan solution. However, it was not widely disseminated until half a century later, according to Kurylyk et al. (2014). Applied to the problem presented above, the Neumann solution relaxes two assumptions of the Stefan solution. First, it allows for the initial temperature in the domain to be below freezing temperature, and second, it allows the temperature distribution within the thawed zone to be nonlinear. Because of this, the resultant thermal gradient from the thawing front towards the frozen zone will induce frozen zone conductive heat transfer. The thawed and the frozen zones are therefore characterized by different thermal properties, and thus two distinct heat conduction equations:

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \quad for\ 0 \leq x \leq X \tag{3}$$

$$\alpha_f \frac{\partial^2 \bar{T}}{\partial x^2} = \frac{\partial \bar{T}}{\partial t} \quad for\ X \leq x \leq \infty \tag{4}$$

where $\bar{T}$ is the temperature distribution in the frozen zone (ºC), and α_f is the bulk thermal diffusivity of the frozen zone (m^2/s). All other parameters are defined the same as in the case of the Stefan solution. While the surface and initial boundary conditions are the same for both solutions, the initial conditions are expressed more generally in the Neumann solution:

Initial conditions: $T(x, t = 0) = T_i$

where T_i is the uniformly distributed initial temperature within the soil (< 0ºC). In addition, it is also subject to a boundary condition at the bottom of the soil column:

Bottom boundary condition: $T(x = \infty, t) = T_i$.

Because the conductive flux into the frozen zone also must be considered, the energy balance at the interface becomes more complex relative to the Stefan solution. Applied for frost penetration in a semi-infinite medium, initially in the unfrozen state at T_0, the Neumann solution can be written as:

$$X = 2\gamma \cdot \sqrt{\alpha_f t} \tag{5}$$

where α_f is the thermal diffusivity of the frozen medium (m^2/s), and γ is a phase change parameter determined by the following expression (Sheng 1990):

$$\frac{e^{-\gamma^2}}{erf\ \gamma} - \frac{k_u}{k_f}\sqrt{\frac{\alpha_f}{\alpha_u}}\left(\frac{T_0 - T_f}{T_f - T_s}\right)\frac{e^{-(\alpha_f/\alpha_u)\gamma^2}}{erfc\ \gamma\sqrt{(\alpha_f/\alpha_u)}} = \frac{L\gamma\sqrt{\pi}}{C_f(T_f - T_s)} \tag{6}$$

Here, $\alpha_i = k_i/C_i$ is the thermal diffusivity, and *erf* and *erfc* are error functions. In special cases where the initial temperature T_0 is equal to the freezing temperature T_f, Eq. (6) reduces to:

$$\gamma e^{\gamma^2} erf\ \gamma = \frac{C_f(T_f - T_s)}{L\sqrt{\pi}} \tag{7}$$

If γ is small, the error function $erf\ \gamma \cong 2\gamma/\sqrt{\pi}$ and $\exp(\gamma^2) \cong 1$, thus γ can be explicitly determined as:

$$\gamma^2 = \frac{C_f(T_f - T_s)}{2L} = \frac{1}{2}\mu \tag{8}$$

where μ denotes the so-called Stefan number. In this case, Eq. (5) becomes equal to the Stefan equation for the freeze case.

Aldrich and Paynter (1966) developed a more practical equation for predicting frost penetration, were they applied a correction factor (λ) to the Stefan solution. After the equation was developed, it was discovered to be identical in nature to an equation previously introduced by Berggren (1943), although in a somewhat different form. Accordingly, their formula was entitled the 'Modified Berggren Equation'. Applied to the thawing problem shown in Fig. 2.7, assuming the same initial and boundary conditions as for the Stefan solution, their solution can be written as:

$$X = \lambda \cdot \sqrt{\frac{2k_u I_t n}{L}} \tag{9}$$

where X is the thaw penetration depth (m) in this case, k_u is the thermal conductivity of thawed soil [W/(m·ºC)], I_t is the local thaw index (ºC·days) based on air temperature (T_a). L is soil volumetric latent heat (kJ/m^3) and n is a dimensionless surface N-factor accounting for differences between air and surface temperatures (Hanson et al. 2010). The λ is a dimensionless correction factor obtained from charts (Lunardini 1980), based on two dimensionless parameters α and μ, respectively, which for the thaw case are given as:

$$\alpha = \frac{T_f - T_0}{T_s - T_f} \text{ and } \mu = \frac{C_u}{2L}\left(T_s - T_f\right)$$

where T_f is the frozen soil temperature (ºC), T_0 is the initial soil temperature (ºC), T_s is the soil surface temperature (ºC), and C_u is the unfrozen or thawed soil volumetric heat capacity. The parameters α and μ take into account the soil temperatures, specific heat and latent heat. For small values of these two parameters, it can be expected that $\lambda \cong 1$, and Eq. (9) will reduce to the Stefan equation, Eq. (2).

The Modified Berggren solution gives good results for seasonal phase change depths even if the surface temperature varies with time (Esch 2004b). In a recent publication, Kurylyk and Hayashi (2016) presented improved correction factors to the Stefan equation to accommodate sensible heat storage during soil freezing or thawing. Kurylyk et al. (2014) also refer to what they term the 'Lunardini solution', which, unlike the Neumann and Stefan solutions, accommodates heat advection via water flow.

The evolving use of numerical methods and software, advances in computer technology, and the availability of PCs and supercomputers have significantly influenced the methods used to solve Stefan problems (Paynter 1999). However, computational simulations also rely on empirical data for boundary conditions and validation, thus attributing even more value to experimental work. Some additional references to modelling work are given in the introduction to Chapter 4.

2.4 Experimental work

Over the last three decades, sensor technology and data acquisition systems have seen great improvements. Sensors and transducers have generally become smaller, rugged, more sensitive and cheaper, accommodating large-scale monitoring of, for example soil moisture variations, that previously was not feasible or too expensive (e.g. Chávez et al. 2011; Chow et al. 2009; El Marazky et al. 2011; Nolz et al. 2013). With automated software and storage capacity no longer an issue, acquiring long-term data records has become considerably easier than it has been in the past. Furthermore, innovative sensor technologies have emerged, allowing for new ways of detecting and monitoring, for example pore ice, soil water content and relative permittivity (e.g. Steelman et al. 2010; Varble and Chávez 2011; Watanabe and Wake 2009; Westermann et al. 2010; Wollschläger et al. 2010).

This study has benefitted from the development. However, since technical advances are outside the scope of the work, the remaining part of this section is referring to experiments related to natural or artificial thawing of frozen ground.

One reference to early field studies is Drew et al. (1958). They investigated naturally occurring thawing in a small area in Point Barrow, Alaska, comparing rate and depth of thaw in Arctic brown soil with similar soils in adjacent, poorly drained areas. One of their findings was that thaw rates and depths are highly related to soil type. Comparing Arctic brown soil to the nearby tundra, they found that Arctic brown soil thawed earlier in the spring, to a greater depth (1 m as opposed to 0.46 in the tundra), and froze earlier in the autumn. However, because they measured thaw depths with a steel probe, the reported thaw depths must be taken as approximate values.

McRoberts (1975), who also studied natural thawing, examined deviations between calculated (Stefan solution) and measured thaw rates. Fifteen experiments (case studies), performed by other researchers during the period from 1961 to 1971, on a variety of soils with varying vegetation and soil moisture content, were compared. He found that the magnitude and range of the rate of thaw were small, and that they generally agreed well with the calculated rates. He concluded that although the model was useful for a variety of field situations, extensions to the theory were required for some cases. This is a reasonable conclusion were the case records complete, but they were not. For example, thermal conductivity, water content and surface temperature were estimated for each case record. Furthermore, soil temperatures were obtained by both measurements and by probing. Taken together, this introduces some doubts about the validity of his findings.

Concerned with winter survival of crops, Hayhoe et al. (1983) used several techniques for measuring frost and thaw penetration at two Uplands sand sites in Canada, one snow cleared, and another with natural snow cover. The sites were instrumented with thermocouples and frost-tubes (Rickard and Brown 1972) for monitoring of soil temperatures, and time-domain reflectometry (TDR) for monitoring of soil moisture. They presented temperature records down to 100 cm over a 3-month period for both sites, showing the isolating effect of snow cover and the very low soil temperatures that can occur in the uppermost 50 cm in soils without such cover. They found that all methods used to measure frost penetration were adequate on the snow-cleared site where large temperature gradients were present. On the other hand, when the gradients were small, as with the snow-covered site, they found that those methods were less suited. They concluded that temperature-based determinations of the frozen zone were less reliable than using systems indicating or measuring the liquid water content of the soil. This differs from the findings presented in Sveen et al. (2017a; 2017b), where the thaw rates calculated from soil temperature measurements corresponded well with similar rates calculated from soil moisture records.

Jumikis (1979), referred to the introduction of this thesis (section 1.2), was one of the first to use the term ‘artificial thawing’, referring to vertically installed cylindrical pipe systems used for hot or cold-water thawing of frozen ground. He presented detailed descriptions and sketches of how the system was used in situ and elaborated on how to calculate the resulting thaw penetration in fine-grained soils. Although he was mainly concerned with artificial thawing of frozen ground, he suggested that by using a coolant instead of a heated fluid, the method might also be good for extracting heat from the soil. In fact, this was an interesting suggestion, because that is how the method is being used today (e.g. Yuan and Yang 2016; Balossi Restelli et al. 2016). In a later publication by Jumikis (1985), similar use of vertically installed electrodes for electrical thawing of frozen soils was described.

Oswell and Graham (1987) reported one of the few full-scale thawing experiments that is comparable to those in this thesis in terms of scope. They evaluated the thaw efficiency of three different artificial methods used for thawing sandy gravel and clay till. The methods were: (1) propane heaters consisting of steel pipes covered with 0.3 m thick blankets of sand, (2) electric heating elements placed on the ground and covered with insulation blankets, and (3) coal placed in straw beds on the surface. Two soil bins, each approximately 7 x 27 m and 2.75 m deep, divided into 3 sections, were thawed over two winters. They found all methods capable of thawing frozen ground, achieving thaw penetration depths ranging from 0.9 to 1.25 m in clay soil, and up to 1.5 m in sandy gravel, both after only 93 hours. Propane heaters performed best, followed by coal fires. Electric heating elements were the least efficient, generating mostly local hot spots just beneath the elements. The time needed for the thaw to penetrate to 0.3 m depth varied from 2 to 8 hours. Although this study is valuable, but it lacks important data. The authors did not provide sufficient information about the soils used in their experiments such as grain-size distribution curves or water content, which renders direct comparison with similar thawing experiments difficult.

Lindroth et al. (1995) reported another artificial thawing experiment, in which microwave techniques were utilized. They conducted an investigation on behalf of the U.S. Bureau of Mines to determine the ability of microwaves to thaw various types of soils, with moisture levels ranging from 7 to 44 %. The field-work was carried out using a truck-mounted 60 kW microwave power generator and antenna, connected by a flexible waveguide (approximately 0.6 x 0.6 m), which was then placed on the ground surface. The method was apparently able to thaw 6–28 cm beneath the guide. Unfortunately, there is no reference in the paper explicitly stating the amount of time spent achieving these thaw depths. Although they recommended further field tests with a 60–100 kW system, no references to such trials were found during the literature study.

Hermansson and Guthrie (2006) reported a more recent, full-scale thawing experiment utilizing low-intensity infrared heating. They evaluated the performance characteristics of a 22 kW infrared tube heater 9.1 m long, suspended 2.4 m above ground, used for thawing of clayey gravels. Thermocouples at 10.5, 20.5 and 30.5 cm depths were used to monitor soil temperatures during the experiments. The thermocouples were mounted inside 19 mm plastic access tubes, which were installed in predrilled holes in the frozen ground. Apparently, the holes were backfilled with sand after installation. As experienced by the author of this thesis, predrilling and backfilling can introduce considerable uncertainties to the soil temperature measurements. The backfill material tends to act as a funnel for surface water during artificial thawing operations, and it is expected that this approach would lead to thaw rates being overestimated. The experimental data were used to calibrate a numerical model of the infrared heating process. They found that ice content had a marked influence on thaw penetration rates in all the simulations, and that air temperature became less important with increasing radiation intensity. Referring to the experiments, they concluded that the method performed well for shallow depths down to approximately 0.2 m, but had limited effect further down.

3. Synthesis

This chapter summarizes the work done in the four papers listed below. A brief background of the work is given for each paper, including aims and method (if applicable). Focus is on main results and findings, summarized at the end of each section. The relationship between the publications, their significance, and suggestions for further work are addressed in Chapter 5.

I Sveen, S. E., and Sørensen, B. R. (2010). "Effective thawing of frozen ground–performance testing of a new thawing method based on hydronic heat (conduction)." *Proc., 3rd European Conf. on Permafrost (EUCOPIII)*, Univ. Centre in Svalbard, Svalbard, Norway.

II Sveen, S. E., and Sørensen, B. R. (2013). "Establishment and instrumentation of a full scale laboratory for thermal and hygroscopic investigations of soil behavior in cold climates." *J. Appl. Mech. Mater.*, 239, 827–835.

III Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017a). "Thaw penetration in frozen ground subjected to hydronic heating." *J. Cold Reg. Eng.*, 10.1061/(ASCE)CR.1943-5495.0000117:31(1).

IV Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017b). "Soil moisture variations in frozen ground subjected to hydronic heating." *J. Cold Reg. Eng.* (submitted).

3.1 Initial experiments

This section refers to the work presented in paper I on initial thawing experiments on various types of soils, carried out in 2007, but not published until 2010.

3.1.1 Background

During the mid-1990s, Ground Heaters Inc., now a division of Wacker Neuson[4], introduced a new defrosting system to the commercial market in U.S. and Canada (Stewart 1996). The system was based on a U.S. patent (Bruckelmyer 1996) originally referring to concrete curing during winter. In 2004, a Norwegian-based company started using the defroster in artificial thawing operations at various sites in and around the city of Narvik. Seeking to improve the method, besides wanting to know more about its capabilities, the company approached the former Narvik University College (NUC).

A collaboration was initiated, resulting in a pilot-project in 2005. The results from the pilot project were inconclusive and suggested further investigations. Recognizing that the method could potentially help prolong the construction season and reduce seasonal lay-offs among their workforce, the company decided to extend the project. With additional funding from Northland County council, a laboratory was established. NUC was in charge of planning and building the

[4] Wacker Neuson SE, Munich, Germany.

necessary facilities, while the company provided a suitable site as well as the defrosting systems used during the experiments. The laboratory was used to facilitate two full-scale thawing experiments during a 4-week period from mid-March to mid-April 2007.

3.1.2 Objectives

The aim of the project was to describe the working principles of the new defrosting system and to evaluate its general performance characteristics when used for artificial thawing of frozen ground. From the company's perspective, mainly working within landscape gardening and related construction work, thaw rates in various types of soils were of particular interest. This is also relevant when considering heat transfer in layered soils. The laboratory was therefore configured with soil bins containing three types of homogenous soils (silty sand, well-graded sand and uniform gravel) with varying texture, gradation and initial moisture content. Each soil bin was instrumented with thermocouples, as shown in Fig. 4, paper I.

3.1.3 Section summary

Two identical experiments were carried out, simultaneously thawing all three soils, using two different defrosting systems. A standard version of the system was used during the first experiment, whereas a different version (higher burner capacity) was used for the second experiment. In addition, heat losses from the pipe surfaces were measured by infrared thermography. Preliminary results were presented in a report (Søraas and Sørensen 2007) to the company, but not published until 2010, i.e., as part of the PhD-work.

The resulting thaw rates, using the standard defroster with the hot-water pipes placed 10 cm apart, covering a ground surface area of approximately 4.5 x 4.5 m, are shown in Fig. 3.1.

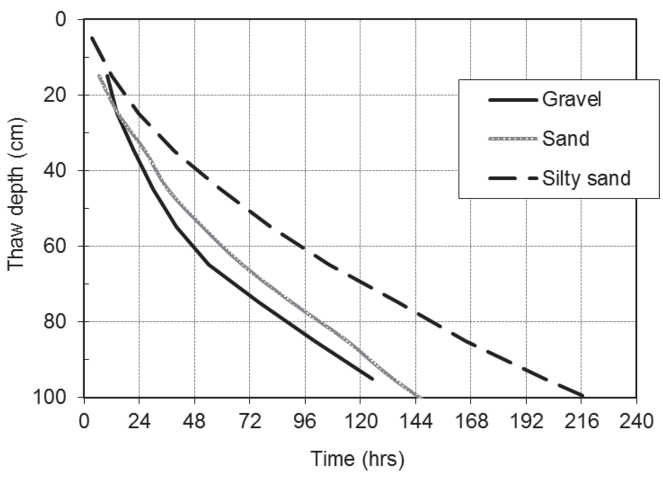

Figure 3.1. Thaw depth (cm) versus time in three types of soils, March 2007 (from Fig. 5, paper I).

The results from both experiments showed no differences between the two defrosting systems with regard to thaw efficiency, although supply temperatures were rising more rapidly when higher burner capacity was used. However, the results were consistent with the company's own experience from in situ trials indicating nonlinear thaw rates. Nevertheless, they were somewhat contradicting with respect to the difference in thaw rates between the various soils. For example, it was not expected that the predominantly convective heat transfer occurring in the comparatively porous and dry gravel would yield the highest thaw rates. Those discrepancies were attributed to parameters not monitored in the initial configuration of the laboratory (soil water content) and differences in initial ice content.

The experiments gave a better understanding of hydronic based thawing and expected thaw rates in various types of soils. They were useful for testing and assessing the functionality of the laboratory, the measurement systems and sensors used, as well as the methodology applied for gathering data. However, only two performance tests based solely on soil temperature monitoring were considered insufficient for generalization.

In retrospect, comparing the results to subsequent experiments at the new frost in ground laboratory (paper III), it appears that the thaw rates presented in Fig. 3.1 were mixed up. Supporting the assumption are logs showing that the terminal blocks connecting the thermocouples to the various soil bins were changed during the first experiment in March 2007. Direct comparisons with thaw rates obtained from the experiments performed in 2012 (paper III), shown in Fig. 3.2, further supports the assumption. Unfortunately, it is not possible to re-examine the wiring connections because the laboratory was later relocated.

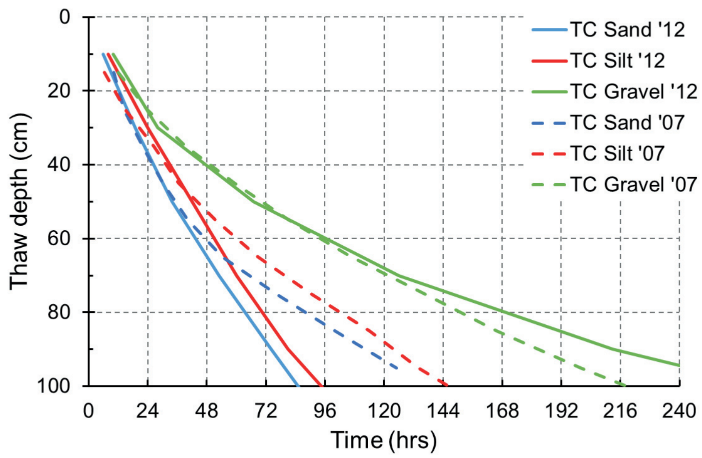

Figure 3.2. Thaw rates compiled from thermocouple (TC) records from 2007 (dotted, see Fig. 3.1) compared with similar obtained from the experiments in 2012 (Fig. 10a, paper III). The legends in the former (2007) are substituted as follows to obtain a better match between the two data sets: *gravel* replaced with 'sand', *sand* replaced by 'silt', and *silty sand* replaced by 'gravel'.

Regardless of the noted uncertainties, the initial efforts presented in paper I demonstrated the potential, applicability and general efficiency of the hydronic thawing method. This, in turn, gave the company the assurance and confidence it needed to continue improving it, leading to several patents and eventually a production company. Today they are one of the leading suppliers of defrosting systems to the commercial market in Europe and northwest Russia.

3.2 Laboratory facilities

This section refers to the work presented in paper II on the establishment of new laboratory facilities for full-scale experiments on frost in ground. Because papers III and IV refer to figures in paper II, the most important ones are included in this section.

3.2.1 Background and objectives

To meet the objective related to designing and building appropriate laboratory facilities suitable for full-scale experiments on frozen ground, the PhD-candidate was assigned as project manager responsible for relocating the original frost in ground laboratory. Unforeseen real estate developments in the area had made it necessary to terminate the ongoing research activities and move the operation to a new location. Fortunately, the situation occurred as another research project was initiated, which led to additional funding being allocated to the relocation project. This gave an opportunity to choose a more suitable location, a wider range and number of sensors, and prepare the site for general-purpose frost in ground experiments, thus fulfilling both the project goals and one of the objectives of the PhD-work.

3.2.2 Location and general considerations

The original location of the frost in ground laboratory was unfortunate in several ways. To begin with, it was located inside the city borders, i.e., exposed and difficult to protect properly. Secondly, it was situated on a privately owned building plot, making it vulnerable to changes in the real estate market and the whims of the owner. Furthermore, the site was located close to the sea level and exposed to solar radiation, which influenced both surface thaw and frost penetration depths. Finally, owing to local ground conditions, it was susceptible to seasonal changes in the groundwater table, which could potentially affect the integrity of the experiments.

These considerations were taken into account when choosing the location for the new frost in ground laboratory. The decision was based on recommendations from the local municipality, and the area (land plot) was bought to ensure institutional ownership. Figs. 1 and 2 in paper II show the new location (N68º26′55″, E17º31′16″), about 6 km east-northeast of Narvik. Other considerations were: shading from direct solar radiation during the coldest winter months, connectivity to the power grid, access by road, proximity to the university, and an area large enough to allow for future expansions.

3.2.3 Soil types and arrangement

A top-view of the soil bin's arrangement within the frost in ground area and an isometric view of a typical soil bin are shown in Figs. 2, 3 and 4 in paper II. An isometric view of all four bins is shown in Fig. 3.3. As opposed to the original arrangement referred to in paper I, the new soil bins were placed at a distance of 6 m from each other to allow for individual thaw progression without interference from adjacent soils. In addition, a control bin was established for documentation purposes, i.e., ensuring the integrity of the obtained results.

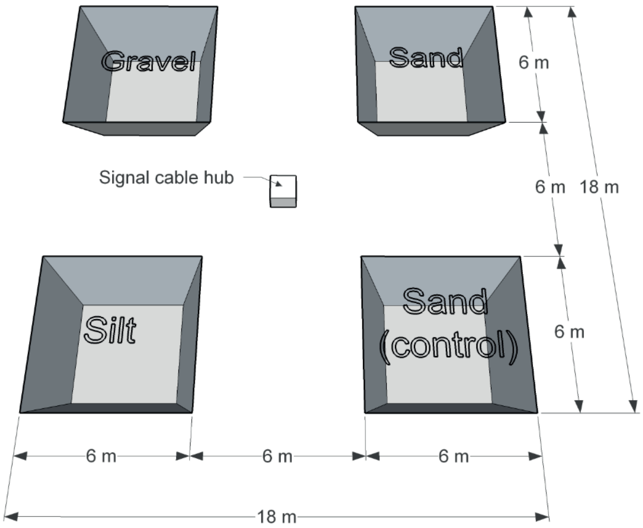

Figure 3.3. Overview of the frost in ground laboratory soil bin arrangement (from Fig. 4, paper III).

Three types of soils were installed in the soil bins: a sand–silt mixture termed 'silty sand', a sand–gravel mixture termed 'gravelly sand', and poorly graded coarse gravel termed 'uniform gravel'. The uniform gravel contains 98.9 % gravel ranging from 8 to 22 mm. Additional information regarding soil classification, density and initial volumetric water content are given in Table 1, paper III. Grain-size distribution curves (GSDs) are shown in Fig. 3.4.

The soils are materials typically used when building foundations, pipe trenches and road bases. In regions with seasonal frost or permafrost, soils such as silty sand would not see much use because of its high proportion of fines, and consequently, its susceptibility to frost. Nevertheless, it was included to complement the other two types of soil with regard to grain-size distribution and to ensure conformity with the initial experiments from 2007 (paper I).

The soil samples in the bins are referred to as being homogenous. In context, that means being of the same type from the ground level down to ~3 m depth. From Table 1 in paper III, it appears that the soil composition of gravelly and silty sand could have been more diverse. Although the GSD-curves in Fig. 3.4 suggest an adequate difference between the two, an even bigger proportion of fines in silty sand would increase its water susceptibility and thus, its potential for standing out when compared with gravelly sand.

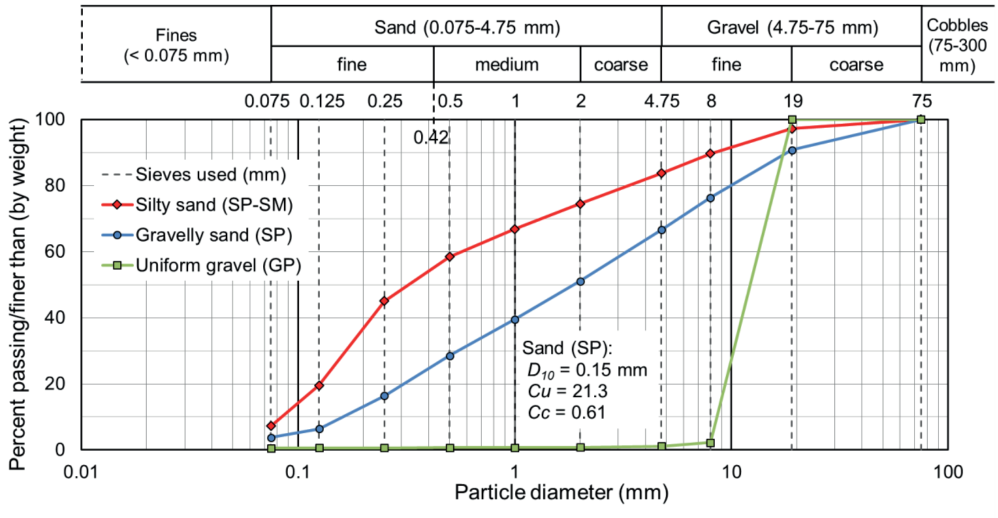

Figure 3.4. Grain-size distribution curves (group classification in parenthesis) for the soils used in the 2011 and 2012 experiments. The effective diameter (D_{10}), coefficient of uniformity (C_u) and coefficient of curvature (C_c) apply only to sand. (From Fig. 4, paper IV).

3.2.4 Instrumentation

The various sensors and data logging systems installed at the site are shown in Figs. 5–8 and Table 1, all from paper II. Features such as applicability (sensibility), reliability, capacity, accuracy and ruggedness were considered when deciding on which measurement systems and sensors to use. Moreover, capacity for connecting auxiliary measurement systems and future expansions were taken into account.

To ensure reliability and secure back up, two types of sensors and measurement principles were chosen for monitoring each of the important parameters. Thermocouples embedded in the soils and thermistor strings in tubes were installed for soil temperature monitoring. Granular resistance blocks and capacitance sensors were installed for the monitoring of frost depths and volumetric soil water content. In addition, a local weather station was installed for collecting air temperature, rainfall, humidity, net solar radiation, wind speed, wind gust and wind direction. Four different loggers were used to collect data from the various sensors, bought from reputable suppliers known for their reliable and well-proven product range.

Identical instrumentation was installed in each of the four soil bins. A specially designed sensor frame (Fig. 5, paper II) was used to ensure the integrity of the sensors prior to, during and after installation. The frames were mounted at the centre of each bin with their bottom parts anchored at 2.16 m below ground surface, giving an effective measurement depth of 1.8 m. To ensure comparable readings from one bin to another, both the sensors and the frames were aligned to each other.

3.3 Thermal response in artificially thawed frozen soils

This section refers to the work presented in paper III on thaw penetration in frozen ground subjected to hydronic heating. Note that this paper deals with the hydronic method in general and the heat transfer and associated thaw rates in particular. The counterpart paper (paper IV), referred to in section 3.4, deals with the remaining results, i.e., phase change and associated soil moisture variations, and how they relate to the former (paper III).

Because papers III and IV are interconnected, this section contains supplementary information applicable for both papers.

3.3.1 Background and objectives

The results presented in paper I gave a general impression of the thaw rates occurring when utilizing the hydronic method for thawing various types of soils. The results were based exclusively on soil temperature records obtained from the experiments carried out at the old frost in ground laboratory. One aim was therefore to assess the validity of the initial findings by replicating the experiments at the new laboratory. Another was providing a systematic description of hydronic based thawing and the underlying technology.

3.3.2 Hydronic heating concept

Modern central heating systems are based on a central heating unit, where the heat is distributed throughout the building typically by forced air through ductwork, or water circulating through pipes. The hydronic thawing system operates in the same manner, using a mixture of water and glycol as the heating medium, as shown in Fig. 1 and 2 in paper I. The main components and principle of operation are shown in Fig. 3.5.

An oil burner is used for heating the fluid in the heating system. A pump ensures circulation of the hot fluid through flexible rubber hoses or pipes connected to a distribution manifold. The manifold divides the flow evenly between up to three pipes, allowing for single, dual or triple pipe operation. When the pipes are laid out on the frozen ground surface, they are covered with combined vapour barrier and insulation blankets to reduce the heat losses during thawing. The system that was used in this study had a 50-L boiler heated by a 103 kW oil burner, attached to three flexible distribution pipes, each 210 m in length and holding approximately 42 L of fluid.

During a short start-up period, the burner ran continuously and at full capacity until the desired set-temperature (typically 100ºC) was reached. At the start, the temperature difference between the fluid supplied by the boiler (constant) and the fluid returning (rising) was at its maximum. As the temperature of the frozen ground surface gradually increased and instigated the thawing

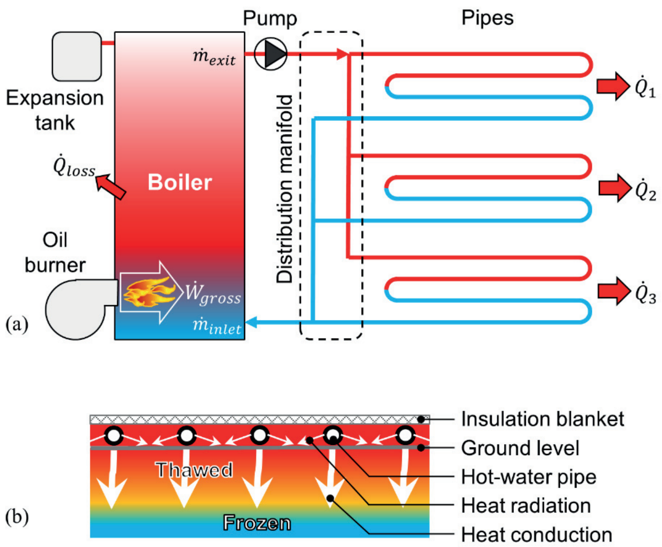

Figure 3.5. a) Main components; b) principle of operation of a hydronic defrosting system during artificial thawing of frozen ground (side view). (From Fig. 2, paper III).

process, the temperature difference gradually decreased. When the ground temperatures became higher, the intermittence factor increased. In practice, this indicated a lower demand for fuel over time. The fuel consumption was proportional to the total heat output from the defrosting system. According to Fig. 3, paper III, the fuel flow rate decreased with time, which indicated that the system delivered a transient heat load during thawing operations.

3.3.3 Results

To evaluate the thaw efficiency of the hydronic-based method, three types of soils were thawed simultaneously. The results presented in paper III were obtained from two, separate experiments carried out during the winters of 2011 and 2012. The spatial and temporal temperature distribution in all soils during both thawing experiments are shown in Figs. 8 and 9 (2012 and 2011, respectively) in paper III. An example of typical soil temperature trends is shown in Fig. 3.6.

In general, soil temperatures were found to be higher and increasing rapidly near the hot-water pipes at the surface. Temperature slopes declined with time and were dampened with increasing depth. Thermal responses in gravelly sand occurred slightly earlier in time compared with silty sand, with uniform gravel responding the slowest and experiencing the lowest temperatures. The time delay between the responses at different depths was found to be nonlinear, i.e., increasing with depth. Both experiments showed similar trends, even though those performed in 2011 to some extent were affected by natural thawing. The occurrence of natural thawing

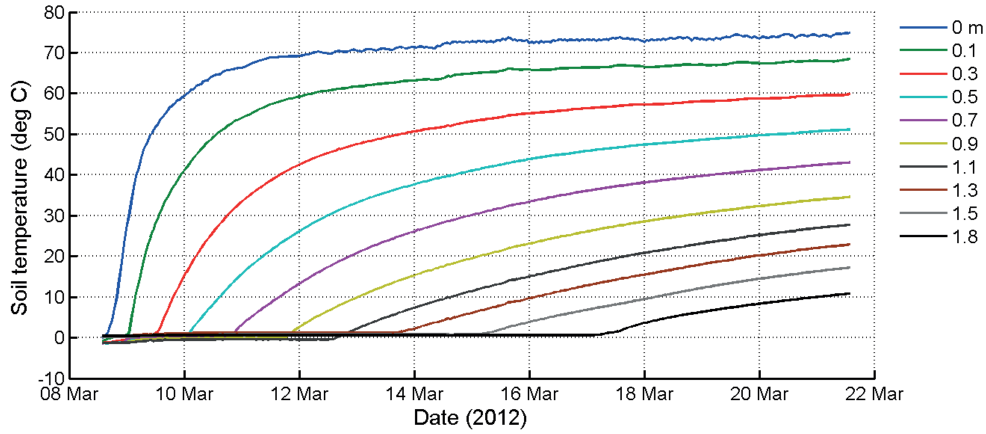

Figure 3.6. Soil temperature distribution in homogenous, gravelly sand subjected to hydronic heating, from 1400 hrs March 8th to 1400 hrs March 21st, 2012, based on hourly thermocouple readings. (From Fig. 8a, paper III).

was apparent from the reversed temperature profiles in the early records, at approximately 0.5–0.9 m depth, for silty sand (Fig. 9b, paper III). Besides some resemblance (i.e. reversed temperature profile) at 0.7 m depth, the same was not as apparent for gravelly sand (Fig. 9a, paper III). From examining the temperature and soil moisture records for the control bin, it was confirmed that natural thawing had started prior to the experiment in 2011.

3.3.4 Section summary

The 2012 records were used to assess thaw penetration. Forty-eight hours into the experiment the thaw had penetrated approximately 0.65 m into gravelly sand, 0.52 m in silty sand and 0.40 m in uniform gravel. The corresponding time needed for the thaw to penetrate to 1.1 m depth was found to be 96 hours (4 days), 108 hours (4.5 days) and 336 hours (14 days), respectively.

The performance characteristics of the method were quantified by the rate at which it was able to thaw various types of soils. The thaw rates were found by calculating the time from the start of thawing to the time when a definite thermal response was observed at the various depths. The soil temperatures near 0ºC were evaluated individually for each depth and soil type. During phase change, the soil temperatures were found to be temporarily settling at approximately 0ºC, also known as the zero curtain effect (Hinkel and Outcalt 1995). The latent heat absorption temporarily halts the soil temperature increase until all the ice contained in the soil at a particular depth has thawed. The time at which the subsequent soil temperature increase occurred, relative to the start of the artificial thawing process, was determined for all sensor depths. The results were calculated for all soil types, thus yielding individual thaw rates as shown in Fig. 3.7. The results were compared with rates obtained from similar experiments

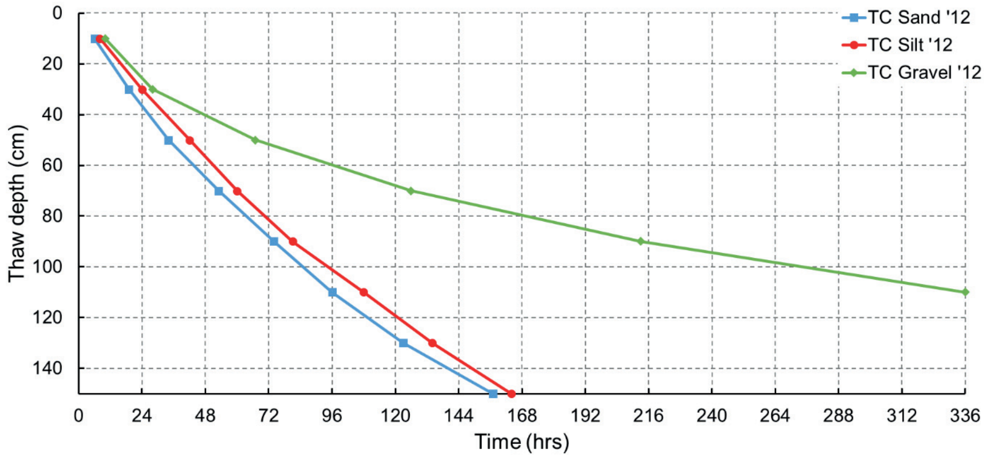

Figure 3.7. Thaw rates based on thermocouple records from 2012 (from Fig. 10a, paper III).

employing other artificial thawing techniques (Table 1). Considering the differences in the experimental setups, methods and soils, hydronic based thawing was found to be a comparatively efficient method for artificial thawing of frozen ground. Furthermore, the thaw rates acquired in this work corresponded well with results obtained from the initial experiments performed in 2007 down to approximately 0.5 m depth. Nonlinearity and variations in burner effectiveness were noticeable below 0.5 m, previously shown in Fig. 3.2, section 3.1.3.

Table 1. Thaw depth versus time listings for artificial thawing methods used on gravelly sand (SP), clayey gravels (GC) and sandy gravel (GW). (From Table 2, paper III).

Reference	Thawing method	Unified soil classification	Time (h) to thaw			
			0.2 m	0.3 m	0.5 m	1.0 m
Sveen et al. (2017a)	Hydronic	SP	13	19	34	85
Sveen and Sørensen (2010)	Hydronic[a]	SP	12	18	35	137
Hermansson and Guthrie (2006)	Infrared	GC	34	>57	-	-
Oswell and Graham (1987)	Propane[b]	GW[e]	-	9	16	37
	Coal/straw[c]		-	10	19	45
	Electric[d]		-	41	52	81

Note: Hermansson and Guthrie (2006) do not present information about thaw depth versus time at 0.5 and 1.0 m depth; the same applies to Oswell and Graham (1987) at 0.2 m depth.
[a]70 kW gross burner capacity as opposed to 103 kW used in Sveen et al (2017a).
[b]System of four steel pipes set in a 0.3 m thick blanket of sand through which hot air from propane burners located at one end passed.
[c]Coal placed on beds of straw and burned directly on the ground surface.
[d]Three 240 V radiant heaters placed below a reflective cover on the frozen surface.
[e]Actual soil classification not listed in reference, described as *sandy gravel* and *clay till*.

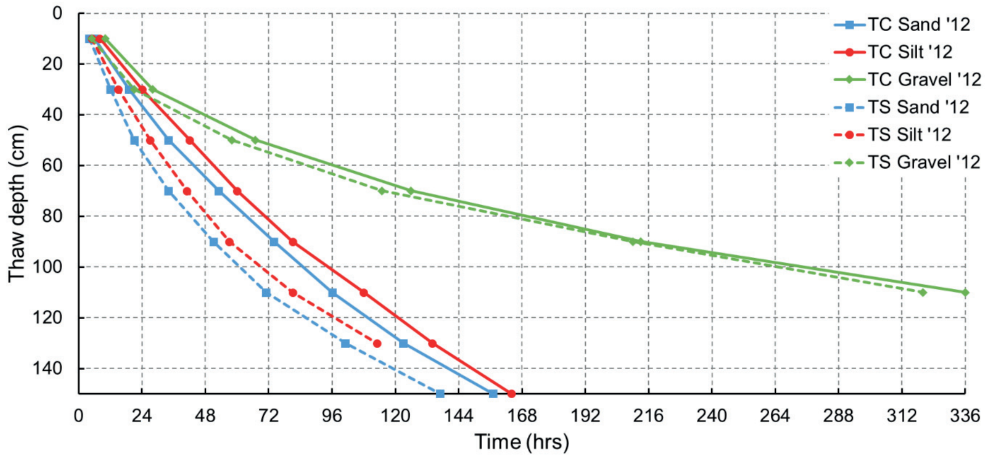

Figure 3.8. Thaw rates compiled from thermocouple readings (TC, solid lines) compared with thermistor string readings (TS, dotted lines) suspended inside access tubes (from Fig. 11, paper III).

In assessing the conformity between the two types of temperature sensors used, it was found that thermistor strings in tubes were overestimating thaw rates in gravelly and silty sand, illustrated by Fig. 3.8. It appeared that the relatively large thermistors (height 50 mm, Fig. 7 paper II) were affected by the thaw front moving downwards well before the small-sized thermocouples (height 6 mm). Convection inside the tube might also be a contributing factor, although an earlier study by Miller (Esch 2004c) showed excellent conformity between direct and indirect soil temperature measurements, even without an insulating annulus between the sensors inside the tube. The differences appeared to diminish with depth, suggesting that the discrepancies might be smaller for depths beyond ~2 m. In uniform gravel (comparatively dryer and much more porous), thermistor strings and thermocouples were found to correspond very well.

3.4 Hydrodynamic response in artificially thawed frozen soils

This section refers to the work presented in paper IV on soil moisture variations in frozen ground subjected to hydronic heating. As previously noted, this paper is a continuation of paper III, and deals with phase changes, the resulting soil moisture variations, and how they relate to the findings presented in paper III.

3.4.1 Objectives

As the final paper in this study, the primary goal was to supplement the findings in paper III by complementary information about the hydrodynamics occurring in the various soils during artificial thawing, and bring together the conclusions. In particular, paper IV was focused on spatial and temporal variations in soil moisture content and soil matrix potential ('water surface tension'), and the associated water redistribution and migration. In addition, soil moisture readings based on capacitance and electrical resistance were compared. Paper IV also presents the results of the simultaneous monitoring of soil temperature and soil moisture variations, and compares the associated thaw rates, which is a novel contribution of this research.

3.4.2 Results

Similar to soil temperatures, variations in soil moisture were monitored utilizing two measurement principles and types of sensors. Tubed capacitance sensors were used to indirectly monitor soil volumetric water content, while resistance blocks embedded in the soil were used for detecting frost. The results presented are from the same experiments as referred to in paper III.

The spatial and temporal soil moisture distribution in all soils during both thawing experiments are shown in Figs. 5 and 6 (2012 and 2011) in paper IV. For reference, corresponding soil temperature and matrix potential trends are shown in Fig. 3.9a and 3.9c, respectively. It was found that before the soil started to thaw, the sensors were reacting only to bound water, ranging from approximately 4–11 volume percent (vol%) in gravelly and silty sand, to less than 5 vol% in uniform gravel. As the defroster was turned on, a short delay was observed before the uppermost sensor (0.1 m) began responding to an increase in unbound water, attributed to the onset of pore-ice melting. The water content continued to rise until a maximum level was reached, i.e., until all pore ice within the sensor's influence area had melted. As the thawing progressed further, a sharp decrease in water content in the uppermost soil layer was observed, attributed to the downward migration of excess water. The decline was found to be more distinct for the sensors near the surface. In silty and gravelly sand, the observed maximum levels down to 1.1 m were generally declining with increasing depth. From that point and downwards, the maximum levels were either greater than or equal to corresponding levels above 1.1 m depth.

The time needed for the sensors at 1.1 m depth to reach maximum water content was found to be 102 hours (4.25 days) in gravelly sand, 107 hours (~4.5 days) in silty sand, and 48 hours (2 days) in uniform gravel. The latter refers to the occurrence of the first peak, while the actual maximum level for the whole period of thawing occurred after 156 hours (6.5 days).

Similar variations in soil matrix potential (Ψ_m) are shown in Figs. 7 and 8 (paper IV), exemplified by Fig. 3.9c. The manufacturer's default calibration equation was used to determine Ψ_m, yielding results ranging from approximately –10 kPa (wet) to more than –80 kPa (dry). In paper IV, Ψ_m was assigned positive values. For frozen soils being thawed, the high end of the scale (<80 kPa) was interpreted as frozen or partly frozen soil, whereas the low end (10–15 kPa) was considered as thawed soil. Those potentials were temperature compensated based on soil temperature records at corresponding depths. The relative time differences between minimum potentials occurring at various depths were examined because they indirectly represent the dynamic (changing) status of the surrounding soil.

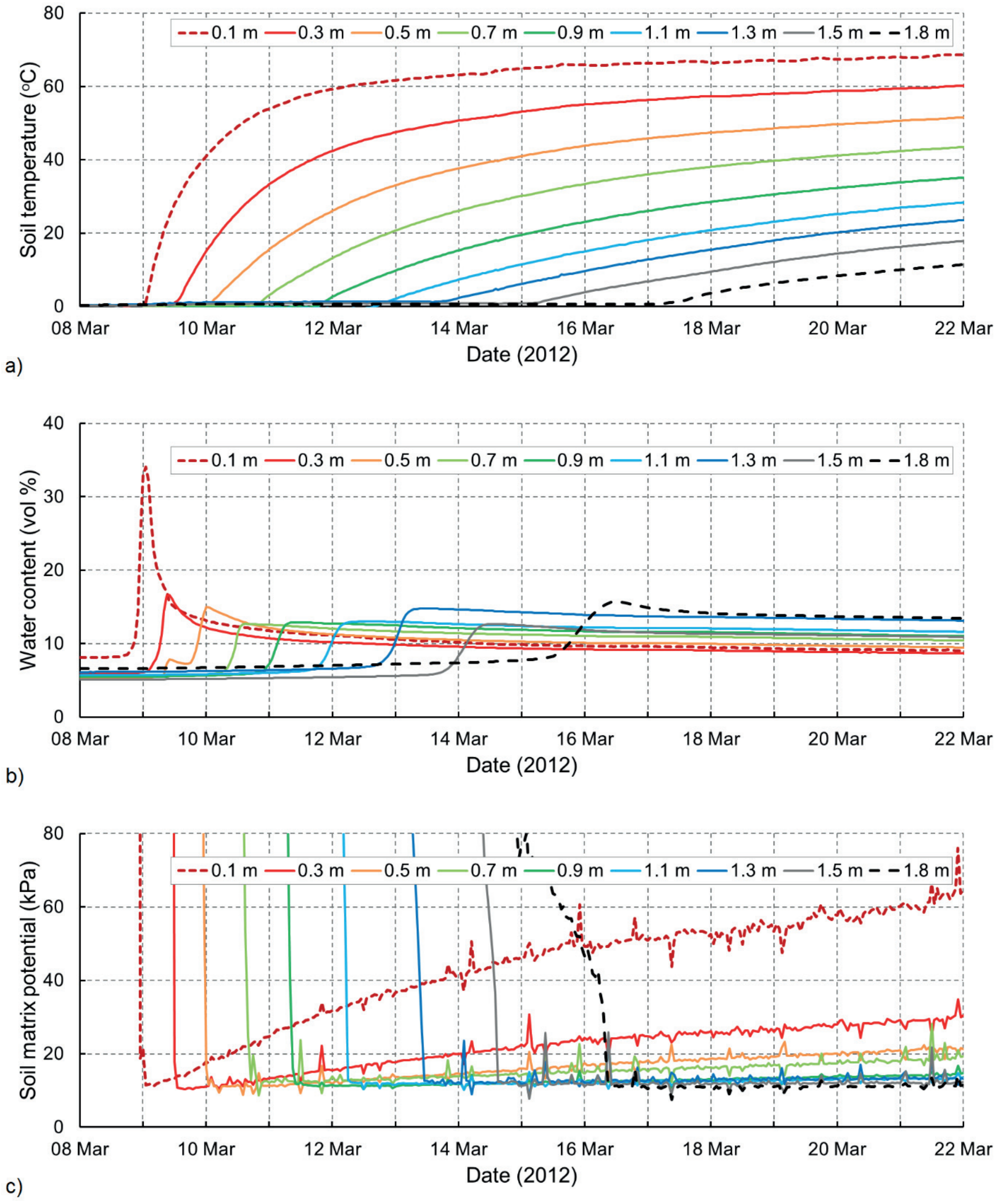

Figure 3.9. Spatial and temporal variations of a) soil temperatures, from Fig. 8a paper III; b) soil water content, from Fig. 5a in paper IV; and c) soil matrix potential, from Fig. 7a in paper IV, in gravelly sand subjected to hydronic heating, March 8th to 21st, 2012.

Soil matrix potentials were found to drop abruptly to about 10–12 kPa in all three soils as the thawing progressed. In gravelly sand (Fig. 7a, paper IV), the time between the drops increased gradually (nonlinearly), resembling the soil temperature responses following phase changes.

This was not the case in silty sand (Fig. 7b, paper IV), where Ψ_m reached minimum levels comparatively earlier in time, especially from 0.9 to 1.5 m depth. At 1.8 m, Ψ_m started low (~15 kPa) and dropped only marginally (to approximately 10 kPa) after one week of thawing, suggesting that the frost had not penetrated this deep at the time of the experiment in 2012. Similar to silty sand, uniform gravel (Fig. 7c, paper IV) differed from gravelly sand in that Ψ_m reached its minimum value considerably earlier. Another difference was a sharp increase in Ψ_m in the upper gravel layer, noticeable at 0.1 and 0.3 m depths.

The time needed for the electrical resistance sensors at 1.1 m depth to report wet or thawed conditions (10–15 kPa) was 88 hours (3.7 days) in gravelly sand, 84 hours (3.5 days) in silty sand and 31 hours (1.3 days) in uniform gravel.

3.4.3 Section summary

Soil moisture variations during thawing from both experiments are compared in Fig. 10 in paper IV. Maximum levels were plotted versus depth, disregarding their time of occurrence, in order to provide a general impression of the redistribution and moisture migration taking place during the process. Accounting for differences in dry density when comparing variations in maximum volumetric water content during thawing, it was found that silty sand (Fig. 10a, paper IV) contained more water than gravelly sand (Fig. 10b, paper IV) and that uniform gravel (Fig. 10c, paper IV) contained the least. This was found to be the case for both experiments, indicating that water holding capacity of soil is, amongst other factors, related to amount of fines and sand content (Table 1 and Fig. 4, both from paper IV).

Comparison between maximum water content *during* thawing and water content *after 12 days* of thawing (Fig. 10, paper IV) showed that water redistribution and migration were more prominent in the uppermost layer for all soils. The trends were similar for both experiments, although differences observed in 2012 (blue colour, Fig. 10, paper IV) were generally slightly smaller compared with those in 2011 (red colour, Fig. 10, paper IV).

A closer examination of the profiles after 12 days of thawing revealed small variations from one experiment to the next. That was somewhat surprising considering the site had experienced changing weather conditions and snow pack in the period leading up to the experiments. The profiles also showed that silty sand held less water in the uppermost layer and more water in the lowermost layer compared with gravelly sand. The slope in uniform gravel was close to vertical (Fig. 10c, paper IV), indicating the water content being nearly the same in the entire soil column.

Fig. 3.10 compares thaw rates calculated from temperature measurements with thaw rates calculated from capacitance measurements. Records from 2011 are omitted because of natural thawing affecting the experiment. Thaw rates were determined by calculating the time from the start of thawing to the time when water contents started dropping from maximum levels. The soil moisture profiles were evaluated individually for each depth and soil type. Because the

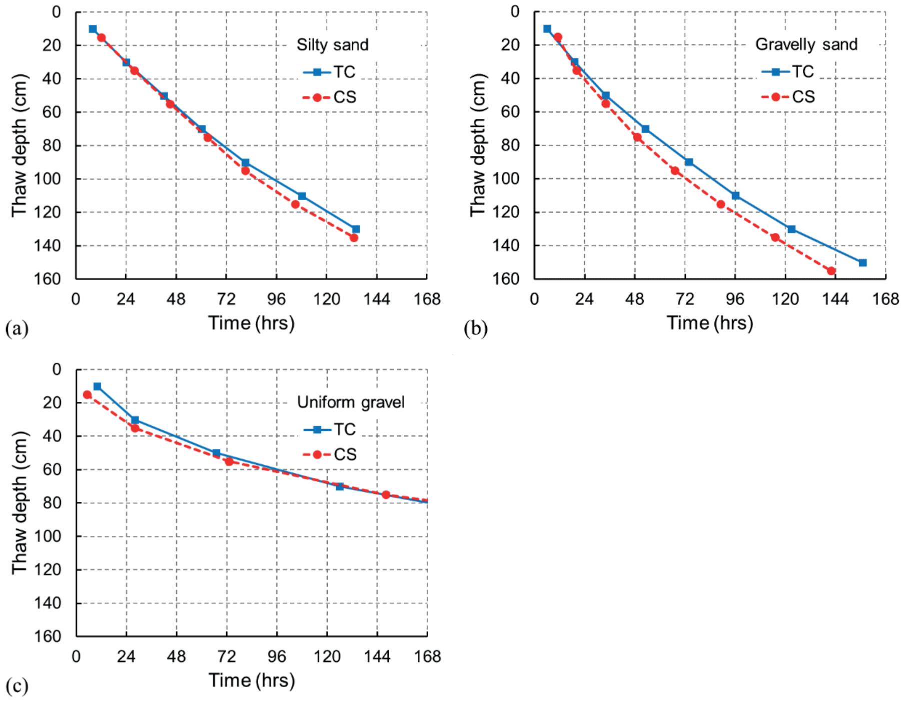

Figure 3.10. Thaw depth versus time calculated from soil temperature (TC-thermocouples) and soil moisture records (CS-capacitance sensors) in; a) silty sand; b) gravelly sand; c) uniform gravel, March 2012 (from Fig. 11, paper IV).

axial influence area of a capacitance sensor extends 5 cm below its centre-line (depth), the corresponding thaw rates are displaced accordingly on the ordinate axis.

Fig. 3.10 reveals that thaw rates calculated from capacitance records (CS) correspond well with thaw rates calculated from soil temperature records (TC) for silty sand and uniform gravel. In silty sand (Fig. 3.10a), thaw rates calculated from capacitance records are slightly overestimated below 0.7 m depth compared with thaw rates calculated from soil temperature records, varying from 29 cm/day after one day (24 hours) of thawing to approximately 25 cm/day after five days (120 hours). In uniform gravel (Fig. 3.10c) the situation is reversed, with rates slightly overestimated above 0.7 m, varying from 31 cm/day after one day of operation to approximately 13 cm/day after five days. In gravelly sand (Fig. 3.10b), capacitance sensors start overestimating thaw rates from about 0.3 m, increasing with depth. The difference is approximately 12 h at 1.0 m depth, and twice that at 1.5 m. The thaw rates in gravelly sand vary from 41 cm/day after one day to approximately 28 cm/day after five days.

The main contribution of the work in paper IV was providing insight to the complicated dynamics of heat and mass transfer occurring during artificial thawing, and showing how those interconnected phenomena interact in practice. This interaction is indicated in Fig. 3.9. Soil temperatures (Fig. 3.9a) in gravelly sand is observed to be lingering around 0ºC while phase change was occurring, i.e., during the time when unbound water content was rising (Fig. 3.9b). It was not until the phase change was completed, i.e., when the water content reached its maximum (Fig. 3.9b) and the soil matrix potential dropped to its minimum (Fig. 3.9c), that soil temperatures started rising above 0ºC.

Except for soil matrix potentials, the trends were found to be similar in silty sand and uniform gravel. Among the sensor types used in this study, only the resistance blocks (which are the basis for soil matrix potential measurements) were found to deviate from the rest. This is consistent with findings published in other recent studies, in which various degrees of success using resistance blocks for determining soil matrix potential were reported (e.g. Chávez et al. 2011; Chow et al. 2009; El Marazky et al. 2011; Nolz et al. 2013; Rudnick et al. 2015; Varble and Chávez 2011).

4. Heat transfer in fully saturated sand

This chapter summarizes the modelling efforts from a working paper (S. E. Sveen, "*Simulating heat transfer in frozen ground undergoing artificial thawing, using COMSOL Multiphysics–part 1*", UiT–Norwegian Arctic University, Norway). The model is basis for a sensitivity analysis, assessing effects of variations in essential operating and design parameters.

4.1 Introduction

Simulating thaw penetration in initially frozen soils – whether induced by natural or artificial means – is quite complex, because it involves thermal diffusion (heat transfer), phase change (latent heat effects) as well as moisture redistribution and migration (mass transfer). Furthermore, frozen soil is a multi-phase material, consisting of solids, pores (gas), bound and unbound water and ice. The thermal properties for most of these constituents change, to some degree, during thawing. Most notably, thermal conductivity decreases by a factor of four, and heat capacity increases by a factor of two when ice changes phase to water (Chengel 2002). In addition, the amount of ingredients present and influences owing to external factors such as varying ambient air temperature, wind and precipitation must be taken into consideration.

In numerical modelling, it is difficult to account accurately for this kind of complexity and interactions, hence simplifying assumptions are often made to isolate or track certain trends. However, even a simple model such as the one presented in this chapter, can be of value when used for assessing effects on the thawing process owing to changes in various input parameters.

Numerous studies have investigated the phenomena of heat and mass transfer in naturally freezing or thawing soils (e.g. Lai et al. 2014; Li et al. 2012; Wu et al. 2015; Xu and Spitler 2014). Flerchinger and Saxton (1989a; 1989b) developed a comprehensive model to describe heat and mass transfer under freezing conditions (SHAW model), which have been tested under a wide range of conditions (Nassar et al. 2000), including natural freezing and thawing (Li et al. 2012). Simulated frost depth was found to be very sensitive to small changes in air temperature (1ºC) and initial snow depth (10 cm). Soil hydraulic parameters were found to have little effect on frost depth, but a large impact on water movement toward the zone of freezing.

Shoop and Bigl (1997) assessed the accuracy of the well-known FROSTB freeze-thaw model when predicting soil moisture migration during freeze and thaw, developed at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) by Berg et al. (1980). They found that the model predicted frost penetration and heave quite well, but tended to overestimate ice formation, which then caused a slower thaw.

In his thesis dealing with numerical modelling of frost and thaw penetration, Sheng (1990) referred both to classical analytical methods and to various numerical methods such as 'front-tracking', 'front-fixing', and 'enthalpy' methods, as well as 'varying inequality' and 'moving finite elements'. He presented a two-dimensional (2D) finite element model (FEM) based on an enthalpy method and compared the results with analytical solutions and laboratory tests. Moreover, he performed a sensitivity analysis, using FEM and finite difference models (FDM), to assess the effects of various material properties, time step and grid size. Amongst other findings, he concluded that both models were more dependent on thermal conductivity and latent heat than on heat capacity; that the frost penetrations depth decreased with increasing water content, and increased with increasing time step; and that the FEM generally predicted larger frost depths than the FDM.

Fig. 4.1 shows a 3D representation of a typical soil bin with a hot-water pipe (red) laid out on soil surface.

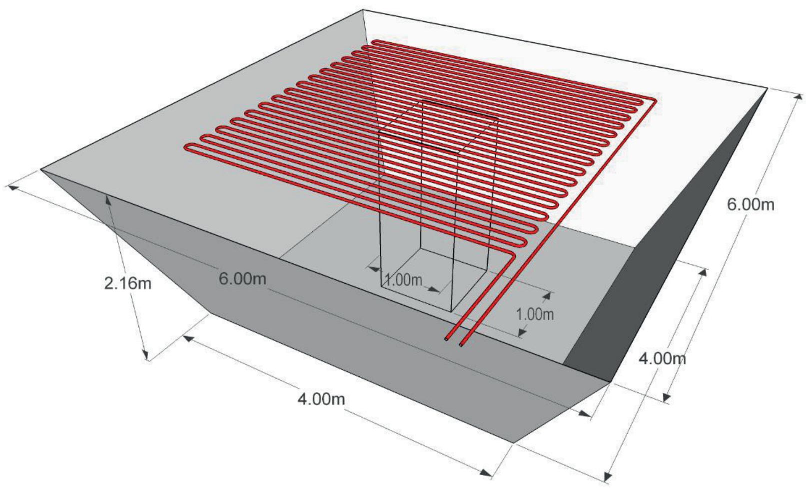

Figure 4.1. Soil bin with a hot-water pipe (red) laid out on ground surface, covering an area of approximately 4.5 m x 4.5 m (from Fig. 5, paper III).

Although the soil bin geometry is well suited for 2D simulations, a 3D model was chosen in this case. Even if a 3D model comes at a comparatively higher computational cost, it is a better starting point for including other physical phenomena when developing the model further. Moreover, the results are easy to compare with actual soil temperature and moisture records obtained from the full-scale experiments in this thesis (Sveen et al. 2017a; 2017b). The computing time is somewhat reduced by modelling the hot-water pipe as a 1D edge-element (line source) on the soil surface instead of a fully 3D-meshed pipe. Assuming fully developed flow (isotropic, Newtonian fluid), the heat transfer is then solved only for the tangential cross-section averaged velocity along the line in contact with the soil. This greatly reduces the number of boundary elements for long pipes, and thus, the time needed for executing the simulations.

The model presented in this chapter is created in COMSOL Multiphysics, making use of its *Non-Isothermal Pipe Flow* and *Heat Transfer in Solids* interfaces. The aim is to assess relative influences on the thawing process owing to variations of particular operating and design parameters of the heat source. First, the model is used to simulate time-dependent, conductive heat transfer in fully saturated, gravelly sand subjected to hydronic heating to obtain a 'baseline'. The baseline results yield the soil temperature distribution with initial values for distance between the pipes, inlet temperature and fluid flow rate, respectively. Second, parametric sweeps are then performed, gradually increasing each of the three input parameters individually. Finally, comparisons of the resulting increase in soil temperature are made to assess their relative effect on the thawing process.

This version of the model does not include phase change. Consequently, effects associated with absorption of latent heat during thawing are not accounted for. In this study, incorporating phases change is defined as further work.

4.2 Model definition

4.2.1 Model geometry, process and boundary conditions

The soil bin geometry shown in Fig. 4.2 is somewhat simplified compared with Fig 4.1. It is made as a block with vertical sidewalls instead of inward-sloped walls. The soil bin covers an area of 6 m x 6 m, extending downwards to 2 m depth. This is slightly deeper than the extent of the soil temperature and moisture sensors used in the experiments, which end at 1.8 m. The bin contains homogenous, gravelly sand at an initial, uniform temperature of 0ºC. The soil surface and upper half of the pipe (Fig. 4.3) are exposed to forced convection (horizontal flow, v = 1.5 m/s). The side and bottom surfaces are isolated from the adjacent soil, with boundary temperatures assumed to be 0ºC.

The hot-water pipe covers an area of 4.4 m x 4.4 m and is used to increase the heat load at the surface boundary, assuming no energy exchange across the remaining boundaries. The fluid inlet and heat flow outlet are at opposite wall boundaries, at the junction (edge) between the surface and the wall, as shown in Fig. 4.2. A mixture of water and glycol (1:1 ratio) flows through the pipe at a rate of 12 L/min, at a velocity of 1 m/s. For stability reasons, the model is set up with an initial fluid temperature corresponding to the soil (0ºC), which is rapidly increased to 94.5ºC during a short time interval at the beginning of the simulation.

The model does not account for phase change (latent heat), heat radiation from the surface or the pipe walls exposed to ambient air, nor work because of pressure action. Values and dimensions of important variables used in the simulation are listed in Appendix 5.

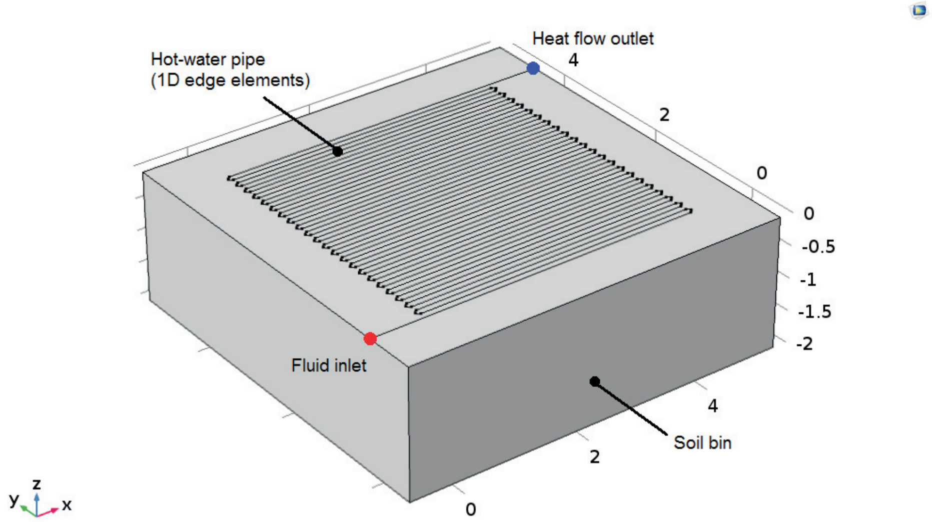

Figure 4.2. Soil bin with hot-water pipe laid out on top. The hot fluid inlet and the comparatively colder heat flow outlet are marked in red and blue, respectively.

The pipe is constructed as a Bézier polygon on a xy-work plane, which corresponds to the soil surface. Represented in 3D, with an arbitrary (default) pipe diameter assigned for visibility, the bottom half of the pipe perimeter appears embedded in the soil, whereas the upper half appears exposed to ambient air, as shown in Fig. 4.3.

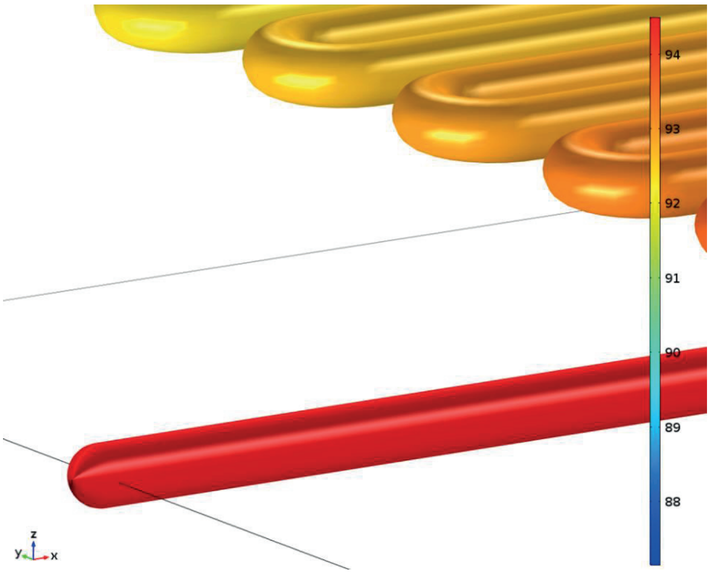

Figure 4.3. A close-up of the hot-water pipe laid out on the ground surface.

In addition to the variables in Appendix 5, an expression for the fluid inlet temperature is introduced, using a smoothed step function (a built-in feature of the software), termed as the 'ramp-up' function. This expression is used for increasing the inlet temperature from 0°C to 94.5°C during the initial simulation steps owing to numerical stability reasons, and is given by the following equation:

$$T_{inlet} = T_{init,soil} + \left(T_{fluid} - T_{init,soil}\right) step1(t[1/h]) \ \ (K)$$

where T_{inlet} is the resulting fluid inlet temperature (K) after the ramp-up function is applied, and *step1(t)* is a time-dependent step function varying from 0 to 1, also given in Appendix 5.

The soil properties used in the model represents the soil properties of gravelly sand from the actual experiments. However, COMSOL's *Heat Transfer in Solids* interface treats soil as a solid in the model, i.e., without pores, ice or water. To reduce the resulting discrepancies, approximate values for soil density and specific heat are calculated from the dry density and volumetric water content of the soil used in the experiments. In turn, those approximations are used to determine the thermal conductivity for fully saturated, gravelly sand. The associated soil properties used in the simulation are listed in Table 2.

Table 2. Soil properties used in the simulation.

Property	Value	Description
ρ	1,695.2 kg/m^3	Soil density
c_p	1,066 J/(kgK)	Specific heat (per unit mass)
k_f	1.5 W/(mK)	Thermal conductivity, frozen

Note: All values are calculated assuming a soil dry density ρ_d of 1,790 kg/m^3 and volumetric water content of 12 vol% (thawed, gravelly sand).

4.2.2 Pipe flow equations

The respective equations for momentum and mass conservation used are as follows (COMSOL 2015):

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} = -\nabla p - f_D \frac{\rho}{2d_h} \boldsymbol{u}|\boldsymbol{u}| \quad (10)$$

$$\frac{\partial A\rho}{\partial t} + \nabla \cdot (A\rho \boldsymbol{u}) = 0 \quad (11)$$

where $\boldsymbol{u}$ is the cross-section averaged fluid velocity (m/s) along the tangent of the centre line of a pipe, p (N/m^2) the pressure, ρ (kg/m^3) the density, d_h (m) the hydraulic diameter (inner diameter in circular cross-sections), and A (m^2) the cross-sectional area of the pipe.

The second term on the right-hand side of Eq. (10) accounts for pressure drop due to viscous shear. COMSOL uses the Churchill (1997) friction model to calculate the Darcy friction factor,

f_D. It is valid for laminar, turbulent flow and the transitional region in between. The Churchill friction model is predefined in the *Non-Isothermal Pipe Flow* interface as:

$$f_D = 8\left[\left(\frac{8}{Re}\right)^{12} + (A+B)^{-1.5}\right]^{1/12} \tag{12}$$

where *Re* is the dimensionless Reynold's number, i.e., the ratio of inertia forces to viscous forces, which determines if the flow is predominantly laminar or turbulent, given by:

$$Re = \frac{\rho u d}{\mu} = \frac{ud}{\nu}$$

and where μ and v are the dynamic and kinetic viscosities, respectively. The factors *A* and *B* in Eq. (12) are defined as (Churchill 1997):

$$A = \left[-2.457 \cdot ln\left(\left(\frac{7}{Re}\right)^{0.9} + 0.27(\frac{e}{d})\right)\right]^{16} \tag{13}$$

$$B = \left(\frac{37{,}530}{Re}\right)^{16} \tag{14}$$

As seen from Eq. (12) and Eq. (13), the friction factor depends on the surface roughness *e* (m) and the pipe diameter *d* (m), in addition to the fluid properties, flow velocity and geometry accounted for through Reynold's number.

The *Pipe Properties* feature is used to select the surface roughness from a predefined list. In this simulation, the surface roughness is set to $e = 1.5{\cdot}10^{-6}$ m, corresponding to the type of pipes installed on the defrosting system used in the experiments. Table 3 shows relevant values calculated by the software. As can be seen from Reynold's number, the pipe flow is turbulent.

Table 3. Parameters calculated by COMSOL.

Parameter	Value	Description
f_D	0.03	Darcy friction factor
Re	8,550	Reynolds number
Nu	111.55	Nusselt number

4.2.3 Heat transfer equations

A built-in energy balance equation in COMSOL's *Non-Isothermal Pipe Flow* interface accounts for the hot water-glycol mixture in the pipe as follows (COMSOL 2015):

$$\rho A c_p \frac{\partial T}{\partial t} + \rho A c_p \boldsymbol{u} \cdot \nabla T = \nabla \cdot Ak\nabla T + f_D \frac{\rho A}{2d_h}|\boldsymbol{u}|^3 + Q_{wall} \tag{15}$$

where A (m^2) is the cross-sectional area of the pipe, c_p [J/(kgK)] is the heat capacity at constant pressure, T (K) the fluid temperature, and k [W/(mK)] the thermal conductivity. The second term on the right-hand side represents the heat dissipated due to internal friction in the fluid. It is negligible for short pipes, but is accounted for in this simulation by activating an internal film resistance in the pipe *Wall Heat Transfer* feature. The term Q_{wall} (W/m) is a source term that accounts for the heat exchange at the pipe-soil interface.

The governing heat transfer mechanism in the soil (solid) is conduction, hence COMSOL uses an equation of the following form:

$$\rho c_p \frac{\partial T_2}{\partial t} = \nabla \cdot k \nabla T_2 \tag{16}$$

In Eq. (16), T_2 is the temperature of the homogenous soil. The source term Q_{wall} comes into effect for the heat balance in Eq. (15) through a line heat source, where the pipe is situated on the soil surface. The *Wall Heat Transfer* feature in the *Non-Isothermal Pipe Flow* interface does this coupling automatically.

Heat transfer from the pipe wall is given by (COMSOL 2015):

$$Q_{wall} = hZ(T_{ext} - T) \tag{17}$$

where Z (m) is the perimeter of the pipe, h [W/(m^2K)] the heat transfer coefficient, and T_{ext} (K) the external temperature outside the pipe. The pipe heat transfer is defined in the *Wall Heat Transfer* feature in the *Non-Isothermal Pipe Flow* interface. Besides internal film resistance (1), the following two nodes are set, where settings/parameters used (listed in Appendix 5) are in parenthesis: (2) wall layer (*k_pipe* and *pipe_t*), and (3) external film resistance (*external forced convection, air, v_air, external pressure 1 atm*). Here, T_{ext} is given by the temperature field computed for the soil by the *Heat Transfer in Solids* interface.

Note that the third node is relevant only for the upper half perimeter of the pipe wall, i.e., the part of the pipe surface area exposed to ambient air, previously shown in Fig. 4.3. The first two nodes relate to heat transfer through the pipe wall and the outer pipe wall temperature, used for computing the temperature field.

In the *Heat Transfer in Solids* interface, T_{ext} is set as a constant (*T_air* = 0ºC) by the *Heat Flux* node, in order to account for external forced convection on the soil surface. The heat transfer coefficient (h_{air}) and the convective heat flux (q_0) are automatically calculated based on the following settings, where the values used (listed in Appendix 5) are in parenthesis: plate length (L = 6 m), fluid (*air*), fluid velocity (U = *v_air*), absolute pressure (p_A = 1 atm), and external temperature (T_{ext} = *T_air*).

A pump ensures circulation of the fluid. In relation to internal forced convection, the heat transfer coefficient (h) depends on the physical properties of the water-glycol mixture and the nature of the flow. It is calculated from the Nusselt number:

$$h = Nu\frac{k}{d_h}$$

where k is the thermal conductivity of the fluid, d_h the hydraulic diameter, and Nu the dimensionless Nusselt number.

In this case, with turbulent flow inside a circular pipe, COMSOL uses the following Nusselt correlation (Gnielinski 1976):

$$Nu_{int} = \frac{(f_D/8)(Re - 1{,}000)Pr}{1 + 12.7(f_D/8)^{1/2}(Pr^{2/3} - 1)} \tag{18}$$

where Pr is the dimensionless Prandtl number given by:

$$Pr = \frac{c_p\mu}{k}$$

From Eq. (18), it follows that the Nusselt number depends on the friction factor, f_D. Thus, the radial heat transfer increases with the surface roughness (e) of the pipe.

The equations describing the pipe flow regime are fully coupled to those governing the soil heat transfer.

4.2.4 Mesh and resolution

There are several options and methods available for generating a polygonal mesh to approximate the geometric domain. In this case, both for the soil and pipe domains, an unstructured (free) tetrahedral mesh is used. The resulting mesh, with element size set to 'finer' for the soil domain and 'normal' for the pipe domain, is shown in Fig. 4.4. With these settings, the resulting mesh consists of 45,206 domain elements, 4,322 boundary elements and 806 edge elements. A separate figure showing the pipe domain mesh is given in Appendix 6.

The scale of the soil domain mesh is set to 1:1:1, i.e., equal element density in x-, y- and z-directions. In case of coarser mesh settings for the soil domain, the density in z-direction must be increased to ensure a fair representation of the heat transfer in the direction most interesting with regard to artificial thawing.

Note that the pipe mesh (Fig. 4.4 and Appendix 6) is shown for horizontal pipe distance of 10 cm. The sensitivity analysis also includes a parametric sweep where the distance between pipes first are doubled (20 cm), and then tripled (30 cm). The respective surface meshes are given in Appendix 7.

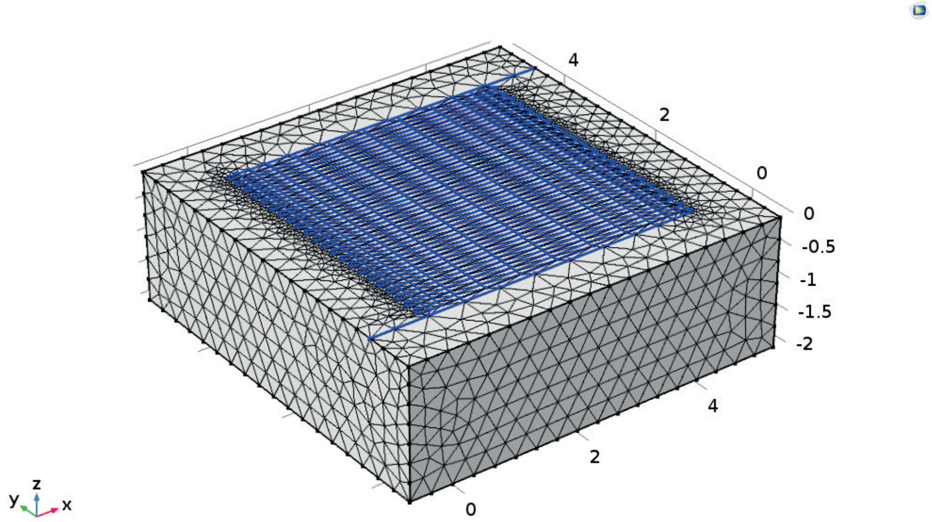

Figure 4.4. Soil (3D block) and pipe (1D edge-element, blue colour) domain meshes. Note that the element size is set to 'finer' for the soil domain and 'normal' for the pipe elements.

4.3 Simulated fluid and soil temperatures

This section contains a selection of graphical representations from the simulation, where what is labelled 'baseline' settings are used. These are a horizontal pipe distance (centre-centre) of 10 cm, fluid inlet temperature of 94.5ºC, and fluid flow rate of 0.2 L/s. The soil domain geometry and other input variables listed in Appendix 5 are unchanged. Supplementary representations such as pipe pressure distribution, velocity, and isothermal contours are computed by default and listed under the *Results* node, but are omitted in this section.

At the end of this section, the simulation results are compared with soil temperature records from full-scale thawing experiments on homogenous, gravelly sand, carried out in 2012. Details about the experiment, hydronic heating system, weather conditions and other relevant information are given in Sveen and Sørensen (2013) and Sveen et al. (2017a).

The pipe conducts heat to the soil, initially at 0ºC. At the beginning, the temperature difference between the fluid inlet (constant) and the outlet (increasing) is at its maximum. As the thawing progresses with time, the difference becomes lower. Fig. 4.5 shows the fluid temperature distribution inside the pipe after 168 hours or 7 days of continuous thawing.

The temperature difference between the inlet (94.5ºC) and outlet after 168 hours is approximately 7ºC, which is about 5ºC smaller compared with the temperature difference found in the experiments for the sand bin at the same time. Hence, the model underestimates the fluid temperature drop through the pipe. The discrepancy would be less if the model did include radiation heat losses from part of the pipe wall exposed to ambient air. However, the model does account for heat losses resulting from forced convection. Increasing the air velocity across the soil surface beyond 1.5 m/s used in the simulation, would increase the convection loss, thus reduce the discrepancy between simulated and measured temperature drops through the pipe.

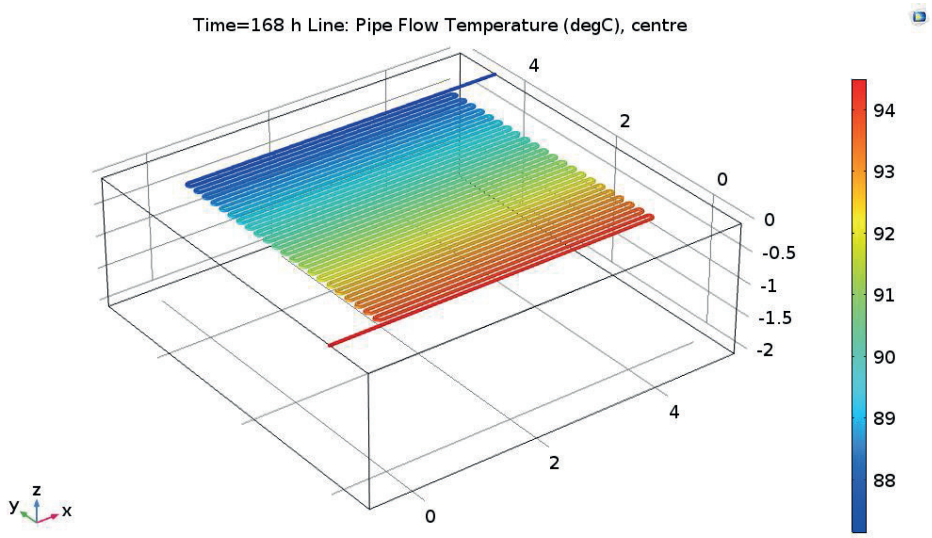

Figure 4.5. Fluid temperature distribution after 168 hours (7 days) of continuous thawing. Note that the displayed temperatures represent the fluid temperatures inside the pipe, at the centre of the flow.

In the experiments, as opposed to the simulations, the pipe was covered with thin, lightweight insulation mats in order to reduce heat losses to ambient air. Consequently, temperatures in the air-gaps underneath the insulation layer become considerably higher than the surrounding air. The comparable higher air-gap temperatures are likely to influence the fluid temperature drop during actual thawing operations.

Figs. 4.6 and 4.7 show soil surface temperature and soil temperature distribution, respectively, after 168 hours of thawing. Even though a temperature trace of the pipe is clearly visible on the ground surface as shown in Fig. 4.6, the surface temperatures are considerably lower than the fluid temperature. Fig. 4.7 shows the soil temperature distribution along five yz-planes. The pipe edges and soil domain limits are included to show the position of the pipe and the extent of the soil block. As indicated in the figure, soil temperatures are high close to the heat source, gradually decreasing with depth (along the z-axis).

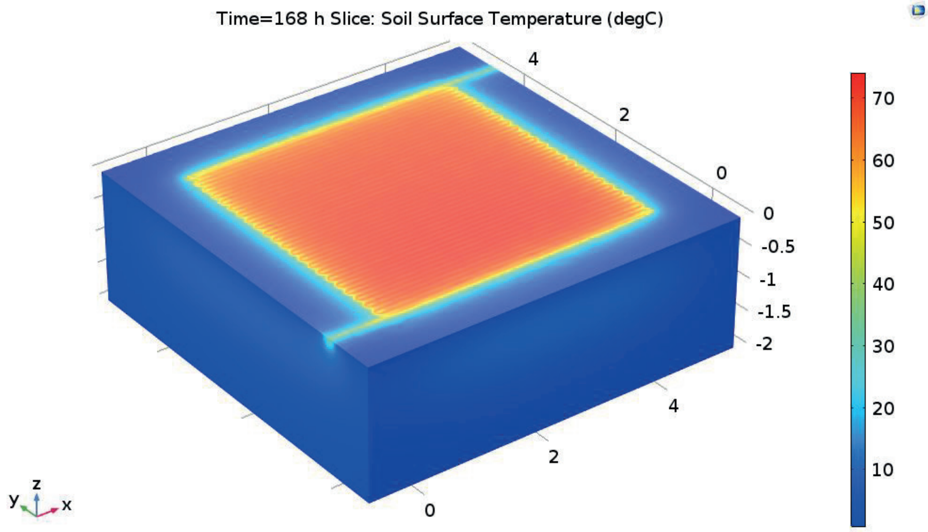

Figure 4.6. Ground surface temperatures after 168 hours of thawing.

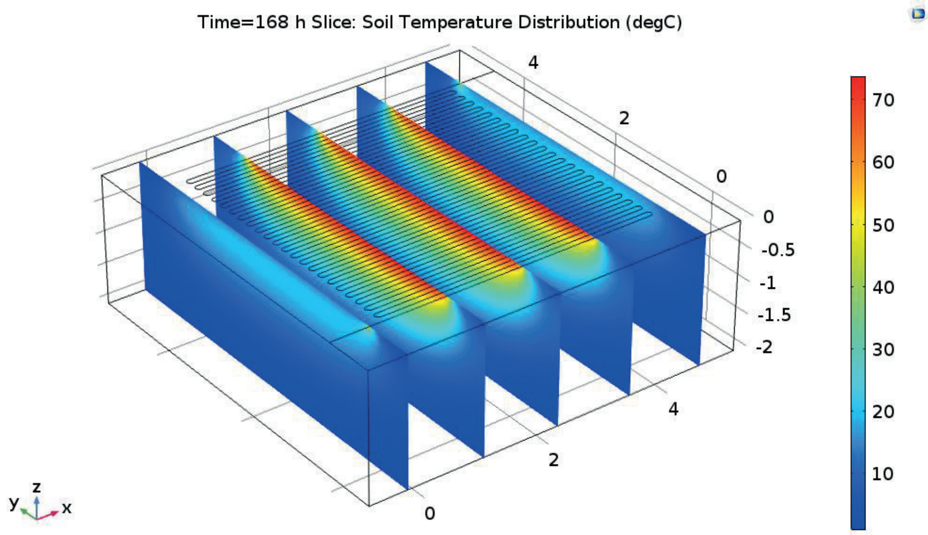

Figure 4.7. Soil temperature distribution after 168 hours of thawing.

Note that when the thawing process is well underway, with the pipe laid out with sufficiently narrow gaps, the isotherms appears continuous at some distance into the ground, as shown in Fig. 4.7.

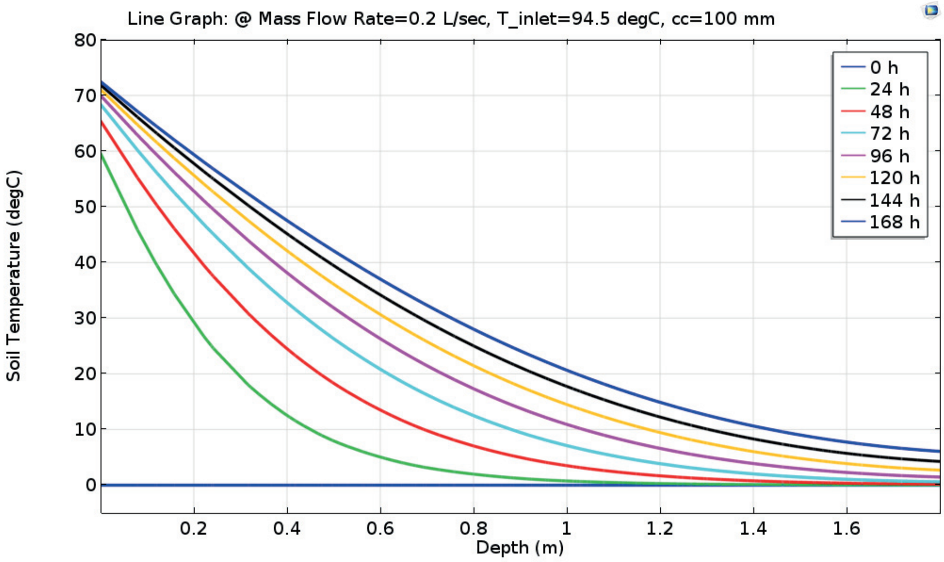

Figure 4.8. Soil temperatures versus depth at various time steps, using baseline settings for pipe distance (cc), fluid inlet temperature (T_inlet), and flow rate.

Fig. 4.8 shows soil temperature as a function of depth and time with baseline settings. The temperature distribution with depth is shown at 24 hour intervals starting from time t_0 = 0 h, covering one week or 168 hours of continuous thawing. From examining the development over time, it can be seen that the soil temperatures decrease as the distance to the heat source at the ground surface increases. A closer examination reveals an increase in soil temperature at 1.8 m after only 48 hours. After 168 hours, the temperature at this depth has reached nearly 7ºC. This differs considerably from the experimental data, which indicated that the soil was still frozen at this time and depth. Additional and similar plots related to the sensitivity analysis (section 4.5) are given in Appendix 9–11.

4.4 Simulated versus measured soil temperatures

Fig. 4.9 shows soil temperatures versus time at various depths over a period of 168 hours, obtained from the simulation. The temperatures are calculated at 10 cm intervals for depths ranging from 0 m to 1.5 m, including 1.8 m (shown in Fig. 4.11). For the purpose of comparison, similar data of soil temperature records from full-scale thawing experiments on gravelly sand performed in 2012 are shown in Fig. 4.10.

Comparing Figs. 4.9 and 4.10, the soil temperatures after 168 hours of continuous thawing obtained from both the simulation and experiments seem to agree fairly well down to approximately 0.7 m. From that depth and downwards, using baseline settings, the model overestimates soil temperatures.

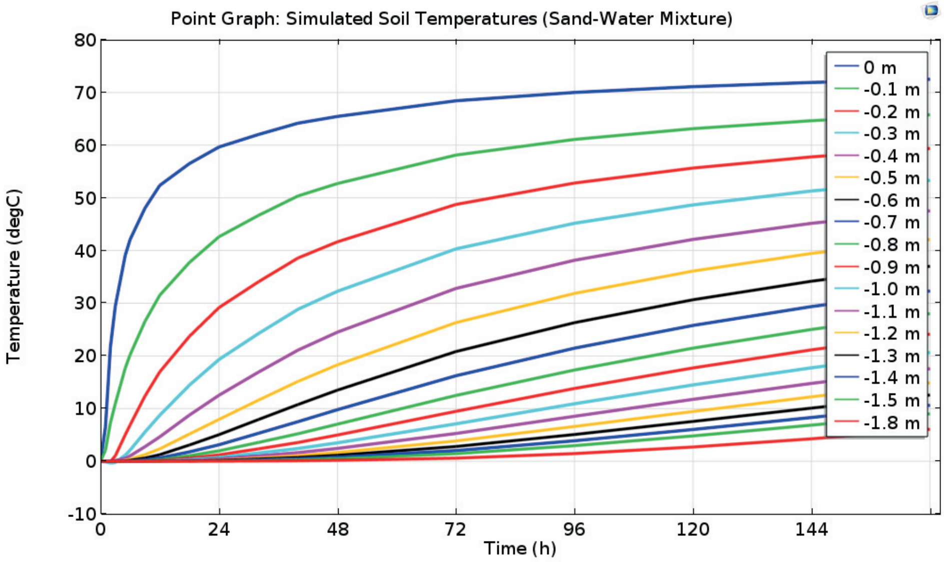

Figure 4.9. Simulated soil temperature trends.

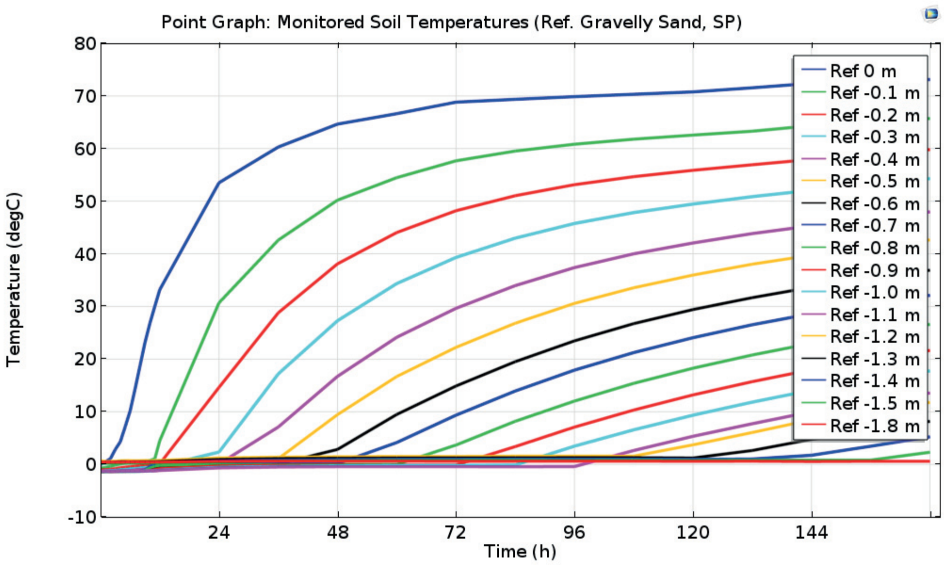

Figure 4.10. Measured soil temperature trends obtained through full-scale experiments made in 2012.

More importantly, the model is not able to reproduce the delayed soil temperature increase during phase change, where temperatures stay around 0ºC (Fig. 4.10) until the transition is complete before starting to rise. Hence, the model overestimates thaw rates by a considerable margin, which is reasonable since it only accounts for heat conduction in solids responding to a surficial heat source.

Some efforts have gone into trying to implement phase change in the model, but without succeeding. For example, COMSOL's *Heat Transfer in Solids* interfaces allows for defining the soil-water matrix as a 'phase change material'. The state of the soil-water matrix can then be separated into frozen (phase 1) and unfrozen (phase 2), respectively. Next, phase transition parameters such as speed of the fluid velocity field, phase change temperature, transition temperature interval, and latent heat from phase 1 to 2 can be defined, before attempting additional simulations. Despite repeated attempts, gradually increasing mesh density and reducing time steps, the solution did not converge. To obtain some benefit from the modelling efforts, a sensitivity analysis was added, focusing on some fundamental parameters of the heat source.

4.5 Sensitivity analysis

Hydronic based thawing and working principles of the defrosting system were briefly described in Chapter 3. In this section, parametric sweeps are made to assess effects on soil thermal regime from changes to essential design and operating parameters of the system. In particular, soil temperature changes resulting from increasing the distance between pipes, fluid inlet temperature, and fluid flow rate are analysed. Changes to other parameters such as pipe roughness, distribution pattern, and pipe insulation thickness were looked into, but not included in this section.

Here, only resulting temperature changes in z-direction are shown since those relate to thaw efficiency. Simulation values are extracted along a vertical line located at the centre of the soil bin. The number of points and associated depths, shown in Fig. 4.11, correspond to the positions and vertical spacing of the thermocouples used in the experiments.

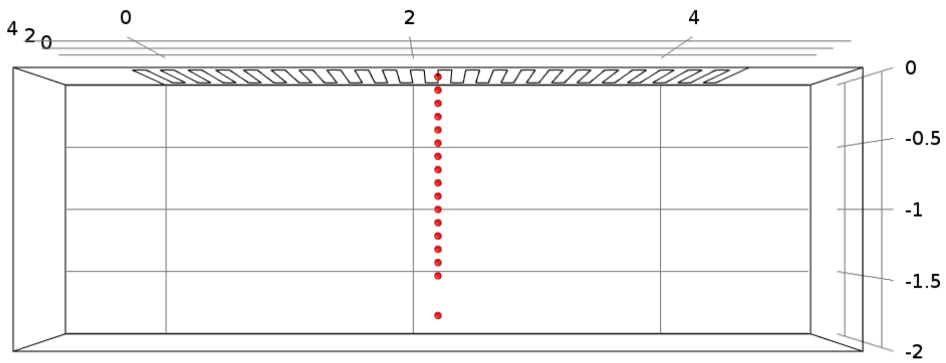

Figure 4.11. Location of fixed points used in the model for calculating soil temperature variations over time (yz-view). The locations correspond to those of the thermocouples used in the experiments.

4.5.1 Effect of distance between pipes

Referring to the defrosting system used in the experiments, the thermostat connected to the boiler is one out of only two operating parameters controlled by the user. In addition, the operator decides on which pattern to apply when distributing the pipe across the ground surface. Depending on the pattern, the horizontal distance or gaps between various parts of the pipe will vary. In the following, this is termed ‘distance between pipes’ or just ‘pipe distance’, even though the pipe is continuous – not divided into parts.

Theoretically, both the pattern and distance between pipes influence heat transfer to the ground. Some patterns yield a more even heat distribution, benefitting from heat exchanged between the hot supply flow and the comparatively colder return flow, while the distance between pipes (i.e. total pipe length) determines the heat flux.

Fig. 4.12 shows how increasing the distance between pipes in steps of 10 cm affects soil temperatures during thawing, compared with a baseline setting of 10 cm. The resulting changes are shown for 24 h time steps, at a fixed depth of 0.5 m. The temperature difference in relation to the baseline is the same, but attenuated with increasing depth (Appendix 8).

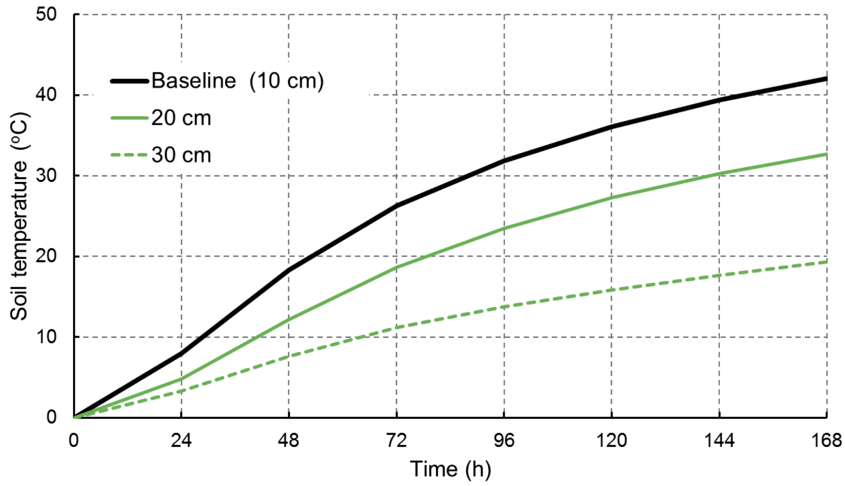

Figure 4.12. Soil temperature changes over time (green) at 0.5 m depth relative to baseline (black), resulting from stepwise increases in distance between pipes.

One week into thawing (168 h), soil temperatures are approximately 22 % lower than the baseline when the pipe distance is increased to 20 cm, and approximately 54 % lower when pipes are laid out with a distance of 30 cm. This makes sense, as the heat flux to the ground decreases with increasing gaps between pipes (total length reduced). With large enough gaps, the soil will thaw unevenly, leaving frozen ridges. The results demonstrate the importance of pipe distance in order to ensure sufficient heat flux for effective thawing.

4.5.2 Effect of inlet temperature

Fluid inlet temperature is the other parameter controlled by the operator. This is actually not only an operating parameter, because besides the thermostat setting, it depends on the installed oil burner effect. Consequently, inlet temperature is also a design parameter of defrosting systems, determining maximum temperature range available for thawing operations.

Fig. 4.13 shows the resulting soil temperature change from increasing the inlet temperature from a baseline setting of 94.5°C by 5 % and 10 %, respectively. The results are shown for time steps and depth similar to those in section 4.5.1.

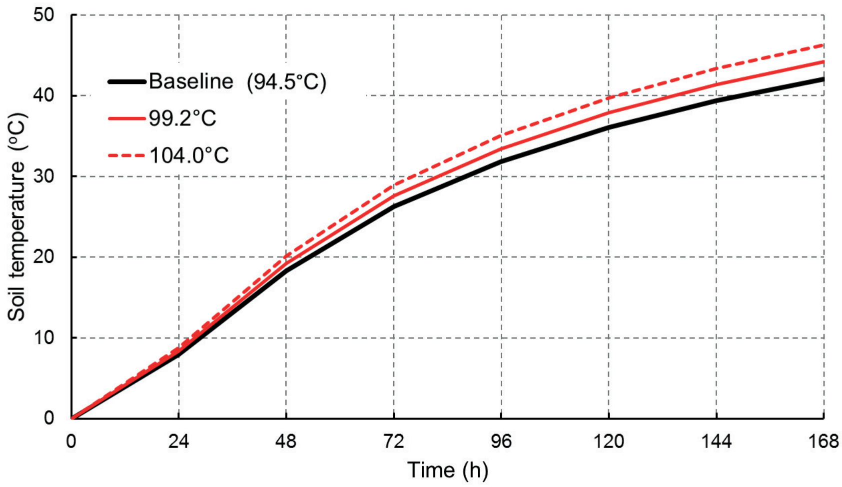

Figure 4.13. Soil temperature changes over time (red) at 0.5 m depth relative to baseline (black), resulting from stepwise increases in fluid inlet temperature.

Referring to differences after one week, the increase in soil temperature is found to be proportional to the increase in inlet temperature. In other words, an increase of 5 % or 10 % from the baseline yields similar increase in soil temperature. The relative differences are the same with increasing depth (Appendix 8), although the temperatures are generally lower.

The proposed increase up to 10 % is within reason, considering that newer defrosting models operate with boiler temperatures up to approximately 105°C. The improvement is typically not achieved by increasing the burner effect, but from tightening the hysteresis of the thermostat. Reducing the hysteresis from, say 5°C to 1°C, results in less intermittence on the burner. In turn, this contributes to maintain a higher average boiler temperature.

On the other hand, increasing the burner effect would obviously allow for higher heat transfer rates to the boiler, thus the potential for even higher supply temperatures.

4.5.3 Effect of flow rate

The capacity of the circulation pump is purely a design parameter. Amongst other factors, the capacity is determined from the expected pressure drop across the connected pipe or pipes. From a design point of view, it is desirable to restrict flow rates in order to maintain a low operating pressure. Moreover, operation safety is another limiting factor, considering the very high fluid temperatures involved.

The pump used in the experiments has the capacity to ensure circulation in up to three separate pipes (á 210 m length) at a flow rate of 0.2 L/s. Fig. 4.14 shows the soil temperature increase resulting from increasing the flow rate from the baseline setting by 50 % and 100 %, respectively. The results are shown for the same time steps and depth as those in the previous sections.

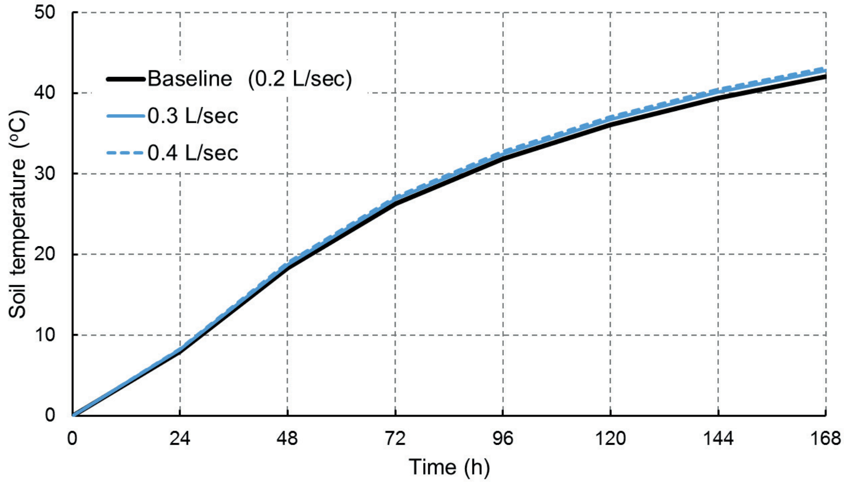

Figure 4.14. Soil temperature change over time (blue) at 0.5 m depth relative to baseline (black), resulting from stepwise increases in fluid flow rate.

Generally, the results show that increasing flow rates have moderate impact on the soil thermal regime compared with other measures. Again looking at the difference after one week, even a 100 % increase (to 0.4 L/s) would result in soil temperatures increasing less than 3 % compared with the baseline setting. At this flow rate, the resulting operating pressure (approximately 7.5 bar) would exceed the maximum limit of which the defrosting system is designed to handle.

Increasing the flow rate by 50 % (to 0.3 L/s), would ensure the system running within design limits, but yield less than 2 % increase in soil temperatures compared with baseline. Although the increase is modest in this case, the effect is greater than, for instance, increasing the surface roughness of the pipe by the same magnitude.

4.6 Section summary

COMSOL Multiphysics has been used to study time-dependent, 3D heat transfer in fully saturated, gravelly sand subjected to hydronic heating. As this represents work in progress, a number of simplifying assumptions have been made. Most importantly, the influence of phase change had to be excluded owing to unforeseen problems of implementing it in the current model. This reduces the significance of the modelling efforts presented here. However, the sensitivity analysis added value to the work in the sense that it provided useful input for further system optimization.

Another assumption was modelling the heat load as a 1D-edge element positioned on the ground surface, utilizing the software's *Pipe Flow Module* capabilities. This eliminated the need to mesh the cross-section of the pipe with a full 3D mesh, reducing the number of boundary elements for long pipes considerably, and consequently, the time needed for computation.

The sensitivity analysis used the existing model as basis for a number of parametric sweeps. The analysis focused on the effects on the soil temperature regime from changes to fundamental operating and design parameters of the defrosting system (Table 4). The extent or magnitude of the proposed changes are within what is considered reasonable from a design point of view.

Table 4. Sensitivity analysis.

Parameter	Baseline	Increase (%)	Soil temperature change
Pipe distance	10 cm	100	−22 %
		200	−54 %
Fluid inlet temperature	94.5ºC	5	+ 5 %
		10	+10 %
Fluid flow rate	0.2 L/sec	50	+ 2 %
		100	+ 3 %

Note: Resulting soil temperature changes are rounded values at 0.5 m depth, at time step 168 h (i.e., after one week of continuous thawing).

If was demonstrated that the soil thermal regime is far more sensitive to changes in pipe distance (i.e. total pipe length distributed across the ground surface) than changes to other parameters investigated. Even though it is obvious that reducing the heat flux would have an effect, the analysis has shown to what extent.

Furthermore, the analysis has shown that moderately increasing design parameters such as the fluid inlet temperature is comparatively more effective than substantial increases in flow rate. However, in choosing one over the other, considerations regarding feasibility, costs and safety issues will most likely take precedence. Additional parametric sweeps showed that an increase in pipe roughness had very limited effect on the soil thermal regime.

Further work should be aimed at implementing phase change, adding geometry such as the insulation mats used in the experiments, and properly account for ambient conditions.

5. Summary

This doctoral thesis addresses the performance characteristics, thermodynamics and hydrodynamics associated with hydronic (waterborne) based thawing of seasonally frozen ground. Its main contributions are the four papers enclosed in the appendices. In addition to an introductory part, the thesis contains a review covering some of the relevant literature in Chapter 2, a synthesis in Chapter 3 and a sensitivity analysis in Chapter 4. The synthesis summarizes the work done in the four papers, and contains a brief background, aims, methodology and main findings for each paper.

The literature review gave insight into research efforts and progress made within frozen ground engineering, provided the terminology and definitions of what constitutes cold regions of the Northern hemisphere, the Arctic, and the types of frozen ground conditions typical for this geographical region. It reviewed early theoretical and experimental work related to frost and thaw penetration in frozen ground, and highlighted gaps in the research work that needed further investigations. The author cited several publications indicating the considerable efforts made by various researchers in their efforts to understand and describe the principles underlying thermal diffusion, moisture movement in freezing soils, and the effects of phase changes and latent heat. It seems that methods currently used to solve such problems have shifted more towards numerical simulations. Although many publications were found on experimental work related to frost in ground, relatively few of those were about artificial thawing of frozen ground, let alone full-scale experiments. That indicated a gap in the knowledge concerning this particular field within frozen ground engineering.

The first paper in the synthesis refers to initial experiments performed in 2007, at the original frost in ground laboratory. Two similar defrosting systems adapted for in situ thawing of frozen ground, but with different oil burner capacities (heat output), were compared. The aims were to assess their efficiency when utilized for artificial thawing of various types of soils. The results revealed no significant differences in overall thaw efficiency between the two systems, but clearly demonstrated that the method posed a potential for rapid thawing. Furthermore, they showed that thaw rates varied considerably with soil type and were decreasing over time (nonlinear). There were also indications of soil moisture having a strong influence on thaw rates in various soils. The preliminary results were presented in a separate report at the end of the project period, but were not published until 2010, as part of this study (paper I).

Recognizing the need for more research into artificial thawing, the promising potential of hydronic heating, and the unanswered questions from the initial experiments, the study referred to in this thesis was initiated. The purpose was to provide a scientific description of hydronic based thawing, investigate heat transfer characteristics and the hydrodynamic responses (mass transfer) occurring during the process, and on that basis assess the method’s performance characteristics. An approach based on full-scale experiments was chosen, building on experience from previous work and well-documented concepts used elsewhere. That led to the existing laboratory facilities being relocated and upgraded to accommodate a broader range of scientific experiments on frozen ground. A description of the new laboratory was published in paper II.

Full-scale thawing experiments were performed at the new facilities in April 2011, and repeated in March 2012. Three types of homogenous, initially frozen soils were thawed simultaneously, using the same procedures each time. The results were published in two separate papers (III and IV). They substantiated the findings from the initial experiments, and provided valuable insight into the combined heat and mass transfer occurring during hydronic based thawing of various soils.

5.1 Design of hydronic defrosting systems

In the reviewed literature referring to hydronic based thawing, focus has been on so-called radial thawing – and not surficial or top-down thawing. Since this study is about the latter approach and includes a limited sensitivity analysis, some general observations and recommendations can be made.

In recognising that artificial thawing depends on an auxiliary heat source, it is evident that the more heat energy produced by the system, the more heat energy is available for thawing operations. Thus, boiler capacity, type of energy carrier, and rate and mode of heat transfer are vital factors influencing thaw efficiency. The sensitivity analysis confirmed that the soil thermal regime is far more sensitive to changes in heat flux than the other parameters mentioned. In practice, this means avoiding too wide gaps between various parts of the pipe and distributing as much as possible of the available length across the surface area.

Both the pattern and distance between pipes influence heat transfer to the ground. Some patterns yield more even heat distribution, benefitting from heat exchanged between the hot supply flow and the comparatively colder return flow. Efforts should be made to ensure that the operator utilizes the optimal pattern for various thawing scenarios.

Moderate increases to design parameters such as the fluid inlet temperature is comparatively more effective than substantial increases in flow rate. The increase in soil temperatures resulting from these particular changes are small enough to warrant considerations regarding feasibility, costs and safety issues before deciding on implementation. Additional parametric sweeps showed that an increase in pipe roughness had very limited effect on the soil thermal regime.

Although the current practice of covering the pipe with combined vapour and insulation blankets is not strictly a design issue, it certainly contributes to the overall goal of ensuring a highest possible heat flux to the ground. Consequently, reducing convective heat losses at the soil surface should be mandatory during thawing operations.

5.2 Conclusions

This study has shown that the efficiency of conduction-based thawing depends on soil type, pore ice (moisture) content and porosity, regardless of the applied heat load. The results strongly indicated that moderate differences in water content, gradation, fines and sand contents were less influential factors relative to void ratio (porosity) and mode of heat transfer.

The highest thaw rates were found in fair-graded soils with little or no fines content, moderate water content and low porosity (i.e. gravelly sand). The thaw efficiency was found to decrease with increasing fines and water content (silty sand) and porosity (uniform gravel). With moderate, initial soil water content, the method was found capable of thawing 1 m in approximately 3.5 days in gravelly sand, ~4.5 days in silty sand, and ~11.5 days in uniform gravel.

The thaw rates were found to be nonlinear, varying from 22 cm/day to 37 cm/day after one day of operation, and from 12 cm/day to 24 cm/day after six days of operation, depending on soil type. Thaw rates compiled from soil moisture records were found to correspond well to those derived from soil temperature measurements in silty sand and uniform gravel. In gravelly sand, the former thaw rates were overestimated below 0.3 m depth, the offset amounting to ~12 h at 1.0 m.

Low-porosity soils with comparably larger amounts of fines and sand (i.e. silty and gravelly sand) were found to become fully saturated during thawing, resulting in a temporary loss of bearing capacity in the uppermost layer. The unbound water content was found to be higher and the water migration more prominent in low-porosity soils. For all soils, water redistribution was found to be more evident in the uppermost soil layer.

It was observed that thaw penetration rates compiled from thermistor records were generally overestimated compared with rates based on thermocouple records. The tubed thermistor strings were also found less suitable for detecting phase changes. Capacitance sensors were found to detect relative differences in soil moisture during thawing operations very well, whereas electrical resistance sensors were shown to dramatically overestimate thaw rates and misrepresent soil status under certain circumstances.

5.3 Main contributions

- This work has provided a scientific description of hydronic heating utilized to thaw frozen ground and assessed the performance characteristics of the method through full-scale experiments. The work has extended the knowledge within the field of frozen ground engineering in general, and about artificial thawing of frozen ground in particular. The work has contributed to improvements and product development of the hydronic based method.

- Central contributions from the work are increased insight to the complicated dynamics of heat and mass transfer occurring during artificial thawing, how those interconnected phenomena interact in practice, and what thaw rates to expect in various soils during the process. Other important findings related to thaw rates are strong indications that moderate variations in water content, gradation, fines and sand content are less influential factors relative to void ratio (porosity) and mode of heat transfer. Moreover, the amount of pore ice changing phase and subsequent water migration both promote and greatly influence the thawing process.
- The work has contributed to the establishment of new laboratory facilities suitable for a broad range of scientific experiments on frozen ground and prepared for future expansions. During the course of the work, the laboratory has been used in related research projects on ice accumulation on sensors suspended in air and cold weather concreting of foundations for power lines. Since it became operational in 2011, it has been collecting valuable historical records of soil temperature and soil moisture as well as meteorological data on an hourly basis.

5.4 Suggestions for further work

With an increased focus on exploration and extraction of oil and gas reserves in the Arctic, research efforts related to frozen ground engineering have gained actuality and received more attention in recent years. In addition, the United Nations' Intergovernmental Panel on Climate Change (IPCC) has published several assessment reports since 1990 on climate change and the implications of increased global temperatures on permafrost and seasonally frozen ground in cold regions. As reported by Vaughan et al. (2013), higher mean annual air temperatures have resulted in significant permafrost degradation and reduced frost penetration depths in seasonally frozen ground. They also report of an increased frequency of freeze-thaw cycling during winter. The renewed interest and this sort of observations underscores the relevance of cold climate research and encourages continued efforts. As such, the work presented in this thesis represents a small contribution.

As this is a case study, supported by experiments, it has allowed for a detailed investigation of the working principles and performance characteristics of hydronic based thawing. The full-scale experiments presented here contribute to reduce scaling errors and related uncertainties. However, a major drawback of this approach was the limited number of experiments performed. Additional thawing experiments are therefore recommended, following the same methodology and procedures as previously. Doing so would also be a good opportunity for collecting frozen core samples prior to thawing. Such samples were not collected in this study owing to lack of access to suitable equipment. Although bound (initial) water content was monitored, the records are insufficient for determining differences in initial ice and water content or ice-water (iciness) ratio between the various soils prior to thawing.

A less demanding alternative to repeated full-scale thawing experiments is just collecting frozen core samples from the various soil bins at the same period during winter, as in the previous experiments. If this limited approach is chosen, the cores should be gathered from the instrumented part of each soil column (down to 1.8 m). The samples should be split into 10 cm cylinders corresponding with the sensor locations. Acknowledging different weather conditions relative to the previous experiments, such sampling would still provide useful information about the initial conditions. Another parameter not monitored during the experiments is thermal conductivity. It is well known that the conductivity of thawed soils are considerably lower than of frozen soils, and that it is highly dependent on ice and water content. Provided investment in an appropriate measurement system is made in the future, the thermal conductivity can be determined from the same samples.

Continued modelling efforts of the artificial thawing process are recommended, properly accounting for the effects of phase change and surface heat losses, taking advantage of the comprehensive data sets collected during the work. Unique for this study, at least compared with the experiments referred to in the literature review, is the simultaneous monitoring of soil temperatures and moisture variations. These data records illustrate the complicated thermo- and hydrodynamics occurring during artificial thawing and should be used to address some of the research questions considered but not treated in this study, as well as for further optimization of the hydronic method.

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7. Appendices

Appendix 1 – Paper I

Sveen, S. E., and Sørensen, B. R. (2010). "Effective thawing of frozen ground–performance testing of a new thawing method based on hydronic heat (conduction)." *Proc., 3rd European Conf. on Permafrost (EUCOPIII)*, Univ. Centre in Svalbard, Svalbard, Norway.

Appendix 2 – Paper II

Sveen, S. E., and Sørensen, B. R. (2013). "Establishment and instrumentation of a full scale laboratory for thermal and hygroscopic investigations of soil behavior in cold climates." *J. Appl. Mech. Mater.*, 239, 827–835.

Appendix 3 – Paper III

Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017a). "Thaw penetration in frozen ground subjected to hydronic heating." *J. Cold Reg. Eng.*, 10.1061/(ASCE)CR.1943-5495.0000117:31(1).

Appendix 4 – Paper IV

Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017b). "Soil moisture variations in frozen ground subjected to hydronic heating." *J. Cold Reg. Eng.* (submitted).

Appendix 5 – Input variables and step-function (Ch. 4)

Appendix 6 – Baseline pipe domain mesh (Ch. 4)

Appendix 7 – Additional pipe domain meshes (Ch. 4)

Appendix 8 – Sensitivity analysis, 1.0 and 1.5 m depths (Ch. 4)

Appendix 9 – Effect of distance between pipe distance (Ch. 4)

Appendix 10 – Effect of inlet temperature (Ch. 4)

Appendix 11 – Effect of flow rate (Ch. 4)

Appendix 1

Paper I

Sveen, S. E., and Sørensen, B. R. (2010). “Effective thawing of frozen ground–performance testing of a new thawing method based on hydronic heat (conduction).” *Proc., 3rd European Conf. on Permafrost (EUCOPIII)*, Univ. Centre in Svalbard, Svalbard, Norway.

Declaration of co-authorship

The idea and concept of the article came from Bjørn Reidar Sørensen.

The paper refers to initial performance tests made in March 2007, at the first (old) frost in ground laboratory, located in Narvik. An abstract and full-length paper were submitted. In addition, a poster was presented at the conference. Although only abstracts were included in the conference proceedings, both the abstract and article itself are included in the current appendix.

Svein-Erik Sveen is the main author and writer of the paper. Outside photos by Heatwork AS and Øyvind Søraas, Svein-Erik Sveen produced all graphics and figures presented in the paper.

Bjørn Reidar Sørensen reviewed and revised the abstract, paper and poster. He has given his consent to the abstract and paper being included in the thesis.

Effective Thawing of Frozen Ground – Performance Testing of a New Thawing Method Based on Hydronic Heat (conduction)

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1 BACKGROUND

1.1 *Applicability in cold regions*

Establishing infrastructure during the coldest months of the year can be challenging because of frozen ground conditions.
Access to effective methods for accelerated or artificial thawing of frozen ground is therefore important to commercial and industrial construction companies, residential contractors, utilities and municipalities operating in cold regions. Successful employment of such methods allows for excavations, ditching and other ground work to take place during winter. Extending the season for such activities is especially beneficial with regard to workforce deployment throughout the year and helps reduce seasonal lay-offs.

1.2 *Traditional methods*

Over the years several methods to facilitate construction work also during winter have been tried, both in regions with seasonal frost as well as in areas with perennially frozen ground (permafrost).
A monograph sponsored by The Technical Council on Cold Regions Engineering (Esch, 2004), gives both a historical overview of the techniques applied by miners during the gold rush to Alaska and northern Canada in the late 1800s, as well as different approaches with the mechanization of mine workings in the early 1900s. Open fire and solar thawing were the first methods used, replaced by cold-water and steam thawing as the development progressed. Also electric thawing is listed.
A more recent method is based on convection, i.e. heated air confined in a suitable contraption placed onto the frozen ground surface. This technique is still in use although the method based on hydronic heat seems more effective and versatile.

2 HYDRONIC HEAT

2.1 *Innovative approach for thawing frozen ground*

The hydronic method is based on known principles and technology – assembled in a way that enables the complete system to deliver the necessary heat for the process. A boiler is used for heating a mixture of water and glycol. Flexible rubber pipes or hoses are connected to the boiler in a closed loop. The hoses are laid out in a serpentine pattern onto the surface to thaw the underlying ground. A pump ensures circulation of the hot liquid.

2.2 *Experimental set-up*

The first full scale performance tests were made in March 2007 at the Frost in Ground laboratory (FiG-lab) in Narvik, using the defrosting system developed by the Norwegian company Heatwork. Three bins (4 x 4 m, 2.5 m depth), each containing various types of homogenous soil, were thawed simultaneously; (a) sandy silt, (b) well graded sand and (c) clean gravel.
A vertical thermocouple string was mounted at the center of each bin, measuring ground temperatures in 10 cm intervals from 5 cm to 155 cm depths, including one at depth 2.05 m and another at depth 2.55 m. Air temperatures, relative humidity and wind speeds were monitored by a weather station at the site.

3 PRELIMINARY RESULTS

3.1 *Thaw rates*

Table 1 shows the thaw rates as a function thaw depth for the various types of soil down to 100 cm depth. The results show that the thaw rate is higher for coarse grained soils compared to fine grained soils. The thaw efficiency is higher the nearer the surface (heat source), gradually declining with increasing depth.

Table 1. Thaw rates as a function of thaw depth.

	Thaw rate		
	Sandy silt	Well graded sand	Clean gravel
Thaw depth	cm/day	cm/day	cm/day
10 cm	21	34	30*
30 cm	18	26	30
50 cm	14	22	26
70 cm	11	19	22
90 cm	10	16	17
100 cm	9	15	16

* Reduced thaw efficiency at low depths for clean gravel.

References

Esch, D.C. (ed.) 2004. *Thermal Analysis, Construction, and Monitoring methods for Frozen Ground*. Reston, Virginia: American Society of Civil Engineers.

First submitted as: Sveen, S. E., and Sørensen, B. R. (2010). "Effective thawing of frozen ground– performance testing of a new thawing method based on hydronic heat (conduction)." *Proc., 3rd European Conf. on Permafrost (EUCOPIII)*, Univ. Centre in Svalbard, Svalbard, Norway.

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EFFECTIVE THAWING OF FROZEN GROUND – PERFORMANCE TESTING OF A NEW THAWING METHOD BASED ON HYDRONIC HEAT (CONDUCTION)

ABSTRACT

A new thawing method based on hydronic heat has taken over as the preferred method for accelerated or artificial thawing of frozen ground. The technique seems superior to conventional methods and has therefore been investigated at the Cold Climate Technology Research Centre (CCTRC) in Narvik. The preliminary tests show promising results with regard to thaw efficiency, and will continue as a part of a PhD study at NUC.

BACKGROUND

In regions with seasonally frozen ground conditions, it is challenging to establish infrastructure and perform maintenance work during the coldest months of the year. Placing foundations or gaining access to buried pipelines for maintenance work inevitably calls for effective methods for thawing of the frozen top layer.

Access to improved methods for accelerated or artificial thawing of frozen ground is therefore important to commercial and industrial construction companies, residential contractors, utilities and municipalities operating in cold regions. Successful employment of such methods allows for excavations, ditching and other groundwork to take place during winter. Extending the season for such activities is especially beneficial with regard to workforce deployment throughout the year and helps reduce seasonal lay-offs.

Over the years several methods to facilitate construction work also during winter have been tried, both in regions with seasonal frost as well as in areas with perennially frozen ground (permafrost).

A monograph by Esch (2004), published by the American Society of Civil Engineers (ASCE), gives both a historical overview of the techniques applied by miners during the gold rush to

Alaska and northern Canada in the late 1800s, as well as different approaches with the mechanization of mine workings in the early 1900s. Open fire and solar thawing were the first methods used, replaced by cold-water and steam thawing as the development progressed. Also electric thawing is mentioned.

A more recent method is based on convection, i.e. heated air confined in a suitable contraption placed onto the frozen ground surface. This technique is still in use although the method based on hydronic heat seems more effective and versatile.

HYDRONIC HEAT

The hydronic method is based on known principles and technology, assembled in a way that enables the complete system to deliver the necessary heat for the thawing process.

A boiler is used for heating a mixture of water and glycol. Flexible rubber hoses are connected to the boiler in a closed loop. The hoses are laid out in a serpentine pattern onto the surface to thaw the underlying frozen ground. A pump ensures circulation of the hot liquid. Figure 1 shows the thawing concept developed the Norwegian company Heatwork.

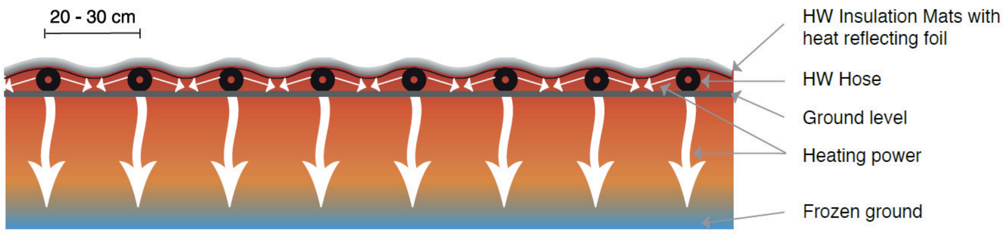


Figure 1. Cross section showing the thawing concept based on hydronic heat, including reflecting insulation blankets on top for reducing the heat loss due to convection. The hoses delivering the heated water-glycol mix are placed directly onto the ground surface, transferring heat to the frozen ground by conduction. (Source: Heatwork)

The thawing method in operation is shown in Figure 2.

Figure 2. Hoses laid out on the area to be thawed, cured or protected from frost (a), insulation blankets covering the hoses to reduce convective heat loss (b), thawed ground ready for ground work (c). (Photos: Heatwork)

PERFORMANCE TESTING

The hydronic method was introduced in USA and Canada back in 1996 (Construction Equipment, 1996), and has since then gradually taken over as the preferred method for thawing of frozen ground also in Northern Europe. In spite of this there seems to have been made small or no efforts to investigate the method in the same thorough manner as the traditional thawing techniques.

As a response to this, the Cold Climate Technology Research Centre (CCTRC) in Narvik has established a Frost in Ground laboratory (FiG-lab) for full scale performance testing and documentation of the hydronic method, shown in Figure 3.

The FiG-lab is the base for the empirical part of an ongoing PhD project at NUC regarding artificial thawing of seasonally frozen ground.

The Fig-lab consists of six square bins filled with different types of homogenous soil to a depth of 2.55 m. In addition, there is a measurement central for data collection.

Figure 3. FiG-lab; Mobile measurement central (in the back) with a weather station attached, including a Heatwork defrosting machine (in the front). (Photo: Ø. Søraas)

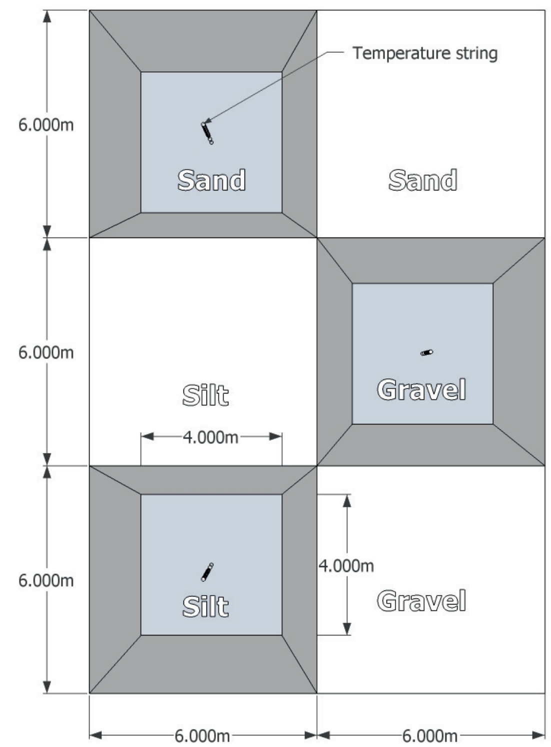
The thermal response at different depths during thawing is detected by a vertical temperature string containing 18 thermocouples, mounted at the centre of each bin down to 2.55 m depth.

EXPERIMENTAL SET-UP

The first performance tests at FiG-lab were made in March 2007, using the defrosting system developed by Heatwork.

Two similar tests were made, simultaneously thawing three different types of homogenous soil (bins) each time, as shown by Figure 4a. The three types of soil were (a) silty sand, (b) well graded sand and (c) clean gravel, grain size distribution curves (GSD's) ranging from predominantly fine to coarse soil.

The thermal response was detected by measuring ground temperatures at the centre of each bin, in 10 cm intervals from 5 cm to 155 cm depths, including one at depth 2.05 m and another at depth 2.55 m, as shown by Figure 4b. Air temperature, relative humidity and wind speed prior to and during the tests were monitored by a weather station at the site.



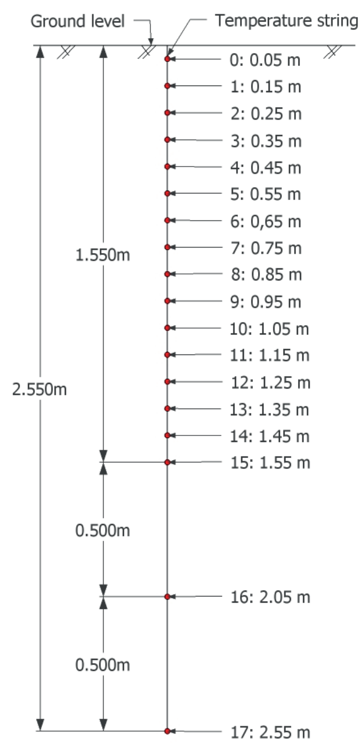


Figure 4. Three types of homogenous soils distributed in six bins (a) (left, top-view), each 2.55 m deep. A thermocouple string is placed at the centre of each bin, measuring ground temperatures from top to bottom along a vertical axis (b) (right, side-view).

The boundaries between the bins consist of a mix of soil of the bins adjacent to each other. The ground surfaces of all bins are horizontal and at the same level.

PRELIMINARY RESULTS

The first test was conducted by the aid of the standard Heatwork defrosting system, with the hoses laid out with 10 cm horizontal distance, covering a ground surface area of 4.5 x 4.5 m of each bin.

The ground surface was free of excess snow and ice cover at the beginning of the test.

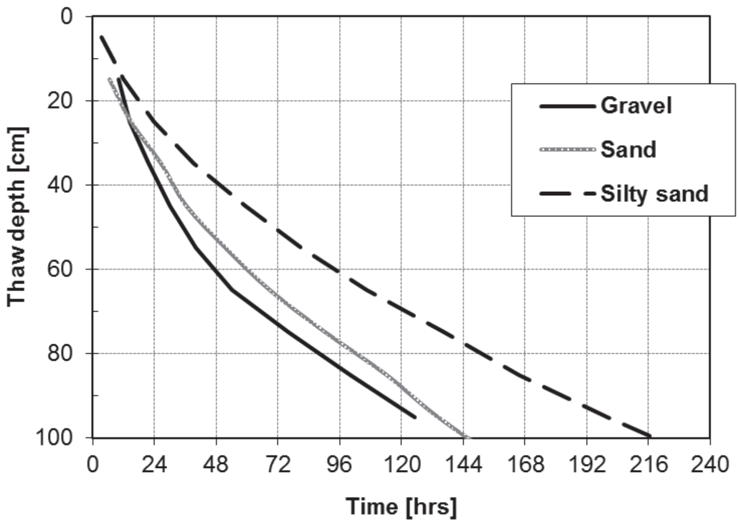


Figure 5 shows the thaw depth vs. time down to 100 cm for the various types of soils. Thaw depths after the first 24 hours of artificial thawing are approximately 38 cm for gravel, 33 cm for well graded sand and 25 cm for silty sand.

Figure 5. Thaw depth (in cm) as a function of time.

The graphs are logarithmic in the beginning, gradually becoming linear as the thawing process continues. This suggests a higher thaw rate close to the surface (heat source), as shown in Figure 6.

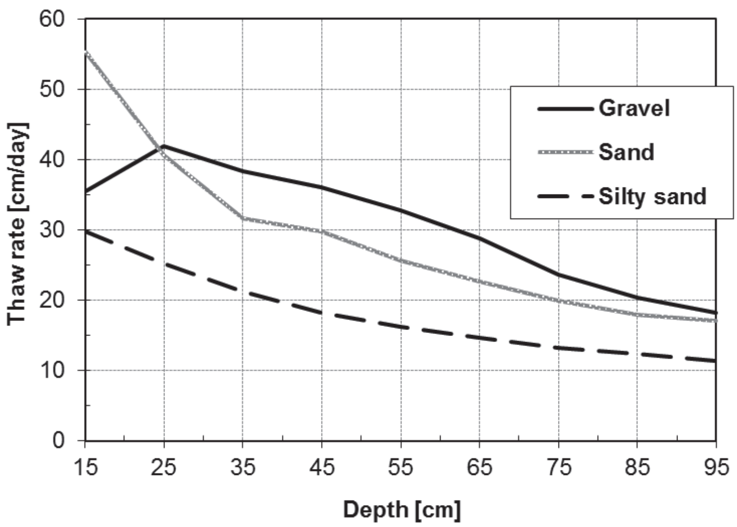


Figure 6 shows that in general the thaw efficiencies are decreasing with depth.

The exception is early in the thawing process (at shallow depth) for uniform gravel, which has a high void ratio and low initial ice content.

Figure 6. Thaw rate (in cm/day) as a function of thaw depth.

Initial water content (w_0) and grain-size distribution curves (GSD's) from when FiG-lab was established during autumn 2006 are shown in Figure 7.

The water content prior to the performance tests in March 2007 were not measured and are very likely to differ from the ones given in the figure, especially for the silty sand and the well graded sand.

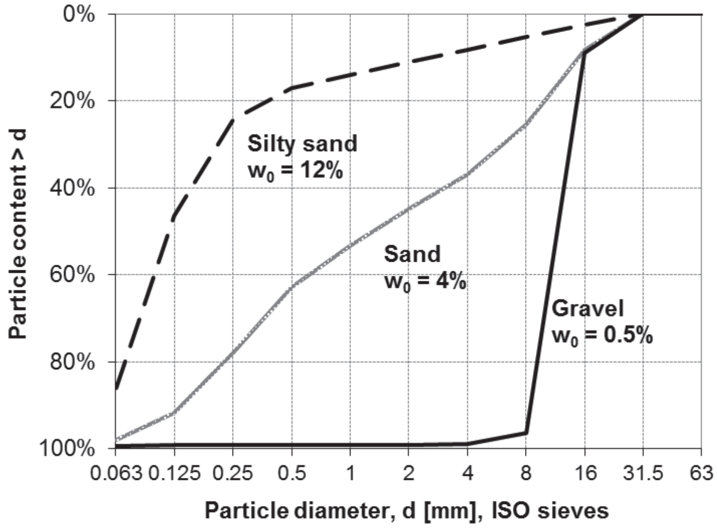


Figure 7. Grain-size distribution curves.

CONCLUSIONS AND FURTHER WORK

The initial performance tests have provided some general impressions regarding the efficiency of the hydronic thawing method utilized on various types of homogenous soil. They also were very useful for testing the functionality of the FiG-lab, the measurement systems and sensors used, as well as the applied method for gathering experimental data.

However, all assessments are based solely on one parameter, i.e. ground temperature, and a very limited amount of experiments. There is also a need to know more of the hydrodynamics taking place during artificial thawing, such as variations in frozen/unfrozen water content and phase changes. Furthermore, more emphasis on air-/ground temperature records, precipitation etc. prior to testing is needed.

A part of the ongoing PhD work is therefore allocated to re-establishing the FiG-lab at a new location, at the same time implementing new functionality in order to ensure more versatile scientific experiments on frozen ground.

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Esch, D.C. (ed.) 2004. *Thermal Analysis, Construction, and Monitoring Methods for Frozen Ground*. Reston, Virginia: American Society of Civil Engineers (ASCE).

Construction Equipment, 1996. *Heaters thaw frost fast*. Article, Issue August 1.

Appendix 2

Paper II

Sveen, S. E., and Sørensen, B. R. (2013). "Establishment and instrumentation of a full scale laboratory for thermal and hygroscopic investigations of soil behavior in cold climates." *J. Appl. Mech. Mater.*, 239, 827–835.

Declaration of co-authorship

The idea and concept of the article came from both authors.

The paper refers to the establishment of the new frost in ground laboratory (N68º26′55″, E17º31′16″), relocated outside Narvik. The paper was presented at the International Conference on Measurement, Instrumentation and Automation (ICMIA 2012), in Guangzhou, China. The conference administration published the full-length article in the Journal of Applied Mechanics and Materials.

Svein-Erik Sveen is the main author and writer of the paper, and produced all graphics, tables and figures presented therein.

Bjørn Reidar Sørensen wrote part of the introduction and reviewed the paper. He has given his consent to the paper being included in the thesis.

Is not included due to copyright

Appendix 3

Paper III

Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017a). “Thaw penetration in frozen ground subjected to hydronic heating.” *J. Cold Reg. Eng.*, 10.1061/(ASCE)CR.1943-5495.0000117:31(1).

Declaration of co-authorship

The idea and concept of the article came from Svein-Erik Sveen. The co-authors were heavily involved in decisions regarding scope and layout.

The paper refers to two separate, full-scale experiments performed in April 2011 and March 2012, respectively, at the new frost in ground laboratory. The paper focuses on the thermal responses and performance characteristics of the hydronic thawing approach.

Svein-Erik Sveen is the main author and writer of the paper, and produced all graphics, tables and figures presented therein.

Thanh Hung Nguyen and Bjørn Reidar Sørensen did a thorough review of the entire paper. They have given their consent to the paper being included in the thesis.

Is not included due to copyright

Appendix 4

Paper IV

Sveen, S. E., Nguyen, H. T., and Sørensen, B. R. (2017b). "Soil moisture variations in frozen ground subjected to hydronic heating." *J. Cold Reg. Eng.* (submitted).

Declaration of co-authorship

The idea and concept of the article came from Svein-Erik Sveen. The co-authors were heavily involved in decisions regarding scope and layout.

The paper refers to the same two experiments as in Paper III, and focuses on hydrodynamics and associated thaw rates and how they relate to similar compiled from the previously published thermal responses.

Svein-Erik Sveen is the main author and writer of the paper, and produced all graphics, tables and figures presented therein.

Thanh Hung Nguyen and Bjørn Reidar Sørensen did a thorough review of the entire paper. They have given their consent to the paper being included in the thesis.

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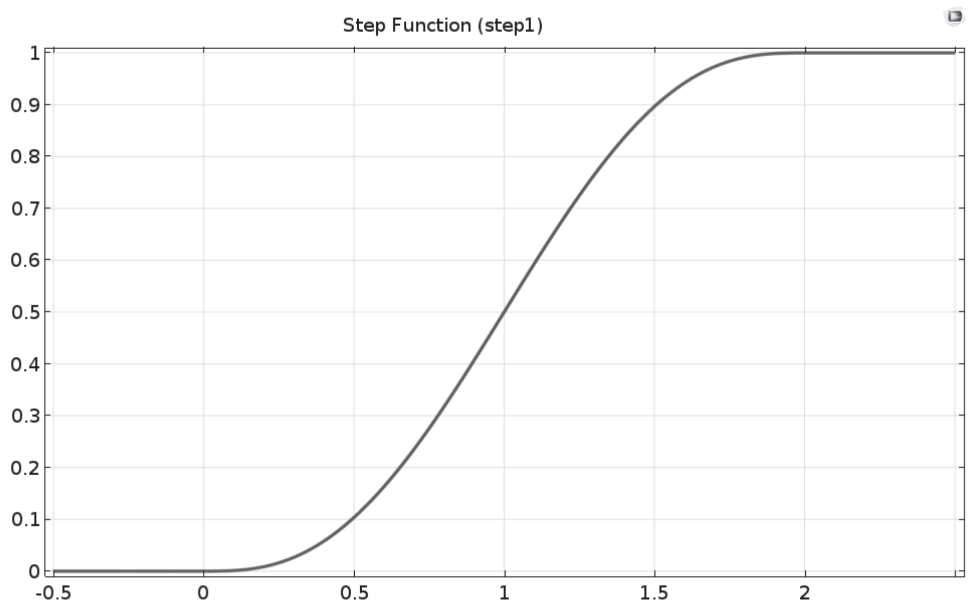
Input variables and step-function (Ch. 4)

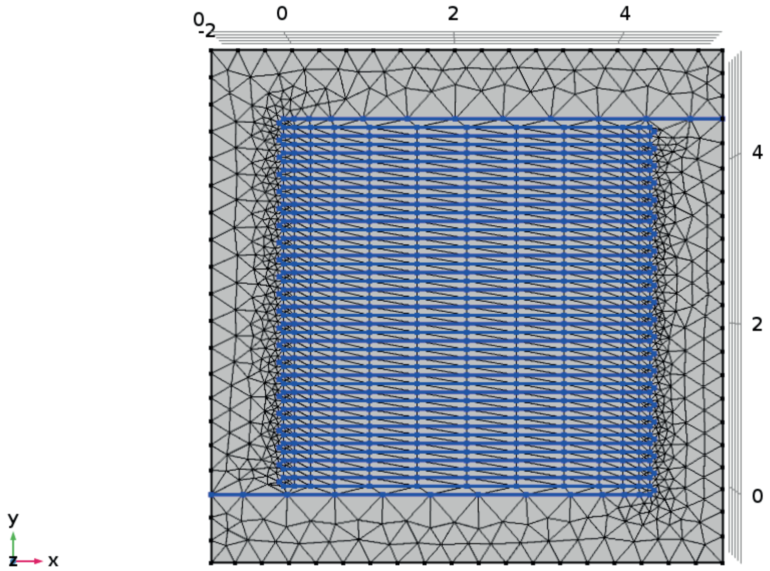
Input variables used in the simulation with their values and dimensions.

Variable	Value	Description
T_init_soil	273.15 K	Initial temperature, soil
T_fluid	367.65 K	Steady-state inlet temperature, fluid
$\dot{Q}_w$	2E-4 m^3/s	Fluid flow rate
e	1.5E-6 m	Surface roughness
bin_w	4.4 m	Bin width
bin_d	4.4 m	Bin depth
bin_h	2 m	Bin height
pipe_di	0.016 m	Pipe diameter, inner
pipe_do	0.024 m	Pipe diameter, outer
pipe_t	0.004 m	Pipe wall thickness
cc	0.1 m	Distance between pipes, cc
l	4.3 m	Linear pipe length
l_arc	0.15708 m	Arc pipe length [*(pi*cc)/2*]
n	44	Number of pipe lengths
L	196.11 m	Total pipe length [*n*(l+l_arc)*]
v_air	1.5 m/s	Horizontal wind speed, air
T_air	273.15 K	Air temperature
k_pipe	0.25 W/(mK)	Thermal conductivity, pipe

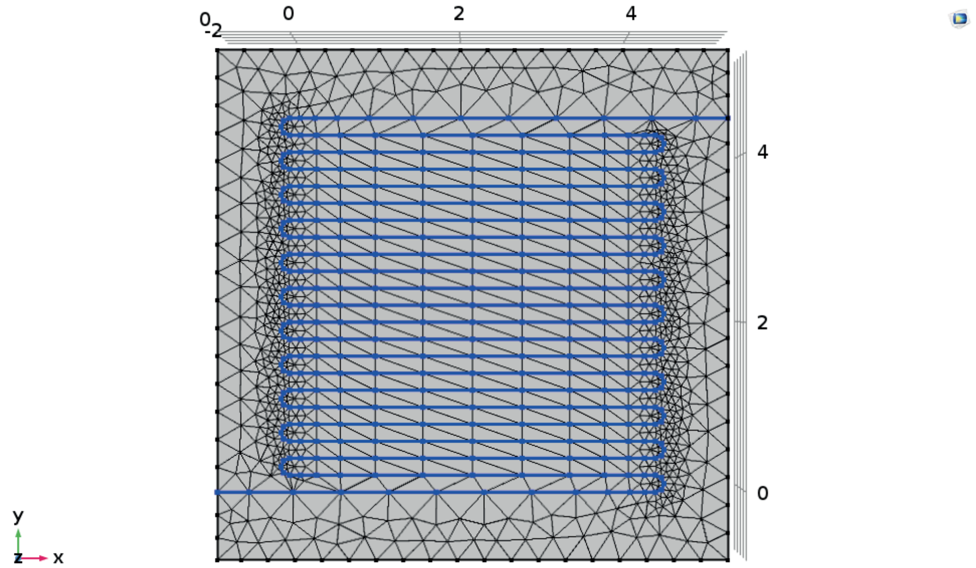


Plot of the ramp-up function (*step1*) used for calculating the fluid inlet temperature during the first simulation steps. The time-unit (x-axis) is ‘second’.

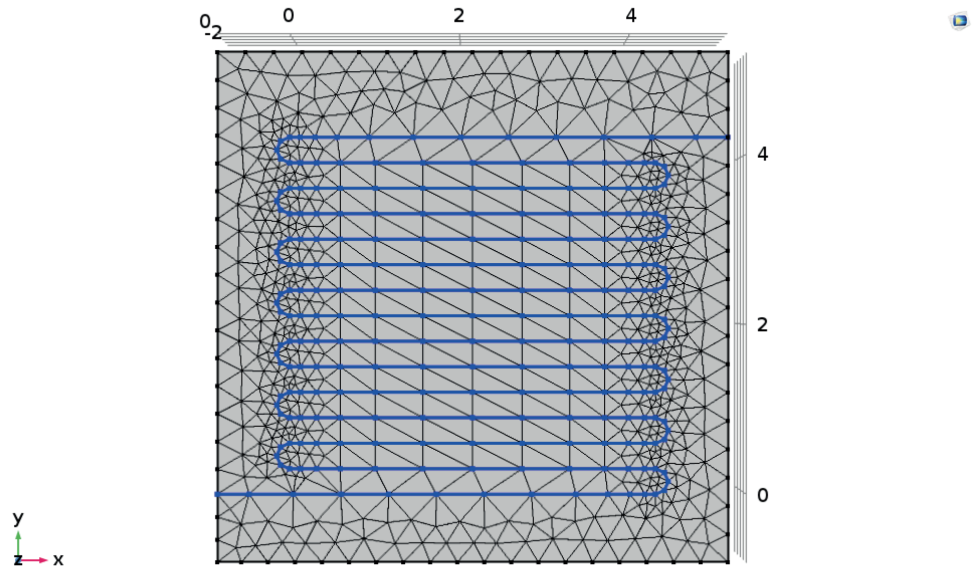
Baseline pipe domain mesh (Ch. 4)



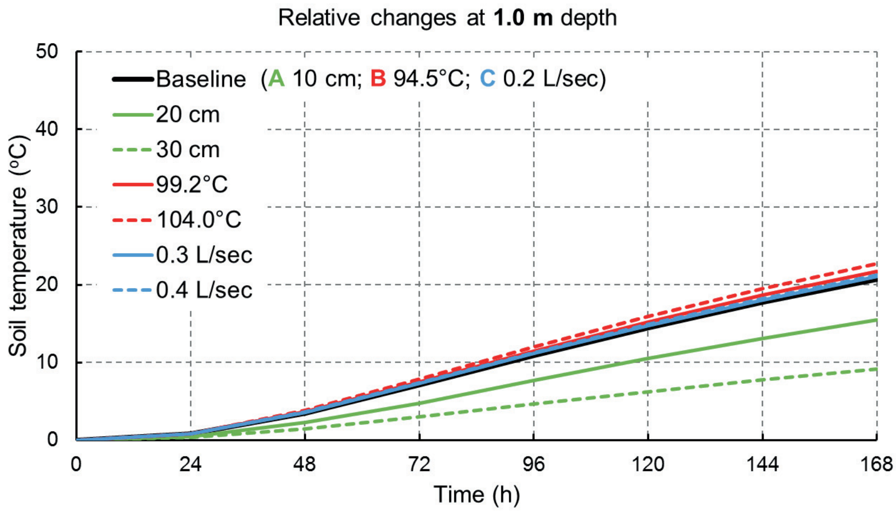
Pipe domain, soil surface (top view), pipe distance 10 cm.



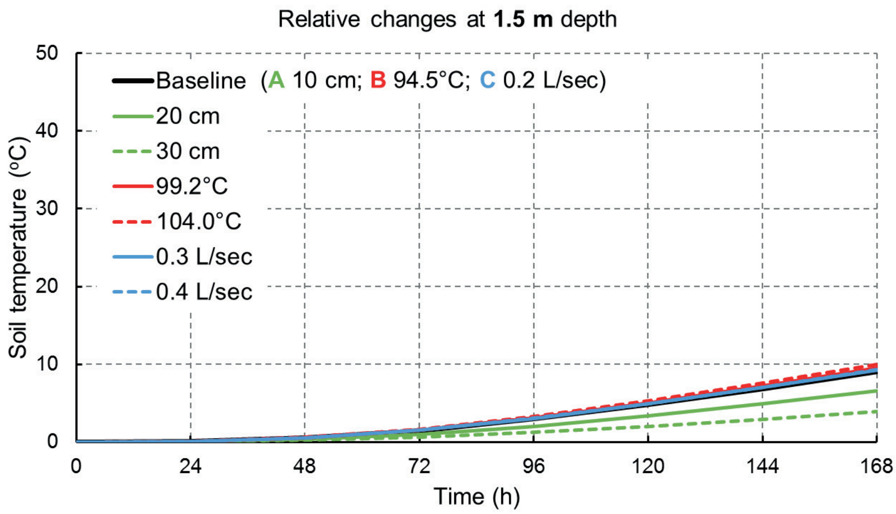
Pipe domain, soil surface (top view), pipe distance = 20 cm.



Pipe domain, soil surface (top view), pipe distance = 30 cm.

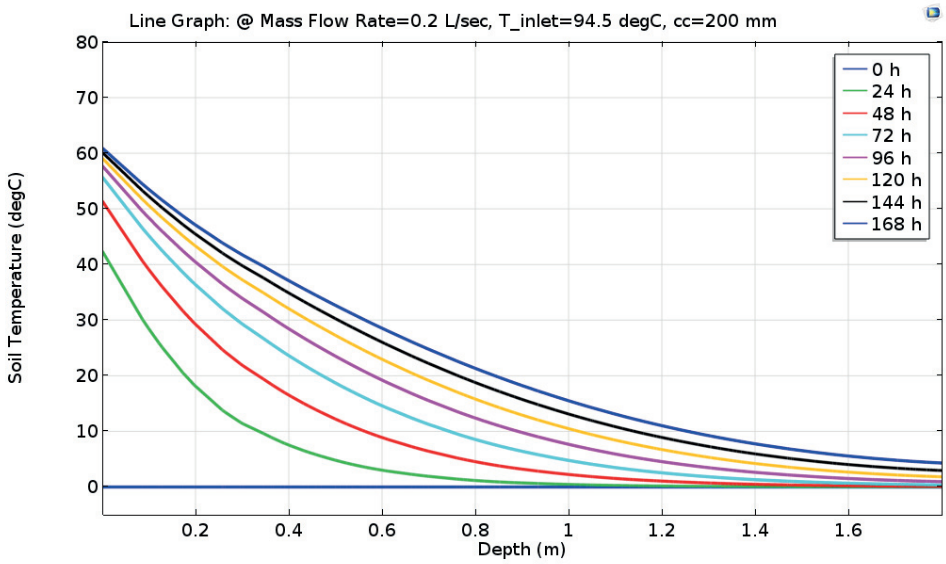


Temperature change over time (at z = 1.0 m) relative to baseline (black), resulting from stepwise increase in pipe distance (green), fluid inlet temperature (red), and fluid flow rate (blue), respectively.

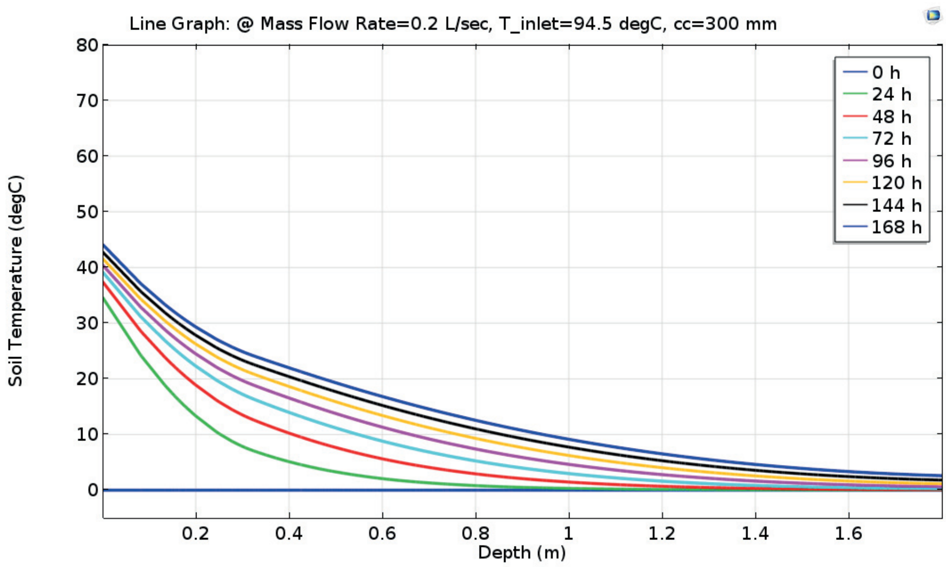


Temperature change over time (at z = 1.5 m) relative to baseline (black), resulting from stepwise increase in pipe distance (green), fluid inlet temperature (red), and fluid flow rate (blue), respectively

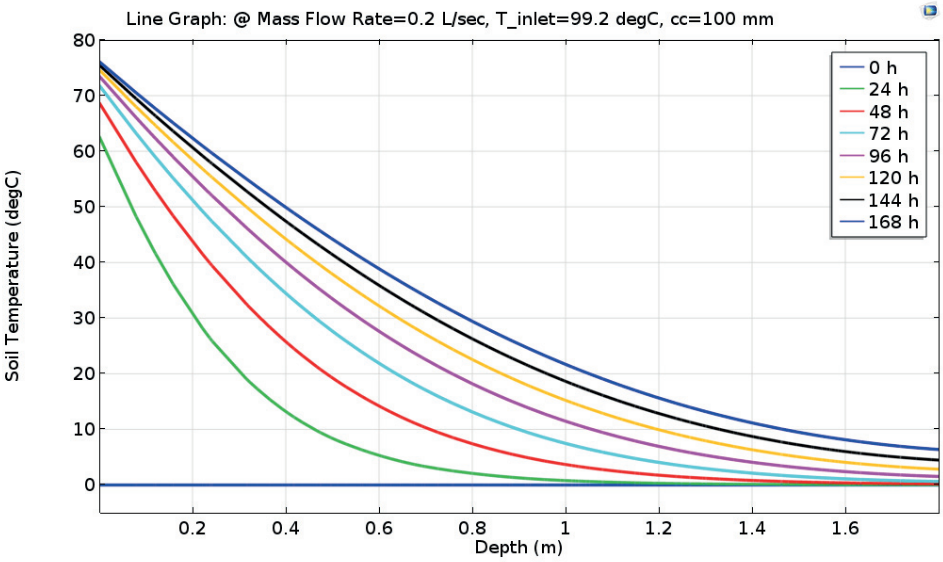
Sensitivity analysis, effect of pipe distance (Ch. 4)



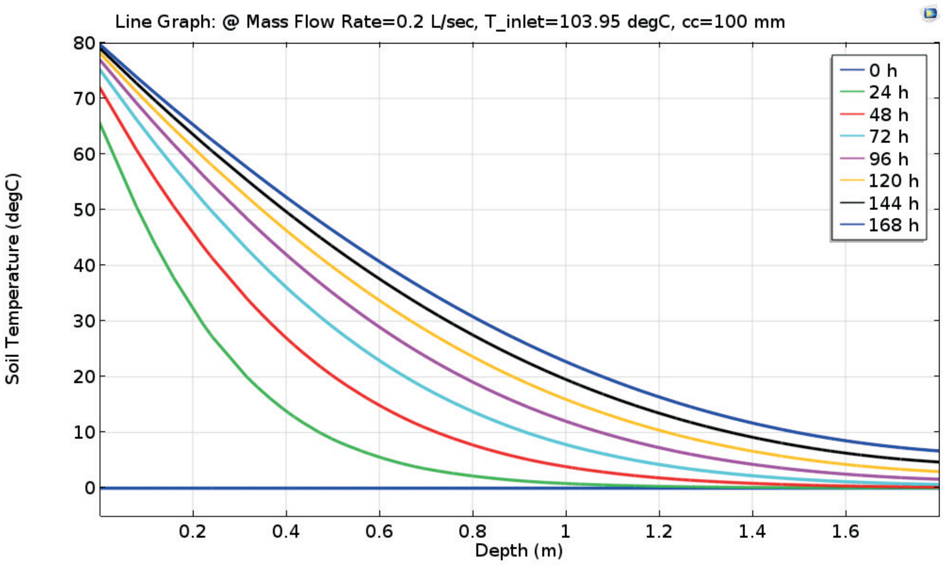
Soil temperatures versus depth at various time steps, pipe distance (cc) increased to 20 cm.



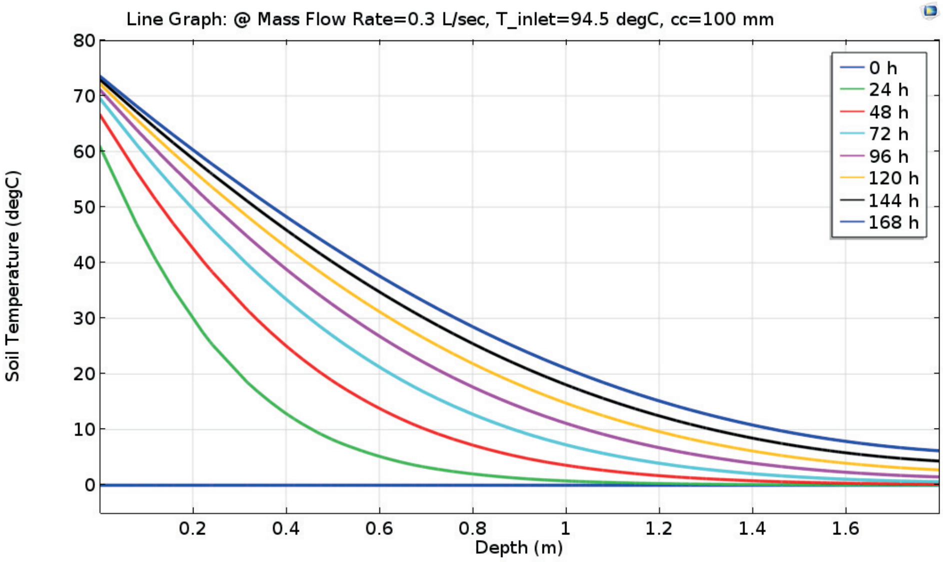
Soil temperatures versus depth at various time steps, pipe distance (cc) increased to 30 cm.



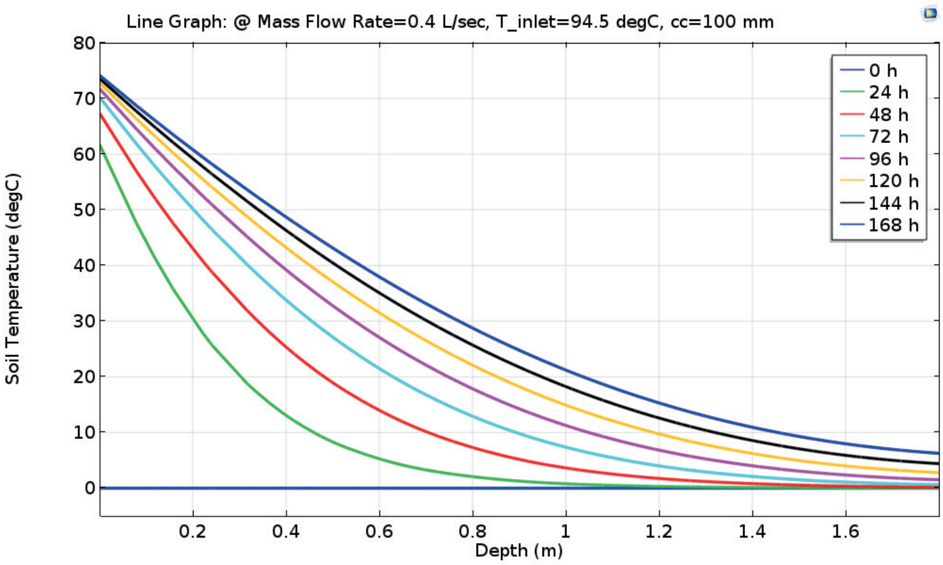
Soil temperatures versus depth at various time steps, inlet temperature (T_inlet) increased to 99.2ºC.



Soil temperatures versus depth at various time steps, inlet temperature (T_inlet) increased to 104.0ºC.



Soil temperatures versus depth at various time steps, flow rate increased to 0.3 L/s.



Soil temperatures versus depth at various time steps, flow rate increased to 0.4 L/s.