**STRESS, DEFORMATION AND MICROMORPHOLOGICAL ASPECTS OF SOIL
FREEZING UNDER LABORATORY CONDITIONS**

by

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ABSTRACT

In this thesis, frost heave is viewed as a process resulting from the interactions between thermodynamic conditions, soil environment controls such as texture, stress/deformation conditions and soil microstructure. A series of laboratory experiments was devised to investigate the links between these aspects. Because a limited number of studies exist on the development of internal stresses and strains in freezing soil, the work focussed on obtaining rheological data using conventional soil strain gauges and prototype stress transducers.

A fine-grained unstructured silt was placed in a column (30 cm diameter by 100 cm length) and subjected to freezing and freeze-thaw cycles from the top down, lasting up to three months. Heat and water flows, as well as stresses and strains were monitored. The frozen soil was sectioned at the end of four of the experiments to examine the soil fabrics that had developed.

From the experimental results, schematic stress and strain curves are proposed. For a single freeze cycle, compressive normal and tensile normal stresses were recorded simultaneously by the measuring devices within the freezing soil profile. Ice lens inception took place when the stress field changed, a condition which occurred either at the frost front level or at the base of the growing ice lens.

Negative and positive strains reflected the different stress states that were sustained below and above the freezing front. Negative strains or soil consolidation took place as stresses increased before the passage of the frost line. Negligible soil strains were recorded as maximum soil consolidation was attained, before soil expansion. Distinct positive strain patterns indicating secondary and continuing heave, were recorded simultaneously throughout a thickness of soil, over a range of temperatures. Ice lens growth mostly took place as secondary frost heave, but continuing heave was measured, and the temperature conditions for both types of heave were determined.

During subsequent freeze-thaw cycles, the stress patterns upon freezing were more complex in the second and third cycles due to previous soil structuration. At thaw, the stress pattern was uniform although positive strains in excess of those generated at freezing were recorded over the course of a few hours.

Specific soil fabrics and features were evident from a single freeze cycle and for freeze-thaw conditions. Formation mechanisms are proposed for certain fabrics and features. A zonation with depth of these fabrics can be linked to the stress strain history of the soil, revealing the links and feedbacks between rheological processes and cryogenic soil structures.

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CHAPTER 1 : INTRODUCTION

1.1 Research context

1.1.1 General

Because the soil deforms as it freezes and thaws, any engineering project undertaken in seasonally frozen or permafrost soils meets with serious practical problems. Specifically, ground freezing causes frost heave which uplifts foundations while thawing decreases the soil strength, resulting in dramatic settlement of roads, foundations and airport runways. In cold regions, special measures must be taken to provide various services and waste management (French, 1976), while specific designs are used for buildings and roads. An extensive review of road construction requirements and maintenance is presented by Ladanyi (1996). Building requirements in cold regions rely on empirical relations derived from experiments pertaining to the frozen strength of soil materials and their creep properties. Thus, a fairly large amount of research concerns the mechanics of frozen soil.

From another viewpoint, researchers seek a better understanding of processes and properties pertaining to the dynamic nature of frost heave, i.e. what happens as the soil freezes. The knowledge derived from such studies inputs

directly into engineering activities but equally into agriculture, ecology (Lundin, 1989), sub-surface hydrology, and permafrost geomorphology. In addition, the need to model frost heave continues to encourage experimentation on freezing soils to clarify relationships between soil conditions and frost heave processes. Because soil freezing is complex, knowledge of certain dynamic properties and key conditions is still lacking. Williams (1986) underlined the potentially harmful consequences of ill-developed projects due to a lack of fundamental knowledge.

1.1.2 Previous research

This thesis explores certain aspects of frost heave through experimental work done at the Geotechnical Science Laboratories, Carleton University. The research was sparked by ideas on the importance of soil rheology in the frost heave process (Wood, 1985; Onysko, 1988; Lundin, 1989; Smith, 1992) and on the implications of continuing heave on soil deformation (Smith, 1985; Smith and Patterson, 1989). Also, research on data provided by soil micromorphology (Van Vliet-Lanoë, 1985) and on the microstructures encountered in permafrost soils (Fox, 1979) generated interest in combining conventional frost heave experimentation with investigations of micromorphology and deformation.

The importance of freezing soil rheology was recognized in the early 1980's. It was stated that "A basic requirement

is the capacity to make quantitative predictions of the magnitude of ice segregation (including the extent to which this continues in the already frozen ground) and of the pressures that can be generated at specific locations and in specific circumstances" (NRC, 1984, p.9). Wood (1985) developed the idea that the heaving pressure (ice pressure) is not only determined by thermodynamic conditions but also by the soil rheological properties, particularly the frozen soil rheology, i.e. how the frozen soil resists the expansive work of a growing ice lens. Once the significance of soil rheology beyond the warmest ice lens interface (as described by the Clausius-Clapeyron equation) was recognised, various attempts to record so-called "internal pressures" by experimentation were undertaken.

The experiments by Wood (1985) were performed in a small closed soil cell. The pressures measured by the instruments were assumed to be ice pressures. Under conditions of confinement or if the frozen soil resisted heave, a gradient of ice pressure occurred across the sample. The measured ice pressures were in agreement with those calculated from the Clausius-Clapeyron equation. Slurries and highly compacted soils showed similar results. With normally consolidated soils, a decrease in frozen soil strength occurred due to the creep of ice (and to some degree to particle movement). Under these conditions, the ice pressure gradient was uniform in the soil. Wood (1985) equated creep with regelation which caused

some confusion. Such definition problems stem from the complexity of the deformation processes.

Experimental work in a larger frost cell, first performed by Onysko (1988), provided different insight into internally measured ice pressures. The section of soil involved was much larger and so were the pressure measuring devices. The pressures obtained during the experiment were not ice pressures but total pressures. The peak internal pressure increased with depth as the temperature gradient declined.

At a much larger scale, under long periods of freezing, experiments in a cold-room facility in Caen, France, provided data on pressures and strains. These longer term experiments showed that ice lenses would continue growing beyond the warmest ice lens (Smith and Patterson, 1989). Thus, creep and continuing heave contribute to irreversible viscoplastic deformations (*sensu* Tsytovich, 1975) of the frozen soil.

Because measurements of pressures generated by ice growth under long-term frost heaving conditions were needed (NRC, 1984), along with more data on the nature of continuing heave under such conditions, the experiments contained in this thesis were devised to provide an integrated picture of what happens simultaneously at all depths in a freezing soil.

Micromorphological observations of the soil used in the cold-room facility in Caen (White, 1992) along with numerous descriptions of natural soil samples (Fox and Protz, 1981; Van-Vliet Lanoë, 1988; Tarnocai *et al.*, 1993) show the typical

structures caused by frost heave. Research into the specific processes leading to these microstructures is needed. Also, their persistence and complexity led the author to believe that the soil fabric may play an important and perhaps overlooked role in frost heave deformation.

1.2 Nature of the research

The various approaches to frost heave research mentioned above reveal not only the complexity of the process of ice formation in soils but also the fact that the various key aspects of frost heave are closely interrelated. The links between these key aspects are illustrated in figure 1.1.

Freezing/thawing cause heat and mass flows that lead to ice formation and stresses in the soil. Stress and deformation are modified by thermodynamic (water and ice pressures) and environment controls (moisture contents, texture and layering) but can also have a feedback effect, as indicated by the arrows in both directions. Also, soil stress and deformation leads to soil structuration and consolidation (aggregate formation, capping of fines, etc) which have a direct influence on soil properties such as hydraulic conductivity. Once a soil structure is developed, it will thus have an effect on subsequent frost heave or thaw deformation. Together, these areas provide an integrated picture of frost heave that predictive models should take into account.

This thesis addresses aspects of frost heaving and thaw by looking at the elements presented in figure 1.1 and the different links between them. A series of laboratory experiments in a large frost cell were performed to record soil stresses and strains (rheology) and to assess soil structures (micromorphology) under two situations: freeze cycles and freeze-thaw cycles. Here, Vialov's (1986) definition of soil rheology is adopted: soil rheology assesses the inception and time-dependent changes of stresses and strains in materials that do not conform to conventional elastic or plastic models.

The cooling cycles were long (over 300 hours) to enable a significant portion of the soil to freeze gradually. The duration of the freezing cycles and the size of the column enable, to an extent, comparisons with conditions observed in the field. The experiments were not intended to test and develop a predictive or engineering model, nor to devise a diagnostic test on frost heave. Therefore the experimental conditions did not focus on replicability, but were meant to be exploratory as they involved a broader approach of frost heave and the use of non-conventional instrumentation such as radio-transmitting stress transducers. In nature, studies on internal stress/strain measurements are not numerous and the instrumentation often borrowed from soil engineering purposes is not specifically designed for freezing soil conditions.

Figure 1.1: Key aspects of frost heave.

The complexity of stress/strains in a freezing soil and the difficulty of isolating the role of one or other soil component is evidenced in this thesis.

1.3 Objectives

The objectives of the present thesis are the following:

- 1- To study the development patterns and magnitude of internally measured stresses and strains in soils under two sets of laboratory conditions: freezing and freeze-thaw cycles.
- 2- Provide refinements to existing frost heave criteria from the rheological data obtained during a freeze cycle.
- 3- To obtain micromorphological data on the types of microstructures which develop in an initially structureless soil under freezing and freeze-thaw cycles, with known thermal/rheologic conditions.
- 4- To assess how soil structure affects the development and magnitude of internally measured soil stresses and strains after freeze-thaw cycles.
- 5- To integrate the experimental information to refine a conceptual model of the stress, deformation and microstructure conditions in freezing soil.

1.4 Structure of the thesis

Chapter 2 presents an overview of the current knowledge of frost heave and exposes some of the basic ideas. Chapter 3 provides details of the experimental conditions and instrumentation, with additional graphs located in Appendix one. A summary of the soil column set-ups and general experimental conditions for each experiment appears in Appendices two and three. In Chapter 4, the stress and strain data obtained during a freezing cycle are interpreted. Appendix two contains extra figures relevant to Chapter 4. Stresses and strains developed during a freeze-thaw cycle are interpreted in Chapter 5 with additional figures located in Appendix three. Chapter 6 discusses the different soil fabrics and features that resulted from the experiments and attempts to relate cryogenic zones to deformation characteristics. The microstructures resulting from these different experiments are described in detail in Appendix four. The summary and conclusions are found in Chapter 7.

CHAPTER 2 : FROST HEAVE REVIEW

2.1 Soil freezing concepts

2.1.1 Introduction

This thesis concerns the integration of results obtained from four investigation areas of frost heave. Following a review of soil freezing features, various concepts related to the four main items of figure 1.1 are presented: thermodynamics, mechanics (rheology), microstructure, and soil environment.

2.1.2 Heat flows

When the surface of an unfrozen soil is exposed to freezing temperatures, heat flows towards the soil surface. When freezing proceeds rapidly, soil water tends to freeze *in situ* i.e., in the soil pores, to form pore ice only. Conversely, if the 0°C isotherm progresses slowly through the soil, and if there is an adequate water supply, water will be drawn upwards to the freezing front because of free energy differences which arise between the ice and water phases due to the temperature gradient. Water that migrates towards the freezing front accumulates a small distance on the cold side of the 0°C isotherm (Dirksen and Miller, 1966; Loch and Kay, 1978; Penner, 1986) and forms segregated ice or ice lenses (figure 2.1).

Figure 2.1: Series of ice layers in Caen silt (experiment #3). The cold side is at the top of the picture. Notice the shear zones at the sides of the sample, near the column walls. A theoretical example cited by Konrad (1994) shows a similar ice lens pattern developed during laboratory step freezing tests (figure 2.2).

To accommodate the volume increase of the interstitial water which freezes *in situ*, and the formation of ice layers, the soil must expand, causing an upward or outward movement of the ground surface defined as frost heave (Harris et al., 1988). In nature, unequal or differential frost heave is caused by soil anisotropy and the complexity of the water displacements associated with ice growth which create stresses within the body of soil. This results in local variations in the elevation of the soil surface.

Soils that heave significantly are labelled frost susceptible. Chamberlain (1981) presents an extensive review of frost heave criteria; the large number of criteria underlines the complexity of the frost heave process (Lundin, 1989). Typically, frost susceptible soils are fine-grained, commonly in the silt range. They exhibit stable aggregates formed by stresses developed during ice lensing (Van-Vliet Lanoë, 1985). Soil matrix rearrangement with freezing determines the soil fabric which is a key element in the frost heave process.

The rate of frost heave has been found to be directly related to the rate of heat removed from the soil (Penner, 1972; Horiguchi, 1979). A decrease in the rate of heat flow during freezing of a fine grained soil will result in the formation of a series of ice lenses. As the rate of freezing slows down, greater frost heave takes place and the ice lenses become thicker and more widely spaced with depth (Williams and

Smith, 1989) (figure 2.2). The location and thickness of the ice lenses are modulated by the frozen fringe characteristics.

2.1.3 Zones in a freezing soil

A saturated fine grained frost-susceptible soil which is under a positive temperature gradient (temperatures increase with depth) may be divided into five zones defined in terms of heat and mass transport characteristics and processes (figure 2.3).

ZONE 1- Cold frozen soil - A cold interface (or cold end), where heat is being extracted, juxtaposed to a thickness of frozen soil. The frozen soil contains pore and/or thin ice lenses. Negligible water redistribution or migration is expected, inasmuch as the unfrozen water content and the hydraulic conductivity have declined to low values.

ZONE 2- Warm frozen soil - A zone of slow moisture intake and redistribution, beginning at the cold side of the warmest ice lens and extending upwards into the frozen soil where "warmer" sub-zero temperatures exist compared to zone 1. The thicknesses of zones 1 and 2 are determined by the temperature gradient, latent heat effects, soil type and structure.

(From Konrad, 1994)

Figure 2.2: Pattern of ice lenses in a soil column under step freezing conditions. T_w and T_s are the temperatures of the warm and cold (segregation) sides of the frozen fringe respectively and T_c is the cold temperature imposed on the system.

Figure 2.3: Zones in a freezing soil. The warmest ice lens and frozen fringe are not to scale.

ZONE 3- Warmest ice lens - The currently fastest growing or warmest ice lens which is fed by water migrating through the frozen fringe (or, as suggested by Miller (1980), by rigid ice moving into the pores of the fringe). The thickness of this layer may vary from a few millimetres to several meters in the case of massive icy beds which are thought to have originated by ice segregation (Mackay, 1973; Pollard, 1990).

Water which is mobilized for ice segregation is found in capillary spaces and as films around soil particles (the adsorbed water layer). The existence of unfrozen water films at temperatures below zero has been extensively demonstrated (Anderson and Hoekstra, 1965; Anderson and Tice, 1972; Burt and Williams, 1976). This water film is widely believed to be between the ice/mineral faces of the soil.

The amount of unfrozen water at any given temperature is represented by the unfrozen water content curve of the soil, as for example, in figure 2.4. The quantity of unfrozen water is independent of the initial soil moisture content (Williams, 1968) and for a soil depends primarily on the temperature and the magnitude of any externally applied pressure (Nersesova and Tsytovich, 1963).

ZONE 4- Frozen fringe - The frozen fringe (Miller, 1980; Loch and Kay, 1978) is defined as a zone of variable thickness, found between the 0° isotherm (or the level at which the first pore ice is encountered) and the base of the warmest ice lens.

The thickness of this zone depends on the magnitude of the temperature gradient, type of soil and overburden pressure. The extent of the frozen fringe has been studied under experimental conditions (Loch and Kay, 1978; Konrad and Morgenstern, 1980; Ishizaki and Nishio, 1988; Penner, 1986) but its characteristics in a field situation have yet to be documented. This zone determines the sensitivity of frost heave models as it appears to be the site of key mechanisms in the ice segregation process (Akagawa, 1988).

ZONE 5- Unfrozen soil -The unfrozen soil below the freezing front, where the hydraulic conductivity is high and where water may move towards the freezing front, or be expelled in the case of rapid freezing. This zone may be subject to matrix consolidation and desiccation as water moves towards the freezing front (Williams, 1963; Mackay and MacKay, 1976).

Figure 2.4: Unfrozen water content fitted curve for Caen silt.

2.1.4 Water flows: cryosuction and expulsion

Movement of the water phase is produced by thermal or osmotic gradients. Specifically, these gradients provoke soil water pressure differences between the base of the warmest ice lens and the water table.

The water's interstitial pressure is the lowest in the frozen fringe zone. The suction in the frozen fringe may also be called cryosuction (Williams and Smith, 1989) because it appears as if the growing ice lens sucks up water from below. Desiccation of the soil layers immediately below the freezing front causes the water to appear in suction to some depth below the 0°C isotherm. Fukuda and Luthin (1980) verified high negative pore water pressures at and below the freezing front.

In a fine-grained soil, a rapid advance of the freezing front, a variation in the frost penetration rate or a change in overburden pressure may cause water expulsion into the unfrozen zone. Expulsion of water in saturated coarse-grained soils during freezing is also possible (Tsytoovich, 1975; Lundin, 1989). Water expulsion during the early stages of a frost heave experiment on saturated New-Hampshire silt was observed by Loch and Kay (1978). Furthermore, frost heave of a soil surface during water expulsion was recorded (Loch and Kay, 1978; Van Vliet-Lanoë, 1988).

According to Miller (1980) frost heave during periods of water expulsion is a by-product of the regelation process. However, no detailed mechanism for water expulsion has been

proposed although it has been included in a frost heave model (Hopke, 1980). It is believed that some expulsion originates either at the upper boundary of the frozen fringe or at the fringe bottom but most of it probably takes place at the 0°C isotherm level (Schellekens, pers. comm.).

Water flow from the unfrozen soil zone to the warmest ice lens zone, through the frozen fringe which contains only pore ice, can be described by Darcy's law:

$$Q = -KjA \quad [1]$$

where Q is the flow rate (cm^3/s); K is the hydraulic conductivity (cm/sec); j is the potential gradient (cm/cm) and A is the area (cm^2).

A sharp decrease in hydraulic conductivity is encountered in the frozen fringe (figure 2.5) due to the presence of pore ice and because of changes in the thickness of unfrozen water films (Hoekstra, 1966; Burt and Williams, 1976). Frozen soils typically exhibit low permeabilities, ranging between 10^{-6} m/s to 10^{-12} m/s between 0°C and -0.45°C (Williams, 1982). In hydraulic models, inception of an ice lens is thought to take place where water flow either diverges or is impeded due to the decrease in permeability (Harlan, 1973; Konrad and Morgenstern, 1980, 1981).

Under steady-state heat flow conditions, the segregation potential model (Konrad and Morgenstern, 1980, 1981) proposes

(From Sheng and Knutsson, 1993)

Figure 2.5: Conditions in the frozen fringe. u_w : pore water pressure; T_s : segregational temperature; T_f : freezing temperature; w : unfrozen water content; k : permeability; x_f : frost front; x_b : warm side of growing ice lens.

simple input parameters (or so-called freezing characteristics) which may be derived from laboratory freezing tests. The following assumptions are made: the overburden pressure is set at zero (the ice phase is therefore under atmospheric pressure), the ice lens and ice masses in the frozen fringe are unstressed when heave begins and the soil skeleton is incompressible. This model predicts the magnitude of frost heave in fine grained soils in terms of the growth of a final ice lens. The freezing characteristics of a soil are defined by Konrad and Morgenstern as:

$$V_0 = SP_0 \nabla T \quad [2]$$

where V_0 is the water intake flux at final ice lens formation (mm/sec); SP_0 is the segregation potential ($\text{mm}^2/\text{°C sec}$); ∇T is the temperature gradient in the frozen fringe (°C/mm). The segregation potential depends on the segregation temperature T_s , or the frozen fringe upper thermal limit and the frozen fringe overall permeability K_f . It is considered that a specific segregation temperature describes the temperature condition at the warmest ice lens side.

2.1.5 Water and ice movements in frozen/thawing soils

Water migration is a key process in determining the magnitude of frost heave. The largest component of heave is generated at the warmest ice lens. Despite the presence of ice in the soil pores, water movement within the frozen soil is

also possible because of the presence and mobility of unfrozen water films, or adsorbed water (Nersesova and Tsytovich, 1963; Hoekstra, 1966; Takashi et al., 1981).

The rigid-ice model (O'Neill and Miller, 1985) implies that such water films surround mineral and ice particles. The hygroscopic adsorbed water layer is seen as capable of sustaining disjoining pressures i.e. it can transport water to the growing ice mass in the frozen fringe while sustaining a compressive stress between the ice interface and the adjacent soil matrix (Gold, 1985).

The rigid-ice model advocates segregated ice growth by progressive invasion by ice of the soil pore space (within a zone that will become the frozen fringe) by a process called regelation. This is the basis of the secondary heave mechanism. The regelation process was demonstrated in an experiment where isolated grains embedded in ice were seen to migrate in the opposite direction of heat flow (Römken and Miller, 1973). As a corollary, the ice phase is assumed to move in the same direction as heat flow, from warm to cold (Miller, 1980).

It is also believed that moisture movement occurring within the warm frozen soil contributes, perhaps significantly, to frost heave when long periods of time are involved. Water migrating to the freezing front by cryosuction would have to move through the frozen fringe, get across and/or around the warmest ice lens and finally accumulate in

the frozen soil. According to some viewpoints (e.g. Konrad, 1994), the warmest ice lens acts as a cutoff to water migration into the frozen soil. In any case, an ice lens was observed to reduce the soil's hydraulic conductivity when it occurs extended across a laboratory soil sample (Burt and Williams, 1976). But in nature, cryotextures are more complex, with more flow paths.

Field and laboratory studies have demonstrated that water migrating to an unfrozen/frozen soil interface may cause the moisture content to increase beyond that interface, within the frozen soil (Parmuzina, 1978; Penner and Goodrich, 1981; Smith, 1985). Several mechanisms for moisture migration into the frozen soil have been proposed :

- Cryosuction or liquid flow to ice masses in the warm frozen zone (Williams, 1982; Smith, 1985).
- Flow in water films due to gravitational potential (Kane and Stein, 1983).
- Migration of the ice phase through the soil by regelation (Miller, 1980) or plastic flow (creep) (Tsyтовich, 1975).
- Simultaneous growth of two ice lenses by water melting from the cold face of a lower ice lens and moving through frozen soil to the base of an upper lens (Ohrai and Yamamoto, 1985).

Under reversed heat flow such as surface thaw, moisture migration to the thaw front takes place. Field experiments have shown that the meltwater migrates downwards into the still frozen active layer, causing moisture increases there

(Parmuzina, 1978) and frost heave (Mackay, 1983). When two thaw fronts exist, such as in a seasonally frozen ground or in laboratory conditions, moisture will also be drawn upwards into the frozen core and may contribute to significant additional frost heave, and increased settlement of the thawed soil.

2.1.6 Types of frost heave

In a freezing soil, several modes of frost heave can be distinguished. Primary frost heave occurs when ice crystals accrete to form a mass that does not penetrate into the soil pores of the unfrozen soil beneath (O'Neill and Miller, 1985). Secondary frost heave takes place when ice develops a fringe which extends into the underlying pores; ice growth occurs within the advancing frozen fringe (Miller, 1980). The expression continuing frost heave (or tertiary heave as used by Miller) has been used to describe ice growth within the frozen soil (Smith and Patterson, 1989) and implies a moisture migration into and through the frozen soil.

A number of field and laboratory studies clearly demonstrate the occurrence of continuing heave (Penner and Goodrich, 1981; Yoneyama et al., 1983; Smith and Patterson, 1989). Smith (1985) observed simultaneous expansion of soil layers in frozen soil in silty clay mud hummocks; the largest part of the frost heave in one site was attributed to ice segregation (90%) of which more than half (55%) occurred at

temperatures below -0.3°C .

In another field study by Furmonavicius and Kuliesius (1989), simultaneous heave and compaction movements were recorded in glacial silty clay to a depth of 1.0 m under air temperatures varying from 0°C to -10°C .

Differential heave in a frozen clay soil was noted by Penner (1970) but a lack of thermal data makes it impossible to say exactly at what negative temperatures it took place. Ohrai and Yamamoto (1985) observed ice lens growth in a frozen saturated clay over a long freezing period of 252 days. In other studies it has been shown that differential strains implying growing ice lenses (water migration) occur within frozen soil (Wood and Williams, 1985; Smith and Patterson, 1989; Williams et al., 1993).

In some views, continuing frost heave is considered a negligible part of the frost heave process (O'Neill and Miller, 1985; Kay and Perfect, 1988; Konrad, 1994). This may be true in small-scale laboratory conditions, but in natural environments where long freezing periods prevail, continuing heave may add significantly to the magnitude of frost heave. Time scale, thermal conditions and soil environment are particularly important in assessing the role of continuing heave. However, the thermodynamic relations and the exact mechanisms behind ice growth in the warm frozen soil are not well understood. There is currently no model of continuing heave.

2.2 Thermodynamic and rheologic perspectives

2.2.1 The Clausius-Clapeyron equation

In a freezing soil, the liquid water pressure and the energy status of the ice are related to the temperature by the Clausius-Clapeyron equation:

$$T - T_o = \frac{(P_w V_w - P_i V_i) T}{L_f} \quad [3]$$

where T is the temperature of the system ($^{\circ}\text{K}$); T_o is the normal freezing point of water ($^{\circ}\text{K}$); P_w , P_i are the pressures in the water and ice phases respectively (MPa); V_w , V_i are the specific volumes of water and ice respectively ($\text{m}^3 \text{kg}^{-1}$); L_f is the latent heat of fusion (J kg^{-1}). If water and ice are to coexist given a change in pressure or temperature, their free energies will change the same amount. This equation is useful to describe relative pressure or volume changes in the ice and water phases when the soil system temperature varies in equilibrium conditions or when the pressure in the ice phase is greater than in the water phase.

The Clausius-Clapeyron equation is applicable under unconstrained and equilibrium conditions. It is not valid if the pressure and temperature of the system are transient. If the soil is constrained, the stress distribution between soil particles, ice and water should be considered (Kay and Perfect, 1988).

The validity of the equation has been questioned within the frozen fringe (Konrad and Morgenstern, 1981) because the water flow interacts with ice-water contents (and possibly with the mineral contacts) and depends on the suction.

2.2.2 Heaving stresses

In the warm frozen soil and in the frozen fringe zones, frost heave stresses are caused by the 9% volumetric expansion of *in situ* water which freezes, and by moisture migration to and freezing at the warmest ice lens. To these stresses are added the wedging effect of unfrozen water moving in films surrounding mineral particles and compressive stresses in the mineral matrix due to desiccation of the soil near the freezing front (Ershov, 1995) and in the unfrozen soil. The amount of heave recorded at the soil surface represents the sum of the strains produced by stresses acting in each soil zone.

The complex nature of the stresses generated by frost heave has been simplified into a mechanical equilibrium approach with pressure-like manifestations (O'Neill, 1983). The ice pressure P_i can be expressed either as a partial pressure of the water that has changed into ice (the $P_i - P_w$ pressure difference of the Clausius-Clapeyron equation) or as an internal pressure, or stress, generating soil strain (Lundin, 1989).

Given the difficulties, if not the impossibility of

measuring frost heave stresses or P_i and P_w in the frozen soil, research on the magnitude of P_i has been focused on quantifying external manifestations of frost heave and finding empirical correlations between certain soil characteristics and the magnitude of frost heave.

Ice/heaving/frost heave/cryogenic pressures are all terms which have been used to specify a resistive force exerted by a rigid structure (or a frozen surface layer) against soil expansion by freezing. Heaving pressures develop if the freezing soil is constrained or if sufficient overburden exists. Since many experiments on heaving pressures were performed to measure the magnitude of forces acting on a fixed load (or piston) placed at the soil surface, the role of overburden and confinement as factors controlling ice pressure is well assessed (Radd and Oertle, 1973; Penner, 1974; Kinoshita et al., 1978; Penner and Walton, 1979). Overburden is a form of confinement; the terms imply a specific direction of resistive stress in comparison with the freezing plane direction of advance. By analogy with compression tests, these experiments may be described as external static loads placed on dynamic (freezing) soil systems.

Attempts to look at the freezing system as if the loading was imposed by the growing ice phase itself are relatively recent. The definition for the generated internal pressures is arbitrary and refers only to the pore contents or the water phases. Clearly, the ice phase can sustain anisotropic

stresses as ice lenses can grow non-parallel to the soil surface as shown by Smith (1992). Moreover, according to some viewpoints, the stress generated in the soil by the growth of an ice lens is counteracted by the strength of the enclosing frozen soil, in which case, deformations will become measurable only if the stress generated by the growing ice exceeds the frozen soil strength (Wood and Williams, 1985b; Smith, 1992; Wood, 1985).

2.2.3 Soil deformation

The magnitude of the strain depends on stress increments, time scale and experimental conditions (Vialov, 1986). The nature of the stresses imposed on the soil matrix/ice network by ice segregation is complex presumably because it varies in time and with location (for example at the ice lens apex or at the edges). The nature of these stresses may be understood, in part, by the strains generated as the soil freezes.

Soil strains have been measured as they developed within a freezing soil (Williams et al., 1993). Large strains occurred as the frost line passed the strain devices (perspex rings with embedded ceramic magnets) and deformations continued in the warm frozen soil. These strains cause changes in soil fabric which, in turn influence the strength and deformation characteristics of the soil during any subsequent freezing.

The soil deformation, or linear strain ϵ is defined as the change in length dl of a soil unit or layer over the initial length l_i of this unit (Popov, 1978; Vialov, 1986):

$$\epsilon = \frac{dl}{l_i} \quad [4]$$

When deformation data for a soil layer is plotted as strain (in %) versus time, a positive strain represents expansion of a soil layer and negative strain indicates a reduction in soil thickness or consolidation.

As ice lenses grow and expand at the frozen fringe, the frozen soil creeps. Creep is a slow deformation of a soil under a constant stress which involves relative movements of soil components and ice flow; it causes secondary consolidation of the soil skeleton (Vialov, 1986). The deformation usually manifests itself as a volumetric strain and is related to the strength of the pore contents.

Creep is defined as (Andersland and Anderson, 1978; Vialov, 1986):

$$\mu = f(\tau, t) \quad [5]$$

where, μ represents creep; τ is volumetric or shear strain and t is time.

In a freezing soil, the inception and development of creep is governed by the development of microcracks, the

breakdown of particle aggregates and the growth of other structural defects (Tsytovich, 1975).

Freezing soils also exhibit stress relaxation (Kinosita, 1966), during which stresses are lessened (presumably by a form of creep strain) while no deformation occurs. Based on small-scale laboratory experiments, it has been suggested that the frozen portion of the soil offers internal resistance to ice lensing (Wood, 1985; Lundin, 1989; Smith and Onysko, 1990). It is thought that many centres of stress development exist in a freezing soil (Wood and Williams, 1985) and that the rheological properties of the frozen soil affect ice segregation.

A conceptual micro-scale model of frost heave, in which rheological properties of the frozen soil are incorporated, was developed by Lundin (1989). The model was tailored to explain two empirical findings regarding pressures in a coarse-grained, frozen soil: 1- a sustained and constant P_i over long periods and 2- an increase in P_i with increasing temperatures. In this model, the growth of segregation ice and the stress relaxation, or creep, of ice are viewed as two compensating processes.

This micro-scale model incorporates: weakness points within the soil where the strength is lowest and where stress relaxation will occur. Water will flow to these regions of relaxation and freeze there, thus cold ice segregation builds up the ice pressure while stress relaxation decreases it. A

"creep effect" was added to the Clausius-Clapeyron equation (Lundin, 1989).

Internal controls that enable the soil to resist deformation or that contribute to strength are: the viscous resistance of the soil structure, the relative soil density, the effective minor principal stress (Mitchell, 1976), the stress history, the soil structure, the temperature and the moisture content (Vialov, 1986).

Because many of these controls operate at a micro scale, soil micromorphology can assist in evaluating their relative importance in frost heave deformations.

2.3 Cryogenic soil micromorphology

Soil micromorphology is the study of soil thin sections under an optical microscope. Basic concepts of the method were developed by Kubiěna in 1938 and later expanded by Brewer (1976), Stoops and Jongerius (1975), Fitzpatrick (1984) and Bullock et al. (1985). Soil micromorphology is concerned with the description and interpretation of soil parts. With micromorphological analysis, relations between morphology and soil forming processes can be established (Bullock and Murphy, 1983).

The method has been used successfully to obtain an understanding of the processes occurring in natural soils subjected to freezing (Fedorova and Yarilova, 1972; Brewer and Pawluk, 1975; Fox and Protz, 1981), and their associated

landforms (Harris, 1981; Van Vliet-Lanoë, 1985; Ballantyne and Harris, 1994). Specific effects of freezing on soil structure have also been investigated experimentally where freeze-thaw cycles were imposed on natural soils and sediments (Konishev et al., 1973; Coutard and Mùcher, 1985; Pawluk, 1988) and geotechnical soils (Kumor, 1989; White, 1992).

2.3.1 Features and fabric types in cryogenic soils

In frost affected soils, ice segregation and thawing will result in distinctive features such as: shear planes, vesicles and injections along shear planes (Coutard and Mùcher, 1985) oriented clay coatings (stress cutans), orientation of coarser particles, soil aggregation (Van Vliet Lanoë, 1985), infilling of primary and secondary pore space and silt cappings or droplets (Romans et al., 1980). Creep of the soil skeleton and ice causes irreversible shears of particles and particle aggregates (Tsytovich, 1975). A thorough analysis of the different features produced by freezing and thawing was conducted by Van Vliet-Lanoë (1985).

Certain types of fabrics are also associated with ice segregation. Conglomeratic, orbiculic and suscitic fabrics were first defined to describe soils in the Mackenzie valley and Yukon coastal plain (Fox, 1979). Banded and isoband fabrics were observed in soils, with little clay content, in the seasonal frost zone of Saskatchewan (Mermut and St-Arnaud, 1981). Laboratory experiments on remoulded natural soils and

sediments showed that repeated freeze-thaw cycles resulted in the formation of granic, matrigranic and porphyric fabrics (Pawluk, 1988). Observations on sub-arctic and arctic soils prompted Brewer and Pawluk (1975) to define the following new fabric groups: fragmoidic, fragmic, granoidic and porphyroskelic. Fox (1994) provides a detailed summary of the typical fabrics of permafrost soils and gives the first comprehensive scheme relating these fabrics to specific frost heave processes (figure 2.6).

However, there is little research linking cryogenic fabrics to known thermal and rheological conditions and often, the freezing and the thawing conditions are not decoupled so the resulting fabrics cannot be definitively ascribed to a specific thermal situation.

2.3.3 Structure effects on frost heave

Frost heave stresses produce structural changes in the various soil zones. The effects of soil features and fabrics, or more generally of the soil structure, on the frost heave process were recognized by Van Vliet-Lanoë (1985, 1991). One way to assess these effects is to evaluate the transport properties of a soil subjected to freezing since changes in hydraulic or thermal conductivity will affect ice segregation.

(From Fox, 1994)

Figure 2.6: Soil fabric types linked with freezing-related processes.

Soil microstructure exerts a direct influence on water migration to the unfrozen-frozen interface and possibly on unfrozen water movements in the warm frozen soil. The soil's hydraulic conductivity is modified primarily during ice segregation which results in thin foliated, platy, short prismatic or granular fabrics (Van Vliet-Lanoë, 1991). The type and distribution of pores also affect the hydraulic conductivity (Oh et al., 1987). Studies by Chamberlain (1989) showed that the void ratio was decreased in fine-grained slurries after only one freeze-thaw cycle. Three freeze-thaw cycles caused a reduction in void ratio in clay and silty clay soils but resulted in large increases in permeability. In some soils the increases in permeability was attributed to vertical shrinkage cracks but for other soils (Hanover silt and CRREL clay) it was due to changes in fabric (Chamberlain and Gow, 1979). In experiments on Caen silt, permeability was increased with exposure to freezing and consolidation was observed at depth within the unfrozen zone (White, 1992). Consolidation may change the friction component of strength, even with a single frost cycle. Furthermore, the amount of unfrozen water or adsorbed water films depends on the area of specific internal surface of the soil which could change due to particle sorting or coating.

Soil particles will reorient even under a single freeze-thaw cycle. This results in strength anisotropy: Alkire and Jashimuddin (1984) measured greater shear strength (by 37%) in

the direction perpendicular to freezing in Manchester silt. For clays, strength increase or decrease depends on increased density or degree of cementation respectively (Chamberlain, 1989). Particle translocation occurs during thaw, which might affect the frost susceptibility of a soil.

Complex input parameters and micro-scale realities related to soil matrix deformation and ice creep, are reflected in recent models indicating a growing recognition of the importance of structure and rheology in the frost heave process (Shen and Ladanyi, 1987; Lundin, 1989; Padilla and Villeneuve, 1992).

From this review it is apparent that frost heave is the result of a complex interaction of various processes. More specifically, research on the interactions between heat and water flows, soil deformations and soil fabric development as they occur in each zone as described in figure 2.3 is needed to gain more information about the nature of frost heave. This thesis is an exploration of the links between some of these processes. The experimental work described in the next chapters is intended to refine the conceptualisation of heave-generated soil deformations and associated matrix structures.

CHAPTER 3 : METHODS

3.1 Experiment preparation

3.1.1 Introduction

The objectives of the experimental program were to assess the heat and water flows, heaving stresses and strains, and cryogenic structures that develop in a soil exposed to prolonged periods of laboratory freezing and thawing. A soil column was used, which had to be fairly large to accommodate an array of instruments and to allow sampling for micromorphological analysis. A large soil column design (30 cm inside diameter by 100 cm length with an open water system) originally developed by the Carleton University Geotechnical Science Laboratories, and first used by Onysko (1988), was adapted for these experiments. The design details can be found in Onysko (1988).

A set of six experiments was conducted. The first two were carried out in the first soil column (Manchester #1 and #2). The four other experiments (Caen #1 to #4) were conducted in a column almost identical to the one used in the previous experiments. However, the pipe section was rebuilt without a plexiglass window and without the fixtures that serve to anchor certain pressure transducers.

3.1.2 Soil column design

The column was built from a 2 cm thick, 30 cm diameter PVC pipe. A section measuring 90 cm long was fitted snugly in a water reservoir by means of a large O-ring (figure 3.1). Separation of the pipe from the water reservoir was prevented by an aluminium retaining plate that surrounded the lower portion of the pipe and which abutted the top rim of the water reservoir. Inside the water reservoir a plexiglass x-shaped frame, upon which rested a coarse and fine wire mesh and a porous filter, served to support the overlying soil column.

The instrumented column was placed inside a low temperature chamber, which served to control the ambient air temperature around 6°C. Heat was extracted from the soil column by a 30 cm diameter cooling plate that rested directly on the soil surface. A cooling bath placed near the chamber circulated ethylene glycol through the cooling plate via insulated inflow and outflow Tygon tubes. A submersible pump (Little Giant Pump Co. Model 1-T) located inside the cooling bath improved the circulation and reduced temperature fluctuations within the bath. The cold end control was the bath temperature sensing element; because of this set-up, temperature coupling between the bath and the cold plate was not constant from one experiment to another due to inevitable heat loss which occurred from the tubing connecting the bath to the cold plate.

To minimize radial heat flow, the column was insulated

with an R-5 styrofoam casing and wrapped in a heavy plastic sheet. Excessive heat loss from the cold plate to the chamber was also minimized by insulation, but without impeding heave. A large rubber tube connected the base of the water reservoir to a distilled water supply. A small industrial fan placed near the top of the controlled temperature chamber improved air circulation and prevented freeze-up of the water in the outlet resting on the chamber floor.

3.2 Column instrumentation and set-up

3.2.1 Temperature measurements

Thermistors were used in the Manchester silt experiments (YSI Model 44004 with a standard resistance of 2252 Ohms at 25°C). In the experiments using Caen silt, temperatures were measured by copper-constantan thermocouples placed at 3 cm intervals (figure 3.2) and located roughly at the centre of the column. The thermocouples were calibrated in an ice-water bath; the accuracy was on the order of 0.01 °C. Temperatures were recorded every hour by a 21X datalogger, except at the start of the experiment when readings were more frequent.

Scale: 1:5,3

Column Design: L. Boyle

Figure 3.1: Soil column

3.2.2 Water supply

An open water system was made by connecting the base of the soil column water reservoir to two 1000 ml loosely covered burettes filled with distilled water. At the beginning of each experiment, the water level was allowed to reach the top of the soil sample to approach saturation conditions; once the water columns had stabilized they were filled to the level of the top of the soil. During the experiments, the burettes were topped up only when the water supply ran low. Water intake and expulsion from the soil column was monitored once to twice daily. The precision of the readings is ± 1 ml.

3.2.3 Heave

A helipotentiometer (Beckman Instruments Inc., Model 5311) was installed to monitor vertical soil displacements (or total heave). This instrument functions as follows: an input voltage of 3 volts is sent across the helipotentiometer and travels through a resistor. The length of the resistor varies when a slider, which is connected to an aluminium moveable arm, is displaced. When the arm which rests on a U-shaped aluminum vertical plate fixed to the cooling plate is displaced, a differential output voltage is obtained. Before each experiment, the potentiometer was calibrated by 2 mm increments (figure A1.1).

Summary of experiment

Soil : Caen silt

Duration : 448 hours (19 days)

Max. depth of freezing : 27 cm

Total water intake : 98.2 ml

Total water expulsion : 72.2 ml

Heave : 0.90 cm

Temperature gradient :

25 hours : 0.153 °C/cm

150 hours : 0.119 °C/cm

375 hours : 0.150 °C/cm

Soil column contents

- : Silt (70 cm total)
- : Sand (20 cm total)

Symbol	Instrument type	Quantity	Size (diameter in cm)	Depth In soil (cm)
Radio-transmitting stress transducer	3	4.5	9 cm, 21 cm, 39 cm
Strain cell	14	2.5	Every 3 cm from surface to 39 cm
Thermocouple	14	—	Every 3 cm from surface to 36 cm last one at 50 cm
Modified Petur Piezometer	3	1.8	3 cm, 15 cm, 30 cm

Figure 3.2 : Experiment set-up, Caen #2.

Figure 3.2: Experiment set-up, Caen #2.

3.2.4 Total soil stress

Petur pneumatic piezometers (Model P-100), manufactured by Petur Instruments Ltd., are built to measure pore water pressures from 21 to 13 790 kPa (3 to 2000 psi). Liquid pressure is exerted on the porous filter at the tip of the instrument; nitrogen gas, sent from the readout instrument through the inflow tube, increases the pressure in the vessel until it equilibrates with the measured pressure. At the equilibrium point, a diaphragm located in the piezometer tip opens and the gas is released via the outflow tube. A valve is connected to the readout instrument. The sensitivity of the piezometer is $\pm 0.1\%$.

The Petur piezometer was modified to measure total pressure (figure 3.3). A silicon oil-filled latex rubber cap of approximately 5 ml capacity, was fitted and clamped tightly onto the tip of the transducer. The modified transducers were calibrated in an air pressure vessel, with a Winter gauge, at ambient temperature to pressures up to 190 kPa (27.5 psi) (figure 3.4) for the Caen experiments and up to 276 kPa (40 psi) for the Manchester experiments. The transducers were tested at freezing temperatures under atmospheric pressure and showed no obvious temperature dependency.

3.2.5 Radio-transmitting stress transducers

Three novel radio-transmitting transducers (serial numbers #4-5572 #4-5573 and #4-5574) were built by Holohill

Modified Petur pressure transducer (actual size)

Figure 3.3: Pneumatic piezometer (Petur Instruments Inc.) was modified to measure total pressure.

Figure 3.4: Modified Petur piezometer calibration curves. The devices were calibrated under increasing and decreasing air pressure. Shown here are the calibration curves for increasing pressure. No hysteresis occurred.

Systems Inc., after a first prototype was designed and tested at the U.S. Army Cold Regions Research and Engineering Laboratories, in Hanover, New Hampshire (Smith, 1988). The device, 4.5 cm in diameter, was designed as a self-contained unit to eliminate bulky readout links (figure 3.5).

The components are contained in a cylindrical brass shell with a diaphragm at the top. The diaphragm is connected to a standard 4-arm strain gauge, linked to a conditioning circuit via a transmitter powered by a lithium battery. A thermistor placed in the device is also linked to the transmitter.

The brass shell is enclosed in a ball-shaped casing: the lower part (hemisphere) is encased in epoxy, the upper part in silicon rubber. Both parts are incompressible, the strain gauge is activated when the casing is pushed up or down (under compression). Loading tests conducted with the prototype in a triaxial cell indicated that the stress measured by the device closely matched the applied stress (figure 3.6).

As the sensor at the top of the device registers a stress, a radio frequency pulse is emitted. A radio-receiver, containing a frequency oscillator, may be tuned in to the stress transducer's emitted pulse. The radio-receiver is connected to a counter which translates the pulse into *in situ* stress and temperature signals. The pulse width varies with the temperature and the pulse interval indicates the stress.

Figure 3.5: Radio-transmitting transducer top view showing sensor (strain gauge) of device #4-5572 (.160 MHz frequency).

Triaxial test: sensor vertical
Confining stress: 345 kPa

49

Triaxial test: sensor vertical
Confining stress: 552 kPa

(From Smith, 1988)

Figure 3.6: Radio-transmitting transducer response under deviatoric stress. A residual stress was recorded upon unloading possibly due to the development of residual frictional stress upon loading.

Each device operates at a specific frequency (the pulse frequencies are 172.160 MHz, 172.199 MHz and 172.120 MHz). The devices are hereafter simply referred to by the last three digits of their pulse modulation: stress transducer #4-5572 is .160 MHz, #4-5574 is .199 MHz and #4-5573 is .120 MHz.

The initial rough pressure calibration, ranging from 0 to 1379 kPa (0-200 psi), provided by the manufacturer was unsatisfactory because the calibration curves differed one from another. It was not possible to pinpoint the source of the problem although a change in the type of battery used, which differed from the one enclosed in the prototype is a possible cause.

Based on previous research about pressures recorded in silty soils, it was expected that stresses to be measured could range between 0 to 345 kPa (0-50 psi) (Geotechnical Science Laboratories, 1989, 1992; Smith and Onysko, 1990; Smith 1988; Wood, 1985). Therefore, a finer calibration of the radio-transmitting transducers, from 7 to 345 kPa (1-50 psi), was performed in a triaxial cell. The cell was filled with deaired water and connected to a Mercury pot pressure system. The calibration was carried out from 9.8 kPa to 329.4 kPa (± 1 psi to ± 48 psi) (figures 3.7 to 3.9 and A1.2 to A1.4). The curves obtained showed some differences in response shape, and device .120 MHz showed step-like variations.

No temperature dependency or significant hysteresis was observed during testing of the prototype (Smith, 1988).

Figure 3.7: Radio-transmitting transducer calibration curve, device .199 MHz. A Mercury pot pressure system was used and calibration was done under increasing mercury head. Calibration A is valid for experiments Manchester #2 up to Caen #2. Battery change and recasing of all devices called for a second calibration (figures A1.2 to A1.4).

Figure 3.8: Radio-transmitting transducer calibration curve, device .120 MHz.

Figure 3.9: Radio-transmitting transducer calibration curve, device .159 MHz.

Temperature calibration was undertaken in a circulating ethylene glycol bath under a cooling trend (figure 3.10). The response of the devices internal thermistors in the freezing soil was not satisfactory, as shown by the results of Manchester #2 experiment (figure 3.11), and because of problems with the counter it was decided to rely on more precise and reliable thermocouples placed beside or on top of the radio-transmitting devices.

For experiments Caen #2 and Manchester #2, the radio-transmitting devices were placed in the middle of the soil column, and for experiments Caen #3-#4, they were located near the column wall.

3.2.6 Soil strain

A Soil Strain Gage apparatus, manufactured by Bison Instruments Inc., was used to measure soil expansion and compaction, by soil layer. The volumetric strain is translated into length strain because of lateral confinement. The apparatus (Model 4101A) consists of sensors (strain gauges) and a control and read-out unit (figure 3.12).

The strain gauges are made of wire coils that are encased in resin covered disks. The gauges are placed in the soil in pairs (figure 3.13) in a roughly parallel and axially aligned configuration. An array of 14 gauges (or 7 pairs), with each device serving alternately as an emitter and a receiver, was used in the experiments, enabling strain measurements over a total interval of 39 cm (refer to figure 3.2). The effects of

Figure 3.10: Radio-transmitting temperature calibration curve.

Figure 3.11: Temperature measurements by a thermocouple inside the radio-transmitting transducer during experiment Manchester #2.

Figure 3.12: Soil Strain Gage readout unit (back) and two strain cells or gauges (forefront). The gauges are embedded in the soil in pairs and record any compression or expansion in the soil in between.

Figure 3.13: Top and side views of Bison soil strain gauges.

rotational or transverse movement of the gauges on the reading are usually negligible. The gauges are linked to the control instrument by RG 174/U coaxial cables. The instrument's internal oscillator provides the excitation signal to one of the disks (input signal) creating an electromagnetic coupling between the disks. A bridge imbalance between the gauges is caused by any variation in their initial separation. The signal current measured by the adjoining disk (output signal) varies accordingly. The bridge balance is established by operating the phase and amplitude controls until the meter reads zero.

Maximum sensitivity of a coil pair is approximately 0.01 cm. The diameter of the strain gauges used in the experiments was 26.5 mm, which, according to the manufacturer's specifications, permits spacing readings from 1 to 4 times the sensor diameter. However, calibration of each pair of sensors showed that the maximum spacing that could be read by the gauges was 2.3 times the diameter and the minimum spacing was ± 0.7 mm less than the sensor diameter (figure 3.14). Although the reason for this discrepancy was not found, the resulting spacing range was sufficient for the ranges expected in the experiments.

Figure 3.14: Bison strain gauge calibration curves at range 1 (R1) from 1.82 cm to 3.7 cm and range 2 (R2) from 3.5 cm to 6 cm. The curves follow a polynomial fit. No impedance due to negative temperatures was noted.

3.3 Soils

3.3.1 Soil preparation

Manchester silt and Caen silt soils were air dried, disaggregated and passed through a 500 micron sieve. Prior to placement in the column, batches of soil were rewetted gradually by spraying distilled water up to the desired water content for compaction. Water content for compaction of Manchester experiments #1-#2 was approximately 5% by mass. For Caen experiments #1-#2, the water content was 6% and for Caen experiments #3-#4, water content for compaction was 17,5% by mass, which corresponds to the lowest part of the Proctor normal test curve. Each soil layer was compacted manually (400-600 blows per layer), and the resulting surface was scraped to reduce the sharpness of contact between layers.

3.3.2 Soil characteristics: Manchester silt

Manchester silt consists of rounded to subangular particles.

- Atterberg limits: Liquid limit: 26% - Plastic limit: 21%
- Specific gravity is 2.73
- Maximum dry unit weight is 1.73 g/cm^3 at a water content of 11.6%
- 95% of the soil particles are less than 0.074 mm in diameter (Alkire, 1980).

3.3.3 Soil characteristics: Caen silt

Caen silt is an aeolian sediment (loess) containing some sand and also chert fragments (which were removed during soil preparation). The grain size curve (figure 3.15) shows the sediment contains mostly silt-size particles (75 to 85%). Clay minerals are present and have been identified as kaolinite, smectite and illite: quartz was also found in the sediment (White, 1992).

- Particle density: 2.665 g/cm^3
- Atterberg limits: Liquid limit: 32% - Plastic limit: 21% - Plasticity I.: 11
- Maximum density 1.86 g/cm^3 at a moisture content of 14.5% (Geotechnical Science Labs, 1992).

3.3.4 Sampling procedures

Unfortunately, Caen #2 samples were lost because sampling was done at room temperature causing rapid ice melting and soil liquefaction. The soil columns from the Caen #3 and #4 experiments were sampled while still frozen, in a cold room. For each soil column, a detailed assessment of the ice lens size and position was made. Samples for total moisture content and thin section analysis were taken.

The soil columns from these experiments were extracted whole from the PVC column so that sampling in the frozen state could take place. At the end of each experiment, the column was removed from the chamber. The base of the column was

Figure 3.15: Grain size distribution for Caen silt.

quickly dismantled and the unfrozen sand and most of the unfrozen silt were dug out from the base. The cylindrical part of the apparatus was then placed on a modified 10-ton hydraulic lab press (Carver, Model B) where a piston capped by a disk-shaped metal plate pushed against the base of the frozen soil. When the applied stress exceeded the adfreezing strength, the soil was forced out of the column. Extensions were added to the piston until the entire frozen soil mass was extruded.

The soil cylinder was placed in a cooler and taken to a cold room. There, the soil cylinder was placed in a specially-designed apparatus which held it in a fixed position. The soil could then be sectioned in half along its length by using a 2-person lumber saw. This 5 foot long saw has widely spaced indentations (2.5 cm long) which prevented clogging of the blade by silt thawing at the cut. The soil half-cylinder was removed from the holding apparatus and was carefully scraped and cleaned.

While in the cold room, pictures of the frozen soil were taken, the ice network was described and samples for moisture content determination were taken. Sample locations for thin section analysis were noted; the soil half cylinder was cut on a band saw into samples of a Kubiena box size: 5 cm height by 6.5 cm wide by 7.5 cm length. The frozen samples were then fitted into Kubiena boxes which provided support during transport and subsequent treatment in the thin section lab.

3.3.5 Sample preparation for micromorphological analysis

A total of 14 samples were taken from experiments Caen #3 and Caen #4, and 2 samples were taken from Caen #1. Soil thin sections were prepared by impregnating the undisturbed soil sample with a polyester resin under a vacuum. Once the resin is cured the preparation procedure for the soil thin section is generally similar to the preparation of a rock thin section.

Because the polyester resin is immiscible with water, all soil moisture down to a water content of 1% must be removed before the impregnation process begins (Sheldrick, 1984). Different methods may be used to remove the soil water, such as replacement of water by acetone and air drying.

Air drying can cause large stress cracks in a soil sample while immersion in acetone causes problems if clay is present. Significant amounts of clay are found in the Caen silt which could slake if combined with acetone and damage the soil structure. Therefore it was decided that air drying was the best method in this case. Shrinkage cracking and any enlargement of lenses were mapped for each sample and no significant change was observed at a macroscale.

Samples from Caen #3 experiment were partly freeze-dried in a cold chamber (mean temperature -10°C) for 4 months then air dried for two months. Because the size of the samples made freeze drying too lengthy, samples from Caen #4 were simply

air dried over a two-month period. Samples were weighed periodically until their weight had stabilized.

Impregnation of the soil samples was done with an unsaturated polyester resin to which are added a catalyst (Methyl Ethyl Ketone Peroxide), an accelerator (Cobalt Naphtenate) and a fluorescent dye (Uvitex OB). The dye, which fluoresces at 435 nm is used to enhance pore space and in this research, any void or crack occupied by ice. The impregnated samples were cut into 1 cm thick slabs. Most slabs displayed various degrees of incomplete impregnation, in voids and particularly cracks. Slabs were placed in aluminium trays and puddled (at least once) with a dilute polyester resin mixture. Slabs were ground on a coarse sand paper lap to remove excess resin and subsequently on 165 μm , 70 μm , 45 μm diamond laps to obtain a smooth finish. Slabs were then photographed under natural light (flash) and longwave ultraviolet light.

The slabs were cut into chips (3.5 cm length by 2.5 cm width and 1 cm thickness), which were ground successively on 165 μm , 70 μm , 45 μm diamond laps until they became flat and reflected light uniformly. Once the chips were mounted on petrographic slides and resectioned, they were polished on diamond laps to attain a final thickness of 15 μm .

3.4 Summary of experimental set-ups

3.4.1 Manchester silt experiments

Manchester silt was used for the first two experiments. The silt is a frost susceptible loess type sediment. It does not contain any organic matter as it was sampled well below the weathering zone. It may be referred to as a remoulded geotechnical soil.

The column used for these experiments was similar to the one described in section 3.1.2 with the exception of a plexiglass window along one side and openings along the opposite side of the column to install fittings to anchor the modified Petur piezometers. Total heave or consolidation was measured with a dial gauge (precision ± 0.01 mm) placed on the cooling plate. The summary of the experiments and the device location for the two Manchester silt experiments is presented in condensed form in Appendix two.

3.4.2 Caen silt experiments

The 4 subsequent experiments were carried out using Caen silt for two reasons: the possibility of comparing results with the larger scale experiments done at the Canada-France pipeline ground freezing project (Geotechnical Science Laboratories, 1988, 1989, 1991) and because the quantities of soil needed were beyond the available reserves of Manchester silt. Larger amounts of soil were needed because the soil

sampling technique used was destructive. The summary of experiments Caen #2 and #3 can be found in Appendix two. Details of experiment Caen #4 appear in Appendix three. Experiment Caen #1 provided scarce data because freezing took place too rapidly, which resulted in formation of pore ice only. No summary will be given for this experiment but resulting soil fabrics provided by the samples are discussed in Chapter 6.

CHAPTER 4 : SOIL STRESS AND DEFORMATION DURING FREEZING

4.1 Introduction

In this chapter, soil stress and strain measurements from freezing tests in Manchester silt (experiments #1 and #2) and Caen silt (experiments #2 and #3) are examined together with total heave data. As soil freezing progressed, stresses developed. An interpretation of stress patterns, ice growth and resulting soil deformations is provided. The information is used to provide refinements of frost heave criteria during a single freeze cycle.

4.2 Stresses developed during freezing

4.2.1 Radio-transmitting transducer devices

In a saturated unfrozen soil, an increase in the effective normal stress σ_e occurs if the pore water pressure μ (neutral stress) is lowered or if the normal stress σ_n increases (Terzaghi, 1959):

$$\sigma_e = \sigma_n - \mu \quad [6]$$

In a saturated frozen soil, the neutral stress is partitioned between the pore ice pressure P_i and the unfrozen water pressure P_w (Miller, 1980):

$$\mu = [XP_w + (1 - XP_i)] \quad [7]$$

where X is the stress partitioning factor.

The radio-transmitting transducers were placed with the sensor oriented towards the cold end of the column. It is assumed that a close contact between the strain gauge (sensor) and the casing was maintained during the experiments. The sensor recorded uniaxial compressive stresses. The radio-transmitting devices recorded changes in compressive normal stresses originating from the overburden (including stress generated by adfreezing), from the soil matrix movements and from internal loading caused by ice lens formation.

It is also thought that the strain gauge in the radio-transmitting device recorded uniaxial normal tensile stresses, likely as a result of orthogonal compressive stresses (with respect to the direction of heat flow). These orthogonal stresses caused the device casing to deform (the casing becomes more egg-shaped), thus putting the strain gauge in tension. Tensile stress readings were obtained during triaxial tests on the prototype, when the device was placed in dry sand, with its strain gauge oriented horizontally (Smith, 1988). Calibration under tensile conditions could not be achieved because a known tensile stress could not be applied to the system (Smith, 1988). Nevertheless, a qualitative assesement of the internal stress trends is of value.

It is difficult to determine which soil conditions generated tensile stresses in the radio-transmitting transducer. When ice lenses begin to form due to freezing, the

soil particles will appear to be moving away from the growing ice body. However, between the lenses, inside a soil aggregate, the soil particles may be pushed together. It is thought that tensile stresses measured by the sensor reflect the expansive heaving forces. Due to the lateral confinement by the soil column wall, and the size of the device as a large inclusion in the soil, these forces were dominantly in the direction perpendicular (orthogonal) to the heat flow.

With the exception of the stresses recorded during experiment Manchester #2, the stress values were near the lower end of the calibration curves indicating small stress variations. Moreover, because part of the data collected displayed values below the bench readings, it appeared that tensile stresses, as defined above, were recorded.

Stress values were extrapolated from the calibration curves and plotted against time; a negative stress value indicates a radio-transmitting transducer signal below the bench reading. Most of the initial stress values obtained at the onset of an experiment were below the bench readings (figures A2.13 a,b,c and A2.17 a,b). These values remain unexplained. They might be related to the transducer counter, the conditioning circuitry or the battery unit (which was different from the prototype). Discrepancies also originate from the stress complexity and from the varying nature of the contacts between the device and the soil during freezing.

The initial stress readings were reset at zero to enable comparisons between the different experiments. A positive slope in a stress-time graph is interpreted as a compressive normal stress while a negative slope represents a tensile normal stress. While the stress magnitudes themselves should be interpreted with caution, there are consistent trends which provide insights to the development and distribution of soil stresses during frost heave. The repeatability of most of the radio-transmitting transducer data and close correlation with the soil strain data make the stress patterns a valuable source of information.

4.2.2 Stress patterns

Figure 4.1 shows schematically the stress trends recorded at three different levels in the soil column under a slowly advancing freezing front.

Near the top of the column, between 1.5 cm and 10 cm depth, rapid frost penetration was accompanied by a markedly short stress increase to a peak (figure 4.1, curve I). Once the frost front had passed the top of the transducer, a tensile stress was recorded. This tensile stress increased (negative slope) very sharply (typically over about 25 hours), then increased at a slow rate for the remainder of the experiment.

In the mid-section, from 16.5 cm to 19.5 cm depth, either a normal compressive stress or a tensile normal stress was

Figure 4.1: Model curve of stress deformation in a freezing soil, as recorded by the radio-transmitting devices. I: stress curve for soil top section (1.5 cm - 10 cm); II: stress curve for soil mid-section (16.5 cm - 19.5 cm); III: stress curve for unfrozen soil (below 20 cm). A and B: stress peaks near and at the frozen fringe level.

recorded at the start of a cold cycle (for example, figures A2.9 or A2.17b). As the frost line approached and passed the transducer top, a double peak was recorded (figure 4.1, curve II, part A and B). Then, as the freezing front progressed to the base of the device a large tensile stress increase occurred. The increase lasted between 50 to 300 hours.

At the base of the instrumented portion of the column, in the unfrozen soil, a normal tensile stress increase was recorded throughout the experiment (figure 4.1, curve III).

While particular features of the stress data recorded during each experiment are difficult to interpret, similar stress trends were observed according to position relative to the frost front: under an advancing freezing front the stresses were either weakly tensile or compressive, peaks characterized the frost front passage and they were followed by large tensile increases.

Figures 4.2 to 4.4 illustrate the detail of the stress trends. They were modified by different factors which may be called stress-modifying or controlling factors.

These factors relate to key features of the experiments:

- a) adfreezing of the soil to the column sides,
- b) incompressible base layer (sand),
- c) consolidation of the silt layers below the advancing frost front and
- d) progression rate of the zero isotherm.

Figure 4.2a: Surface heave, water intake and stress curves for experiment Caen #2.

Figure 4.2b: Zero isotherm progression for experiment Caen #2.

Figure 4.3a: Surface heave, water intake and stress curves for experiment Caen #3.

Figure 4.3b: Zero isotherm progression for experiment Caen #3.

Figure 4.4a: Surface heave, water intake and stress curves for experiment Manchester #2.

Figure 4.4b: Zero isotherm progression for experiment Manchester #2.

a) adfreezing to the column sides

Adfreezing of the soil sample to the column sides occurred during the experiments, as suggested by the periods of negligible surface heave. A Teflon liner had been used in earlier tests but did not prevent adfreezing. While the experiment set-up did result in some lateral confinement, the effects of adfreezing were apparently confined to a narrow zone along the column walls. The numerous ice lenses across the frozen sample did not display bending near the column sides. Periods of adfreezing, resulting in confinement were followed by periods of free heaving, as evidenced by the shear zones in figure 2.1. These experimental artifacts reproduce certain field conditions such as when a frost susceptible soil freezes next to a coarser grained soil, resulting in anchoring, or when soil freezing proceeds unevenly such as in a mudboil.

Compressive normal stresses above confining values under an advancing freezing front were caused by matrix consolidation to which is added a downward-transmitted heave component. Generally, downward-transmitted heave was recorded when the frost line was close to the top of the sensor. When soil adfreezing at the column sides impeded heave at the surface, for example at 19.5 cm depth in experiment Caen #3, it caused a long ramped stress increase in the soil (figure 4.3a, between 0 and 200 hours at 19.5 cm depth). Compressive normal stress increases were also recorded during experiment

Manchester #2 at 20.5 cm between 50 and 350 hours at 20.5 cm depth (figure 4.4a). Heaving stresses which are not dissipated by heave due to adfreezing will result in significant compressive stresses in the unfrozen soil. Slight tensile stresses in the soil before the frost front or in the never frozen soil, such as in experiment Caen #2 are difficult to interpret (figure 4.2a, from 0-250 hours at 16.5 cm depth). Unless the transducer was compressed laterally or if a gap opened above the sensor, they are unexplainable.

b) incompressible layer

Significant compressive stresses were recorded far below the frost front in the unfrozen soil, for example in experiment Manchester #2 (top at 35.5 cm depth, figure 4.4a and 4.4b). In this case the presence of an incompressible sand layer 10 cm below the base of the device enhanced the stress buildup (refer to figure A2.5 for the experimental set-up).

c) silt consolidation below the frost front

The magnitudes of the normal stress increases were not the same at different levels in the soil column. The stress increase in the mid-layer was generally larger because segregated ice was pushing against a consolidated unfrozen soil base (figures 4.2a and 4.3a).

d) zero isotherm progression

When the freezing front approached the transducer located at mid-column depth (right above the sensor), smaller variations of ice stresses (or P_i) were measured. The double

stress peaks (A and B) show the local stress variations near and at the frozen fringe level. Compressive normal stresses increased for a first peak when the frost front was at 1 cm above the top of the sensor and for a second peak as the freezing front actually reached it. The corresponding water flows monitored at the column base indicate variations in P_w . Both curves may be analyzed under two different situations.

In a confined situation, under conditions of no surface heave, such as in experiment Caen #2, increases in ice pressure were accompanied by water expulsion and decreases in ice pressure by water inflows (figures 4.2a and 4.2b). For example, between 211-239 hours, the stress decrease was accompanied by a large water intake of $1.5 \text{ cm}^3 \text{ hour}^{-1}$. At 239 hours the ice pressure rose again for about 25 hours during which the water flow was reversed. Changes in stress near the frost front could be sustained over very long periods when the frost front progression was very slow and when surface heave did not occur, e.g. between 325 hours and 1250 hours (Manchester experiment #2, figure 4.4a and 4.4b).

Under conditions of surface heave (unconfined soil), increases in water intake reflected increases in suction at the ice front; this occurred as the ice pressure rose (experiment Caen #3, figure 4.3a and 4.3b). Such variations in pore water pressures are predicted by the Clausius-Clapeyron equation.

Once the frost front had passed the top of a transducer

and the soil froze gradually around the upper hemisphere of the device, significant normal tensile stresses were recorded. They appear as a negative slope after the double peak. Large lateral forces occurred because ice growth was resisted by the soil column sides and the device itself (the soil expands in all directions when freezing), and because the soil resistance was greater in the direction perpendicular to the freezing plane. The normal tensile stress decrease was relatively rapid in the top layers but extended longer in the mid-layers (over 50 hours) because the rate of zero isotherm progression declined (figures 4.2b to 4.4b).

Within any experiment the duration of the increasing tensile stress varied with depth due to different cooling rates. In addition, the tensile normal stress magnitudes recorded were independent of the soil cryotexture observed at the end of an experiment. For example, in experiment Caen #3, a tensile increase of appx. 240 kPa was recorded at 4.5 cm and 19.5 cm depth. However, the frozen silt column top part contained numerous small ice lenses while the middle section displayed a pattern of more widely spaced, larger ice lenses (refer to figure 2.1).

The experimental data indicate that the soil before freezing was much more sensitive to stress-modifying factors such as textural layers, adfreezing, freezing front penetration and moisture contents. The soil exhibited non-uniform stress fields with depth and time. Once the soil was

in the process of freezing only tensile stresses were recorded. The stress magnitudes were larger in mid-section when heave was impeded.

4.2.3 Petur pressure transducers

Modified piezometers were installed in the soil column for experiments Manchester #1 (devices anchored to the soil column wall) and Caen #2 (unanchored). These devices measure total stress or envelope pressure, i.e. any force generated by the water/ice or soil skeleton or a combination of both.

The anchored transducers used in experiment Manchester #1 show the influence of the measuring set-up (figures 4.5a and 4.5b). Generally, the anchored devices displayed much larger pressures increases and different patterns than the unanchored devices used in the Caen #2 experiment (see figures 4.6 and 4.11). This points out the unavoidable influence of the device set-up and of the size of the sensor surface on internally measured soil pressures.

Pressure rises were recorded by two transducers at the passage of the freezing front. Peak pressures attained 186 kPa (27 psi) at 25 cm depth, and 183 kPa (26.5 psi) at 35 cm depth (figure 4.5a and 4.5b). Prior to the rise, a slight increase in pressure was measured. This could be attributed to the downward pressure exerted by the soil matrix as the frost front approached, and/or to soil consolidation.

Surface heave ceased from about 400 hours until near the

Figure 4.5a: Pressure recorded at 25 cm depth for experiment Manchester #1.

Figure 4.5b: Pressure recorded at 35 cm depth for experiment Manchester #1.

end of the experiment at 2200 hours. Shortly before the end, the soil suddenly started to heave again (figure A2.3). While the soil was adfrozen to the sides of the column, the internal pressures were sustained over 1000 hours at both depths (25 cm and 35 cm). The pressure build-up occurred as the temperature slowly decreased to -0.5°C at the coldest transducer (35 cm depth).

The increase in pressure during adfreezing increased the pore water pressure, indicated by the minimal absorption of water from the burettes (figure A2.4). Water extracted from just below the frost front to the growing ice lenses, caused soil desiccation. This desiccation, added to the downward-transmitted heave component (no surface heave) could explain the slow ramped increase in pressure at 35 cm depth. Once heave resumed around 2200 hours the pressures dropped but did not return to their initial values.

In experiments done by Onysko (1988), using Manchester silt with an identical soil column set-up, similar maximum pressure values were obtained. Pressures of 172 kPa (25 Psi) at 25 cm depth and 310 kPa (45 Psi) at 35 cm depth were recorded (figure 4.6). In the present experiments, the maximum pressures 186 kPa (± 27 Psi) were sustained due to very small temperature gradients and adfreezing effects at the column sides. Because of the uneven stiffness of the rubber bulb, the modified transducer is more likely to record compressive normal stresses than tensile normal stresses.

(From Onysko, 1988)

Figure 4.6: Pressure measurements from modified Petur transducers.

At a different scale, a small frost heave cell containing Caen silt was used to assess the role of ice and frozen soil creep on the development of pressures and the magnitude of frost heave (Smith, 1992). Two small, anchored pressure transducers (2 cm long by 0.35 cm diameter) recorded peak pressures of 170 kPa (cold end, in frozen soil) and 30 kPa (warm end, in unfrozen soil). It was pointed out that these pressures were less than predicted by the Clausius-Clapeyron equation, assuming that the devices were recording P_i (Smith, 1992). Since the cell was maintained at temperatures of -0.5°C (cold end) and $+0.1^{\circ}\text{C}$ (warm end), this difference might be explained by the fact that ice was still actively growing, as the temperature of the growing ice lens cold end T_c , which value was measured in the present experiments, was not reached. Smith (1992) interpreted a pressure increase in the unfrozen soil as downward-transmitted heave stress. Possibly, the same mechanism explains the rises in pressure measured below the frost line by several Petur transducers in a large scale experiment in Caen silt (data in Geotechnical Science Laboratories, 1992).

4.2.4 Discussion

The experimental results provide evidence that compressive and tensile stresses are generated in the soil before and after the passage of the frost front respectively. Moreover, the array of instruments indicates that normal

tensile and compressive stress fields were sustained on either side of the frost front during freezing. The mechanical stress gradients in the soil are thought to cause moisture migration from regions of high to low compressive pressures or from regions of low to high tensile or shear stresses (Lundin, 1989; Ershov, 1995).

Coexistence of two stress states, from compression in the unfrozen soil, to tension in the frozen soil was demonstrated in a simulation model (Shen and Ladanyi, 1987). Figure 4.7 illustrates that stresses are zero somewhat behind the frost front, presumably where the warmest ice lens is growing. The data from experiments Caen #2, #3 and Manchester #2 support Miller's (1980) idea that the effective stress must be zero at the inception of an ice lens (figure 4.8). Peaks A and B in the stress/time curve show where the effective stress is zero (figures 4.2 to 4.4). In the next section, these peaks are examined in more detail.

4.2.5 Ice lens growth conditions from stress data

The temperature conditions of ice inception and growth were obtained by looking at the stresses at mid-column between points A and D (figures 4.9 and 4.10). The curve inflection at point A marks a slight change in stress between the unfrozen soil and the freezing front, while point B corresponds to the transition between the frozen fringe zone and the warmest ice lens. Ice segregation took place until point C.

(From Shen and Ladanyi, 1987)

Figure 4.7: Calculated stress fields in a freezing soil.

(From Miller, 1980)

Figure 4.8: Stress conditions in the frozen fringe.

Temperatures measured at the top of the device decreased from about -0.05°C at point A, to -0.87°C at point C (tables 4.1 and 4.2). Temperature values obtained at time A are interpreted as T_{ff} , the freezing front temperature. Slightly lower values, between -0.065°C and -0.09°C , were measured in Caen silt by Wood (1985).

A pronounced stress decrease took place between points B and C (figures 4.9 and 4.10). The inferred segregation temperatures T_s at time B, for experiments Caen #2 and Caen #3, at 16.5 cm and 19.5 cm depth, were -0.29°C and -0.25°C respectively. The colder segregation temperature for Caen #2 is ascribed to impeded surface heave due to adfreezing. The tensile stresses were sustained over long periods indicating that ice lenses continued to grow at temperatures lower than T_s , over a significant thickness of soil. This view is supported by many authors (Penner and Walton, 1979; Yoneyama et al., 1983; Ohrai and Yamamoto, 1985; Smith and Patterson, 1989; Ershov, 1995). At point C, the inferred cold end temperature T_c of a growing ice lens was attained (-0.80°C and -0.87°C). From that time on, the stresses were much reduced. According to figure 2.4, very little unfrozen water remains in Caen silt below -1°C .

From the strain data (section 4.3) between the times corresponding to points A to C, it is apparent that under conditions of no surface heaving, expansion occurred at T_{ff} and the frozen fringe was the heave "engine" as postulated by

Figure 4.9: Transducer signal, experiment Caen #2. The top of the device is at 16.5 cm depth. The large signal decrease indicating tensile stresses takes place between points A (257 hours) and C (304 hours). Temperatures measured at these and other times appear in the table below.

A	B	C	D	
257 hours	266 hours	304 hours	450 hours	
-0.05°C	-0.29°C	-0.87°C	-1.31°C	16.5cm (top)
0.44°C	0.29°C	-0.16°C	-0.77°C	21 cm (base)

Table 4.1: Measured temperatures at the top and base of the radio transmitting device located at 16.5 cm depth, experiment Caen #2.

Figure 4.10: Transducer signal, experiment Caen #3. The top of the device is at 19.5 cm depth.

A	B	C	D	
240 hours	288 hours	364 hours	455 hours	
-0.05°C	-0.25°C	-0.80°C	-1.02°C	19.5 cm (top)
0.41°C	0.26°C	0.03°C	-0.14°C	24 cm (base)

Table 4.2: Measured temperatures at the top and base of the radio transmitting device located at 19.5 cm depth, experiment Caen #3.

Miller (1980). However, when the soil surface was heaving, the ice lens was the heave "engine" of the soil because the soil layer enclosing a device began to expand when the top reached T_s .

After the large stress decline in experiment Caen #3, a weak tensile stress was sustained (point C to point D). Expansion of the layer of frozen soil in which the pressure device was embedded was recorded. Deformation continued as the temperatures at the device's top and base reached -1.02°C and -0.14°C respectively (point D). Thus, heave continued until the base of the device reached T_s .

For experiment Caen #2, no soil expansion was recorded at the level of the device between points C and D but the gradual slope could indicate stress relaxation. Due to the device configuration the frozen soil resistance could be measured only when the soil at the base of the device had reached the growing ice lens cold temperature.

Similar tensile stresses were also sustained in the top soil layers, under fairly low temperatures, such as -2.68°C for experiment Caen #3, presumably because stresses were not dissipated.

Figure 4.11 shows results derived from the unanchored Petur transducers. The pressures originate from ice growth, local soil conditions such as water expulsion (first 50 hours at 15 and 30 cm depth) and increase in effective stress due to downwards-transmitted heave (surface heave was impeded)

associated with water inflow (at 30 cm depth from 200 hours).

Similar to the radio transducers, the top Petur device, because of relatively rapid freezing and little overburden showed little pressure increase when the soil froze.

The transducer located at mid-column depth showed a more complex pattern. The approach of the freezing front was signalled by a slow rise in pressure of 17.2 kPa (2.5 psi), from 115 to 215 hours (figure 4.11).

Temperature conditions for secondary heave were inferred from figure 4.11 (table 4.3). The highest pressure was attained at 15 cm (at 215 hours, point B) at which time the segregation temperature T_s -0.28°C was reached at 13 cm this agrees quite well with the value of -0.29°C obtained using the radio-transmitting transducer at 16.5 cm depth).

A double peak (points B and C) characterized the approach of the freezing front. After T_s was reached, the pressure suddenly dropped and then rose again after 239 hours as the freezing front reached the base of the bulb. At 257 hours, the pressure decreased again, below confining values, when T_c (calculated as -0.85°C) was reached at the upper face. Interestingly, the highest pressures were due to downward-transmitted heave, not to segregated ice growth. Ice growth lifted the overburden from the rubber bulb which explains why the pressure at the end of freezing is slightly lower than the initial pressure.

Figure 4.11: Results of modified Petur pressure transducers in experiment Caen #2. Temperatures of the soil layer enclosing the device appear in the table below. Letters A to D are used to compare with the main stress trends recorded by the radio-transmitting transducers (see figure 4.2a).

A	B	C	D	
115 hours	215 hours	233 hours	239 hours	
-0.01°C	-0.46°C $T_s: -0.28^\circ\text{C}$	-0.68°C	-0.78°C	12 cm (13 cm)
0.42°C	0.07°C	0.14°C	-0.08°C	15 cm

243 hours	257 hours	333 hours	
-0.89°C	-1.13°C $T_c: -0.85^\circ\text{C}$	-1.87°C	12 cm (13 cm)
-0.04°C	-0.31°C	-1.16°C	15 cm

Table 4.3: Temperatures of soil layer enclosing the Petur transducer located at 15 cm depth. The base of the transducer is at 15 cm depth, and the top roughly at 13 cm depth. Temperatures at 12 cm and 15 cm were measured by thermocouples, at 13 cm they were calculated.

Possibly the same interpretation applies to earlier experiments by Onysko (1988) (figure 4.6). The increase in pressure corresponds to the approaching frost front (compressive normal stresses) and the ramped decrease in stress marks a change in stress field due to the establishment of a tensile stress which occurs after the piezometers reach temperatures of about -0.09°C .

4.3 Soil strains during freezing

4.3.1 Experimental conditions

In the strain graphs, each pair of gauges represents a soil layer nominally 3 cm in thickness. Due to soil infilling and compaction procedures, most gauge-pairs were separated by soil layers slightly more or less than 3 cm. The exact location of the strain gauges is taken into account in the analysis, but in the graphs and the discussion, a nominal placement interval of 3 cm is used for simplicity.

The strain gauges were positioned at 4 cm from the column wall in experiment Caen #2 and at 2 cm in experiments Caen #3 and #4. Thermocouples were placed at the same depths but were not attached. Therefore, some differential displacement of the sensors may have occurred. This is considered in the analysis. When the Caen #3 sample was sectioned, seven strain gauges were accidentally cut and exposed. Some gauges were tilted relative to the horizontal plane, to a maximum of 12° . The

error in strain sensitivity for a rotation of $\pm 10^\circ$ is not significant and is generally less than 10% for rotations below $\pm 20^\circ$ (Bison Instruments manual).

4.3.2 Typical deformation curve

Soil layer strains were similar for all the experiments done in Caen silt. The strain curve shown in figure 4.12 provides a model of the deformation of a soil layer as it froze progressively. This curve is typical of the mid-column layers (9 cm to the depth of maximum frost front final position) where periods of negative and positive strain occurred consecutively.

At the beginning of a freezing cycle, the soil layer displayed negative strain, indicating soil compression. Negative strains were largest at the start of an experiment (section a, figure 4.12). Then followed a transition period during which maximum compression was attained and the soil underwent only a slight negative strain while partly or totally frozen (section b). Depending on the experiment, these negative strain periods lasted from 10 to 100 hours.

Soil compression, or consolidation, results from the slow extrusion of water from pores and structural discontinuities (Liu and Evett, 1990; Whitlow, 1990). Under laboratory conditions, consolidation of an unfrozen soil occurs when the total normal stress is increased by an applied load while lateral deformation of the sample is prevented. In the absence

Figure 4.12: Schematic strain curve determined from the relative displacements of the strain gauges. It represents the deformation of a soil layer as it freezes. The expansive deformation may be divided in secondary and continuing heave (Schellekens, pers. comm., 1996). Primary heave is considered negligible.

of loading in the experiments the occurrence of negative strains throughout the soil column, from the beginning of a freeze cycle, points to the effects of cryosuction.

Before freezing, the total normal stress is constant. As the pore water pressure declines with the onset of negative temperatures, the effective normal stress becomes higher via an increase in intergranular contacts due to cryosuction. When the stresses generated by cryosuction exceed the preconsolidation stresses, the soil matrix consolidates.

Soil consolidation in a laboratory sample devoid of ice lenses was first reported by Williams (1963) and interpreted as the result of negative pore water pressures developed during freezing. Konrad (1989) observed consolidation in Devon silt, below the warmest ice lens, as a result of the increase in effective stress. This consolidation process affects the entire soil profile provided that the continuity of water films is maintained intact and no significant amount of air is present in the soil pores.

After the compression period, as the segregation temperature was attained, three distinct expansion phases characterized the layer: a period of large expansion (figure 4.12, section c) followed by a period of decreasing positive strain (section d) and a final period where little or no positive strain was measured (section e). Expansion periods of a soil layer (figure 4.12, sections c and d) varied from 70 to 190 hours.

The expansion of any soil layer begins when secondary heave takes place between two strain gauges. Primary heave or expansion due to pore ice freezing is considered negligible in these experiments. Secondary heave, or heave occurring in the frozen fringe/warmest ice lens zone, corresponds to the largest increase in gauge separation (figure 4.12, section c). Later, the gauge separation continues to increase (positive strain) but at a declining rate (figure 4.12, section d). Simultaneously, the spacing between the underlying strain gauge pair increases. These displacements show that section d defines continuing heave of the soil layer. In other words ice lens growth occurs beyond the warmest ice lens (figure 4.12, sections d and e).

Specific sections of this curve characterize the deformation of soil layers at other depths. The top soil layer (0-3 cm) expanded immediately at the onset of freezing (figures 4.13a and A2.17a). The soil layers further down (3-9 cm) displayed negative strains over a few hours only before expanding (figure 4.13b and A2.17a). Below the final frost front position, in soil which remained unfrozen, negative strains continued throughout the experiment (figure 4.13d).

4.3.3 Thermal conditions for secondary and continuing heave

To determine the thermal conditions under which secondary and continuing heave occurred, the temperatures measured at

Figure 4.13a: Top soil layer strain, experiment Caen #2.

Figure 4.13b: Strain of a series of soil layers, experiment Caen #2, from 3 cm to 15 cm depth.

Figure 4.13c: Strain of a series of soil layers, experiment Caen #2, from 15 cm to 24 cm depth.

Figure 4.13d: Strain of a series of soil layers, experiment Caen #2, from 24 cm to 39 cm depth. The soil remained unfrozen throughout the experiment.

each strain gauge pair location, for experiments Caen #2 and #3, were compiled (tables 4.4 and 4.5).

For experiment Caen #2, the temperatures measured at the end of the rapid expansion period (section c) at the upper strain device level, varied from -0.65°C to -0.92°C , while for Caen #3 the temperatures ranged from -0.67°C to -0.95°C . The ranges are similar to, and fall within the range of T_c values inferred from the radio-transmitting transducer data. The segregation temperature is reached either at the lower gauge or below. The strain data indicate that the largest heave occurred at temperatures between the T_{ff} and T_c down to temperatures approaching -1.0°C .

The temperature range for continuing heave can not be easily specified because the thermal gradient, unfrozen water content, frozen hydraulic conductivity and structural controls vary with each soil and with time. The occurrence of continuing heave is determined either by direct observation of ice lens growth in the frozen soil or indirectly from the strain devices. In the experiments, continuing heave, and the associated temperatures were assessed by looking at the period of simultaneous heave of two adjacent soil layers (refer to figure 4.12).

Expansion of a soil layer continued until the upper gauge reached temperatures around -1.07°C to -1.53°C and when the lower gauge attained temperatures between -0.66°C to -0.95°C with the exception of the 6-9 cm depth soil layer from

Depth (cm)	Expansion period (hours)	Temperatures (°C)		
		initial	end of section c rapid expansion	end of section d decreasing expansion
6-9	16.5-112	-0.90* 0.19	-0.65* -0.05	-0.76* -0.20
9-12	51-239	0.01 0.04	-0.71 -0.36	-1.17 -0.78
12-15	196-280	-0.22 0.27	-0.89 -0.04	-1.53 -0.73
15-18	243-312	-0.04 0.03*	-0.73 -0.64*	-1.07 -0.87*
18-21	284-448	-0.64* -0.54*	-0.92* -0.70*	-1.17* -0.84*
21-24	353-448	-0.75* -0.48	-0.84* -0.51	-----

Table 4.4: Temperatures measured at the strain gauge locations for experiment Caen #2. The depth of the gauges delimiting a soil layer are indicated in the left column. Refer to figure 4.13 to see at which times on the strain curve the temperatures were selected.

*: calculated temperatures

Depth (cm)	Expansion period (hours)	Temperatures (°C)		
		initial	end rapid expansion	end decreasing expansion
6-9	22-94	0.44	-0.78	-1.50
		0.51	-0.02	-0.95
9-12	46-144	0.02	-0.95	-1.25
		0.43	-0.28	-0.67
12-15	94-215	-0.28	-0.77	-1.31
		0.30	-0.15	-0.75
15-18	190-334	-0.30	-0.75	-1.27
		0.04	-0.30	-0.91
21-24	314-504	-0.14	-0.67	-----
		0.18	-0.14	

Table 4.5: Temperatures measured at the strain gauge locations for experiment Caen #3. Data missing for layer 18-21 cm because of readout failure.

experiment Caen #2. As the cooling continued, decreasing positive strains indicated a further depletion of unfrozen water for ice growth, at boundary temperatures between -0.7°C to -1.5°C , or at temperatures lower than T_c at the base of a soil layer. This defines the warm frozen soil conditions.

The strain data support the idea that the most significant stress changes (large tensile stress increase) correspond to the largest soil deformations or to secondary heave. Stress signal variations recorded in periods of continuing heave were minimal.

4.3.4 Strain magnitudes

Strain values for each individual soil layer for experiments Caen #2 and Caen #3 are shown in tables 4.6 and 4.7. The negative strains range between 0.6% to 16.6%. The positive strains range between 0.6% and 26.9%. Strain magnitudes vary from one experiment to another due to differences in experimental conditions such as initial water content, thermal gradient and freezing duration.

Because significant negative strains took place at the onset of freezing, the ensuing positive strains reflect only the apparent expansion due to absolute values of ice growth. The real soil expansion is the sum of the negative and positive strains, and appears in the last columns of tables 4.6 and 4.7 as the net final strain. For example, for experiment Caen #3, table 4.7, the real expansion of soil

Soil layer (cm)	Initial thickness (cm)	Negative strain (%)	Positive strain (%)	Net final strain (cm)
0-3	5.84	0	0.61	+ 0.03
3-6	2.37	0	9.93	+ 0.23
6-9	2.82	- 0.6	14.36	+ 0.42
9-12	2.69	- 2.77	24.64	+ 0.74
12-15	3.12	- 5.68	5.18	+ 0.34
15-18	2.76	- 6.45	5.00	+ 0.32
18-21	2.69	- 5.88	10.28	+ 0.43
21-24	2.42	- 6.19	6.20	+ 0.30
24-27	2.70	- 9.36	--	--
27-30	3.09	- 5.82	--	--
30-33	2.20	- 5.23	--	--
33-36	2.46	- 5.13	--	--
36-39	3.26	- 4.46	--	--

Table 4.6: Negative and positive soil strain values (3 cm layers), experiment Caen #2. The last column is the net increase in thickness of the layer.

Soil layers (cm)	Initial thickness (cm)	Negative strain (%)	Positive strain (%)	Net final strain (cm)
0-3	3.13	0	11.9	+ 0.37
3-6	2.85	- 2.3	14.8	+ 0.55
6-9	2.36	- 5.3	17	+ 0.53
9-12	2.31	- 6.2	18.7	+ 0.57
12-15	2.40	- 7.8	26.9	+ 0.83
15-18	3.21	- 14.9	5.1	+ 0.64
18-21	2.63	- 10	13.7	+ 0.62
21-24	2.57	- 9.7	26.2	+ 0.92
24-27	3.24	- 16.6	1.6	+ 0.59
27-30	2.13	- 15.1	--	--
30-33	3.67	missing data	missing data	--
33-36	2.10	data	data	--
36-39	2.07	- 7.5	--	--

Table 4.7: Negative and positive soil strain values (3 cm layers), experiment Caen #3.

layer 15-18 cm is 20% or 0.64 cm, compared to the apparent expansion of 5.1% or 0.16 cm.

This implies that a change in pore geometry occurs below the progressing frozen fringe and that the final moisture content of the frozen core will be in excess of the amount of heave.

4.3.5 Deformation processes during frost heave

The deformation of the soil column on either side of the freezing front is obtained by adding soil layer strains above and below the advancing freezing front (figures 4.14 and A2.19). The strains reflect the different stress conditions.

In the early freezing stages, steep temperature gradients prevailed (for example $-0.31^{\circ}\text{C}/\text{cm}$ at 12 hours in experiment Caen #2). Results from the early stages (0 to ± 90 hours) of experiments Caen #2 and #3 show that total soil consolidation exactly compensated for the total soil expansion (figure 4.14 and A2.18). At least 25% of the total soil consolidation took place within the first 24 hours. This contradicts the opinion that cryosuction effects are measurable only when the freezing rate is slow and when significant ice lenses have time to grow. Minimal water intake occurred during the first 24 hours showing that the soil consolidation yielded water to growing lenses (less than 20 ml for Caen #2 and Caen #3). The consolidation effects are indicated by the negative strain rates below the frost line (figure 4.15 and A2.19a). The

layers closer to the surface showed larger negative strain rates. A similar process, where volume increase due to ice lens formation was compensated by soil compression, was observed in clays by Eigenbrod et al. (1996).

Later in the freezing cycle, from 24 to 90 hours (figure 4.2a) significant water expulsion occurred and coincided with a decline in the freezing rate. Water expulsion occurred because the void ratio decreased below the frost line, making locally extruded water available to feed very small ice lenses; because a small portion of soil was freezing compared to a large portion of unfrozen soil consolidating, excess porewater was generated and expelled ahead of the freezing front.

In the first 2 to 3 days of the freezing cycle, the water flows (intake/expulsion) were opposite to the expected flows with respect to the freezing rates because of rheologic controls. Stresses in the unfrozen soil favoured primary porosity loss as the large packing pores and capillaries drained and closed.

After 2 to 3 days of freezing, declining temperature gradients occurred ($-0.15^{\circ}\text{C}/\text{cm}$ and $-0.03^{\circ}\text{C}/\text{cm}$ for experiments Caen #2 and #3 respectively), and while consolidation continued it did so at a much slower rate (figure A2.19b). Soil expansion became larger than consolidation. The uninstrumented silt portion could account for this discrepancy but slower consolidation rates suggest secondary consolidation

Figure 4.14: Soil expansion and compression on either side of an advancing freezing front.

Figure 4.15: Negative strain rates, Caen #2

from extraction of unfrozen water by cryosuction effects in the advancing frozen fringe. Large water intakes were recorded after about 150 hours in Caen experiments #2 and #3, signalling a change in suction to compensate for the reduction in hydraulic conductivity. At this stage of soil freezing, the prevailing influence of the frozen fringe characteristics and conditions on water flows is apparent. Maximum consolidation was attained ahead of an expanding soil layer. Soil moisture was depleted to a significant depth (2 cm to 5 cm) below the frozen fringe. Similar considerable contraction caused by desiccation of the soil layers up to 2 cm below the frozen fringe was noted by Ershov (1995). Tsytovich (1975) had identified the compressibility of soil layers below the frost line as a main influence on the magnitude of normal frost heave forces.

4.4 Summary and refinements of frost heave criteria

Internally measured "tensile" (i.e. expansive, with a larger orthogonal to heat flow component) and compressive stresses were recorded simultaneously while heave of the surface occurred. Below the advancing freezing front, normal compressive stresses were caused by consolidation due to cryosuction and downward-transmitted heave stress. Sensitivity of the soil to stress modifiers such as adfreezing (confinement), rate of zero isotherm progression and textural

differences was larger before freezing.

Changes in the stress fields occurred at the frost front and at the base of the warmest ice lens. It appears the effective stress becomes zero at both these levels. Miller (1980) has proposed that the effective stress reaches zero at the cold end of the frozen fringe.

In the frozen fringe and warm frozen soil zones, the radio-transmitting transducers recorded significant normal tensile stresses. The segregation temperatures inferred from the experiments were between -0.26°C and -0.30°C . The warm frozen soil zone sustained larger (expansive) tensile stresses than compressive stresses. Vertical and horizontal components of heave were also noted by Smith (1992) during ice segregation.

Pressure transducer configuration play an important role as to the nature of measured deformations. For example, the unanchored pressure transducers recorded much smaller stresses than the anchored transducers. Uncertainty as to the nature of the contacts between sensors and the soil components (ice, water, mineral) prevents an in-depth analysis of measurement artefacts. The results also underline the difficulty of measuring P_i uniquely; the recorded stresses were small and soil/ice matrix stresses were measured only in two directions by a device representing a relatively large inclusion in the soil. One would need many very small sensors oriented in different directions, mimicking the surfaces of a few quartz

grains to obtain a picture of the stresses acting in the soil at the level of an ice lens.

Freezing of the soil also resulted in differential deformations. Zones of compression and expansion developed simultaneously as the freezing front advanced. While the strain data were in good agreement with the stress data, the stresses measured were not very large, in contrast to the magnitude of consolidation and expansion. Net layer increases of 0.23 cm to 0.92 cm were measured for soil layers averaging 3 cm in thickness. Ice segregation took place over a thickness of soil as shown by stress and strain data. Soil expansion was caused by secondary frost heave and continuing heave, but the largest positive strains were produced within a frozen zone at temperatures below -0.65°C and -0.95°C . No significant heave took place below temperatures of -1.07°C to -1.53°C .

At the beginning of a freezing cycle, consolidation of the unfrozen soil zone was significant (primary porosity loss) and water expulsion was observed. Therefore, modification of the soil matrix occurred even before the freezing front arrived. Later during freezing, consolidation below the warmest ice lens was localised within the frozen fringe (secondary consolidation) and depended on the ice pressure variations. The resulting soil structuration was visible as macro cryozones (Chapter 6). The experimental results do not support a simple rhythmic ice lens model because they show that the stress environment varies with depth.

CHAPTER 5 : STRESSES AND DEFORMATIONS DURING FREEZE-THAW CYCLES

5.1 Introduction

In this chapter, results from experiment Caen #4 are analysed to assess the development of stresses and strains under freeze-thaw conditions. This soil was subjected to two consecutive freeze-thaw cycles followed by a single freeze cycle, for a total duration of 1482 hours. Stress changes were monitored by two radio-transmitting transducers located at 4 cm depth and at 16.5 cm depth. Figure A3.1 of Appendix 3 provides the details of the experimental apparatus.

5.2 Stress patterns during freeze-thaw cycles

The results obtained from the radio-transmitting transducers during the freezing portion of the freeze-thaw cycles were similar to the experiments described in Chapter 4. The stress pattern resulting from repeated freezing displayed the same general trends as the model curve obtained from a single freezing cycle (figure 4.1). Essentially, compressive normal stresses occurred in the unfrozen soil before the freezing front passage (figure 5.1, phases b and c of the

curve), and tensile stresses were recorded after the freezing front passage. However, after the soil had been submitted to one freeze-thaw cycle, two new stress trends developed: a short stress decrease in the unfrozen soil, measured by both devices, and a significant compressive stress, recorded in the frozen soil at 16.5 cm depth (figures 5.2 and 5.3 phases a and d of the curve). Both trends reflect changes in soil structure, as will be seen further.

Unlike freezing where several changes in the stress field occurred, the stress curves obtained during thaw show a simpler pattern. After a sharp drop in stress build-up at the onset of thaw, there was a two-fold stress increase (figures 5.1 and 5.2, phases e and f of the curve).

5.2.1 Stress and deformation during freezing

Chronologically, the sequence of stresses may be described as follows. At the start of the freezing cycles #2 and #3, stresses decreased below the advancing frost line (figures 5.2 and 5.3, phase a). During this period, water was expelled from the soil column base. Near the top of the column, stress decreases (tensile stresses) exceeding 100 kPa were associated with negative soil strains. These ranged from approximately 2.3 mm to 5.2 mm per 3 cm layer, compared to negligible negative soil strains at the beginning of freezing cycle #1 (figures 5.5 and 5.6).

Figure 5.1: Radio-transmitting transducer data for experiment Caen #4, Freeze-thaw cycle #1. Sections b to f refer to the major stress trends.

Figure 5.2: Radio-transmitting transducer data for experiment Caen #4, freeze-thaw cycle #2. Sections a to f refer to the major stress trends.

Figure 5.3: Radio-transmitting transducer data for experiment Caen #4, freeze cycle #3.

In the soil column mid-layers, stress decreases during phase a were less than 15 kPa and caused little soil consolidation (less than 1%).

Compressive stresses were recorded around 16.5 cm depth, in the unfrozen soil. The stresses peaked at 109 kPa during the first freezing run (figure 5.1), 121 kPa and 129 kPa during freezing runs #2 and #3 respectively (figures 5.2 and 5.3, phase b). Simultaneously, negative strains of 3.5% to 4% (compared to 7% for run #1) for cycles #2 and #3 respectively, were observed in the unfrozen soil layers until the temperature dropped below 0°C.

Once the soil near the transducer at 16.5 cm depth began to freeze, large tensile stresses of 146 kPa and 129 kPa were recorded for freeze cycles #2 and #3 respectively (figures 5.2 and 5.3, phase c). In the top part of the column, minor tensile stresses continued until the experiment was terminated, but positive strains were not detected over that period.

Finally, from the mid-freezing point to the end, large compressive stresses developed again, but only in the frozen soil above the heaving layers (figures 5.2 and 5.3 phase d).

The stress phases are interpreted as follows:

Phase a

Phase a of the stress curve relates to changes in soil structure caused by previous freezing. The short stress reversal recorded by the devices once the top few centimeters

of soil began freezing is associated with the onset of secondary compaction. The compaction stresses are alike desiccation and produced tensile stress around the device. At the end of freeze-thaw cycle #3, the soil had developed a complex microstructure of prismatic/platy aggregates and of voids representing 20% to 30% of the thin section area (Appendix four). The strain data shows that a similar structure had developed after freeze cycle #1; for the upper 15 cm of soil, they indicate a reduction in pore space as the upper three centimeters of soil froze (figures 5.4 and 5.5). Water was expelled for about 2 days. These positive pore pressures dissipated slowly because of lateral confinement and consolidation of the unfrozen silt after the first freezing run. Furthermore, water expulsion may have contributed to the translocation of fines to the bottom part of the column, changing the grain size distribution.

Compaction ahead of the freezing front accounts for the largest negative strains in the soil layers between 3 cm and 15 cm depth. Pore space reduced ahead of the freezing front caused up to 17% soil compaction at the top of the column, compared to 1% compaction around 16 cm depth. Further down in the soil, compaction continued after the water flow was reversed and as the frost line progressed.

Phase b

Increasing compressive stresses recorded in the unfrozen soil can be related to the downward stress originating from

ice growth in the upper layers, and to cryosuction which caused additional soil consolidation close to the frost line. At 16.5 cm depth, the compressive stress was roughly equal in magnitude for freezing runs #2 and #3 which may indicate that the soil, after one freeze-thaw cycle, attained its maximum unfrozen soil compressive strength. Soil consolidation was about 3.5%. Deformed vesicles and degenerated vesicle rings observed in the soil thin sections demonstrate that the mineral matrix recorded compressive stresses.

Phase c

In the soil mid-section, the tensile stress due to ice segregation decreased slightly with each freeze-thaw run and the positive strain was much less in freezing runs #2 and #3 (figures 5.2 and 5.3). These variations in positive strain are unrelated to total water intake but reflect the soil microstructures which developed during freeze-thaw cycling. Between 12 and 22 cm depth, a very dense soil matrix was observed with fine planar pores (the location of thin ice lenses, approximately 0.5 mm). Likely, the soil mid-section did not grow larger ice lenses because of a decrease in unfrozen water content due to loss of fine mineral fraction. Moreover, the vughy pore structure did not favor moisture migration to the lenses because it held capillary water, not adsorbed water, and also because the pores were not interconnected.

The top layers showed an increase from 12.9% to 18.4 % in

positive strain with the number of freeze-thaw cycles (figures 5.4 to 5.6). At the end of the experiment two large ice lenses were observed across the top of the sample.

Phase d

In the warm frozen soil zone, near the end of the freezing run, the stress field became largely compressive as the bottom layers heaved and stress was transmitted through the ice/soil matrix from the expanding layers at the base, to the mid-layers (figures 5.2 and 5.3, section d). Stresses did not dissipate as very little heave took place at the surface due to soil adfreezing along the column sides. Also, thinner ice lenses than in the previous experiments may have led to less stress being released by ice creep. The ice lenses were separated by platy soil aggregates of uniform thickness across the column.

At the base of the column, the unfrozen soil layers became more consolidated with each freeze-thaw cycle.

5.2.2 Ice growth at the frozen front final position

Towards the end of freeze cycle #3, around 1274 hours, a variation in the water level was induced by refilling the water burettes (figure A3.12). Following this, a large water intake of 400 ml occurred but did not cause a soil profile warming (figure A3.10b, Appendix 3). Positive strains recorded at the base of the frozen soil core indicate a significant permeability despite the underlying consolidated unfrozen soil

layers. Two ice lenses grew at the frost line final position, resulting in an ice-rich zone towards the base of the column between 27 cm and 33 cm depth (figure 5.3, section d). The temperature conditions at growth were nearly isothermal (figure A3.10b). The segregation temperatures can be compared for both lenses at the inception of large positive deformations. The temperatures measured at the upper strain gauges were -0.27°C and -0.24°C at 27 cm and 30 cm respectively. This compares to the T_g of -0.25°C and -0.29°C of the other experiments. The ice lens at 27 cm depth was still actively growing when ice accumulated simultaneously at 30 cm (figure 5.7). This generated compressive stresses in the cold frozen upper soil zone as seen in figure 5.3.

5.2.3 Stress and deformation during thaw

In contrast to the stresses developed during freezing, the thawing stresses were uniform with depth and over time. The stress-time curve showed a two-fold compressive stress increase for both the top and the middle devices (figures 5.1 and 5.2, phases e and f). The stresses recorded at the end of the thaw cycle were approximately the same as the initial stresses.

The first section of the stress curve (figures 5.1 and 5.2, phase e) corresponds to the gradual thawing of the frozen core; the inflexion point marks complete thaw. The increase in compressive stress began once the cooling bath was turned off.

Figure 5.4: Soil strain for layers at 1 to 3 cm depth, for each cycle.

Figure 5.5: Soil strain for layers at 3 to 15 cm depth, for each cycle.

Positive strains were measured throughout the soil column from 0 cm to 24 cm depth for thaw cycle #1, and from 0 cm to 30 cm depth for thaw cycle #2 indicating growth and/or enlargement of ice lenses. The total expansion values per soil layer after freezing and thaw refreezing are compared for each freeze-thaw cycle (table 5.1). Data compiled in table 5.1 shows that heaving during the thaw cycle represents a significant percentage of the total soil layer expansion.

During freeze-thaw cycle #1, the growth of segregated ice during thaw accounted for 11.1% to 54% of the total expansion of the soil layers. The increases in soil layer thickness took place over very short periods of time: about 70 hours for thaw run #1 (compared to 190 hours for the freeze run) and 85 hours for thaw run #2 (409 hours for the freeze run).

The deformation values due to ice growth during thaw for freeze-thaw cycle #2 reached 10.7% to 91.6% of the total expansion by soil layer. More upwards water migration during ice formation at thaw explains the larger proportion of heave in cycle #2 (72 ml for freeze-thaw cycle #2 compared to 22 ml for freeze-thaw cycle #1). This water was available for ice growth at both thaw fronts. The maximum positive thaw deformation was measured between 18-21 cm depth. Ice grew as water migrated up from the unfrozen zone to the lower thaw front, and percolated downwards from the thawing surface to

	Freeze - thaw cycle #1			Freeze - thaw cycle #2		
Depth (cm)	Freeze expan. (mm)	Thaw expan. (mm)	Thaw expansion (% of total)	Freeze expan. (mm)	Thaw expan. (mm)	Thaw expansion (% of total)
0-3	4.6	0.6	11.5%	5.8	0.7	10.7%
3-6	2.1	0.5	19.2%	1.95	1.18	37.6%
6-9	1.6	0.9	36%	1.38	0.8	36.6%
9-12	1.1	1.3	54%	2.0	2.0	50%
12-15	1.4	0.6	30%	0.4	0.9	69.9%
15-18	1.4	0.3	17.6%	0.3	0.5	62.5%
18-21	0.8	0.1	11.1%	0.1	1.1	91.6%
21-24	0.9	0.2	18.1%	2.4	1.0	29.4%
24-27	unfrozen soil			1.6	0.4	20%
27-30				0.6	0.4	40%

Table 5.1: Soil layer expansion due to ice segregation during freezing and during thaw (refreezing ice).

the upper thaw front. As the ice grew near both thaw fronts, normal compressive stress fields developed simultaneously around both devices embedded in the frozen soil, demonstrating that stresses at thaw can be divided into two unequal components of stress. Part of the ice pressure created by ice growth was released by heave of the upper thawed layers while the other part was dissipated by compression of the soil below the growing ice. Compressive stresses tended to decrease as more and more heave was dissipated upwards, with less resistance by adfreezing, as shown by the inflection leading into the second portion of the stress-time curve. In other experiments on silty clays, most ice segregation during thaw took place between 0°C and -0.35°C (Solomatin and Xu, 1994).

The second section of the stress curve occurred in thawed, warming soil (figures 5.1 and 5.2, section f). The overall increase in normal compressive stresses may be linked to an increase in the total weight of the overlying soil. The water intake curve indicated a net upwards water intake movement, most likely due to soil aggregate rewetting.

The final stress values at thaw increased from one cycle to the next for approximately the same water intake. At the end of the first thaw cycle, the stresses were 175 kPa (4 cm depth) and 30 kPa (16.5 cm depth). By the end of the second thaw cycle they were 275 kPa (4 cm) and 75 kPa (16.5 cm). This may indicate a gradual decrease in soil strength with the

number of freeze-thaw cycles, i.e. the supportive strength of the matrix decreased.

In the unfrozen zone, while segregated ice grew at the nearby thaw front and heave was recorded, soil consolidation ceased and in some layers a slight positive strain was recorded, indicating an increase in water content and perhaps a swelling of clays. The clay content of Caen silt ranges between 10 % to 20 % and tests on the silt indicated the presence of smectite, illite and kaolinite clay minerals (White, 1992). Kaolinite does not expand significantly with increasing water content but illite and particularly smectite exhibit swelling properties.

The experimental data shows that significant amounts of frost heave can accompany thaw. This may damage structures buried in seasonal freezing areas as soil layer expansions of up to 54% were measured. Growth of ice during thaw has been measured in field sites in permafrost zones by increases in soil water content (Guodong, 1983). Moisture migration in laboratory experiments on thawing soils caused ice segregation and increases in soil thickness of 1.9 mm (low water content) to 5.5 mm (high water content) for samples 20 cm in height by 10 cm in diameter (Solomatin and Xu, 1994). In the present experiments, it is demonstrated that soil compression in the unfrozen soil can mask the real magnitude of frost heave during thaw, particularly when deformation is recorded only at the soil surface.

Loss in total strength at thaw was significant after a single freeze-thaw cycle. Damage to civil structures may be caused not only by increases in moisture content at thaw, but by the changes in soil structure which will also destabilize the soil and decrease its strength (Booth, 1981).

5.2.4 Total soil strain

Deformation features for the upper 36 cm of the soil column for the freeze-thaw experiment are shown in figure 5.8 and compared to the total water intake in figure 5.9. While different strain budgets were observed by layer level, the net effect of the freeze-thaw cycles was an increase in soil volume. With each cycle, the negative strains at thaw became larger while the amount of positive strain during freezing remained about the same. The total water intake increased for each cycle: 22.2 ml (#1), 72.2 ml (#2) and 395.8 ml (#3) (see figure A3.1) but the significant water intake most likely contributed to the growth of the larger lenses at the base of the frozen soil.

The freezing-induced microstructures became permanent at the end of the first freeze-thaw cycle and the soil profile displayed complex pore structures and leaching of fines at and below the frost line lowest position. The surface heave measurements do not reflect the increase in soil column length of nearly 6 cm. The total heave measured at the surface was very small (0.44 cm, for freeze-thaw cycle 1, 0.28 cm for

Figure 5.8: Soil column strain.

Figure 5.9: Total water intake.

freeze-thaw cycle 2 and 0.28 cm for freeze-thaw cycle 3). It is possible that some of the heave was balanced by compression of the uninstrumented silt. Such a phenomenon was observed in clays where volume increases due to ice lensing and volume decreases due to soil compression (via rises in effective stresses) cancelled each other out and resulted in zero net heave (Eigenbrod et al., 1996).

5.3 Overview

In the freeze-thaw experiment, the stress pattern was uniform at thaw when ice growth from moisture (or ice) migration took place, but at freezing, different stress trends were observed. Zones of different stress conditions developed on either side of the freezing front as with the freezing only experiments, but after one freeze-thaw cycle, structures developed in the soil which favored new stress trends.

The silt, which was presumably mostly structureless at the start of the experiments (with the exception of some compaction discontinuities), developed a complex porosity (voids and cracks), textural changes (migration of fines) and long platy units. These microstructures altered the rheological properties of the soil and caused directional and magnitude changes in the development of stresses during freezing.

Cryosuction effects on the soil matrix were detected by the radio-transmitting devices at freeze run #2 and onwards at mid-depth. The cold frozen soil recorded significant compressive stresses from heave of the base layers and little stress relaxation occurred. The number of freeze cycles affected the magnitude of stress in tension but not in compression. Tensile stresses were generated either during negative or positive soil strains. Frozen compressive stresses were smaller than the unfrozen compressive stresses. The largest tensile stress were recorded in the unfrozen soil in the top layer while in the mid-layer the largest tensile stress was recorded in frozen soil.

While different strain zones (expansive and compressive) developed within the soil profile, the net deformation of the frozen core was positive.

CHAPTER 6 : FROZEN SOIL MICROMORPHOLOGY

6.1 Introduction

The experiments conducted on Caen silt yield direct evidence of the types of soil fabrics and features associated with freezing and thawing conditions. They provide some valuable insights to the interpretation of the processes leading to cryogenic fabrics and features in fine-grained soils. The samples collected from experiment Caen #3 underwent a single freeze cycle. Samples taken from Caen #4 were subject to two freeze-thaw cycles and a freeze cycle; therefore, they contain signatures of both thermal conditions.

In the first part of the chapter, typical fabrics and features of both experiments are outlined. In the second part, stress/strain zones are delineated and compared to the cryostructures of Caen #3 and Caen #4. Finally, the influence of fabric on deformation characteristics of the silt subjected to freeze-thaw cycles will be discussed.

6.2 Description of thin sections

6.2.1 Microscope investigation

The location and identification numbers of the samples taken from the frozen silt are given in figures 6.1 and 6.2. From the 6 soil samples taken from experiment Caen #3, 15 thin sections were prepared (figure 6.1). The changes in structure with depth, as well as horizontally within a layer, could be assessed. A total of 21 thin sections were made using the 8 samples of experiment Caen #4 (figure 6.2). Of the 2 samples from Caen #1, 4 thin sections were prepared.

To describe the different fabrics, several levels of observation were used. Macroscale observations were made by using slides of the slabs illuminated with natural and longwave ultraviolet light. Next, the overall microstructure of the slabs and thin sections was examined under a standard Olympus stereomicroscope with a Burton medical light at low magnifications ranging from 10x to 40x. The thin sections were then examined under magnifications of 50x to 320x under transmitted and cross-polarized light using a Wild M400 microscope. Microscope photographs of the thin sections were taken at different magnifications. The thin section descriptions were made according to the systems of Brewer (1976) and Bullock et al. (1985). Specific fabric terms developed by Fox and Protz (1981), Stoops and Jongerius (1975)

Kubiena box	
Sample number	Depth (cm)
C3/1	1-8.5
C3/2	9-16.5
C3/3	9-16.5
C3/4	20-26.5
C3/5	20-26.5
C3/6	27.5-34

Slab number	Thin section
C3/1/5	a*
C3/1/3	d, e
C3/2/2	b
C3/2/5	c
C3/3/2	b
C3/3/6	c
C3/4/4	a
C3/4/6	c
C3/5/2	a, b
C3/5/7	c, d
C3/6/3	a
C3/6/5	b

* : The lower case letters represent a thin section made within the slab. The complete thin section number is

C3 / 1 / 5 a
 box slab thin section

Figure 6.1: Location and identification numbers of samples for experiment Caen #3.

Frozen soil half-cylinder face (scale 1:3.3)

Kubiena box	
Sample number	Depth (cm)
C4/1	1-8.5
C4/2	9-16.5
C4/3	9- 16.5
C4/4	17-22
C4/5	22-27
C4/6	27.5-32.5
C4/7	19.5-27
C4/8 [*]	40-46.5

^{*}: Sample not illustrated on diagram.
It was taken in the unfrozen soil at room temperature

Slab number	Thin section
C4/1/9	b ^{**}
C4/1/2	c, d
C4/2/5	a
C4/2/2	c
C4/3/6	b
C4/3/9	c, d
C4/4/Lt	a
C4/4/3	c
C4/5/4 Hz	a, b
C4/5/2	c, d
C4/6/7	a, b
C4/6/5	c
C4/7/6	a
C4/7/2	d
C4/8/3	a
C4/8/5	d

^{**} The lower case letters represent a thin section made within the slab. The complete thin section number is

C4 / 1 / 9_{box} b_{slab thin section}

Figure 6.2: Location and identification numbers of samples for experiment Caen #4.

and Brewer and Pawluk (1975) were also used. A short glossary of the micromorphological terms used in the descriptions is provided at the end of the thesis.

6.2.2 General observations

Macroscopically, the cryotexture of the frozen soil core of Caen #3 experiment was very different from the core of Caen #4 experiment, as shown in figures 6.3 and 6.4. Many ice lenses, ranging from 0.5 mm to 3 mm in thickness, were observed in the frozen sample of Caen #3, while Caen #4 contained mostly very thin ice lenses equal or less than 1 mm in thickness with larger ice lenses located near the top and at the bottom of the frozen core.

Because identical conditions were not achieved for both experiments during their first freezing run (see section 4.3.2b), it is not possible to view the cryotextures of Caen #3 and Caen #4 as a sequence. However, specific fabrics and features can be associated with the thermal conditions within each experiment regardless of other conditions.

6.2.3 Vertical zonation

At a macroscale, distinct cryogenic soil zones were delineated for experiments Caen #3 and #4. Five zones for Caen #3 (four frozen and one unfrozen) and six zones for Caen #4 (four frozen and two unfrozen) were outlined on the basis of planar void dimensions and attitude, aggregation and porosity.

These zones are outlined in figure 6.5. A detailed thin section description for each cryogenic zone appears in Appendix four. A description of one thin section from experiment Caen #1 is also included in Appendix four to illustrate the fabric resulting from rapid soil freezing.

The micromorphological and macroscale observations showed a very close correspondence. This provides indication that the zonation made at a larger scale is relevant at the microscale. Based on the thin section descriptions, the cryogenic attributes characteristic of each set of experimental conditions were compiled.

6.3 Cryogenic fabrics and features

6.3.1 Fabrics resulting from a single freeze cycle

The soil from experiment Caen #3 showed a strongly developed grade of aggregation. Fragmoidic, fragmic and platy fabrics were dominant as a direct result of segregated ice growth (figures 6.3 and 6.6). Such fabrics were first described by Brewer and Pawluk (1975) but it was not clear at the time if they originated from freeze-thaw processes. Later, such granic and fragmoidic fabrics were generated experimentally by freeze-thaw cycles in initially unstructured soils (Pawluk, 1988). They were also observed in Caen silt after four freeze-thaw cycles (White, 1992) and in permafrost soils (Tarnocai et al., 1993).

Figure 6.3: Cryotexture of experiment Caen #3. The lenses, shear zone, rounded aggregates and numerous rounded vesicles were produced after 1 freeze run (no thaw). Smallest square is 0.5 mm (9 cm to 16.5 cm depth) (ultraviolet light).

Figure 6.4: Cryotexture of experiment Caen #4 after 3 freeze, 2 thaw runs. The vesicles are deformed within thin platy aggregates. Larger lenses are located in the packing layers. The sample covers a transition between two cryogenic zones; notice the more compact structure at the base of the picture (9 cm to 16.5 cm depth) (ultraviolet light).

Figure 6.5: Cryogenic zones for experiments Caen #3 and Caen #4.

Figure 6.6: Soil aggregates delimited by smooth, partly accommodated planar voids (Caen #3, C3/2/2b). The aggregates were created after one single freeze cycle (no thaw) (9 cm to 16.5 cm depth) (normal light).

Figure 6.7: In the unfrozen soil, two parallel planar voids due to packing; they have unaccommodated sides and show variable widths (Caen #4, C4/6/2). Note the presence of vesicles (smallest square equals 0.5 mm) (40 cm depth) (ultraviolet light).

From the present experiments, it appears that fragmoidic, fragmic and platy fabrics may be generated in an initially unstructured, saturated soil, by a single freeze cycle. Intense ice segregation was also apparent from the abundant moderately accommodated planar voids which had smoothed walls, formed presumably from the ice pressures on the soil matrix. These planar voids are unlike the compaction planar voids found in the unfrozen soil which show irregular walls and variable widths (figure 6.7).

Abundant vesicles were observed throughout the profile, including the unfrozen soil (figures 6.7 and 6.8). Vesicles result from the expansion and movement of gas (air) bubbles (Brewer, 1976); the causes for air entrapment and movement appear multiple. Van Vliet-Lanoë (1988) explains their origin by air expulsion during thaw, while Bunting (1977) believes they originate either by soil drying or by pressures due to movements in the freezing active layer. Harris (1983) demonstrated that vesicles originated from thixotropic soil wetting and that freezing was not necessary.

Such a process explains the presence of vesicles in experiment Caen #3, as they are definitely not a thaw feature. These round voids originated during soil wetting to moisture conditions around 17.5%, which corresponds to the lowest part of the Proctor normal test curve. Many of the vesicles were arranged in a circular pattern. This could indicate air expulsion around small (dry) soil aggregates during wetting.

The vesicles were subsequently weakly altered by ice segregation. Those in the frozen soil had very smooth walls compared to the vesicles in the unfrozen soil, indicating they had been modified by ice growth. Preferential nucleation of ice in the vesicles was also apparent from the thin ice lenses that radiated from the vesicles (figure 6.8). This was observed in the first 9 cm of soil where freezing was relatively rapid.

The soil profile was characterized by an orbiculic fabric throughout, even in the unfrozen soil, although it was a rare occurrence in that zone (figures 6.8 and 6.9). Orbicular arrangements have been described from natural soils (Fedorova and Yarilova, 1972; Fox and Protz, 1981) although no specific mechanism has been proposed for this fabric.

Reorganization of the coarse and fine fractions occurred during freezing of the silt. Textural pedofeatures such as quartz grains plastered around vesicles were observed. Striated fabrics (sepic fabrics) were also a dominant arrangement of the fine fraction (figure 6.9). Striated fabrics were also observed in the unfrozen soil. This type of fabric may be attributed to stresses generated by cryosuction below the freezing front. Furthermore, it appears that striation resulted from slow freezing. No such fabrics were observed in experiment Caen #1 which froze very rapidly and where only asepic fabrics were generated (see figure 6.13).

Figure 6.8: Near the soil column top, rounded vesicles which may have been the site of ice nucleation and propagation as shown by the planar pores (Caen #3, C3/1/3e). Note the orbiculic fabric, (1 cm to 8.5 cm depth) (crossed-polarized light).

Figure 6.9: Compact aggregates between thin ice lenses loci (Caen #4, C4/4/3c). Stippled-speckled granostriated fabric. Orbiculic fabric and some vertical alignment of grains (9 cm to 16.5 cm depth) (cross-polarized light).

6.3.2 Fabrics resulting from freeze-thaw cycles

Freeze-thaw cycles resulted in the development of abundant and complex voids: vesicles, mammilliated vughs, thin planar voids and smaller cracks between the planar voids (figure 6.10). The small cracks were not aligned with heat flow; they could be frost desiccation cracks within the aggregates. The aggregation was more weakly expressed than for Caen #3, possibly due to drier conditions (figures 6.4 and 6.10). In experimental work involving freeze-thaw of soil cores, Pawluk (1988) demonstrated that the microstructures obtained under dry conditions were similar to the ones obtained at saturation, but their expression was weaker.

A few vesicles were in ring arrangement. These rings degenerated into a circular void/crack pattern with increasing depth (figure 6.10). Most single vesicles were deformed. There were no vesicles in the unfrozen soil. Either they were erased due to thaw of the frozen soil above or the changes created by the stresses below the frost front modified the rheologic properties and did not favor vesicle formation.

Striated fabrics were common; the mosaic fabric was dominant. Orientation of clay particles is often observed in permafrost soils (Tarnocai et al., 1993).

Strong displacements of the coarse and fine fractions were associated with freeze thaw-cycles. Clusters of coarse grains were observed and they became more frequent with depth. A geyuric fabric was typically observed at depth (figure

6.11). Accumulation of coarse and fine materials occurred at planar void and vugh outer walls, in the unfrozen soil, below the freezing front last position (figure 6.12).

A weak orbiculic fabric was found in the soil. The orbiculic arrangement consisted occasionally of a double layer of coarse grains. Alignment of coarse particles (suscitic fabric) began to appear after two-freeze thaw cycles.

The unfrozen soil for both experiments typically displayed a porphyroskelic fabric and no aggregation. White (1992) also recognized porphyroskelic and granoidic fabrics in Caen silt which had remained unfrozen after four freeze-thaw cycles. The fabric of experiment Caen #1 (rapid freeze) was also porphyroskelic (figure 6.13). Porphyroskelic fabrics appear to originate from soil consolidation due to cryosuction or to rapid freezing. In addition, the same fabric may result from external compaction such as in the Caen experiment in France (White, 1992).

6.3.3 Summary and interpretation of soil fabrics

A summary of the different thermal and water phase conditions leading to the formation of specific fabrics is presented in table 6.1.

Lens-shaped aggregates formed under slow freezing conditions (single freezing cycle), but with several freeze-thaw cycles the aggregates became elongated and flat. Platy aggregates also formed at depth during freezing only.

0.65 mm
└───┘

Figure 6.10: Complex void fabric generated after two freeze-thaw cycles (Caen #4, C4/4/3c). Note degenerated vesicle rings with small desiccation cracks (17 cm to 22 cm depth) (normal light).

0.2 mm
└───┘

Figure 6.11: Close to the freezing front final position, vuggy/gefuric fabric due to freeze-thaw (Caen #4, C4/5/2d). Clusters of coarse grains are present (22 cm to 27 cm) (cross-polarized light).

0.65 mm
└────────┘

Figure 6.12: Accumulation of coarse and fine material at planar void sides in the unfrozen soil (Caen #4, C4/6/5c). (27.5 cm to 32.5 cm) (normal light).

0.2 mm
└────────┘

Figure 6.13: Porphyroskelic fabric due to rapid freezing with pore ice formation, experiment Caen #1.

Thermal conditions	Fabric/Feature	Figure
Slow freezing (single freeze cycle)	<ul style="list-style-type: none"> - Frigmoidic, fragmic fabrics - Platy fabrics at depth - Close packing of aggregate skeleton at depth - Sepic and insepic fabrics - Quartz minerals around vesicles 	<ul style="list-style-type: none"> - 6.3, 6.6 - 6.4 - 6.9 - 6.8, 6.9 - not shown
Rapid freezing	<ul style="list-style-type: none"> - No aggregates (no planar voids) - Porphyroskelic fabric - Asepic fabrics - Orbiculic fabric 	<ul style="list-style-type: none"> - 6.13 - 6.13 - 6.13 - 6.8, 6.13
Freeze-thaw	<ul style="list-style-type: none"> - Long platy aggregates - Complex porosity - Lattisepic and gefuric fabric - Close packing of aggregate skeleton at depth - Suscitic fabric - Deformation of vesicles and ring vesicles - Coarse grain clusters - Pedofeatures at planar pore sides 	<ul style="list-style-type: none"> - 6.4 - 6.10 - 6.11 - 6.4 - not shown - 6.10 - not shown - 6.12
Unfrozen soil	<ul style="list-style-type: none"> - Unaccommodated planar pores - Porphyroskelic fabric 	<ul style="list-style-type: none"> - 6.7 - not shown
Non-specific	<ul style="list-style-type: none"> - Grain argillans - Orbiculic fabric 	<ul style="list-style-type: none"> - not shown - 6.8, 6.13
Water movements		
Capillary rise	- Vesicle formation (micro-aggregate wetting creates vesicle ring)	- 6.3, 6.8
Cryosuction	- Striated fabrics (sepic, mosepic and weak lattisepic)	- 6.8, 6.9, 6.11

Table 6.1: Summary of fabrics.

The significant compressive stresses measured below the frost line and in the frozen soil contributed to this change in aggregate aspect, which reflects a change in the ice lens attitude and the rheological properties of the soil.

At depth, in the freezing experiment and with repeated freeze-thaw, the aggregate matrix became very dense presumably due to consolidation by downwards oriented heave and to cryosuction near the freezing front. This did not appear to affect the hydraulic conductivity significantly in the freeze-thaw experiment, as large ice lenses grew at the bottom of the column. Possibly, the compaction planar voids may have facilitated the water flow.

The spacing, thickness and horizontal length of the ice lenses are related to the speed of the freezing front progression; very rapid freezing generated a massive cryogenic structure (porphyroskelic, no soil aggregates).

Table 6.1 shows that vesicles were formed during saturation of the soil. Vesicles were preserved during slow freezing of the soil. Under repeated freezing, the soil stresses distorted the vesicles and ring vesicle formations. At depth, with freeze-thaw cycles, the vesicles were erased and a complex pore structure developed. It was shown in Chapter 5 that the increased porosity developed during freeze-thaw cycling affects stress development when freezing resumed.

Because stresses with differing resulting vectors develop in a freezing soil, the coarse and fine fractions of the soil will become aligned and oriented as shown by the presence of suscitic and sepic fabrics. Coarse fraction arrangements such as suscitic fabric (coarse grains vertically aligned) were specifically generated under freeze-thaw conditions.

Fine fraction (very fine silts and clays) reorganisation leading to sepic fabrics were common for both freezing and freeze-thaw conditions but were more developed in the latter case. With freeze-thaw cycles, a lattice-like fine fraction orientation was generated (lattisepic fabric). This shows that the soil recorded two main directions of stress.

Furthermore, it appears that cryosuction in the unfrozen soil created B-fabrics similar to freezing (see appendix four) i.e. fine particles will also reorient in water under suction. Unfrozen soil compression upon freezing may have also played a role in the clay fraction alignements.

The thin section examination also revealed that the significant differences in cryogenic signatures between Caen #3 and Caen #4 were repeated in the unfrozen soil, mainly the characteristics of porosity and groundmass. For example a well-defined lattisepic fabric in the frozen soil of Caen #4 would also be weakly defined in the unfrozen soil.

The soil's fine fraction is also subject to translocation when temperatures fluctuate above and below zero. This is apparent in experiment Caen #4 where the fines accumulated

preferentially along planar pores and large vughs at the base of the soil column; such a fabric is called gefuric. These internal changes in texture and grain coatings (argillans) may have an influence on the frost susceptibility of the soil after it has been frozen and thawed a number of times. Most importantly, the translocation of fines will change the unfrozen water content distribution and affect moisture migration to and between ice lenses.

Certain fabrics and features were classified as non-specific, i.e. they were not related to a particular thermal or moisture condition (table 6.1).

Grain argillans (clay coatings or skelsepic fabric) were found everywhere in the soil and in both experiments. This (textural) pedofeature was either residual or was due to wetting/drying of the soil. Orbiculic fabric (coarse grains arranged in circles) was common under freezing and freeze-thaw conditions and a rare occurrence in unfrozen soil. Pore ice formation, which creates local stresses may have resulted in micro-sorting features such as orbiculic fabric, but because it was also found in the unfrozen soil, it is more likely caused by cryosuction. Local stresses generated by ice are also evidenced by the smoothing of planar pore sides and the interior of some vesicle walls.

6.4 Overview

The cryogenic zones reflect different stress/strain conditions which prevailed during freezing and thawing. In turn the experiments indicate that the rheological and thermodynamic conditions are modified by changes in soil fabric such as aggregate shape, leaching of fines and porosity changes, not only after several freeze-thaw cycles but as soil freezing takes place. It was also shown that textural, anisotropical and density changes occur in the soil before the passage of the freezing front. Elongated, platy soil units are found at depth where there is some resistance to heave from the upper frozen soil.

Soil behaviour may also be affected by the small but numerous secondary ice lenses that exist within the aggregates. Moreover, the formation of desiccation cracks (i.e. more or less sub-vertical cracks) in compacted aggregates in the freeze-thaw experiments could change the rheological behaviour. It has been observed that overconsolidation may be countered by an increase in vertical permeability due to shrinkage cracks that occur below the freezing front (Chamberlain and Gow, 1979). Because of this cracking, the water pressure may be suddenly relieved and the suction is lost (Williams, personal comm., 1995).

One problem with the microstructure analysis is that no sample devoid of freezing effects was prepared. The soil in

the unfrozen zone cannot be used as a standard because the experiments show that several processes affect it: consolidation, cryosuction effects, textural changes.

The experiments described in the preceding chapters have shown that the soil began to deform from the beginning of the cooling cycle. The stress and deformation conditions were not limited to the frozen soil above the warmest ice lens but occurred over the entire soil. The diverse fabrics which developed from an initially uniform soil are the result of processes more complex than those presently incorporated in most theories of soil freezing and ice segregation.

CHAPTER 7 : SUMMARY AND CONCLUSION

7.1 Overview

The laboratory experiments reported in this thesis focussed on how stresses and deformations are generated in a soil under freezing and thawing, and the resulting changes in soil microstructure. A conceptual model, put forward in Chapter 1 (figure 1.1) postulates that thermodynamics and the soil environment characteristics both control the stress and deformations which occur in a freezing soil. In turn, these soil stresses generate specific soil microstructures and result in frost heave and thaw settlement. This thesis provides new information on each of the elements of the suggested frost heave process model, and establishes the existence of links and feedbacks between the elements.

7.1.1 Key stress and strain features

- As a soil freezes, stresses develop simultaneously above and below the frost line. Significant normal compressive stresses occur in the unfrozen soil while "tensile" stresses (orthogonal to heat flow) develop in the frozen fringe and warm frozen soil zones. Identical stress trends may occur under different soil thermal and moisture conditions (ex: unfrozen vs freezing). Generally the freezing "tensile" stresses were larger than compressive stresses in the frozen soil.
- After one freeze-thaw cycle, the internal stress patterns were altered. Water expulsion was measured at the beginning of each frost run, after one thaw run, stresses during the water expulsion period were measurable (detected).
- The experiments show that the effective stress reaches zero not only at the colder end of the frozen fringe as proposed by Miller (1980) but also at the freezing front.
- Different stress fields develop during freezing and during thaw. During thaw, stresses are uniform throughout the soil profile.

- Measured segregation temperatures for the Caen silt were between -0.25°C and -0.29°C . Maximum ice growth (e.g. largest soil expansion) took place until the temperatures reached between -0.65°C and -0.95°C . At lower temperatures, positive soil strain was measured, but below temperatures of -1.06°C to -1.50°C soil expansion was not detected.
- Soil expansion during a single freeze cycle averaged 2.3 mm to 9.2 mm per 3 cm soil layer. Expansion was significantly larger in the freeze-thaw experiment. Soil layers increased from 0.1 mm to 2.0 mm per 3 cm soil layer during short thaw expansion periods due to ice lens growth. This points to a damage potential to structures during thaw which is not exclusively tied to thaw settlement.
- This significant deformation at thaw refreezing is due to soil structuration. Because of freezing, the ice lenses are in place and water is supplied to them by suction and percolation from the surface. Due to warmer temperatures, more unfrozen water is available and the soil viscosity increases (it behaves more like a viscous fluid than a plug) which favors frost heave.
- A net increase in soil volume was measured in the column during freeze-thaw cycles.

- The frost heave is dissipated in the soil by two components, one towards the soil surface and the other towards the unfrozen soil. Heave is compensated, to a degree, by soil consolidation which was significant in Caen silt.
- Experiments have shown that two adjacent soil layers may expand simultaneously by continuing heave. When the lower layer begins to heave, the upper layer is in a decelerating positive strain period.

7.1.2 Key micromorphology features

- Soil freezing and thawing cause irreversible deformations in the soil. The experiments demonstrated that distinct morphological features appeared after a single freeze-thaw cycle. These features persisted and either developed or were altered (vesicle ring formation) in further freeze-thaw cycles.
- Aggregate (ice lens attitude) shape, thickness, length and spacing is conditioned by the rate of frost penetration but also by the stresses that develop under the frost line and the resistance of the frozen soil. The ice lens attitude will have an effect on the soil's rheological properties.

- Stresses that develop during freezing and thawing are reflected in the various soil fabrics such as suscitic and orbiculic fabrics, orientation and translocation of the fine fraction. It is believed that cryosuction forces also play a role in soil structuration.

7.2 Links between model components

In the experiments, internally measured soil stresses and deformation characteristics were linked to soil environment conditions (layering, anchoring at sides, resistance of a frozen upper layer) and thermodynamic controls (temperatures, ice pressures). It is apparent from the micromorphological analysis, that soil structuration has a feedback effect on the frost heave process as it will ultimately change the controls. Factors such as unfrozen water content, pore structure, ice lens attitude/thickness and soil density are modified as the soil freezes and after several freeze-thaw cycles. The resulting effect on the controls may be one that will enhance frost heave and surface deformation or decrease the magnitude of frost heave. It may also enhance the magnitude of frost heave during thaw. Frost heave is often analysed at the frozen fringe/warmest ice lens level but it appears that all the zones of the freezing/thawing soil are locations of deformations and fabric changes which influence the process of secondary heave.

7.3 Conclusion

It has been mentioned that the state of stress in all constituents of the soil appears homogenized at the macroscopic level (O'Neill, 1983). The instrumentation used in the experiments does not belong to the microscopic scale but has nevertheless shown the non-uniform nature of the stresses in the soil as freezing proceeds. Experimental results indicated the links and feedbacks between stresses and fabric, and the influence of fabric, or soil structure, on the frost heave process.

Soil freezing may be compared to a loading of the soil with the added complexities brought by the heat and moisture flows. More research is needed in the investigation of stresses in freezing soils and the associated structure changes, and particularly how they affect the processes at the frozen fringe level. Generally, more data on the frozen fringe characteristics at the field scale should be obtained. Experiments in which it would be possible to sample for microfabrics at different times and at specific depths during the freezing cycle would be useful. Techniques for tracing unfrozen water movements to and beyond the warmest ice lens should be developed or expanded from existing equipment.

As much as possible, projects involving long-term field observations should incorporate micromorphology sampling within and below the pedon. Such material would be useful for soil classification purposes but also for a more integrative approach of the frost heave process and of permafrost history.

The process of continuing heave also needs further theoretical advancements to support the growing body of empirical evidence.

**APPENDIX ONE
CALIBRATION CURVES**

Figure A1.1: Helipotentiometer calibration curve for Caen #2 experiment. Calibration by 2 mm increments.

Figure A1.2: Radio-transmitting transducer calibration curve, device.199 MHz, calibration B.

Figure A1.3: Radio-transmitting transducer calibration curve, device .159 MHz, calibration B.

Figure A1.4: Radio-transmitting transducer calibration curve, device .120 MHz, calibration B.

APPENDIX TWO
EXPERIMENTAL RESULTS FROM FREEZING TESTS IN MANCHESTER AND
CAEN SILT : EXPERIMENTS MANCHESTER #1 - #2, CAEN #2 - #3.

Location of instruments in soil column

Summary of experiment

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Soil : Manchester silt

Duration : 2290 hours (95 days)

Max. depth of freezing : 45 cm

Total water intake : 219.2 ml

Total water expulsion : 87.6 ml

Heave : 6.2 cm

Temperature gradient :

150 hours : 0.022 °C/cm

733 hours : 0.035 °C/cm

1653 hours : 0.025 °C/cm

Soil column contents

: Silt (80 cm total)

: Sand (10 cm total)

Symbol	Instrument type	Quantity	Size (diameter in cm)	Depth In soil (cm)
(T)	Thermistor	8	—	0 cm, 15 cm then every 10cm
(P)	Anchored modified petur piezometer	6	1.8	15 cm then every 10 cm except last which is 10 cm from base

Figure A2.1: Experiment set-up, Manchester #1.

Figure A2.2: Temperature profile, experiment Manchester #1.

Figure A2.3: Surface heave, experiment Manchester #1.

Figure A2.4: Water intake, experiment Manchester #1.

Figure A2.5a: Pressure recorded at 15 cm depth for experiment Manchester #1.

Figure A2.5b: Pressure recorded at 45 cm depth for experiment Manchester #1.

Figure A2.5c: Pressure recorded at 55 cm depth for experiment Manchester #1.

Figure A2.6: Experiment set-up, Manchester #2.

Figure 2.7: Temperature profile, experiment Manchester #2.

Figure 2.8: Surface heave, experiment Manchester #2.

Figure A2.9: Total water intake, experiment Manchester #2.

Figure A2.10a: Stress signal, experiment Manchester #2, top at 10 cm depth.

Figure A2.10b: Stress signal, experiment Manchester #2, top at 25 cm depth.

Figure A2.10c: Stress signal, experiment Manchester #2, top at 35.5 cm depth, in the unfrozen soil.

Location of instruments in soil column

Summary of experiment

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Soil : Caen silt

Duration : 448 hours (19 days)

Max. depth of freezing : 27 cm

Total water intake : 98.2 ml

Total water expulsion : 72.2 ml

Heave : 0.90 cm

Temperature gradient :

25 hours : 0.153 °C/cm

150 hours : 0.119 °C/cm

375 hours : 0.150 °C/cm

Soil column contents

: Silt (70 cm total)

: Sand (20 cm total)

Symbol	Instrument type	Quantity	Size (diameter in cm)	Depth In soil (cm)
Radio-transmitting stress transducer	3	4.5	9 cm, 21 cm, 39 cm
Strain cell	14	2.5	Every 3 cm from surface to 39 cm
Thermocouple	14	—	Every 3 cm from surface to 36 cm last one at 50 cm
Modified Petur Piezometer	3	1.8	3 cm, 15 cm, 30 cm

Figure A2.11: Experiment set-up, Caen #2.

Figure A2.12a: Soil temperature profile, experiment Caen #2, from 0 cm to 15 cm depth.

Figure A2.12b: Soil temperature profile, experiment Caen #2, from 18 cm to 33 cm depth.

Figure A2.13a: Radio-transmitting transducer stress signal, experiment Caen #2. Top at 5.5 cm depth.

Figure A2.13b: Radio-transmitting transducer stress signal, experiment Caen #2. Top at 16.5 cm depth.

Figure A2.13c: Radio-transmitting transducer stress signal, experiment Caen #2. Top at 39 cm depth.

Location of instruments in soil column

Summary of experiment

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Soil : Caen silt

Duration : (actual) 575 hours (23 days)
(monitored) 455 hours (19 days)

Max. depth of freezing : 30 cm

Total water intake : 205.2 ml

Total water expulsion : 22 ml

Heave : 1.10 cm

Temperature gradient :

25 hours : 0.198 °C/cm

150 hours : 0.148 °C/cm

375 hours : 0.163 °C/cm

Soil column contents

- : Silt (70 cm total)
- : Sand (20 cm total)

Symbol	Instrument type	Quantity	Size (diameter in cm)	Depth In soil (cm)
Radio-transmitting stress transducer	2	4.5	9 cm and 24 cm
Strain cell	14	2.5	Every 3 cm from surface to 39 cm
Thermocouple	14	—	

Figure 3.18 : Experiment set-up, Caen #3.

Figure A2.14: Experiment set-up, experiment Caen #3.

Figure A2.15a: Soil temperature profile, experiment Caen #3, from 0 cm to 15 cm depth.

Figure A2.15b: Soil temperature profile, experiment Caen #3, from 18 cm to 33 cm depth.

Figure A2.16a: Radio-transmitting transducer signal, experiment Caen #3, top at 4.5 cm depth.

Figure A2.16b: Radio-transmitting transducer signal, experiment Caen #3, top at 19.5 cm depth.

Figure A2.17a: Soil strain by layer, 0 cm to 9 cm depth experiment Caen #3. Missing data due to readout failure.

Figure A2.17b: Soil strain by layer, 9 cm to 21 cm experiment Caen #3.

Figure A2.17c: Soil strain by layer, experiment Caen #3.

Figure A2.18: Soil column deformation, experiment Caen #3.

Figure A2.19a: Negative strain rates, experiment Caen #3.

Figure A2.19b: Negative strain rates, experiment Caen #3.

APPENDIX THREE
EXPERIMENTAL RESULTS FROM FREEZE-THAW TESTS IN CAEN SILT:
EXPERIMENT CAEN #4.

Summary of experiment

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Soil : Caen silt			
	Freeze Thaw 1	Freeze Thaw 2	Freeze Thaw 3
Duration (hours / days)	336/14	602/25	544/22
Total water intake during freezing (ml)	22.2	72.2	395.8
Total heave (cm)	0.44	0.28	0.28
Max. depth of freezing (°C / cm)	24	30	30
Temperature gradient at 150 hours (°C / cm)	0.170	0.148	0.154

Soil column contents

	: Silt (70 cm total)
	: Sand (20 cm total)

Symbol	Instrument type	Quantity	Size (diameter in cm)	Depth In soil (cm)
	Radio-transmitting stress transducer	2	4.5	6 cm and 21 cm
	Strain cell	14	2.5	Every 3 cm from surface to 39 cm
	Thermocouple	14	—	

Figure A3.1: Experiment set-up, experiment Caen #4.

Figure A3.2a: Soil temperature profile, experiment Caen #4, freeze-thaw cycle 1, from 0 cm to 15 cm depth.

Figure A3.2b: Soil temperature profile, experiment Caen #4, freeze-thaw cycle 1, from 18 cm to 33 cm depth.

Figure A3.3: Surface heave, experiment Caen #4, freeze-thaw cycle 1.

Figure A3.4: Total water intake, experiment Caen #4, freeze-thaw cycle 1.

Figure A3.5a: Radio-transmitting transducer signal, experiment Caen #4, freeze-thaw cycle 1, top at 4 cm depth.

Figure A3.5b: Radio-transmitting transducer signal, experiment Caen #4, freeze-thaw cycle 1, top at 16.5 cm depth.

Figure A3.6a: Soil temperature profile, experiment Caen #4, freeze-thaw cycle 2, from 0 cm to 15 cm depth.

Figure A3.6b: Soil temperature profile, experiment Caen #4, freeze-thaw cycle 2, from 18 cm to 33 cm depth.

Figure A3.7: Surface heave, experiment Caen #4, freeze-thaw cycle 2.

Figure A3.8: Total water intake, experiment Caen #4, freeze-thaw cycle 2.

Figure A3.9a: Radio-transmitting transducer signal, experiment Caen #4, freeze-thaw cycle 2, top at 4 cm depth.

Figure A3.9b: Radio-transmitting transducer signal, experiment Caen #4, freeze-thaw cycle 2, top at 16.5 cm depth.

Figure A3.10a: Soil temperature profile, experiment Caen #4, freeze cycle 3, from 0 cm to 15 cm depth.

Figure A3.10b: Soil temperature profile, experiment Caen #4, freeze cycle 3, from 18 cm to 33 cm depth.

Figure A3.11: Surface heave, experiment Caen #4, freeze cycle 3.

Figure A3.12: Total water intake, experiment Caen #4, freeze cycle 3.

Figure A3.13a: Radio-transmitting transducer signal, experiment Caen #4, freeze cycle 3, top at 4 cm depth.

Figure A3.13b: Radio-transmitting transducer signal, experiment Caen #4, freeze cycle 3, top at 16.5 cm depth.

APPENDIX FOUR
MICROMORPHOLOGICAL DESCRIPTIONS OF TYPICAL FABRICS RESULTING
FROM FREEZING ONLY (CAEN #3) AND FROM 2 FREEZE-THAW CYCLES
(CAEN #4) .

Basic mineral components*
experiments Caen #3 and Caen #4:

Coarse/fine limit at 10 μm .

a. Coarse fraction:

Loess material containing well sorted rounded to sub-angular quartz minerals, micas, some opaque larger minerals, and rare lithofragments. Some organic material and reddish nodules probably iron rich.

b. Fine fraction:

Groundmass composed of very fine silts and clays. Clays commonly as bi-refrangent coatings on the coarse fraction.

*: The basic mineral components for the Caen silt are relatively simple and do not vary with depth as in a natural soil, therefore, only one detailed description is needed. No significant amount of organic material is found in the soil.

Thin section description

Experiment: Caen #3

Thin section no.: C3/1/5a

Depth of zone: 0-6 cm

Cryogenic zone 1 (see figure 6.5)

1. Microstructure: Lenticular structure with hair-size vertical cracks in the first 3-4 cm depth. Sub-horizontal planar voids are displaced with respect to these vertical cracks. Aggregates overlap in a tile-like arrangement. Soil shows a well developed orbiculic fabric. Large crack is an artefact which occurred during drying of the sample.

a. Aggregates: Moderately to strongly developed peds sub-vertically oriented. The aggregates are ultra-fine to medium lenticular, 0.5 to 2 mm in thickness, separated by partly accommodated planar voids arranged sub-horizontally. Very fine discontinuous intra-aggregate cracks.

b. Voids: Equant to oblate vesicles cover about 20-30% of the total area. The vesicles 0.1 to 1 mm across are often arranged in circles. A few larger vesicles, 1-2 mm in diameter occupy 5-10% of the total area. Abundant planar voids are undulating, have smooth sides and vary in thickness from 0.05 to 1 mm. The extremities of planar voids and fine cracks are rounded or taper off.

2. Related distribution pattern: Fragmoidic to fragmic.

B-fabric: Stipple-speckled (insepic plasmic).

3. Pedofeatures: Grain coatings (grain argillans) around coarse mineral grains. Quartz minerals plastered on outer vesicle walls.

Thin section description

Experiment: Caen #3
Thin section no.: C3/1/3e
Depth of zone: 6-9 cm transition
Cryogenic zone 2

1. Microstructure: Larger and longer aggregates than above. Aggregates are horizontally aligned and planar voids are sub-horizontal. Common orbiculic fabric.

a. Aggregates: Lens-shaped aggregates, 1.5 to 4 mm in thickness and variable in length.

b. Voids: Vesicles occupy 30-35% of total area. Intra and inter-aggregate vesicles more abundant than in soil above, commonly 0.1 to 1.5 mm in diameter. Vesicle walls are very smooth and well rounded. They are commonly arranged in circles. Very fine criss-crossing cracks intersect with the vesicles. The contact between these cracks and the vesicles is very sharp. Abundant undulating and smooth partly accommodated planar voids. Some planar voids end with a vesicle or have rounded extremities but more commonly taper off.

2. Related distribution pattern: Fragmic.
B-fabric: Stipple-speckled.

3. Pedofeatures: Thin coatings around coarse mineral grains. Layer of quartz grains plastered against vesicle walls.

Thin section description

Experiment: Caen #3
Thin section no.: C3/3/6c
Depth of zone: 9-22 cm
Cryogenic zone 3

1. Microstructure: Complex structure. Large platy units, several centimeters long delimited by horizontal smooth planar voids.

Very compact intra-aggregate matrix. Large shear zone near column wall. Common orbiculic to partly orbiculic fabric.

a. Aggregates: At the macroscale, aggregates are 1.5 to 3 cm thick. At the upper microscale level (63x), soil shows large platy units 3 to 10 mm thick separated by smooth partly accommodated planar voids 0.5 to 3 mm thick. Smaller aggregates 0.3 to 0.5 mm thick within the platy units are separated by planar voids 0.3 to 1.2 mm thick. A third level of very small cracks, 0.03 mm thick, is found within those smallest aggregates. Planar voids and cracks have tapered ends.

b. Voids: Most equant vesicles are 1 mm in diameter, many are deformed (oblate). They occupy 5-10% of the thin section area.

2. Related distribution pattern: Platy to fragmic to fragmoidic from low to higher magnifications.

B-fabric: Stippled-speckled-granostriated to weak reticulate striated (Weak lattisepic-skelsepic).

3. Pedofeatures: Moderate to poor coarse sorting around vesicles. Coatings around mineral grains with continuous orientation. Few occurrences of iron oxide stained fine grained nodules.

Thin section description

Experiment: Caen #3

Thin section no.: C3/4/4a

Depth of zone: 22-30 cm. Freezing front last position

Cryogenic zone 4

1. Microstructure: Aggregates very compact and wavy. Shear planes near column walls. Small (1 cm length) lenticular aggregates mixed with larger aggregates. Weak orbiculic fabric.

a. Aggregates: Aggregates very compact with intra-aggregate pores (vesicles) and cracks. The small cracks are always close to the planar voids.

b. Voids: Planar void thickness very variable within same observation level. Planar voids zig-zag and show kinks. Intra aggregate vesicles, 0.2 mm mean diameter, deformed (oblate, many horizontally oriented), generally showing no preferred orientation, but can be arranged in a ring in which case they are often joined by a crack pattern. Vesicles take 5-10% of area.

2. Related distribution pattern: Platy, occasionally fragmic.
B-fabric: Stipple-speckled, weak reticulate striated

3. Pedofeatures: Discontinuous coarse sorting around vesicles. Coatings around mineral grains with continuous orientation.

Thin section description

Experiment: Caen #3

Thin section no.: C3/6/5b

Depth of zone: 30 cm and +. Unfrozen soil

Cryogenic zone 5

1. Microstructure: Vesicular microstructure. Some cracks due to drying. Few matrix grains arranged in circles.

a. Aggregates: No aggregation.

b. Voids: Abundant large vesicles, over 2.5 mm in diameter occupy 2% of the thin section surface while smaller vesicles (0.5 to 2.5 mm diameter) take up to 30% of the area. Small vesicles are very rounded and have undulating inner boundaries. They are equant irregular to oblate with no preferred direction of deformation. Larger voids are smooth subangular equant to oblate. A few smaller vesicles are in rings.

2. Related distribution pattern: Vesicular porphyric (vesicular porphyroskelic)

B-fabric: Weak reticulate-striated and granostriated (weak lattiseptic-skelsepic)

3. Pedofeatures: Grain coatings.

Thin section description

Experiment: Caen #4

Thin section no.: C4/1/2d

Depth of zone: 1-2 cm

Cryogenic zone 1 (see figure 6.5)

1. Microstructure: Platy aggregates separated by very fine wavy sub-horizontal planar voids. Common orbiculic, occasional suscitic microstructure. Deformed vesicles in rings.

a. Aggregates: Platy aggregates 0.7 to 4 mm thick.

b. Voids: No rounded vesicles, they are all deformed (prolate, mammilliated). Mammilliated vughs very irregular. At a macroscale continuous smooth planar voids spaced ± 3 cm (ice lenses in packing layers). Short discontinuous undulating planar voids (less than 0.5 mm thick) are partly accommodated and have smooth walls. Most planar voids have rounded extremities. Voids take at least 30% of thin section area.

2. Related distribution pattern: Fragmic (partially accommodated) to fragmoidic.

B-fabric: Reticulate-striated-mosaic speckled

3. Pedofeatures: Grain coatings. Coarse grain clusters. Some quartz grains around small voids.

Thin section description

Experiment: Caen #4
Thin section no.: C4/2/5a
Depth of zone: 2-12 cm
Cryogenic zone 2

1. Microstructure: Complex zones of prismatic and vughy microstructure. Weakly developped crack pattern with partly accomodated sides. Occasionnaly orbiculic-suscitic.

a. Aggregates: Weakly developped aggregates, some sub-rounded aggregates.

b. Voids: Chambers and vughs (0.05 to 0.3 mm) occupy 20-30% of total area. Some of the vughs are connected by cracks (positionned like channels). Macro vughs are degenerated vesicle rings (see sketch below). Most vugh walls are smooth and sub-rounded. The planar voids have variable widths. Interaggregate voids are irregular to smooth. Some matrix clusters are detached within the planar pores (could be related to impregnation process).

2. Related distribution pattern: Fragmoidic.

B-fabric: Stipple-speckled to mosaic-speckled (insepic to mosepic)

3. Pedofeatures: Some thicker grain argillans. Few concentrations of iron-rich clays.

Thin section description

Experiment: Caen #4
Thin section no.: C4/4/3c
Depth of zone: 12-22 cm
Cryogenic zone 3

1. Microstructure: Dense coarse matrix. Vughy microstructure. Platy aggregates of uniform thickness. Elliptically arranged deformed vesicles. Discontinuous orbiculic fabric with several layers of coarse grains. Occasional suscitic.

a. Aggregates: Weakly developed aggregates, a few millimeters thick. Some sub-rounded aggregates.

b. Voids: Very fine planar voids (0.5 mm thick) continuous across sample. Intra-aggregate, discontinuous, partly accommodated very fine planar voids. These planar voids are strongly curved, and have irregular walls. Oblate vesicles and irregular mamilliated vughs 0.2 to 1.5 mm in diameter.

2. Related distribution pattern: Frigmoidic.

B-fabric: Mosaic-speckled to weak reticulate striated (mosepic to weak lattisepic).

3. Pedofeatures: Grain coatings.

Thin section description

Experiment: Caen #4
Thin section no.: C4/5/2c
Depth of zone: 22-28 cm
Cryogenic zone 4

1. Microstructure: Complex vughy structure. Some vughs are located along very small fracture planes. Large platy aggregates. Only a few planar voids. Groundmass translocated to planar voids sides.

a. Aggregates: Large platy aggregates 0.5 to 10 mm.

b. Voids: Complex porosity reaches over 40% of total area. Mammilliated vughs. Some vertically oriented chambers. Irregularly spaced planar voids with a maximum thickness of 0.2 mm. Larger planar voids oblique to heat flow. Their sides are smooth and partly accommodated. A few rare vesicles.

2. Related distribution pattern: Frigmoidic, at higher magnifications intra-aggregate RDP is gefuric//porphyroskelic.

B-fabric: Stippled-mosaic-speckled (skel-mosepic).

3. Pedofeatures: Grain coatings. Coarse material concentrated and packed along planar voids. Sorting of coarse grains in clusters. Rare discontinuous coatings on voids.

Thin section description

Experiment: Caen #4

Thin section no.: C4/6/7b

Depth of zone: 28-40 cm. Freezing front last position and unfrozen soil

Cryogenic zone 5

1. Microstructure: Two large upper planar voids (1-2 mm thick) with smooth partly accommodated sides at final location of freezing front. Below those voids, a few discontinuous wavy, unaccommodated planar voids with irregular walls have coarse matrix concentrations on either (outer) sides.

a. Aggregates: No aggregation.

b. Voids: Complex porosity. Discontinuous wavy planar voids, interconnected vughs, and few vesicles. Irregular vughs in ring arrangement, arcuate and mamilliated metavughs.

2. Related distribution pattern: Vughy porphyroskelic//vughy gefuric in places.

B-fabric: Mosaic-speckled

3. Pedofeatures: Matrix and groundmass accumulations near planar voids. Grain coatings. Coarse grains in clusters (frequent).

Thin section description

Experiment: Caen #4

Thin section no.: C4/8/3a

Depth of zone: 40 cm and +. Unfrozen soil

Cryogenic zone 6

1. Microstructure: Separate complex fabric. Complex vughy structure.

a. Aggregates: No aggregates but cracks at packing levels. Short planar voids have unaccommodated sides with large vughs within. A few smaller unaccommodated undulating cracks (0.05 mm thick) are found in the aggregates.

b. Voids: Many irregularly shaped vughs randomly distributed. Larger vughs are mamilliated. Some vughs are connected by small cracks. Rare vesicles. Planar voids are short and discontinuous.

2. Related distribution pattern: Vughy gefuric (vughy agglomeroplasmic)/porphyric near planar pores.

B-fabric: Stipple-speckled.

3. Pedofeatures: Accumulation of matrix and groundmass along the planar pore outer sides and around the vughs. Grain coatings.

Thin section description

Experiment: Caen #1

Thin section no.: C1/3/3a

Depth of zone: 40 cm and +

1. Microstructure: Massive. Common orbiculic fabric. No aggregation.

a. Aggregates: No aggregates.

b. Voids: No planar voids. A few small equant vesicles occupying not more than 5% of area.

2. Related distribution pattern: Porphyric (close to one space porphyroskelic).

B-fabric: Speckled (asepic-skelsepic).

3. Pedofeatures: Grain coatings.

GLOSSARY OF SOIL MICROMORPHOLOGY TERMS

Channel: Void that is significantly larger than those resulting from normal packing of single grains. It generally has a cylindrical shape, an approximately equal diameter throughout the length, and lacks sharp termination.

Fabric: The physical constitution of soil material as expressed by the spatial arrangement of solid particules and associated voids.

Fragmic: Relatively densely packed, accommodated discrete units without coating on units, or bridges between units.

Fragmoidic: As with fragmic but the units are not discrete, appearing to be fused at contact.

Gefuric fabric (agglomeroplastic): A related distribution pattern. The coarser particles are linked by braces of finer material.

Grain argillan: Coating of a grain composed dominantly of clay minerals.

Groundmass: 1- A general term for the coarse and fine material which forms the base material of the soil. 2- Relatively fine material in which coarse particles and pedofeatures occur.

Microstructure: Microstructure encompasses all aspects of soil structure that are revealed when the soil material is examined at a magnification of 5x or greater.

Orbiculic fabric: Skeleton grains disposed in circles or ellipses.

Pedofeatures: Discrete fabric units present in soil materials recognisable from adjacent materials by a difference in concentration of one or more components.

Peds: Units used for description of the field structure. Compound clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness.

Planar voids (planes): Voids that are planar according to the ratios of their principal axes. Variable diameter along length terminating in at least one sharp edge. May be visible over long distances.

Porphyric fabric: The large fabric units occur in a dense groundmass of smaller units. Interstitial pores at the scale of the distribution pattern are absent.

Porphyroskelic fabric: The plasma occurs as dense groundmass in which skeleton grains are set after the manner of phenocrysts in a porphyric rock.

Related distribution pattern: The distribution of individuals with respect to individuals of different type.

Sepic fabrics: Fabrics which have recognizable anisotropic domains with various patterns of preferred orientation i.e. plasma separations with a striated extinction pattern.

Suscitic fabric: Vertically (or near vertically) oriented skeleton grains which sometimes have accumulation of fines at the base of the grains.

Vesicle: Relatively large voids (other than packing voids) whose walls consist of smooth, simple curves. They may be classified according to the ratios of their principal axes, for example prolate, equant or oblate.

Vugh: A relatively large void, other than a packing void, usually irregular and not normally interconnected to voids of comparable size.

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