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CRYOGENIC ALTERATION OF A FROST SUSCEPTIBLE SOIL

by

THOMAS LESLIE WHITE, B.E.S., B.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Science
Department of Earth Sciences

Carleton University

Ottawa, Ontario

March 2, 1992

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submitted by Thomas Leslie White, B.E.S., B.A.
in partial fulfilment of the requirements for
the degree of Master of Science

Thesis Supervisor

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Date: May 5 1992

ABSTRACT

Micromorphological, computer image analysis, and physical properties testing performed on a frost-susceptible soil after exposure to four freeze-thaw cycles have revealed evidence of internal movement, reorganisation of soil fabric components and pore space distribution. Fragmoidic, fragmic and porphyroskelic fabric types were observed to have developed from the silt's granoidic fabric as a result of cryogenic alteration. The resulting morphology is inferred to be responsible for an order of magnitude increase in hydraulic conductivity in fragmoidic and fragmic fabric types, and for an order of magnitude decrease in hydraulic conductivity in zones of the silt where porphyroskelic fabric had developed in response to additional compaction.

Computer image analysis observations revealed that macroporosity accounted for between 55 to 75% of the total porosity that characterised the fragmoidic fabric, 31 to 39% of the total porosity of a granoidic fabric, and accounts for between 15 to 20% of the total porosity of porphyroskelic fabric.

Changes in hydraulic conductivity, pore size distribution and water retention characteristics are inferred to be responsible for the resultant increase in frost-heave potential of the soil.

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During the past three years of study at Carleton University, I have been fortunate to be involved with an active, friendly group of individuals who have been generous with their time. In particular, I wish to acknowledge my thesis advisor, Dr. Peter J. Williams for his guidance in formulating this thesis and for many hours of informative discussion. I also wish to thank Dr. Ken Torrance who, prior to his departure on sabbatical, provided guidance in the fields of clay mineralogy and soil physics. The success of my research is due, in some measure, to the cooperation of Dr. Cathy Fox and Mr. Ray Guertin of Agriculture Canada's Research Branch, Land Resources Research Centre, who helped tremendously in sorting out many of the technical aspects of micromorphological research and who provided me with much cheerful encouragement. Similarly, I am indebted to Dr. Brigitte Van Vliet-Lanoe of the Centre de Geomorphologie, CNRS, Caen, France who provided me with many hours of informative discussion in the field of micromorphology during my stay in Caen as Project Manager.

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CHAPTER ONE

Introduction

1.1 Background

There is probably no engineering construction so much subjected to the pervasive effects of the environment as Canada's service infrastructure of water distribution systems, sewage collection systems and petroleum distribution systems.

Where buried services traverse cold regions, the problems of providing safe foundations are increased by various effects which include landslides, slope failures, and ground settlement or expansion associated with frost action. Freeze-thaw cycles and the thermodynamic nature of the soils traversed are responsible for severe deterioration of the network.

The extent to which sewers, water lines and pipelines are damaged each winter and spring reveals a weakness inherent in engineering approaches to design and in construction practices. In 1985, it was estimated by the Federation of Canadian Municipalities that rehabilitation costs for existing infrastructure were about six billion dollars for roads, 2.4 billion for sewers and two billion for water lines. For some of these systems, the proposed

rehabilitation will require in situ repair and redesign, and for others, total replacement.

Failure of service networks and the unusual remedial procedures required to reestablish services create profound economic and personal hardship to individuals and damage to the environment. The extent of the problem varies according to region and is most severe in northwestern Canada. In Edmonton, for example, there is an average of 4.4 breaks to municipal services daily, with a peak of 30 breaks in one day in the worst winter period. The cost to the City of Edmonton for repair is in the order of five million dollars per year.

Frost-action, the annual frost heaving and the thaw weakening of surficial soils causes water lines, sewage collection systems, and petroleum distribution systems to heave and settle, often resulting in their failure. Abrupt changes in soil texture and heave susceptibility lead to more substantial heaving of the one soil compared with another soil, and may produce a sharp differential heave or displacement. The effect is to produce (more or less) a "step" with the correspondingly high pipe stresses that follow from such sharp curvatures (Williams, 1986). A better understanding of the interaction between frost susceptible soils and service networks, specifically when subjected to freeze-thaw cycling, would help to improve our existing cold regions engineering acumen.

Whereas the general effects of freezing of the ground are well known and often studied, this thesis examines the changes brought about in soil microstructure by cryogenic alteration, and their effects on physical properties.

1.2 The Dynamic Nature of Freezing Ground

Freeze-thaw cycling and cold temperatures bring about changes in physical properties of subgrade soils. Freezing and thawing of fine grained soils has been frequently observed to change the engineering properties (especially hydraulic conductivity and shearing resistance) of these soils (Williams, 1957; Chamberlain and Gow, 1979; Mackay, 1983; and Van Vliet Lanoe, 1985).

Freezing affects the arrangement of soil pores and particles; that is, the structure of the soil and these freezing effects persist to some degree after the soil is thawed (Williams and Smith, 1989). When frozen, fine-grained soils such as clays and silts are generally very strong at least at low temperatures. Because of this, freezing has at times been used to temporarily stabilise soils during construction of retaining walls, foundations and tunnels. However, freezing does more than bond soil particles together. The behaviour of frozen soil retains the complexities of its main structural components of ice and soil matrix but, in addition, is subject to complications arising from the unfrozen water interface

between the ice and soil particles (Williams, 1982). Negative pore water pressures generated during freezing at temperatures just below 0°C are such that there is movement of water, ice and skeleton components of the soil. The dynamic nature of frozen ground expresses itself in both macro and micromorphological changes which take place as a function of freeze-thaw cycling.

Changes in soil structure caused by freezing and thawing are related to one dominant process. Freezing a frost-susceptible soil, when it is exposed to ample supplies of water, will result in ice segregation (usually as layers or lenses) and frost heave.

Ice segregation occurs in soils when chemical potential imbalances originating in the region of ice lens formation increase the soil moisture tension gradients. This in turn causes soil water to flow toward the growing ice lenses (Figure 1.1). Penner (1961) observed that ice segregations in frost-heaved laboratory samples were composed of small crystals orientated with their long axis in the direction of heat flow during the segregation.

In slowly freezing fine-grained soil, ice lenses develop in medium-size pores $>50\text{ }\mu\text{m}$ in diameter at a temperature slightly below 0°C behind the freezing front (Williams and Wood, 1985). As the temperature decreases, the pore water freezes in progressively smaller pores, and the

FIGURE 1:1
ICE LENS FORMATION

Modified from: B. Van Vliet-Lanoe. Frost Effects in soils.
In Soils and Quaternary Landscape Evolution. J. Board-
man Ed., J. Wiley and Sons Ltd., 1985, p. 118.

chemical potential is gradually lowered. Significant amounts of liquid water can exist in soil-water systems in equilibrium with ice at temperatures considerably below 0°C. This water exists in small capillaries and as films adsorbed on the surface of soil particles (Burt and Williams, 1976).

Ice-lens formation and spacing are controlled by the thermal and hydraulic balance at the freezing front; that is, where ice is formed. As long as the pore water pressure in the as yet unfrozen soil remains higher than the pore pressure at the ice-water interface, the ice lenses continue to grow and form in a series, one below the other, thus reflecting changes of the thermal-hydraulic balance at the freezing front.

The ice and pressure resulting from this process can be determined from the following form of the Clausius-Clapeyron relations (Williams, 1982):

$$T - T_0 = \frac{(P_w V_w - P_i V_i) T}{L}$$

where T is the segregation freezing temperature, T_0 is the normal freezing point, L is the latent heat of fusion, V is specific volume, P is pressure, and the subscripts w and i represent water and ice phases. The relevance of this equation has been confirmed by experimental studies. After the ice nucleates and begins to grow, a negative pressure

gradient develops, and water begins to flow toward the growing ice lenses.

Suction forces (low pore-water pressure) cause an increase in the effective intergranular stress and a lowering of the soil's moisture content in the immediate vicinity of the ice lens, producing desiccation of the underlying sediment and the development of shrinkage cracks. The initial lens therefore cannot grow beyond a certain point because of the desiccation of the underlying unfrozen soil as water is extracted by suction.

Once the capillary feed is blocked, ice lenses can continue to grow by the slow migration of still-unfrozen adsorbed water (Burt and Williams, 1976) along the face of mineral grains. Using X-ray photography, Penner and Goodrich (1980) were able to document the apparent continued growth of ice lenses within the frozen soil. Observations reported recently by Smith and Patterson (1989) suggest that a considerable thickness of soil can be affected by moisture movement and the accumulation of ice during frost heaving.

1.3 Cryogenic Effects on Soil Structure

The occurrence of repeated freeze-thaw cycles in soil and granular base material during a winter have been widely studied. The effects of freeze-thaw cycling on the frost susceptibility and structure of soils have, however,

generally been ignored (Chamberlain, 1981). Experiments carried out in laboratories at Caen, France and Liege, Belgium illustrate that both platy and prismatic structures, as well as vesicles develop under appropriate conditions (Van Vliet-Lanoe, 1984). Platy structures were similarly observed to develop in saturated soil materials subjected to repeated cycles of freezing and thawing (Dumanski, 1964).

Chamberlain and Blouin (1978) reported reductions in void ratio and large increases in vertical permeability. They attributed these changes to particle reorientation and reduction of particle spacing due to the thinning of water films. They concluded that the permeability increased because of the formation of polygonal shrinkage cracks and/or the reduction of the volume of fines. The structural changes were attributed to the development of strong soil moisture suction in the freezing zone. This causes an increase in the effective stress in the region immediately beneath a freezing front and the formation of ice lenses. In clay soils, this results in a shrinkage of the soil structure, the formation of cracks and a change in the pore size distribution.

In recent research reported by Chamberlain (1990), the freezing and thawing of silt and clay slurries cause an increase in the vertical permeability and density at depth in soil specimens. These changes were observed to alter the frost-heave potential of the soil from the first freeze-

thaw cycle to the second and third cycles. This complex process of the structural alteration of soils is not well understood and should therefore be taken into consideration when trying to assess the frost-heave potential of a soil.

1.4 Micromorphology of Soil

Kubiena's book "Micropedology" (1938) established the direction of micromorphology for many years. Its main theme was the use of the microscope to study the morphology of soils as a basis for interpreting the processes involved in soil genesis.

In the microscopic fabric we are able to read the history of the soil as we may a book. We need only to learn to interpret that which we find in it. (Kubiena, 1938)

This approach was further developed in his "Entwicklungslehre des Bodens", published in 1948, in which he used micromorphological evidence to support a generic approach to soil development.

Until recently, micromorphological interpretations of soil genesis have been based on many assumptions and hypotheses about soil behaviour and soil-forming processes. As Brewer (1973) indicated, "recognition of microscopic features begin with accumulating data on the optical properties of the constituents that form the features". Interpretation of the processes involved in the formation of soil features depends on hypotheses of soil-forming

processes as well as some knowledge of both chemical and physical properties (Bullock, 1981).

Today, micromorphology is used primarily in the study of soil genesis. Micromorphology is continually contributing to a fundamental understanding of soil-forming processes and the morphological features which they produce. To date, most micromorphological research has been restricted to in-depth studies of soils which have not been subjected to cryogenic alteration. The micromorphological study of soil structures created by cryogenic processes has been under-utilised. Although some work has been carried out by scientists in the Soviet Union, little literature has been translated and published in North American journals. Micromorphology combined with physical and chemical test methods of soil investigation could, it is hypothesised, help us to gain a better understanding of soil processes such as freeze-thaw, which may affect the frost susceptibility of soil and their mechanical and thermal properties in the frozen state.

Whereas thin sections are often used to obtain information about the genesis of a soil (as in the case of a pedologist), a geotechnical engineer needs information that can be used to predict the behaviour of a soil. This poses a new challenge for micromorphology. Misinterpretation about the genesis of a soil is generally of little or no consequence to an engineer who arrives at the wrong

conclusion, except for a certain amount of lost pride. The misinterpretation with regard to predicting the behaviour of soils for engineering purposes can be catastrophic. At present, engineers are in the process of accumulating data about the behaviour of soil fabric types and ultimately, may be able to make correlations between behaviour and fabric (Fitzpatrick, 1984).

It is the intent of this thesis to evaluate whether or not micromorphological techniques can be utilised to evaluate microstructural alterations that frost-susceptible soils may undergo when exposed to a series of freeze-thaw cycles. Micromorphology could prove to be a practical technique for the assessment of a soil's frost-heave potential over the life expectancy of a service network.

In order to properly evaluate microstructural alterations that a frost-susceptible soil may undergo when exposed to several freeze-thaw cycles, a program of laboratory evaluation and field research was undertaken. The specific objectives of this study were:

- 1) To determine the extent to which a frost-susceptible soil may undergo microstructural alteration, that is, reorganisation of its fabric components and pore space distribution, when exposed to freeze-thaw cycling;
- 2) To evaluate to what degree changes in soil fabric are

reflected by changes in physical properties of the soil; and

- 3) To discuss the implications that changes in a soil's susceptibility to heave have for engineering design of Canada's service infrastructure, specifically, in the case of this study, its gas pipeline distribution systems.

Chapter Two of this thesis describes the conditions under which sampling and observation were carried out in a controlled environment facility in Caen, France. Cryogenic alteration of the thermal and hydraulic regimes of the frost-susceptible soil, and the dependence of these on various controlled ambient conditions are reported. Chapter Three consists of the study of the soil's micromorphology, that is, the arrangement of soil particles and pore-size distribution. Chapter Four details the results from a program of laboratory evaluations undertaken to determine changes in physical properties, specifically, saturated hydraulic conductivity and soil-water desorption of the frost susceptible soil after being subjected to freeze-thaw cycling. Chapter Five presents the results from a program of study which utilised computer Image Analysis to characterise the void-space distribution and macro porosity of the soil. Lastly, Chapter Six consists of a summary and conclusions.

CHAPTER TWO

Sampling and Observation in a Controlled Environment Facility

2.1 General

Sweden, France, the U.S.A. and Japan all have full scale controlled environment laboratory facilities in which large scale cold climate engineering experiments can be conducted. Remarkably enough, although Canada has more perenially frozen ground than any other country except perhaps Russia, and is subjected to seasonal freezing, it has no such controlled environment laboratory facility even today (Williams, 1986).

Acting on a proposal from its French colleagues, Carleton University Geotechnical Science Laboratories joined forces in the early 1980's with French scientists and engineers to examine the effects of freezing soil on a simulated buried gas pipeline. A suitable facility was available in France. This facility has also provided the opportunity for many of the studies described in this thesis.

The controlled environment facility is located at the Centre de Geomorphologie, Caen, France operating under the auspices of Centre National de la Recherche Scientifique, Laboratoire Central des Ponts et Chaussees, and Energy,

Mines and Resources, Canada. This totally enclosed, temperature controlled test facility consists of a refrigerated hall 18 m long by 8 m wide and 5 m high. The base of the trough of the facility is 1.75 m deep and was specially prepared to isolate the thermal and hydraulic regimes (Figure 2.1). The facility has been described in detail by Burgess et al (1982) when the experiment was initially set up, and again after additional instrumentation was added by Carleton University's Geotechnical Sciences Laboratories (1986).

The Canada-France ground freezing project comprised a team of Canadian and French scientists, engineers, technicians and graduate students, of whom I was one, in a multi-disciplinary project involving many aspects of soil freezing and thawing, as well as the particular effects of freezing soils of different frost heave susceptibilities. The research project, which consisted of four successive freeze-thaw experiments of varying lengths and different operating conditions was initiated in 1982 and terminated in August 1989. The ambient air temperature was maintained at -0.75°C throughout all four freeze cycles. The temperature of the chilled pipe has varied from -2°C for the first freeze cycle, increasing to -5°C for the second freeze cycle and finally to -5.25°C for the third and fourth cycles. The water table was maintained at 90 cm beneath the soil surface throughout each cycle, thus ensuring optimum conditions for

FIGURE 2.1

LONGITUDINAL CROSS-SECTION OF THE CAEN EXPERIMENT

ice lens formation in the frost susceptible silt. Sampling of soil for the studies to be described was carried out at various locations around the pipe.

2.2 Cryogenic Alteration of Caen Silt

The study has shown that freezing of soil results in heaving of the soil and the chilled pipe it contains (Figure 2.2). Since the chilled pipe traverses soils of differing heave susceptibilities, differential heave occurs, which has with each successive cycle resulted in increasing residual pipe curvature (Figure 2.3). Cryogenic deformation of the soil structure may be inferred from the residual surface configuration which has become increasingly deformed after each successive freeze-thaw cycle (Figure 2.4). The increasing relief has resulted from the effects of several processes, including frost-heave, thaw-settlement and the mechanical stresses imposed by the pipe and the frozen soil annulus which surrounds the pipe (Geotechnical Science Laboratories, 1990).

Ice segregation in Caen silt has resulted in consolidation of the soil, so that it has become progressively lower after each thaw consolidation phase in elevation relative to the non-frost-susceptible sand used in the experiment. The continuing internal deformation of frozen soil produced by small movements of ice, moisture and

FIGURE 2.2

SURFACE HEAVE OF CAEN SILT - FOURTH FREEZE CYCLE

modified from: Geotechnical Science Laboratories, 1990.
Canada - France Ground Freezing Experiment Phase VIII.
Fourth Freeze Cycle Report to Earth Physics Branch,
Energy Mines and Resources, p.60.

FIGURE 2.3
RESIDUAL PIPE CURVATURES AFTER EACH FREEZE - THAW CYCLE

from: Geotechnical Science Laboratories, 1990. Canada - France Ground Freezing Experiment Phase VIII. Fourth Freeze Cycle Report to Earth Physics Branch, Energy Mines and Resources, p. 37.

FIGURE 2.4
RESIDUAL SURFACE DEFORMATION

Modified from: Geotechnical Science Laboratories, 1990.
 Canada - France Ground Freezing Experiment Phase VIII.
 Fourth Freeze Cycle Report to Earth Physics Branch,
 Energy Mines and Resources, p. 58.

soil particles which collectively may produce creep (Williams, 1986) is thought to be responsible for the irreversible deformation which has taken place.

While employed as Project Manager for the latter stage of the Fourth Freeze Cycle and the full thaw-consolidation phase of the experiment between January and September 1989, it became apparent to the writer that inconsistencies existed between the predicted and reported behaviour of the frost-susceptible silt. In spite of the careful attention to maintaining the thermal and hydraulic regimes similar for cycles two, three and four, the heave susceptibility of the silt appeared to have increased. It is theorised that changes in the frost-susceptible soil's fabric may be responsible for increasing the frost-heave potential of the soil and account for residual deformations and changes to the thermal and hydraulic properties of the silt.

2.3 Cryogenic Alteration of Thermal Regime of Caen Silt

Figure 2.5 shows the position of the 0°C isotherm at Day 100 for the third and fourth freeze cycles in the silt near the B-B cross section (4.4 m from the sand-silt transition). The figure shows that the depth of frost penetration from Cycle 3 to Cycle 4 has increased. From this it may be inferred that changes in the silt's thermal conductivity have taken place. Thermal conductivity has increased from one cycle to the next in response to

FIGURE 2.5
POSITION OF 0 °C ISOTHERM IN CAEN SILT,
DAY 100 OF THIRD AND FOURTH FREEZE CYCLES

consolidation of the silt in zones of intense ice segregation. Figure 2.6 shows the 0°C isotherm position for select dates in the silt near the B-B cross-section for the fourth freeze cycle. As is shown, proximity to the pipe greatly affects soil freezing. About 2 m from the centre of the pipe axis, freezing of the silt is controlled by ambient air conditions (-0.75°C).

Figures 2.7 and 2.8 show the position of the 0°C isotherm normal to the pipe axis near the B-B cross section for days 68 and 482 respectively of the fourth freeze cycle. The penetration of the 0°C isotherm is greatest near the pipe-soil interface and decreases as a function of distance from the pipe and distance below the ground surface. These figures also show the increasing thickness of the frozen annulus of the soil surrounding the pipe and changes in the 0°C isotherm altitude. The position of the ground surface illustrates that greater amounts of heave are occurring in the soil annulus surrounding the pipe compared to the soil at distance from the pipe axis.

2.4 Cryogenic Alteration of Hydraulic Regime of Caen Silt

Gravimetric water content data was obtained from soil cores at the end of the fourth freeze cycle (White, 1990). The values of water content from core samples taken along the B-B axis in the silt beside the pipe, 0.5 m from the side of the pipe and 1.0 m from the side of the pipe are

FIGURE 2.6
POSITION OF 0 °C ISOTHERM IN CAEN SILT
THROUGHOUT FOURTH FREEZE CYCLE

from: Geotechnical Science Laboratories, 1990. Canada -
 France Ground Freezing Experiment Phase VIII. Fourth
 Freeze Cycle Report to Earth Physics Branch, Energy
 Mines and Resources, p. 13.

FIGURE 2.7
POSITION OF 0 °C ISOTHERM IN CAEN SILT
ALONG THE B-B AXIS, DAY 68, FOURTH FREEZE CYCLE

FIGURE 2.8
POSITION OF 0°C ISOTHERM IN CAEN SILT
ALONG THE B-B AXIS, DAY 482, FOURTH FREEZE CYCLE

summarised in Table 2.1.

The data shows a decrease in the moisture content of the silt at a distance of 0.5 m from the pipe where suction induced by a very large frozen soil annulus around the pipe is at its greatest. In addition, the data indicates the position of the 0°C isotherm at the end of the fourth freeze cycle (Figure 2.8). The depth of the 0°C isotherm corresponds to the boundary between soil which had been exposed to freezing and is now characterised by a high moisture content, and underlying soil which had not been exposed to freezing. The soil immediately below the zone exposed to freezing lost water to the soil layer above via desiccation, and is now characterised by much lower moisture contents.

Moisture content data obtained from the core sample at the end of the fourth freeze cycle indicates higher gravimetric water contents than those reported after the second and third freeze cycles. Figure 2.9 indicates an overall increase in the volume of water added to maintain the water-table at a constant depth during the first 180 days of the fourth freeze cycle compared to the same period for the third freeze cycles. Table 2.2 shows how the total volume of water added during the first 90 days of the fourth freeze cycle was slightly more than that for the previous second and third freeze cycles.

TABLE 2.1
GRAVIMETRIC WATER CONTENTS FOR CORE SITES IN SILT
SECTION 0.5 m FROM B-B AXIS AFTER THE 4TH FREEZE CYCLE

Depth (cm)	Side of Pipe	0.5 m from side of pipe	1.0 m from side of pipe
0 - 20	20.9	36.3	41.1
20 - 40	32.8	31.9	39.5
40 - 60	37.9	30.5	53.4
60 - 80	37.0	37.3	18.2
80 - 100	42.2	28.4	
100 - 110	50.7		
110 - 120	21.3		

FIGURE 2.9

WATER UPTAKE BY CAEN SILT, FREEZE CYCLES THREE AND FOUR

TABLE 2.2
RATES AND AMOUNTS OF WATER ADDED DURING SECOND,
THIRD AND FOURTH FREEZE CYCLES

<u>Freeze Cycle</u>	<u>Time Period (days)</u>					
	0 - 30		30 - 60		60 - 90	
	Total		Rate		Total	
					Rate	
Second	1176	39.2	2303	37.5	3348	34.8
Third	1550	51.1	2925	45.8	3993	35.6
Fourth	1900	63.3	3050	50.8	4090	45.4

Total is in litres and Rate is in average litres per day

The increases in gravimetric water content from the third to fourth freeze cycles reflect continuing reorganisation of soil skeleton components and structural changes of Caen silt fabric. The increased water holding capacity of the silt indicates that changes in the soil's fabric may have been brought about by the actions of intense segregated ice-lensing. Ice lenses may be responsible for increasing the soil's permeability and for increasing its frost heave susceptibility.

2.5 Field Research and Sampling

In order to confirm this hypothesis and the preliminary findings reported by White (1991), field work was undertaken in France in April of 1990 to examine and sample the fabric of Caen silt that has developed as a result of cryogenic alteration. A total of twenty-nine undisturbed Kubiena Box samples and twenty-nine core samples were taken from five soil profiles located in two sample pits situated along the B-B axis 4.4 metres from the silt/sand transition (Figure 2.10). The sample profiles were referenced to the side of the pipe and measured above and below the centre of the pipe, side of the pipe, 0.5 m from the side of the pipe, 1.0 m from side of pipe, and 3.0 m from the side of the pipe (Figure 2.11). Careful attention was paid to sampling methodology and procedures outlined in Sheldrick (1984), and

FIGURE 2.10
LOCATION OF SAMPLE PITS ALONG THE B-B AXIS

FIGURE 2.11
SAMPLE LOCATIONS IN PROFILES ONE THROUGH FIVE
ALONG THE B-B AXIS

Position of Isotherms Day 482,
 Fourth Freeze Cycle

every effort was taken to maintain samples in an undisturbed condition (that is, to minimise damage to the samples such as stress cracks). Plate 2.1 depicts both sample profiles three and four in the sample pit, and Plate 2.2, the Kubiena sampling boxes and sampling cores used to obtain undisturbed samples from Profile 5..

All undisturbed soil specimens were returned to Canada and placed in storage in a temperature controlled (10°C) and humidity controlled (50%) room at Agriculture Canada, Research Division, Ottawa, Canada, until micromorphological laboratory space at Agriculture Canada became available for use in August 1990.

PLATE 2.1

SAMPLE PIT ONE - B-B AXIS

Profiles Three and Four, with Kubiena sampling boxes (a)
positioned in profile

PLATE 2.2

UNDISTURBED SAMPLES IN PROFILE FIVE

Kubiena Sampling Box (a) and Sampling Core (b)

CHAPTER THREE

Microstructural Alteration of Caen Silt

3.1 General

In order to properly evaluate internal movement and reorganisation of soil fabric components, and alteration of pore-space distribution, a laboratory study of Caen silt's micromorphology (arrangement of soil particles and pore space) was undertaken. The specific objectives of this were:

- 1) To determine the extent to which distinct cryogenic fabrics had developed in the Caen silt after exposure to four freeze - thaw cycles; and
- 2) To determine whether the observed cryogenic fabrics have a distinct spatial distribution both within the soil annulus surrounding the buried chilled pipe and in the soil at distance from the pipe.

3.2 Sample Preparation for Micromorphological Study

Microscopic observation of soil fabric and pore space distribution was undertaken after the undisturbed, vertically oriented Kubiena box samples had been impregnated with a polyester resin.

Since polyester resins are immiscible with water, water must be removed from the soil prior to impregnation. There

are two methods of water replacement: air drying and the removal of soil water with acetone. The choice of method will depend upon the requirement of the study. Air drying may result in substantial shrinkage of soil specimens containing clay minerals; this may be unsuitable for studies which require quantitative data, for example pore space analysis (Sheldrick, 1984). Given the presence of between 10 to 20% clay size minerals in Caen silt (White, 1991), and the possibility that swelling clay minerals such as vermiculite and smectite may be present, this method was deemed unsuitable for the purpose of this study. Exchange with acetone maintains the sample morphology close to sample conditions and thus provides greater confidence for characterisation of the observed features. Murphy (1982) discusses the advantages of acetone replacement of soil-water for pore-space analysis in mineral soils.

Soil thin sections and block specimens were prepared over a period spanning August 1990 to June 1991 (inclusive) from the undisturbed Kubiena box samples after they had undergone soil-water replacement with acetone and subsequently impregnation with a polyester resin containing a fluorescent dye (Uvitex 0B, Ciba Geigy). The method for sample impregnation is widely documented, having been described in detail by Osterkamp (1977), Fitzpatrick (1984), Sheldrick (1984) and White (1991).

The use of thin sections under a polarising microscope with plain or polarised transmitted light and incident light, and block specimens by image analysis facilitates the description of the arrangement of soil particles and voids as well as provides information on particular features and how they are interrelated. Characterisation of the voids, their shape, size and arrangement may be undertaken and quantitative information obtained by using computerised image analysis instrumentation (Bullock and Thomasson, 1979). Micromorphology of the thin sections was described according to Brewer (1973) and a glossary of micromorphology terminology (Howes and White, 1991). Soil fabric descriptions were made from vertically oriented thin sections at 6 x and 25 x magnification. These provided an indication of the gross morphology that characterises the structure of the soil fabric (Fox, 1979). Each of the thin sections was oriented vertical to the surface. All of the micromorphological research was carried out at Agriculture Canada's Research Branch, Land Resources Research Centre (LRRC).

3.3 Cryogenic Fabric Observations

Distinct gross morphologies were observed to have developed in the samples taken from the zone within the soil profile exposed to four freeze-thaw cycles. Van Vliet Lanoe et al (1985) noted that soil structures developed

directly in response to freezing and thawing processes, and that the structures were stable and maintained their distinctive morphology through subsequent disruption.

The dominant morphology which has developed in the zone exposed to repeated freeze-thaw cycles is a fragmoidic fabric (Plate 3.1, 40 cm below the bottom of pipe; Plate 3.2, 80 cm below the surface at the side of the pipe). The fragmoidic fabric designates morphology having planar voids and separate, coalesced, often elongated soil units; such fabric was interpreted by Van Vliet Lanoe (1985) to result from ice-lens formation, and shown by Pawluk (1988) to form from repeated freeze-thaw cycles. The fragmoidic fabric was observed to change to a fragmic fabric as a function of changes to the thermal gradient (Figure 2.6) and increasing depth below the pipe and increasing distance away from the buried chilled pipeline (Plate 3.3, 1.0 m from the pipe, 20 cm below surface; and Plate 3.4, 60 cm below the bottom of the pipe). The fragmic fabric designates morphology having compact aggregates separated by planar voids. Maximum planar void widths of up to 0.3 mm were observed in the fragmoidic fabric in the frost-bulb below the pipe, and immediately adjacent to the buried chilled pipeline. Planar pores were observed to decrease in width as the fabric changed from a fragmoidic to a fragmic fabric where maximum pore width (up to 0.07mm) was observed.

PLATE 3.1

FRAGMOIDIC FABRIC

40 cm Below the Bottom of the Pipe

10 mm

Planar Voids (a) separating coalesced,
often elongated soil units (b).

PLATE 3.2

FRAGMOIDIC FABRIC

80 cm Below the Surface, at the Side of the Pipe

10 mm

Planar Voids (a) maximum width 0.3 mm

PLATE 3.3

FRAGMIC FABRIC

1.0 m from the Pipe, 20 cm below Surface

10 mm

Compact aggregates (a) separated by planar voids (b)

PLATE 3.4

FRAGMIC FABRIC

60 cm Below the Bottom of the Pipe

10 mm

Planar voids (a) maximum width 0.07 mm

In contrast, Plate 3.5 (80 cm below surface, 0.5 m from pipe) and Plate 3.6 (60 cm below surface, 3.0 m from pipe) show a much denser granular structure which characterises the soil taken from zones in the profile not exposed to freezing. The dominant morphology in this zone is granoidic fabric with random zones of porphyroskelic fabric. The granoidic fabric distribution designates morphology having irregular weakly interconnected voids separating coalesced aggregates. Figure 3.1 illustrates the spatial distribution of observed cryogenic fabrics in the soil and surrounding the pipe and as a function of depth below surface and distance from the buried chilled pipe.

Lithic discontinuities and stratification of sediment first observed by Dumoulin et al (1987) were also confirmed in the thin sections made from samples taken from the surface layer above and beside the pipe, and at a distance of 0.5 m from the side of the pipe, the depth at which the pipe was installed. Equipment and people on the ground surface along the pipe caused some compaction of the soil. The dominant morphology in these zones (Plate 3.7) exposed to additional compaction is Porphyroskelic fabric, the morphology of which is characterised by a dense ground mass with few to no distinct voids.

The location of segregated ice-lenses in the silt profile relative to both the ground surface and at distance

PLATE 3.5

GRANOIDIC FABRIC

80 cm Below Surface, 0.5 m from Pipe

10mm

Irregular weakly interconnected voids (a)
separating coalesced aggregates (b)

PLATE 3.6

GRANOIDIC FABRIC

60 cm Below Surface, 3.0 m from Pipe

10 mm

Granoidic fabric (a) with random zones
of porphyroscopic fabric (b)

FIGURE 3.1
SPATIAL DISTRIBUTION OF CRYOGENIC FABRIC
ADJACENT TO A BURIED CHILLED PIPE

- PORPHYROSKELIC FABRIC
- FRAGMOIDIC FABRIC
- FRAGMIC FABRIC
- GRANOIDIC FABRIC

PLATE 3.7

PORPHYROSKELIC FABRIC

10 mm

from the buried chilled pipeline is shown in Plate 3.8. Ice-lens spacing was observed by the author at the end of the fourth freeze cycle to vary from closely spaced ice-lenses (5 mm to 10 mm apart) in the upper soil layer, to ice-lenses spaced 20 mm to 30 mm apart at greater depths and at distances from the pipeline. Planar voids were observed in the fragmoidic fabric to be closely spaced (1.0 mm to 2.0 mm, Plate 3.1). At depth the spacing was observed to become more irregular and range from 2.0 mm to 5.0 mm apart where the fragmic fabric was seen to have developed (Plate 3.3).

The development of this pattern of spacing is typical of a slow freezing soil characterised by a predominately silty texture whose capillary fringe is within the water table. Under the steady water supply conditions such as those maintained in the Caen experiment where the flow of heat exceeds the rate of latent heat release, ice-lenses have continued to grow, forming in a series one after the other.

The observed spacing between the planar voids reflects the change in thermal and hydraulic balance at the freezing front, that is, where ice formed. Spacing was observed to increase as the rate of cooling and lower hydraulic conductivity of the silt decreased as a function of depth from the surface and distance from the buried chilled pipe-

PLATE 3.8

SPATIAL DISTRIBUTION OF SEGREGATED ICE LENSES
ADJACENT TO A BURIED CHILLED PIPELINE

line. Figure 2.6 illustrated the position of the 0°C isotherm in silt as a function of time for the fourth freeze cycle of the Caen experiment. At 1 m from the centre of the buried pipe one can clearly see that the rate of cooling has decreased as a function of depth.

Planar void orientation appears to be influenced by the thermal gradient as was the observed spacing of the ice-lenses (Smith and Williams, 1990). The orientation of the planar pore also appears to have been influenced, albeit to a lesser extent, by the attitude of the 0°C isotherm as it extends downward from the ground surface and away from the chilled pipe and its frozen soil annulus. Isotherm attitude may be a critical cause as well as a consequence of some deformation structures (Washburn et al, 1973).

3.4 Cryogenically induced translocation of skeleton and plasma

Evidence of rearrangement of both the skeleton grains (mineral grains) and plasma (clay size fraction) was then observed at magnifications of 6x and 25x within samples of Caen silt which had developed fragmoidic and fragmic fabrics.

Examination of the thin sections revealed that internal movement of skeleton grains (comprised primarily of the mineral quartz), and plasma had taken place. Present in the

thin sections was evidence of clay accumulation, vertical alignment of skeleton grains and banded micro structures also described in literature as isobands.

Plate 3.9 illustrates how, in the fragmoidic fabric, iron-oxide-coated clay minerals (a) have accumulated on the upper surface of a partially accommodated planar void (b). The accumulation of plasmas has occurred above what was probably a former ice-lens. Internal movement could be inferred from the tendency for accumulations to occupy voids left behind by segregated ice-lenses.

Corte (1966) reported on experiments which involved cycles of freezing the soil from its surface, or from the bottom up, and then thawing from the surface. He inferred from the grain-size analysis of the soil samples that during the freezing process there is a tendency for fine particles (<0.074 mm) to migrate to the freezing plane.

Internal reorganisation of soil material can be inferred from the tendency for vertical or near vertical alignment of individual skeleton grains (Fox and Protz, 1981). The displacement and reorientation of skeleton grains shown in Plates 3.10 and 3.11 (magnification 6x and 25x respectively) may have resulted from ice-lenses or crystals of ice at the base of these grains. Kaplar (1965) illustrated that when freezing is from the top down in an open system test, like that conducted in the Caen ground freezing experiment, skeleton grains become reoriented when

PLATE 3.9

CLAY ACCUMULATIONS IN FRAGMOIDIC FABRIC

500 μ m

Clay accumulations (a) on upper surface of a partially
accommodated planar void (b)

PLATE 3.10

VERTICAL ALIGNMENT OF SKELETON GRAIN IN FRAGMOIDIC FABRIC

500 μ m

Vertical and near-vertical alignment of soil
quartz skeleton grains (a) (x6)

PLATE 3.11

TRANSLOCATION OF SKELETON GRAIN IN FRAGMOIDIC FABRIC

500 μ m

Near vertical alignment (arrow) of quartz skeleton
grain (a) with ground mass infillings (b) (x25)

the adfreeze force around it is greater than the forces holding it in place. The total movement experienced by the skeleton grains from their initial position depends upon the heaving rate of the soil and the time required for the 0°C isotherm to penetrate down to a level below the skeleton grains. Thawing of the ice-lenses and soil material adjacent to these coarse skeleton grains would take place after the skeleton grains have thawed because of the higher thermal conductivity of the skeleton grains (made up of quartz whose thermal conductivity (k) is 8 W/m.K compared to the surrounding ground mass and plasma whose k value is in the order of 1.8 W/m.K). The thawed finer material could slump into the space formerly occupied by the ice-lenses, thus preventing the return of these grains to their original positions.

Corte (1966) distinguished different types of frost sorting, that is, processes by which migrating particles were sorted into uniform particle size. Vertical sorting occurred when freezing and thawing took place from the surface causing the larger particles to move upward in relation to the smaller particles.

The near-vertical or vertical alignment of these grains can be attributed to differential movement (French, 1976). The top of the grain would be captured by the advancing freezing front while the base remains unfrozen. Depending

on the shear strength of the unfrozen soil, the axis of the skeleton grain may undergo rotation with the tendency being toward vertical alignment.

Plate 3.12 shows iron-oxide-coatings on clay accumulations which have formed a series of bands (a) above a partially accommodated planar void (b). Here it is clear that preferential mobilisation of fines to surmount banded sediments and "pressure stress accumulations" (Bunting, 1983) adjacent to melted lenses are a major process. The clay fraction, in fact, records the cryogenic stresses (Van Vliet-Lanoe, 1991).

Banded fabric in soil was first described and its origins explained by Kubiena (1938). He recognised this phenomenon as an indication of downward movement of soil solution which, upon drying, formed alternating horizontal layers rich or poor in plasmic substances. In work carried out by Brewer and Pawluk (1975) and Bunting (1983), soils of the Canadian Arctic and subarctic regions have been observed to exhibit evidence of banding. The most common horizontal structure observed by Pawluk and Brewer (1975) was an isoband and banded fabric in some soils from Devon and King Christian Island, N.W.T.

As shown in Plate 3.13, the microband fabric which has developed in the Caen silt fabric type is a banded fabric consisting of discrete lens-like micro units oriented more or less parallel to the soil surface and which range from

PLATE 3.12

MICROBANDED FABRIC IN CAEN SILT

10 mm

Accumulations of clay particles with associated iron oxides
form a series of bands (a) above a partially accommodated
planar void (b)

PLATE 3.13

MICROBANDED FABRIC IN CAEN SILT

10mm

Discrete lens-like micro units (a) oriented
more or less parallel to soil surface

0.3 to 1.0 mm in thicknes and 2 to 5 mm in length. The upper portion of the band appears to contain a higher content of fine silt and clay-sized particles with associate iron-oxides which form a distinct upper surface.

The presence of microbanded fabric in the Caen silt is consistent with findings reported by Mermut and St. Arnaud (1981). They noted that banding is most strongly expressed when a soil's clay content is less than 15% and where there is uniformity in the size of the coarser fraction, which, in the case of Caen silt, is between 75 to 90% in the silt size fraction. The occurrence of microbanding is also restricted to soils which are subjected to frost action under hydraulic regimes similar to those maintained in the Canada-France ground freezing experiment, where moisture conditions were kept between field capacity and saturation over the duration of the experiment.

It is difficult at this stage to theorise whether these assemblages of banded accumulations formed during one freeze-thaw cycle, or represent the work performed by all four experimental freeze-thaw cycles. Future frost effects research to be undertaken by the author at the Centre de Geomorphologie on a number of different frost susceptible soils will hopefully clarify this question and help gain a better understanding of the mechanisms responsible for these

and other micromorphological assemblages.

CHAPTER FOUR

Physical Properties of Caen Silt

4.1 General

In order to properly evaluate the micromorphological and hydraulic alteration that Caen silt has undergone, a laboratory evaluation consisting of grain-size analysis, mineralogical analysis of clay-size fraction, hydraulic conductivity determinations and soil-water desorption determinations was undertaken. The specific objectives of this evaluation were:

- 1) To determine physical properties exhibited by Caen silt samples taken from zones in the sample profiles which had been exposed to freezing and zones in the profile which had not been; and
- 2) To relate these physical properties to the development and arrangement of the soil fabric types described in Chapter 3.

4.2 Soil Characteristics / Grain Size Analysis

The frost susceptible soil is eolian in origin and composed of about 3 to 10 percent sand (2.0 to 0.076 mm), 75 to 85 percent silt (0.076 to 0.002 mm) and 10 to 20 percent clay (0.002 mm); a grain size distribution curve is given

(Figure 4.1). Atterberg limit determinations of Caen silt placed its liquid limit at 32%, and its plastic limit at 21%. It can be designated as ML (medium loam) by the Unified Soil Classification System.

4.3 Mineralogy of Clay Size Fraction

The grain size analysis of Caen silt indicated that between 10 to 20% of the silt grain size is in the clay size fraction. This observation necessitated a complete mineralogical analysis of the clay particles to identify whether or not swelling clays such as smectite were present. It was felt that from an understanding of the constituent clay minerals present, possible inferences could then be made regarding the development and arrangement of the soil fabric. The type of clay minerals identified in the silt were also ultimately responsible for determining the method of soil water removal which would be used when preparing the undisturbed specimens for micromorphological analysis.

Samples of the clay size fraction were separated by sedimentation. Scanning electron microscopy and X-ray diffraction analysis were carried out on orientated glass slides onto which suspensions of the clay size fraction were allowed to dry.

Electron micrographics from dried suspensions of clays from a zone in the profile subjected to freezing, and from a zone not exposed to freezing, were produced at

FIGURE 4.1

GRAIN SIZE DISTRIBUTION CURVE OF CAEN SILT

both 1,000 times and 5,000 times magnification. A comparison of the relative abundance of clay size particles present in the zone exposed to freezing (Plate 4.1 at 1,000 x magnification) and in the zone not exposed to freezing (Plate 4.2 at 1,000 x magnification) was made. The micrographs indicate that there appears to be a higher percentage of fines present in the zone not exposed to freezing. From this and micromorphologic observations (Plate 3.9) it may be inferred that translocation of the clay size fraction of the silt has taken place.

Micrographics produced at 5,000 x magnification for the zone exposed to freezing (Plate 4.3) and the zone not subjected to freezing (Plate 4.4) reveal the presence of several types of minerals in the clay size fraction. Prominent in both plates is the well-crystallised, six-sided, plate shaped clay mineral kaolinite, and some weathered grains of the mineral quartz distinguished by its conchoidal fractures. Also present in both plates are irregular flake shaped aggregates which appear as stacking units without regular outlines. X-ray analysis was then conducted in an attempt to identify these irregular masses, and confirm the presence of the identified minerals quartz and kaolinite.

The standard procedure for X-rays consisting of three series of diffractograms was followed for the analysis of the orientated specimens. In the test series two

PLATE 4.1

ELECTRON MICROGRAPH OF CAEN SILT SAMPLE
EXPOSED TO FOUR FREEZE CYCLES (1,000x magnification)

PLATE 4.2

ELECTRON MICROGRAPH OF CAEN SILT SAMPLE

NOT EXPOSED TO FREEZING (1,000x magnification)

PLATE 4.3

MICROGRAPH PRODUCED AT 5,000x MAGNIFICATION
FOR SAMPLE OF CAEN SILT EXPOSED TO FREEZING

The well crystallised, six-sided, plate shaped
clay mineral kaolinite is present (a).

PLATE 4.4

MICROGRAPH PRODUCED AT 5,000x MAGNIFICATION
FOR SAMPLE OF CAEN SILT NOT EXPOSED TO FREEZING

Plate shaped clay minerals (a) and the mineral
quartz (b) distinguished by its conchoidal fractures.

specimens were prepared from the zone exposed to freezing and two specimens were prepared from samples taken from the zone not exposed to freezing. All specimens were X-rayed as is (untreated) at relative humidity of 50% at 20 °C, and produced the same X-ray diffraction patterns (Figure 4.2), thus inferring that the same minerals are present in both zones.

A second series of X-rays was then undertaken with a single specimen saturated with 50/50 glycerol - water mixture after overnight soaking. A final series was undertaken after this same specimen was heated to 400 °C for one hour in a muffle furnace, cooled and X-rayed. According to the d-spacings produced by the three conditions (Figure 4.3), the clay minerals kaolinite, illite and smectite were identified present in Caen silt. The minerals kaolinite and illite were identified in all three of the test series while the clay mineral smectite was identified only after performing test series two and three.

4.4 Saturated Hydraulic Conductivity Determinations

Dallimore (1984) reported that repetitive freeze-thaw tests can dramatically affect the heave characteristics of Caen silt. In his frost heave test, cylindrical specimens of remoulded silt which had not been previously frozen were prepared to a density of $1.73 \times 10^3 \text{ kg m}^{-3}$, similar to the

FIGURE 4.2

X-RAY DIFFRACTION PATTERN FOR CAEN SILT SPECIMEN
EXPOSED TO FREEZING AND SPECIMEN NOT EXPOSED TO FREEZING

FIGURE 4.3
X-RAY DIFFRACTION PATTERNS FOR CAEN SILT
UNTREATED, GLYCEROL - WATER AND AT 400 °C

According to the d-spacings the clay minerals Kaolinite (a)
 illite (b) and smectite(c) are present in Caen silt.

Also quite prominent is the mineral quartz (d)

density used in the ground freezing experiment. After the first freeze - thaw cycle it was observed that the vertical permeability of the reconsolidated thawed samples increased from $8 \times 10^{-8} \text{ cms}^{-1}$ to $3 \times 10^{-7} \text{ cms}^{-1}$. Detailed examination of sections of the test specimens suggests the increase in the permeability was due largely to an increase in the hydraulic conductivity in the portion of the sample frozen during the test. The hydraulic conductivity of the portion of the sample not exposed to freezing was found to decrease from 10^{-8} to 10^{-9} . Structural changes attributed to intense ice lensing, it is believed, may be responsible for creating paths for increased flow of water.

The undisturbed core samples taken from zones of the five soil profiles which had been exposed to freezing and from zones which had not been exposed to freezing were prepared and instrumented with a constant head device developed by Klute (1965) for the measurement of hydraulic conductivity. Plate 4.5 illustrates the laboratory apparatus used at Agriculture Canada Land Resources Research Centre (LRRC) in which 15 specimens were investigated at the same time.

Calculations of hydraulic conductivity (K) can be determined from the following equation:

$$K = \frac{(QL)}{(AT H)}$$

PLATE 4.5

HYDRAULIC CONDUCTIVITY LABORATORY APPARATUS

Caen Core Specimens instrumented with
constant head apparatus (a).

where K is saturated hydraulic conductivity (cm s^{-1}), Q is the volumetric flow over a period of time T , L is the length of the core specimen (cm), T is time in seconds, A is the cross sectional area of the core (cm) and H is the hydraulic head difference in cm.

All test results are plotted on a cross section of the sample site locations along the B-B axis (Figure 4.4). Overall, the test results indicate a pattern of hydraulic conductivity similar to the changes reported by Dallimore. Hydraulic conductivity values at 3.0 m from the side of the buried pipe were $10^{-4} \text{ cm s}^{-1}$ compared to much higher values (one order of magnitude) $10^{-3} \text{ cm s}^{-1}$ in zones below (in the frost-bulb) and immediately adjacent to the buried chilled pipeline where segregated ice-lensing was observed by Smith and Williams (1989) to be the most intense (Figure 4.5). In strong contrast, much lower hydraulic conductivity values ($2 \times 10^{-5} \text{ cm s}^{-1}$ to $8 \times 10^{-5} \text{ cm s}^{-1}$) were observed on material that was frozen, from immediately above the buried pipe where additional compaction was reported and in the zones of the soil profile along the B-B axis not exposed to freezing. These observations are an order of magnitude lower than the values recorded at 3.0 m from the pipe.

Some variations in hydraulic conductivity from the general pattern were also observed. This suggests that, in spite of the elaborate pretreatment of the silt used in the experiment, differences in packing are present in the soil

FIGURE 4.4

SATURATED HYDRAULIC CONDUCTIVITIES FOR

CAEN SILT SPECIMENS SAMPLED FROM PROFILE ALONG B-B AXIS

FIGURE 4.5

ICE LENS ORIENTATION AROUND A CHILLED BURIED PIPE

modified from: S.L. Smith and P.J. Williams, 1990. Ice lens orientation around a chilled buried pipe. Proceedings, Fifth Canadian Permafrost Conference, pp. 8.87. NRC - Centre d'étude Nordiques, Laval University.

profile. Hydraulic conductivity values at 60 and 80 cm below surface, .5 m from the side of the pipe were one order of magnitude lower in this zone. Micromorphologic observations (Figure 3.1) indicated that porphyroscopic fabric had developed in this zone where compaction associated with installation of the buried pipe took place.

4.5 Soil-Water Desorption Determinations

The relationship between the soil-water content and the soil-water suction is a fundamental part of the characterisation of the hydraulic properties of soils.

Soil-water data provides information on pore-size distribution, density and porosity which is valuable for characterising soils for various applications related to drainage, liquid waste disposal and frost heave potential.

Soil - water desorption curves are determined by applying a negative potential to a specific volume of soil for sufficient time to allow the pores which will drain at the applied suction to do so. The equilibrated sample is weighed and this value is used to calculate the water content for the applied tension.

Following the completion of hydraulic conductivity determinations, the twenty-nine core samples were prepared for water desorption measurements. When the cores had equilibrated for the appropriate amount of time (Sheldrick, 1984) at the desired pressure head, the samples were removed

from the tank's suction plate and weighed.

Calculations of volumetric water content, bulk density and porosity can be determined from the following equations:

$$\text{Gravimetric Water Content (\%)} = \frac{\text{Mass of Wet Soil} - \text{Mass of Dry Soil}}{\text{Dry Soil}}$$

$$\text{Bulk Density (g/cm}^3\text{)} = \frac{\text{Mass of Dry Soil}}{\text{Volume of Dry Soil}}$$

$$\text{Porosity (\%)} = \frac{\text{Bulk Density}}{\text{Particle Density}^*}$$

* where Particle Density = 2.65 g/cm³.

Data analysis was conducted using computer programs. (Please refer to Appendix A for program listing. All test results for the core specimens taken from the five soil profiles located along the B-B axis are plotted and presented in Figures 4.6 through 4.10. Overall, the test results indicate patterns in bulk density, porosity and soil - water retention similar to those observed for saturated hydraulic conductivity.

Tables 4.2 through 4.5 indicate that overall sample density values increased for Profiles 2 through 5 as a function of depth. Porosity values of 46% and 44% were observed to be in zones below (in the frost bulb) and immediately adjacent to the buried chilled pipe where

FIGURE 4.6

SOIL - WATER DESORPTION CURVES
CAEN SILT CORE SAMPLES FROM PROFILE
ABOVE AND BELOW PIPE

FIGURE 4.7

SOIL - WATER DESCRIPTION CURVES

CAEN SILT CORE SAMPLES FROM PROFILE AT SIDE OF PIPE

FIGURE 4.8

SOIL - WATER DESORPTION CURVES

CAEN SILT CORE SAMPLES FROM PROFILE

0.5 m FROM SIDE OF PIPE

FIGURE 4.9

SOIL - WATER DESORPTION CURVES

CAEN SILT CORE SAMPLES FROM PROFILE LOCATED 1.0 m FROM
SIDE OF PIPE

FIGURE 4.10

SOIL - WATER DESORPTION CURVES

CAEN SILT CORE SAMPLES FROM PROFILE LOCATED 3.0 m
FROM SIDE OF PIPE

2

of/de

2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

PIONEERS IN METHYLENE BLUE TESTING SINCE 1974

MicroD

1900 COUNTY ROAD 9, BIRMINGHAM, AL 35207 USA
TEL 812 426 7867 FAX 812 426 7867 TLE 8100000000

TABLE 4.1

PHYSICAL PROPERTIES AND MOISTURE RETENTION CHARACTERISTICSOF CAEN SILT, PROFILE ONE (ABOVE AND BELOW PIPE)

Sample #		1	2	3	4	5	6
Density g/cm ³		1.620	1.663	1.536	1.589	1.490	1.474
Approx. Porosity		.3888	.3725	.4195	.4004	.4377	.4439
Moisture content @ tension of (cc/cc @ cm H ₂ O)	+0	.3721	.2770	.3836	.3579	.3567	.4429
	-5	.3405	.2567	.3570	.3361	.3316	.4177
	-10	.3358	.2539	.3266	.3308	.3209	.4121
	-20	.3183	.2511	.3200	.3091	.3148	.4079
	-40	.3104	.2368	.3096	.2993	.2855	.3616
	-60	.3063	.2304	.3048	.2908	.2815	.3616
	-80	.3034	.2304	.3048	.2908	.2815	.3616
	-100	.3008	.2229	.3003	.2838	.2766	.3555
	-150	.2981	.2175	.2965	.2791	.2738	.3521
	-225	.2929	.2118	.2913	.2742	.2692	.3478
	-350	.2899	.2066	.2858	.2676	.2658	.3433

TABLE 4.2

PHYSICAL PROPERTIES AND MOISTURE RETENTION CHARACTERISTICS
OF CAEN SILT, PROFILE TWO (SIDE OF PIPE)

Sample #		1	2	3	4	5	6
Density g/cm ³		1.404	1.474	1.417	1.551	1.549	1.528
Approx. Porosity		.4700	.4437	.4654	.4148	.4156	.4234
Moisture Content	+0	.4644	.4164	.4029	.3644	.3678	.3863
@	-5	.3578	.3546	.3586	.3373	.3552	.3353
Tension	-10	.3353	.3365	.3446	.3321	.3510	.3258
of	-20	.3183	.3206	.3161	.3272	.3469	.3175
(cc/cc	-40	.3016	.3073	.2964	.3214	.3358	.3090
@	-60	.2925	.2998	.2848	.3173	.3245	.3026
cm H2O)	-80	.2869	.2955	.2782	.3145	.3197	.3001
	-100	.2821	.2917	.2733	.3120	.3161	.2976
	-225	.2643	.2806	.2584	.3013	.3036	.2895
	-350	.2566	.2748	.2503	.2959	.2970	.2853

TABLE 4.3

PHYSICAL PROPERTIES AND MOISTURE RETENTION CHARACTERISTICS
OF CAEN SILT, PROFILE THREE (.5 m FROM SIDE OF PIPE)

Sample #		1	2	3	4	5	6
Density g/cm ³		1.617	1.476	1.507	1.586	1.561	1.618
Approx. Porosity		.3897	.4429	.4314	.4017	.4108	.3894
Moisture Content @ Tension of (cc/cc @ cm H ₂ O)	+0	.3250	.4041	.4009	.4097	.4130	.3797
	-5	.3006	.3727	.3653	.3648	.3845	.3233
	-10	.2963	.3691	.3351	.3597	.3811	.3197
	-20	.2931	.3659	.3281	.3552	.3669	.3170
	-40	.2881	.3077	.3106	.3466	.3606	.3141
	-60	.2855	.3014	.3044	.3377	.3579	.3117
	-80	.2830	.2977	.3003	.3354	.3556	.3112
	-100	.2807	.2938	.2966	.3334	.3529	.3108
	-150	.2771	.2888	.2918	.3319	.3503	.3033
	-225	.2707	.2837	.2856	.3261	.3448	.2986
	-350	.2653	.2782	.2793	.3241	.3397	.2943

TABLE 4.4

PHYSICAL PROPERTIES AND MOISTURE RETENTION CHARACTERISTICS
OF CAEN SILT, PROFILE FOUR (1.0 m FROM SIDE OF PIPE)

Sample #		1	2	3	4	5
Density g/cm ³		1.547	1.566	1.397	1.574	1.591
Approx. Porosity		.4162	.4089	.4727	.4061	.3994
Moisture Content @ Tension of (cc/cc @ cm H ₂ O)	+0	.3437	.3879	.3976	.3932	.4372
	-5	.3110	.3391	.3515	.3436	.3684
	-10	.3076	.3334	.3430	.3350	.3611
	-20	.3050	.3279	.3347	.3313	.3539
	-40	.3017	.3225	.3218	.3273	.3448
	-60	.2979	.3173	.3127	.3233	.3377
	-80	.2951	.3145	.3072	.3193	.3321
	-100	.2922	.3112	.3005	.3158	.3261
	-150	.2864	.3067	.2891	.3042	.3088
	-225	.2818	.3005	.2781	.2919	.2961
	-350	.2764	.2957	.2629	.2758	.2758

TABLE 4.5

PHYSICAL PROPERTIES AND MOISTURE RETENTION CHARACTERISTICS
OF CAEN SILT, PROFILE FIVE (3.0 m FROM SIDE OF PIPE)

Sample #		1	2	3	4	5
Density g/cm ³		1.540	1.418	1.421	1.474	1.535
Approx. Porosity		.4189	.4649	.4639	.4436	.4209
Moisture Content	+0	.3698	.4139	.4335	.3917	.4108
@	-5	.3269	.3806	.3915	.3412	.3702
Tension of	-10	.3198	.3462	.3802	.3318	.3628
(cc/cc	-20	.3090	.3276	.3709	.3228	.3515
@	-40	.2960	.3011	.3144	.3161	.3356
cm H ₂ O)	-60	.2878	.2892	.2957	.3116	.3247
	-80	.2826	.2830	.2876	.3090	.3142
	-100	.2783	.2774	.2809	.3056	.3083
	-150	.2654	.2680	.2692	.3006	.3005
	-225	.2575	.2624	.2623	.2909	.2938
	-350	.2501	.2554	.2563	.2888	.2886

intense segregated ice lensing has made the soil more conducive to greater water contents.

Higher density and lower porosity values were observed in the samples taken immediately above the pipe and from samples taken at the surface at distances of .5 m, 1.0 m and 3.0 m from the side of the pipe.

Description curves (Figures 4.6 to 4.10) produced from the test data indicate that a distinct pattern of void size distribution has developed in the Caen silt.

Calculations for size distribution of voids is based on the moisture tension curve that relates the amount of water in the soil in equilibrium with the suction applied. Void size calculations are based on the capillary rise equation:

$$h = \frac{2S \cos \theta}{pgr}$$

where h is the height of rise in a capillary tube with radius r, S is the surface tension of water with density p, g is the acceleration due to gravity, and θ is the contact angle between water and soil (assumed to be zero) (Baver, 1975).

This equation simplifies to the usable expression

$$r = \frac{(2S/pg)}{h}$$

where r is the radius of the pore in millimetres and h is the amount of suction in centimetres of water with which the water in the void is held in equilibrium. It should be noted that since voids in soils are highly irregular and

ill-defined, the exact dimension of the void is not readily expressed.

Desorption curves (Figure 4.6, above and below the pipe) and Figure 4.8 (0.5 m from side of pipe), when compared to Figure 4.9 (1.0 m from side of pipe), show variations in water retention exist between zones of the profiles which have been exposed to freezing compared to zones of the profiles not exposed to freezing.

The most significant variation in water retention at different suctions was observed between the core samples taken from above and below the pipe. Water retention ranged from 20% for samples located above the pipe to 34% for a sample located below the pipe at tension of -350. A much narrower range of water retentions was exhibited by core samples located in Profile Four (Figure 4.9) and Profile Five (Figure 4.10). Overall, water retention varied by as little as 2% throughout Profile Four and by only 5% throughout Profile Five.

Low porosity values (38%) were observed throughout the surface layer of the sample area and are attributed to the compaction of this zone by equipment and foot traffic over the operating life of the experiment.

Water holding capacity and higher porosity values (46%) within the zones of the soil where intense segregated ice lensing was observed would, one could reason, create more

macro sized pore space ($> 60 \text{ um}$) which is responsible for this zone's higher water holding capacity. In contrast, water retention and calculated porosity for the profiles located 1.0 m and 3.0 m from the side of the buried chilled pipe where little freezing took place, were observed to be more uniform.

The presence of the clay mineral smectite in Caen silt may be responsible for the alteration of pore-size distribution.

Samples for moisture

retention measurements are first wetted to a suction of 0.005 bar, the first equilibrium point, and then desaturated. The initial wetting could, it is hypothesised, cause swelling of smectite which would change pore space compared with pore space as it originally existed in its field state at the time of sampling.

4.6 Implications for Frost Heave Potential

Given that both the carefully controlled thermal and hydraulic regimes for each of the freeze/thaw cycles have remained similar in the Caen experiment, it can be inferred that the reported changes in the soil's fabric and physical properties, (specifically, saturated hydraulic conductivity and water retention characteristics) have altered its heave susceptibility. Chamberlain (1988) illustrated that the freezing and thawing of silt and clay slurries cause an

increase in the vertical permeability and density at depth in his test specimens. These changes were observed to alter the frost heave potential of the soil from the first freeze-thaw cycle to the second and third cycles. Subsequent freeze-thaw permeability test results performed by Chamberlain et al (1990) on four compacted frost susceptible soils also illustrated the extent to which their vertical permeability was increased as a function of freeze-thaw cycling (Figure 4.11).

Table 4.2 indicates how, after each successive freeze-thaw cycle of the Caen experiment, cycles two to four (inclusive) for Day 100, the frost-heave susceptibility of the silt continued to increase.

TABLE 4.2
HEAVE OF PIPE IN CAEN SILT (Day 100)

Freeze Cycle	Heave (cm)	%Increase
Second	9.88	--
Third	10.77	9
Four	11.40	5.8

The increasing frost susceptibility of Caen silt has been brought about by intense segregated ice-lensing which created the fragmoidic fabric adjacent to and beneath the buried pipe. The observed changes in hydraulic conductivity

FIGURE 4.11
FREEZE - THAW PERMEABILITY TEST RESULTS FOR
FOUR COMPACTED CLAYS

from: Chamberlain et al., 1990, Effect of Freeze-thaw cycles on the permeability of Macrostructure of Soils, Proceedings, International symposium Frozen soil Impacts on Agriculture, Range and Forest Lands, Spokane Washington, p. 100.

and water retention attributed to intense ice-lensing have developed as a result of high soil moisture suctions in the freezing zones. This causes an increase in the effective stress in the region below the freezing front during the formation of segregated ice-lenses. The ice-lensing has been responsible for increasing the soil's vertical permeability in the near surface layer, permeability which has remained unaltered and has possibly been increased by each subsequent cycle. Increased porosity associated with macro pore spaces left behind by intense ice lensing is responsible for the increasing hydraulic conductivity of the silt.

While the permeability of the zones of Caen silt exposed to freezing have been observed to increase and thus permit increasing amounts of water to migrate to the freezing front where ice accumulation was observed to be greatest, the situation at depth has been observed to be quite different. Consolidation which may be due to frost induced suction has resulted in a full order of magnitude decrease in the silt's hydraulic conductivity, and a reduction in its water retention characteristics.

The reported findings for changes in hydraulic conductivity of Caen silt core specimens clearly indicate that zones of the sample profile not exposed to freezing have become less permeable and more dense after several thaw

consolidation phases, while conversely, zones of the sample profiles exposed to freezing have experienced an increase in vertical permeability.

CHAPTER FIVE

Measurement and Characterisation of Voids by Image Analysis

5.1 General

To better characterise the macro void size distribution evident in the micromorphology of the silt, a laboratory study utilising computer image analysis was undertaken. The specific objectives were:

- 1) To determine void size distribution and macro porosity exhibited by Caen silt samples taken from within the soil annulus surrounding the buried chilled pipe and in the soil at distance from the pipe; and
- 2) To relate macroporosity to the total porosity values derived from soil-water desorption determinations reported in Chapter 4.

5.2 Computer Image Analysis

The use of an image analyser on photographs prepared from polished blocks or thin sections to measure and characterise void size distribution was first demonstrated by Jongerius et al (1972). Similar work has been conducted by others including Bullock and Thomasson (1979), Murphy, Bullock and Turner (1977) and Delgado and Dorronsoro (1983). Their work has shown that very valuable information can be obtained with regard to the shape, frequency and orientation.

of voids. The methodology for image analysis is widely documented, having been described in detail by Bullock (1980), Delgado (1981) and Ringrose-Voase (1984).

The introduction of image analysing computers provided soil scientists with a means of rapidly quantifying components in thin sections or prepared block specimens. The main advantages of image analysis are that measurement and characterisation of macro pores can be coupled with a visual appreciation of their type and distribution. The method of image analysis is very accurate as 500,000 points are analysed in each field of view. The principle of the technique is that an image formed from a photograph taken of a thin section under a microscope, or in the case of this study, from a black and white photograph (Plate 5.1) taken of the flat surface of the prepared block specimens (Plate 5.2), is scanned by an epidiascope on a plumbicon television camera. The signal from the scanner is passed to a detector module where 500,000 points of the image, each one square and adjoining, are then analysed for their grey level. Voids are measured by setting the instrument to detect a corresponding grey level. The instrument is then set to detect a particular grey level corresponding to the features of interest and the level relating to the strength of the signal. Figure 5.1 illustrates the process by which discrimination of the image according to the grey level

PLATE 5.1

FRAGMOIDIC FABRIC

BLACK AND WHITE PHOTOGRAPH FOR IMAGE ANALYSIS

10mm

Prepared Block Specimen (40 cm below pipe)

PLATE 5.2

FRAGMOIDIC FABRIC

COLOUR PHOTOGRAPH OF PREPARED BLOCK SPECIMEN

10mm

Prepared Block Specimen (40 cm below pipe)

FIGURE 5.1

DISCRIMINATION OF THE IMAGE ACCORDING

TO THE GREY LEVEL SETTING

from: Delgado, M. and C. Dorronsoro, 1983, "Image Analysis"
 from Soil Micromorphology, edited by P. Bullock and
 C.P. Murphy, A. B. Academic Publishers, pp. 73.

settings is undertaken.

Once the requisite grey level setting has been made, the image signal is analysed by a computer in the following stages: an image is produced; the image is scanned and displayed on a television screen (Plate 5.3); and the image is enhanced and void spaces are discriminated (Plate 5.4). Measurement of the number of voids per each category of void width from the image are then plotted (Figure 5.2). All of the image analysis research was carried out at Agriculture Canada's Research Branch, Land Resources Research Branch (LRRC) using its Koestron IBAS system computer image analyser.

The basic parameters measured in this study include total field area of specimen, and area of voids and total porosity of each block specimen. Measurements were derived by using the number and length of chords (horizontal intercepts, Figure 5.3). Minimum void diameters of 0.1 mm were measured in this evaluation of macro pore size distribution which has developed in the silt as a result of intense segregated ice. Data acquisition and analysis was conducted using modified computer software developed at LRRC (please refer to Appendix I, computer program listings).

PLATE 5.3

IMAGE PRODUCED FROM BLACK AND WHITE PHOTOGRAPH

DISPLAYED ON TELEVISION SCREEN

10 mm

Image scanned from black and white photograph of
block specimen as it is displayed on screen

PLATE 5.4

IMAGE IS ENHANCED AND VOID SPACES ARE DISCRIMINATED

10mm

Outline of void spaces are discriminated
and highlighted in green

PLATE 5.5

VOID SPACE MEASUREMENT OF IMAGE

10mm

Highlighted void spaces are measured using
number and length of chords

FIGURE 5.2
VOID SIZE AND FREQUENCY

```

file      : test
parameter : Width
counts    : 226
lower bound : 0.0
upper bound : 2.0
underflow  :
in range   : 226
overflow   :
classes    : 1
modul      : 0.13333
min.class  : 0.0
max.class  : 1476.0
  Statistics
minimum    : 0.05995
maximum    : 0.58135
sum         : 281.4
medianvalue : 0.18243
mean       : 0.12410
variance   : 0.08382
std.dev.   : 0.05496
skewness   : 1.9
kurtosis   : 6.6
  
```

FIGURE 5.3

HORIZONTAL PROJECTION GIVEN BY TOTAL NUMBER OF CHORDS

Size distribution can be obtained from horizontal
projection given by total number of chords

from: Murray, C.P., P. Bullock and R.H. Turner, 1977. "The measurement and characterisation of Voids in Soil Thin Sections by Image Analysis.", Part J, Principles and Techniques. Journal of Soil Science, 1977, 20, p. 502.

5.3 Void Size Distribution and Macro Porosity

Concurring with both the micromorphological observations reported in Chapter 3 and the soil-water desorption tests noted in Chapter 4, the two-dimensional prepared block specimens revealed that void size distribution and calculated macro porosity display a similar spatial pattern.

Void size distribution patterns (the number of voids plotted against range of void diameters) for each of the twenty-eight specimens from the five profiles located along the B-B axis of the Caen experiment are plotted and presented in Figures 5.4 (profile located above and below the pipe) through 5.8 (the profile located 3 m from side of the pipe). Overall, the test results indicate that there is a similar trend (albeit on a two-dimensional level) in changes in macro void size distribution as a function of depth below the buried chilled pipe and distance from the pipe. Findings reported by Walker (1982) indicate that it is inevitable that the two dimensional image will underestimate the extent of the macropores. In order to overcome this limitation the method would require the rather laborious and time consuming analysis of serial sections in order to determine the three dimensional pattern and pore continuity. This was beyond the scope of this study.

Table 5.1 indicates that overall sample macro porosity values were highest in zones located beneath (31.4%) and

FIGURE 5.4

VOID SIZE DISTRIBUTION

OF CAEN SILT, PROFILE ONE (ABOVE AND BELOW PIPE)

FIGURE 5.5

VOID SIZE DISTRIBUTION

OF CAEN SILT, PROFILE TWO (SIDE OF PIPE)

FIGURE 5.6

VOID SIZE DISTRIBUTION

OF CAEN SILT, PROFILE THREE (0.5 m FROM SIDE OF PIPE)

FIGURE 5.7

VOID SIZE DISTRIBUTION

OF CAEN SILT, PROFILE FOUR (1.0 m FROM SIDE OF PIPE)

FIGURE 5.8

VOID SIZE DISTRIBUTION

OF CAEN SILT, PROFILE FIVE (3.0 m FROM SIDE OF PIPE)

TABLE 5.1
TOTAL VOID AREA & MACRO POROSITY CHARACTERISTICS
OF CAEN SILT SAMPLES, PROFILES ONE THROUGH FIVE

Profile/ Sample	Macro Porosity %	Total Area of voids (chord counts)	Total Field Area (chord counts)
1/ 1	5.87	152.24	2591.19
2	17.74	467.60	2636.50
3	31.43	828.69	2636.50
4	17.33	457.01	2636.50
5	13.40	353.36	2636.50
6	22.39	590.39	2636.50
2/ 1	7.66	207.29	2636.50
2	18.09	476.92	2636.50
3	28.13	741.68	2636.50
4	9.38	247.37	2636.50
5	39.95	947.73	2636.50
6	13.30	350.78	2636.50
3/ 1	6.95	183.37	2636.50
2	9.71	255.93	2636.50
3	25.92	660.62	2636.50
4	11.96	315.35	2636.50
5	15.36	405.05	2636.50
6	13.46	354.87	2636.50
4/ 1	7.28	191.86	2636.50
2	11.55	304.49	2636.50
3	13.47	355.14	2636.50
4	15.47	407.89	2636.50
5	13.93	367.20	2636.50
5/ 1	13.16	347.00	2636.50
2	18.99	500.55	2636.50
3	11.33	298.67	2636.50
4	18.03	475.34	2636.50
5	18.47	486.90	2636.50

immediately adjacent (35.8%) to the buried chilled pipe, and at 0.5 m (25.9%) 40 cm below the surface where intense ice-lensing was observed to occur. Overall the macro porosity determined by image analysis for these zones account for between 55 to 75% of the total porosity values presented in Chapter 4 of this thesis. Figure 3.1 clearly shows how these sample areas correspond to a zone in the Caen silt where a fragmoidic fabric has developed. This fabric was shown to be characterised by higher hydraulic conductivity (10^{-3} cm s⁻¹) compared to 10^{-4} cm s⁻¹ for zones in the profile not exposed to freezing. In contrast, much lower porosity values were determined from samples taken from the surface layer immediately above the buried chilled pipe (5.87%), at 0.5 m from the side of the pipe (9.78%), and at 1.0 m from the side of the pipe (7.28%). Macro porosity in the surface layer of the experiment accounts for only between 15 to 20% of the total porosity of this zone. These lower macro porosity values correspond well with the much lower hydraulic conductivity values (10^{-5} cm s⁻¹, Figure 4.4) determined for this zone in which a porphyroskelic fabric was observed to have developed (Figure 3.1).

Figure 5.4 illustrates how a wide variation in void size distribution developed throughout the entire sample profile located immediately above and below the buried pipe. Immediately above the pipe where the sample morphology was

identified as being a porphyroskelic fabric, image analysis results indicate that macroporosity averaged 7%, and that the observed voids fall within the 0.1 mm to 0.5 mm size range and account for only 10% of the total porosity. In contrast, the samples located immediately below the pipe where the sample morphology was observed to be fragmoidic in character have developed a wider range of void sizes (0.1 to 1.0 mm). The data indicates that maximum pore sizes up to 1.0 mm in width had developed in this zone where intense ice-lensing was observed to have developed, and that these larger voids contribute 75% of the total porosity exhibited by this zone.

Void size distribution for samples at 20 cm below surface, in Profiles 4 and 5 located 1.0 m (Figure 5.7) and 3.0 m (Figure 5.8) respectively from the side of the buried chilled pipe, displayed a narrower range of void size widths (between 0.1 mm and 0.7 mm). Micromorphological observations (Figure 3.1) clearly illustrate that fragmic and granoidic fabrics located in this zone have fewer, more widely spaced planar voids. Table 5.1 indicates that calculated macro porosity values for Profiles 4 and 5 have a much lower range of values. At 1.0 m from the buried pipe macro porosity values ranged between 7.3 to 15.5% and at 3.0 m from the side of the pipe ranged between 11.3 to 18.5%. Overall these macro porosity values account for between 30 and 40% of the total porosity in this zone. Table 5.2

summarises the relationship that exists between total porosity and macro porosity determined by image analysis and the identified morphology for each of the sample profiles 1 through 5. The macro porosity values for zones of the profile not exposed to freezing averaged two times higher than samples displaying a porphyroscopic morphology, and averaged one half of the macro porosity displayed by samples taken from zones of the profile which were exposed to freezing. Hydraulic conductivity data from the samples taken from Profiles 4 and 5 at depth beneath 20 cm had mean values of 10^{-4} cm s⁻¹ compared to 10^{-5} cm s⁻¹, typical of the porphyroscopic fabrics located at the surface and immediately above the buried chilled pipe.

TABLE 5.2
COMPARISON OF MACRO POROSITY AND TOTAL POROSITY

Profile No.	Depth (cm)	Total Porosity %	Macro Porosity %	% Total Porosity Macropore	Micro-morphology
1	2-7	38.8	5.8	15.0	Porphsk.
	64-64	41.9	31.43	75.0	Fragmoidic
	115-120	44.3	13.4	31.0	Fragmic
2	5-10	47.0	7.86	16.8	Porphsk.
	59-64	46.54	24.23	47.9	Fragmoidic
	144-149	41.4	13.30	32.2	Fragmic/ Granoidic
3	2-7	38.7	6.95	18.0	Porphsk
	59-64	43.1	25.9	60.1	Fragmoidic
	119-124	38.9	15.36	39.5	Granoidic
4	2-7	41.6	7.28	17.5	Porphsk
	41-46	47.3	17.47	37.0	Fragmic
	84-89	40.6	13.9	34.2	Granoidic
5	2-7	41.8	13.6	31.6	Fragmic
	60-65	46.4	18.0	39.0	Granoidic

Porphsk = Porphyroskelic fabric

CHAPTER SIX

Summary and Conclusions

6.1 General

The use of micromorphological techniques to evaluate micro structural alteration that a frost susceptible soil may undergo when exposed to a series of freeze - thaw cycles should now be considered. The thermodynamic conditions within frozen ground at temperatures just below 0°C are such that there are continuing translocations of water, ice and the displacement of small particles. This method has, upon evaluation, proven capable of providing some insight into the dynamic nature of frozen ground which expresses itself in changing soil morphology.

The information presented in this thesis provides a detailed picture of the continuing internal deformation of frozen soil which results in the reorganisation of soil fabric components and alteration of void space distribution.

Micromorphology combined with physical property test methods of soil investigation has helped open the door to a better understanding of the cryogenic processes. These processes are responsible for the development of new fabrics, changes in permeability, and for increasing the frost heave potential of the soil.

6.2 Summary of Results

The major findings of this thesis are summarised as follows:

1) Microstructural Alteration of Caen Silt

- a) Distinct cryogenic fabrics have developed from the silt's granoidic fabric after exposure to four freeze-thaw cycles. The dominant morphology which has developed is a fragmoidic fabric characterised by planar voids (whose widths measured up to 0.3 mm), and separated, coalesced, often elongated soil units. The fragmoidic fabric was observed to change to a fragmic fabric as a function of increasing distance away from the buried chilled pipe and depth. This fabric is characterised by compact aggregates separated by planar voids with a maximum width of up to 0.07 mm. Lithic discontinuities created by compaction of the silt by equipment and people were identified as porphyroskelic fabric whose morphology is characterised by a dense ground mass with few or no distinct voids.
- b) Spatial distribution of planar voids of varying diameter and spacing was observed to mirror the location and spacing of segregated ice lenses. The development of this pattern of spacing is

typical of a slow freezing soil characterised by a predominantly silty texture whose capillary fringe is within the water table.

- c) Cryogenically induced translocation of both skeleton grains and plasma was observed. Evidence of clay accumulation on the upper surface of planar voids, near vertical alignment of skeleton grains and microbanded fabric was observed in the thin sections.

2) Physical Properties of Caen Silt

The program of physical properties research presented indicates that:

- a) Cryogenic alteration of the hydraulic properties of Caen silt is related to the reported change in the silt's morphology. Hydraulic conductivity determinations made from silt which had not been exposed to freezing averaged 10^{-4} cm s⁻¹ compared to higher hydraulic conductivities (one order of magnitude) 10^{-3} cm s⁻¹ in zones below and immediately adjacent to the buried chilled pipe where a fragmoidic fabric had developed. Hydraulic conductivity values were one order of magnitude lower 10^{-5} cm s⁻¹ in zones of the silt where

porphyroclastic fabric had developed in response to additional compaction.

- b) Soil-water desorption data indicates that a variation in water retention exists between samples located in zones where intense ice segregation occurred, and those from zones in the profile which were not exposed to freezing. Water retention ranged from 20% for samples located above the pipe to 34% for sample located below the pipe at a tension to -350 (cm H_2O). A much narrower range of water retentions was exhibited by Profile Five (3.0 m from side of pipe) where little freezing took place. Water retention ranged from 25% for samples located at surface to 28% for samples located at depths not exposed to freezing.
- c) Porosity values as high as 46% were observed in zones which had been exposed to freezing (in the frost-bulb) while zones which underwent additional compaction or were not exposed to freezing averaged between 38 to 40%.
- d) Increased porosity associated with macro pore spaces (planar voids) left behind by intense ice-lensing is responsible for the increasing

hydraulic conductivity of the silt. It can be inferred that the reported changes in saturated hydraulic conductivity and water retention characteristics have contributed to the increasing alteration in the frost heave susceptibility of the soil from the first freeze-thaw cycle to the second, third and fourth cycles.

3) Measurement and Characterisation of Voids by Image Analysis

The program of computer image analysis of prepared block specimens presented indicated that:

- a) Void size distribution patterns varied spatially as a function of depth below the surface and distance from the chilled pipe.
- b) Macro porosity values were observed to be highest between 31.4% and 35.8% in zones where planar voids were observed to be most concentrated and account for between 55 to 75% of the total porosity of silt which had developed a fragmoidic fabric. In contrast, macro porosity in the surface layer of the experiment where a porphyroskelic fabric had developed accounts for only between 15 to 20% of the total porosity of

this zone. Finally, macro porosity determinations made of samples taken from zones not exposed to freezing (granoidic fabric) were observed to range between 13 and 18% and account for between 31 to 39% of the silt's total porosity.

6.3 Conclusions

The observations reported in this thesis indicate that micromorphology is an attractive laboratory method which can be utilised to make better correlations between soil behaviour and fabric. The investigations performed during the microstructural, physical properties and image analysis components of this thesis suggest that proper characterisations of soil behaviour can be achieved by combining microscopic observations of soil fabric and pore space distribution with physical property testing.

While the focus of this thesis has been placed on evaluating micromorphological alterations of a frost susceptible soil when exposed to a series of freeze-thaw cycles, numerous other applications of micromorphology could be envisaged. Micromorphology could be utilised to better assess the dynamic nature of frost susceptible soils and their interactions with engineering structures such as water distribution systems, sewage collection systems and energy distribution systems. Micromorphology could prove to be a

practical technique for the assessment of a soil's frost heave potential over the life expectancy of such service networks. A better understanding of the interaction between frost susceptible soils and service networks, specifically when subjected to freeze-thaw cycling would help to improve our existing cold regions engineering acumen.

Finally, it is the author's view that more micromorphological research should now be undertaken on various frost susceptible soils. This research would help clarify what cryogenic processes are responsible for alterations of frost susceptible soils' fabric, and help us gain a better understanding of the mechanisms responsible for some micromorphological assemblages reported in this thesis.

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APPENDIX I

PROGRAM FOR IMAGE ANALYSIS

LWHITE.MCR

Friday, October 11, 1991 1:27 pm

Page 1

* D:/scis/macros/lwhite v1.2

* ed Aug./91

* Kontron IIRAS System

* Kontron AT: 386-based with 4 meg on;

* Array processor is the MIAP2 model, and has 16 meg image RAM.

* Data files on floppy disks are in ASCII.

* File names ending in 'x' include Kontron parameters:

* " " " " 'c' " derived " ;

* " " " " 'c' " chord data.

* VARIABLES

global TOT_POR_bc, TOT_AREA, TOT_PER, FIELD_AREA, width

TOT_POR_bc=TOT_PER=TOT_AREA=FIELD_AREA=width=0.0

flag=1=0

reply="y"

filename="Filename"

* SETUP

dos "del d:/scis/data/*.000"

resetbar

setframe "5753"

loadlut "grey"

clearallc

external MINAREA

MINAREA=1

* CALIBRATE

*tvon

*tvaver 1,11,4.4

*tvoff

*scalegeom 1, "1:1-scale", 0.0

* ACQUIRE AN IMAGE

for (i=1:(=7:i=1+1):write

write " PHYSICAL SETUP"

write

write " CAMERA HEIGHT: 25.1 cm."

write " CAMERA LENS : 100 mm.; plus 50 mm tube."

write " SELECT SWITCH: A" 131

pause

```

while (1)
  clearallcv
  for (i=1:1(8:1=1+1):write
  read " Please enter a file name: 6 characters max. ".filename
  for (i=1:1(4:1=1+1):write

  tvon
  beep 99,0333
  write " Switch on base light and position the sample:"
  write
  write
  pause
  tvaver 1,11,4,4
  tvoff
  beep 99,333
  write " Switch off the lights"
  pause
  for (i=1:1(8:1=1+1):write

* PROCESS IMAGE

  invert 1,11
  copy 11,1
  lowpass 1,2,25,25,15
  subtract 1,2,3,3
  scalar 3,4,0,192,1,255,0,255,2
  erincont 4,5,5,2
  copy 5,4
  beep 99,399
  write " Outline the useful area of the sample."
  write
  normim 4,4,8
  scalar 4,20,0,255,1,176,0,255,2
  copy 20,4
  eraseoutside 4,5,0

* MEASURE TOTAL AREA

  scalgeom 1,"white",_OFF,0
  external AREA
  beep 99,399
  dis2lev 5,6,1,255,_ON,0,1
  identify 6,7,_ON,_OFF
  loadlut "grey"
  measobj 7,"objcb",_OFF
  FIELD_AREA=AREA

```

* MEASURE OBJECT-SPECIFIC PARAMETERS

```

InitObj AREA
InitObj ANGLEDMAX
InitObj ANGLEDMIN
InitObj DCIRCLE
InitObj DMAX
InitObj DMIN
InitObj FCIRCLE
InitObj FSHAPE
InitObj PERIM

```

```

while (4)

```

```

    write

```

```

    write

```

```

    write " Discriminate the pores ."

```

```

    write

```

```

    write

```

```

    dis2lev 5.5,1.255,_ON,_ON,1

```

```

    contour 6.5,7,7.255,_ON,_ON

```

```

    display 7

```

```

    reply="y"

```

```

    write

```

```

    read " Is the discrimination OK (y/n) ",reply

```

```

    if (reply=="y"):break

```

```

endwhile

```

```

identify 6,7,_ON,_OFF

```

```

loadlut "grey"

```

```

for (i=1:(6:i=1+1)):write

```

```

    beep 39,333

```

```

    fni=filename+"x"

```

```

    DBerase fni

```

```

    fnifv(i)=AREA,PERIM,width,DCIRCLE,DMAX,DMIN,ANGLEDMAX,ANGLEDMIN,FCIRCLE,FSHA-

```

```

    PE

```

```

    DBcreate fni,"fnifv"

```

```

    tempfv(i)=AREA,PERIM,DCIRCLE,DMAX,DMIN,ANGLEDMAX,ANGLEDMIN,FCIRCLE,FSHAPE

```

```

    DBerase "temp","tempfv"

```

```

    DBcreate "temp","tempfv"

```

```

    DBopen "temp","tempfv"

```

```

while (2)

```

```

    Meas0 7

```

```

    if (_STATUS):break

```

```

    DBappend "temp"

```

```

endwhile

```

```

DBclose

```

```

DBopen "temp","tempfv"

```

```

DBopen fni,"fnifv"

```

```

while (2)
  DBread "temp","temp.v"
  if (_STATUS):break
  width=0.25*(PERIM-150*(PERIM-150*AREA))
  DBaotend fn1
endwhile

DBclose
outlist fn1,"width",15,0,1,3,1,0,0,3,2,1,1000,00,"id:".fn1

DBerase "temp"
DBopen fn1,"fn1.v"
TOT_AREA=0.0
TOT_PER=0.0

while (2)
  DBread fn1
  if (_STATUS):break
  TOT_AREA=TOT_AREA+AREA
  TOT_PER=TOT_PER+PERIM
endwhile

TOT_FGR_pc=(TOT_AREA-FIELD_AREA)*100.0

fn2=filename+"c"
fn2fv()=TOT_FGR_pc,TOT_PER,TOT_AREA,FIELD_AREA
DBerase fn2
DBcreate fn2,"fn2.v"
DBopen fn2,"fn2.v"
DBwrite fn2,"fn2.v"
DBclose
outlist fn2,1

```

* MEASURE CHORDS

```

ChordmaskX 3,766,11
ChordX 6,7,11
resetbar
external FERETA
identify 7,8,_ON,_OFF
fn3=filename+"c"
fn3fv()=FERETA
DBerase fn3
DBcreate fn3,"fn3.v"
display 8
measob) 8,fn3,_OFF
reply="y"
write
beep 33,333

reply="y"
read " Measure another sample (y/n) ":reply
if (reply!="y"):break
endwhile

```

CONVERT FILES

```

reply="y"
beep 99,999
read " Convert the data files ?? (y/n) " .reply

while (reply=="y")
  write
  write
  write " Convert to 1) ASCII."
  write "                2) LOTUS 123. or"
  write "                3) DBASE III format."
  write " or                4) Quit?"
  write
  beep 99,999
  option=1
  read "          SELECT BY NUMBER. = ".option. " = "
  if ((option/1) + (option/4)) :endwhile
  if (option==4) :break
  dos "cd c:/soils/data/cd/cd.c00"
  write
  write
  write "          INSERT A FORMATTED DISK IN DRIVE A:"
  write
  beep 250,1200
  pause
  dos "md a:/data"
  if (option==1) :dos "convert -f c:/soils/data/*.c00 a:/data"
  if (option==2) :dos "convert -i c:/soils/data/*.c00 a:/data"
  if (option==3) :dos "convert -c c:/soils/data/*.c00 a:/data"
  for i=1:(5-i=1-1) :write
  write
  beep 99,999
  read " Convert to another format ?? (y/n) " .reply
  if (reply=="y") :break
endwhile

beep 99,999
write
write
write "          WARNING"
write
write " Copying all IBAS files to floppy disk"
write " ENSURE PRESENCE OF FLOPPY"
beep 250,1200
pause
dos "md a:/c00"
dos "copy c:/soils/data/*.c00 a:/c00"
dos "cd c:/soils/data/*.c00"

stop

```

APPENDIX II

PROGRAM FOR SOIL - WATER DESORPTION ANALYSIS

```

1. REM PROGRAM TO CALCULATE MOISTURE CONTENT OF CORE SAMPLES FROM TENSION TABLE
2. REM THIS PROGRAM WILL ACCEPT UP TO 12 TENSION SETTINGS.
3. REM
4. REM
5. REM
6. REM
7. REM *****
8. REM
9. REM
10. ON ERROR GOTO 20000
11. DIM HORI(25,25),INDATA(25,18),OUTDATA(25,14),KSAT(25)
12. KEY OFF
13. CHECK 0
14. GOTOB 1000 : INPUT "INPUT NUMBER OF TENSION SETTINGS- ";NUMTENS
15. GOTOB 1000 : INPUT "INPUT NUMBER OF SAMPLES - ";NUMSAMP
16. FOR I=1 TO NUMTENS%
17. GOTOB 1000 :PRINT "INPUT TENSION #";I-6:INPUT " ";INDATA(0,I)
18. NEXT I
19. GOTOB 1000:INPUT "IS DATA TO BE ENTERED FROM FILE (F) OR TERMINAL (T) ";IR
20. IF NOT (IR$(1,1) = "F") THEN GO
21. IF NOT (IR$(1,1) = "T") THEN GO
22. FOR I=1 TO NUMSAMP
23. CL=0
24. GOTOB 1000:PRINT "1. SAMPLE NUMBER "
25. LOCATE 11,1:PRINT "2. DEPTH OF HORIZON "
26. LOCATE 12,1:PRINT "3. NT.WT. SAND+GLASS+LTD "
27. LOCATE 13,1:PRINT "4. NT.WT.GLASS BEADS ADDED"
28. LOCATE 14,1:PRINT "5. NT.WT. CYLINDER "
29. LOCATE 15,1:PRINT "6. NT.WT. CAN "
30. LOCATE 16,1:PRINT "7. GR.WT. OVEN DRY "
31. LOCATE 17,1:PRINT "8. KSAT "
32. LOCATE 10,30:INPUT " ";INDATA(I,1)
33. LOCATE 11,30:INPUT " ";HORI(1,I)
34. LOCATE 12,30:INPUT " ";INDATA(I,2)
35. LOCATE 13,30:INPUT " ";INDATA(I,3)
36. LOCATE 14,30:INPUT " ";INDATA(I,4)
37. LOCATE 15,30:INPUT " ";INDATA(I,5)
38. LOCATE 16,30:INPUT " ";INDATA(I,6)
39. LOCATE 17,30:INPUT " ";KSAT(I)
40. LOCATE 20,1:INPUT "INPUT NUMBER TO CORRECT (1-8) ";IC
41. IF IC = 0 THEN 140
42. IF IC < 1 GOTO 125
43. LOCATE 10,30:PRINT " "
44. LOCATE 10,30:INPUT " ";INDATA(I,IC+10) GOTO 120
45. IF IC > 2 THEN 132
46. LOCATE 11,30:INPUT " ";HORI(1,I)
47. GOTO 120
48. LOCATE 10,30:PRINT " "
49. LOCATE 10,30:INPUT " ";INDATA(I,IC+10)
50. GOTO 120
51. CL=0
52. FOR I=1 TO NUMTENS%
53. LOCATE 20,1:PRINT "1. INPUT GR.WT. WET @ TENSION OF ";INDATA(0,I)
54. NEXT I
55. FOR I=1 TO NUMTENS%
56. LOCATE 20,1:INPUT " ";INDATA(0,I)
57. NEXT I

```

```

110 LOCATE 12,1:PRINT "
120 LOCATE 12,1:PRINT "INPUT NUMBER TO CORRECT (1 = NUMBERS 1-5 INPUT 0 = 0)
130 IF CC = 0 THEN 170
140 LOCATE 12,4,41:PRINT "
150 LOCATE 12,3,41:INPUT " " ; INDATA(1,1)
160 GOTO 170
170 NEXT I
180 GOTO 400
190 REM READ DATA FILE
200 GOSUB 1000: INPUT "INPUT DATA FILE NAME " : F$
210 OPEN F$ FOR INPUT AS #1
220 FOR I=1 TO NUMSAMP
230 INPUT #1,INDATA(1,1)
240 INPUT #1,HORIZ$(1)
250 FOR J=2 TO NUMTENS+6
260 INPUT #1,INDATA(1,J)
270 NEXT J
280 INPUT #1,KGATS(1)
290 NEXT I
300 CLOSE #1
310 REM CALCULATE RESULTS
320 GOSUB 1000: PRINT "PLEASE WAIT WHILE I CALCULATE ."
330 FOR I=1 TO NUMSAMP
340 VOL=347.5-(INDATA(1,3)/1.5)
350 GRWT=INDATA(1,6)-INDATA(1,5)-INDATA(1,3)+INDATA(1,2)
360 NTWT=GRWT-INDATA(1,4)-INDATA(1,2)
370 OUTDATA(1,1)=NTWT/VOL:OUTDATA(1,2)=1-(OUTDATA(1,1)/2.65)
380 FOR J=3 TO NUMTENS+2
390 OUTDATA(1,J)=(INDATA(1,J+4)-GRWT)/VOL
400 NEXT J
410 NEXT I
420 REM OUTPUT
430 IF $:CHR$(12):PAGEW=132
440 GOSUB 1000: INPUT "GET PRINTER TO TOP OF PAGE, INPUT NUMBER OF COPIES, AND
450 IF NC=0 THEN PRINT CHR$(7):GOTO 505
460 LPRINT CHR$(27)"L"(CHR$(51))
470 WIDTH "LPT1:";132
480 FOR CC=1 TO NC
490 LPRINT "COPI #   DEPTH/      kgat      DENSITY      APPROX.
500 LPRINT "          HORIZON   (cm, h)   (g/cm)   POROSITY
510 LPRINT "
520 FOR I=7 TO NUMTENS+6
530 LPRINT USING "+###":INDATA(0,I);
540 LPRINT " ";
550 NEXT I
560 LPRINT
570 FOR I=1 TO NUMSAMP
580 LPRINT USING "####.#":INDATA(1,1);
590 LPRINT " ";
600 LPRINT USING "%      " :HORIZ$(1);
610 LPRINT " ";
620 LPRINT USING "###.##"KGATS(1);
630 LPRINT " ";
640 LPRINT USING "%####"OUTDATA(1,1);
650 LPRINT " ";
660 FOR I=2 TO NUMTENS+2
670 LPRINT USING ".####":OUTDATA(1,I);
680 LPRINT " ";
690 NEXT I
700 LPRINT
710 NEXT J
720 LPRINT LFS
730 NEXT CC
740 GOTO 20000
1000 GOSUB 1001 TO 1:RETURN
20000 IF ERR=4 THEN RESUME 280
20010 IF ERR=53 THEN PRINT CHR$(7):CHR$(7):PRINT "FILE NOT FOUND"
20020 END

```


END

24/1 2/92

FIN