**ICE INTERACTION WITH A RUBBLE MOUND BREAKWATER:
A CASE STUDY**

by

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The undersigned recommend to the Faculty of Graduate Studies and Research acceptance of the thesis **"Ice Interaction With A Rubble Mound Breakwater: A Case Study"** submitted by Kevin J. MacIntosh, B.Sc., P.Eng., in partial fulfillment of the requirements for the degree of Master of Engineering.

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ABSTRACT

This thesis describes a program of field measurements and the analysis of data describing the action of ice on a rubble mound breakwater. In 1984 a rubble mound breakwater was built at North Bay. The design of this structure is unique. The structure consisted entirely of 100 to 450 mm stones, which are many times smaller than the armour stones required to protect a conventional breakwater from wave action under similar conditions. The smaller stones are effective since the voids allow wave action to propagate into the breakwater and dissipate their energy within the structure. Concern was expressed about the formation and action of ice on this breakwater. As no prototype information on analytical procedures was available to assess protection problems, a comprehensive field study was required to determine if problems would occur.

The field study, undertaken throughout the winter of 1984-85, included the use of an array of thermocouples installed within the breakwater to record internal temperatures, water column temperature measurements, surveys of the external profile of the berm and surrounding snow and ice conditions, determination of the ice properties surrounding the breakwater using crystallographic techniques, and observations concerning ice-structure interaction.

Lake Nipissing's ice growth and deterioration during the winter of 1984/85 was consistent with other years taking less than one week from the time of first permanent ice to complete freeze over in mid-December. A maximum ice thickness of 92cm was recorded versus the average annual maximum thickness of 72cm. Water level changes and air temperatures were comparable to other years.

The investigation provided several interesting results concerning the response of the breakwater to ice action.

- 1) No significant ice inclusions formed within the berm due to the combination of heat provided by the lake water and insulation from the overlying snow and ice. Consequently, the voids within the breakwater were never filled with ice.
- 2) Failure and deterioration of the ice surrounding the breakwater occurred in such a manner that the ice did not move any stones from the breakwater either by plucking or by pushing. The buildup of spray ice on the surface of the breakwater was not sufficient to create any substantial loads or influence the stability of the breakwater slope.
- 3) The profile developed by wave action on this breakwater was advantageous in protecting the breakwater against damage from ice.

Based on the results obtained during the winter of 1984-85, no problems with this type of breakwater are anticipated in similar locations.

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CHAPTER 1

INTRODUCTION

1.1 General

The design of any structure built in northern climates including, offshore navigational aids, offshore islands, wharves, and breakwaters, where ice may form around the structure, requires careful consideration of ice-structure interaction. Since little information is available on the topic, especially for breakwater structures, the designer must anticipate the possible effects of ice in contact with the structure.

Published procedures for the design of breakwaters are concerned with the action of waves and little or no guidance is provided in relation to the action of ice. Design considerations include the selection of a design wave height, the directions of wave attack, allowable agitation levels behind the breakwater and around harbour entrances, and the amount of acceptable overtopping and runup. Once these parameters are defined the designer considers the availability of construction materials and ease of constructing a design which meets the site requirements.

The majority of breakwaters in existence consist of a core of rubble or quarry run protected by filter layers and a covering armour layer. The armour layer consists of individually placed large stones or concrete armour units which must have sufficient mass so that they are not displaced by either wave or ice loadings.

A new concept for the design of breakwaters was recently developed in Canada which requires substantially smaller armour stones and simplifies breakwater construction. The new design relies on the porosity within the relatively wide armour layer to resist hydraulic loadings. The concept has been thoroughly tested for many locations and proven successful in resisting wave forces. However, because of the small armour stone size and the lack of historical prototype information in cold climates, the effects of ice interaction with this structure could not be predicted. Literature reviews on the mechanisms of ice interaction with surface piercing structures also show that there is limited information on rubble mound breakwaters.

The smaller armour stone in the new design created the possibility of ice related problems which do not exist when larger stones are used on the surface of the breakwater. For example, if ice inclusions remained in the armour layer, after spring breakup on the surrounding water body, the wave action would be concentrated at the surface of the structure and would not be dissipated within the structure. Since the performance of the armour layer in the new design is dependent on porosity the smaller stones at the surface would be displaced under these conditions. Other

concerns included the possibility of stones being plucked from the surface by attached ice sheets during water level changes and displacements caused by moving ice sheets. For these reasons it was necessary to obtain some prototype experience with this type of structure as soon as possible.

In 1984, a rubble mound breakwater structure based on this design concept was constructed on Lake Nipissing, North Bay Ontario. This construction provided an opportunity to monitor the performance of the breakwater structure particularly in its response to ice action. A second breakwater exists at the same site which was constructed using a traditional armour stone design. This allowed a comparison of the two designs to be made under the same ice conditions. Therefore, a detailed field investigation was undertaken to monitor the performance of the breakwater during the first winter of its service life. Figure 1.1 shows the location of Lake Nipissing and the marina which is protected by this breakwater. Figure 1.2 provides a plan view of the marina including breakwaters, docks and proposed land developments.

In order to properly assess the breakwater design the field study included: temperature measurements of both the interior of the breakwater and surrounding water column; surveys of the berm and local snow and ice conditions; determination of the ice characteristics of the ice in the lake and marina; and the observation and documentation of the modes of ice-structure interaction.

FIGURE 1.1 LOCATION OF NORTH BAY MARINA

FIGURE 1.2 PLAN VIEW OF NORTH BAY MARINA

1.2 Literature Review: Ice Forces on Marine Structures

The relevant literature available on the topic of ice-breakwater interaction discusses four principal types of ice forces. Although other related topics were researched, the literature was either not directly applicable to the topic of ice-breakwater interaction or insufficient material was available to warrant individual discussions. These topics include the freezing patterns of dams, interstitial freezing of rock tailings, and ice push features on shorelines. They have been worked into the discussions of the four most common types of ice forces presented below, (Gerard, 1984).

- 1) "Static" ice forces can be generated as a result of icing of the structure above the water level and by thermal expansion of the surrounding ice sheet. Steady pressures can also be generated on the structure by surrounding stationary ice sheets. Winds and currents create drag forces on the ice which are transmitted to the structure as static loadings.
- 2) Dynamic ice loads result from moving ice floes acting on stationary structures. The ice floes are moved through open water by either winds or currents until they contact the structure creating a dynamic load.
- 3) Ice jams, pressure ridges and ice piles create a variety of forces on surface piercing structures. These ice formations create loads on the structure which differ from static and dynamic loads. A complex situation exists where the moving ice loses a substantial amount of its energy in creating ice piles in front of the structure.
- 4) Uplift and drawdown forces are caused by the influence of fluctuating water levels on ice which had adhered to the surface of the structure. As the water level rises buoyancy forces are generated on the submerged ice and subsequently on the structure. Dropping water levels expose the adhered ice creating downward gravitational loads on the structure.

The analysis of ice forces on structures is not only complicated by the fact that more than one of the above forces may be acting at any one time but, also by the complex nature of ice and its many different failure modes. A review of the types of ice forces that act on marine structures is provided here with an emphasis on those most relevant to breakwater design.

1.2.1 Static Ice Forces

Static ice forces on hydraulic structures can be generated in many ways. Icing of the structure caused by waves breaking on the structure, thermal expansion of the surrounding ice sheet and the steady pressure created by winds and currents acting on the surrounding ice sheet all create static forces on the

structure.

The ice formed on a structure due to breaking waves is termed 'spray ice' (Minsk, 1980). Spray ice can have either a milky appearance or a dark glazed appearance depending on the conditions under which it is formed. If the spray freezes rapidly due to very cold temperatures on the surface of the breakwater the ice will contain entrapped air and have a milky appearance. In contrast, glaze ice is formed when the water droplets have sufficient time to flow over the accreting surface prior to freezing. The flow of the water before freezing allows the entrapped air to escape giving the ice a clear appearance and higher density.

The majority of available data and research into spray icing is related to ships and vertical walled structures. The information obtained cannot be directly related to breakwater icing because of the differences in how waves interact with permeable sloping structures versus vertical walled structures.

Icing on breakwaters constructed in freshwater areas frequently occurs during fall storms before the lake freezes over. Figure 1.3 provides an example of the extent of icing possible on rubble mound breakwaters constructed in the Great Lakes. Spray ice probably binds the individual armour stones within a breakwater, however there is no experimental evidence that such ice action enhances the bulk strength characteristics of the armour stone fabric. When there is no ice present within the voids of the breakwater, friction and interlocking between stones resist wave forces and slope failure. If ice is present in the voids, adhesion between the ice and stones, ice strength alone, and interlocking and friction between the stones all become factors.

Another form of static ice force is generated when changes in air temperature cause thermal expansion of the ice sheet surrounding the structure. The magnitude of these forces depends on several factors including meteorological conditions (ie: rate of temperature change), ice thickness and structure, snow cover, cracks in the ice, structure slope, and topography of the surrounding beaches (Drouin and Michel, 1974).

Drouin and Michel (1974) examined the problem of thermal expansion of ice sheets in locations where a boundary exists around a limited water area. They presented an example calculation using a 61cm thick ice sheet restrained perpendicular to a dam crest with rocky vertical walls surrounding the reservoir.

The calculations were completed for both columnar and snow ice with varying snow and thermal gradients. For example, with no cracking or snow layers for insulation, thermal pressures of 43,000kg/m were calculated for columnar ice and 27,500kg/m for snow ice. A thin snow insulating layer (10cm) dropped the thermal forces to 13,000kg/m for columnar ice and 10,800kg/m for

FIGURE 1.3 BREAKWATER ICING ON GREAT LAKES (Wortley 1984)

snow ice.

Mansikkaniemi (1970) noted that the thrust of expanding ice is greatest in small lakes and in closed bays. In these situations there is less opportunity for the stress in the ice to be taken up by internal creep deformation or by buckling of the ice sheet.

Adams et al (1976) completed a study of ice push features on Gillies Lake. Gillies Lake is located on the Bruce Peninsula between Lake Huron and Georgian Bay. It was concluded that thermal expansion of the ice sheet was not a probable explanation for the ice push features noted around Gillies Lake. Several reasons were given for this conclusion: the number and magnitude of ice push features did not increase in the narrower portions of the lake; many furrows changed direction part way along their path and were not necessarily perpendicular to the shoreline as would be expected if caused by thermal expansion of the ice sheet; and a correlation between wind direction and average ice push features "hinted at the existence of a wind effect" (Adams et al, 1976). It was also noted that the snow cover, inevitably present on lakes in this area, caused a significant reduction in the influence of changes in air temperature. The results of the Gillies Lake study were especially relevant to North Bay because it is located in the same area.

A third form of static ice force is created when either wind or water currents influence an ice floe positioned against a marine structure. The maximum static force created in this situation occurs immediately before the ice sheet begins to move and fail by either bending or crushing.

Wind is generally considered to be the predominant driving force behind moving ice sheets, (Arya, 1973), (Langleben et al, 1975), (Smith, 1972), (Seifert et al, 1972). Wind blowing over the surface of an ice sheet induces shear stress at the level of the ice sheet. The magnitude of the shear stress depends on several parameters including the aerodynamic characteristics of the ice surface and the stability of the boundary layer. Lake characteristics are also important. Large lakes with an orientation parallel to the predominant wind direction, a long partial ice season, and gently sloping shorelines favour wind blown ice effects.

Numerous studies have been completed which investigated wind stresses over ice, roughness parameters, and ice motion in response to wind forces (Smith et al, 1970), (Langleben, 1972), (Thorndike and Colony, 1982).

Danys (1979) investigated the magnitude of the wind forces on light piers in Lac St. Pierre. An equation was developed to represent the total force exerted by the wind on an ice sheet.

$$F = 0.132 \times C \times (u)^2 \times A$$

where: C = parameter based on ice surface texture

u = wind speed (m/s)

A = area of ice sheet (m^2)

1.2.2 Dynamic Ice Forces

The most complex form of ice structure interaction occurs when moving ice floes come into contact with a coastal structure creating dynamic ice loadings. The magnitude of dynamic ice forces depends on several factors including the flexibility and shape of the structure, strength and mechanical properties of the ice, and the relative movement of the ice with respect to the structure (rate of load application, angle of floe attack). The magnitude of the load applied to the structure depends on the mode and degree of the ice failure as a result of interaction with the structure. The five different failure modes are bending, buckling, impact, crushing and splitting (Wortley, 1982).

Where ice action takes place on inclined slopes failure by bending and buckling predominate. Crushing, impact and splitting are other possible failure modes. Bending failures occur when the ice sheet rides up the structure slope and fails in flexure before crushing failures are established. Buckling failures are generally the initial stage of ice piling adjacent to a sloping structure. In this case the leading edge of the floe is stopped by the structure while the driving force continues, leading to a buckling failure and ice pileup. Impact loads occur when the motion of the ice floe is stopped before crushing or bending failures have developed. Impact loads may occur on a breakwater depending on the floe size and velocity, and the structure slope and roughness. Crushing failures occur when the ice fails over the entire ice-structure contact area. Splitting failures are a common occurrence on narrow vertical structures such as bridge piers. They are not considered to be a factor of major importance in the design of breakwaters for ice forces.

Numerous authors, referred to in the following paragraph, have addressed the problems associated with calculating dynamic ice-structure loads and emphasized the complexity of the situation. Friction between the ice sheet and the structure, crushing and bending stresses, drag forces between the water and

ice, and gravitational effects of ice piled on the structure all comprise the dynamic forces to be considered in a dynamic loading analysis.

A large proportion of the papers on dynamic ice forces are related to forces on bridge piers, (Gerard 1978, Haynes 1975, Neill 1976, Sun and Ing 1984, Haynes 1983), offshore lighthouses, and conical and cylindrical structures (Danys 1975, Kato 1983, Reinius 1971, Wessels 1984, Morris and Sodhi, 1984). These papers contain useful information on dynamic ice-structure interaction; however, the most applicable papers relate to ice forces on relatively wide sloping structures. Timco (1984), Sanderson (1984), Blanchet and Metge (1984), Croasdale (1981), Kry (1980), Frederking (1979), Sorensen (1978), Tryde (1977), and Danys (1979) have all completed either model studies, field work, or empirical analysis of dynamic ice forces on wide sloping structures.

The maximum horizontal loads on a breakwater occur when ice fails in crushing along the length of the contact area. Danys (1979) calculated the maximum horizontal loads on artificial islands constructed in Lac St. Pierre by applying a shape factor of 0.6 to account for the structure's slope reducing the loads. Although the crushing loads should be considered, it is probably unlikely in the case of a breakwater with slopes of 5:1 (horizontal:vertical) and flatter near the water line. The vertical edge of the incoming ice sheet would be unable to make solid contact with the breakwater and the large horizontal loads associated with crushing failures would not occur. The ice will simply ride up the structure slope and fail in flexure once it contacts the steeper slope near the crest of the breakwater. Michel (1984) discusses a similar situation, namely the response of sacrificial beach islands in the Arctic to interaction with ice. In this case the combination of a relatively flat slope near the water line and a steeper slope at the crest will initiate ice pile-up on the structure's slope.

1.2.3 Uplift and Drawdown Forces

Vertical forces are generated on coastal structures when a floating ice sheet is affected by a change in water level. The vertical forces generated can vary substantially depending on the strength of the ice sheet, degree of adhesion of the ice to the structure and on the geometry of the structure. Other factors which influence the uplift force are the rate and frequency of water level change. Several authors have addressed this problem including Wortley (1982), Nevel (1968), and Kerr (1975).

Wortley (1982) provides a method of determining the minimum uplift loads for circular piles by assuming that a circumferential crack develops at some distance from the pile. This thin plate analysis requires that the ice sheet thickness be less than the embedded pile diameter.

Nevel (1968) provides a method of determining the uplift force of a floating ice sheet whose edge is rigidly frozen to a long structure. As the water level rises the ice sheet bends, exerting an uplift force on the structure. Although this method is applicable to timber cribs and other straight walled structures, it does not form an accurate representation of the behaviour of ice on a breakwater. The behaviour of ice during water level changes along a breakwater can be speculated as falling somewhere between the behaviour exhibited on straight walled structures and piles. Because the ice cannot effectively surround the stones on a breakwater, as it does with piles, the uplift forces on piles are not representative. Also, because a rubble mound breakwater does not have a smooth surface the uplift forces exerted on a walled structure are not representative. However, the uplift forces are eccentric (assuming the ice is only frozen to one side of the stone) as is the case of a walled structure and they can act on relatively small individual units analogous to piles.

No specific information exists on the uplift forces of ice on a breakwater, however, several factors indicate that the uplift forces are probably less than those experienced by piles and by straight walled structures. As mentioned by Wortley (1982) the angular nature of quarried stone used in rubble mound breakwaters would tend to cause stress concentrations in the ice. These stresses would create cracks effectively reducing the uplift force. Also, ice formations between stones on the breakwater would increase interlocking between stones and increase the forces required to "pluck" stones from the breakwater. Therefore, it is to be expected that the uplift forces on armour stones are substantially less than those experienced by piles. As discussed later, the results of this study support this hypothesis.

1.2.4 Broken Ice Accumulations

Ice ridges and pileups are a common occurrence in many areas. The necessary conditions to initiate ice ridging and pileups include large moving ice sheets with a limited amount of open water. The Beaufort Sea is a prime example of an area with the correct ice climatology for the formation of ice ridges and pileups against offshore structures.

The interaction features necessary to cause ice pileups include a wide enough structure to prevent clearing of the fractured ice and sufficient ice movement or driving force to fragment the ice and create a pileup.

Depending on the characteristics of the ice pileups, or rubble field surrounding a structure, as well as the structure's characteristics, ice pileups can either magnify or decrease the ice/structure interaction forces. Both first year and multi year ice accumulations have been identified in the Beaufort Sea, each having its own characteristics. However, since multi year

ridges are not a possibility in Lake Nipissing, their characteristics will not be discussed here.

First year ridges are generally composed of blocks of ice loosely held together by friction, gravity and bouyancy forces. In addition, the surface layer is often refrozen to help consolidate the mass. It is generally thought that the existence of a rubble field created from first year ice, adjacent to a wide structure, reduces the ice-structure interaction forces (Croasdale 1981, Bercha 1980).

In the case of first year ridges, the energy of the incoming ice sheet is partially expended in consolidation of the loosely packed ice ridge. This results in a reduction of the forces transmitted to the structure in comparison to a ridge free situation. As the ice sheet interacts with the rubble, bending and flexure failures predominate, with buckling and shear failures occurring to a lesser extent.

Bercha (1980) and Croasdale (1981) provide methods of evaluating the loads created during the formation of rubble fields and ice pileups. In the method proposed by Bercha (1980), the degree of consolidation can be varied whereas Croasdale (1981) provides a more simplified method of calculating the pressure exerted by a first year ridge on a wide structure. Parmerter and Coon (1973) provide a summary of the mechanics of rubble formation for floating ridges which is applicable to North Bay. In another frequently referenced paper, Kry (1977) provides methods of evaluating the forces generated by fully consolidated, grounded rubble.

1.2.5 Case History of Ice Related Problems with Breakwaters

The documentation of ice related problems with breakwaters is very limited, however, there is some discussion on the topic, and analogies to other situations are made by several authors.

- a) Czerniak (1981) discusses the design of rubble mound structures under ice attack, emphasizing the lack of information on the topic. Analogies between ice-breakwater interaction and naturally occurring boulder pavements, subjected to ice forces along the Mackenzie River, are discussed. The boulders pack into the river mud forming a relatively smooth surface which is very stable under ice loads. Individual boulders are occasionally removed and later replaced by boulders from upstream. The relatively flat slopes along the river bank make the comparison to breakwater slopes questionable.
- b) The experiences of the St. Lawrence Parks Commission along the St. Lawrence Seaway where large field stones were placed along the bank is more relevant to breakwater design. In 1958 twenty-five miles of shoreline protection and two breakwaters were constructed of field stones ranging from 0.1

to 15 tonnes. To date these structures have not required any maintenance with the exception of erosion problems unrelated to ice forces.

- c) Danys (1979) reported the use of quarry run rock, 10% larger than 0.75 m^3 and 10% smaller than 0.15m in diameter, to construct artificial islands in Lac St. Pierre. Four islands were built in 1967-68 to control ice movement by retaining the ice cover in place. Three islands were constructed using only the quarry run rock with no armour stone placed on the slopes. One island had 0.6 to 1.0m diameter armour stones placed on the outer slopes. Ten years after the original construction all four islands required the placement of armour stones in the range of 0.6 to 1.0m in diameter. Danys does not discuss what criteria were used to determine the slope protection sizes. The erosion of these islands was attributed to settlement, waves, currents, and large moving ice floes. Danys (1979) noted that "storm waves and waves created by passing ships wash out finer particles, dislodge rip rap, and may even result in local erosions. Moving ice causes an even larger displacement of stones on the slopes." Danys also comments that "ice initiates local damage to the slope, or enlarges the existing erosion" and that "ice forces themselves do not affect stability of these islands". One island had a horizontal berm surrounding it which caused the incoming ice sheets to ground and create an ice barrier in front of the island. Another feature was the construction of a steeper slope (1.5:1 hor.:vert.) at the top of the island. This feature was proven to be effective in reducing the amount of ice ride up.
- d) Brunn and Johannesson (1971) refer to a rubble mound breakwater at Knudshoved in Denmark with 1:2 slopes which suffered "considerable damage to the armour layer". Although very few details are given, the damage is attributed to ice piling on the breakwater slope in March 1963.
- e) Other experience in the Gulf of St. Lawrence and Great Lakes indicates that spray ice forms over the breakwaters providing a protective coating which binds the armour stones together (Ploeg 1984). Figure 1.3 shows the extent of spray ice buildup on a breakwater in Lake Superior (Wortley 1984).
- f) Ettema (1983) completed a study into the effects of ice on a proposed causeway for a port development in Nome, Alaska. Both large and small scale movements of ice with an average ice thickness of 1m were predicted for the area. The ice loads were considered to be critical enough to require model studies. Model studies of ice sheets overriding the causeway showed that armour stones greater than 8 tonnes would not be readily dislodged by the moving ice. Ettema's study did not investigate what minimum size of rip rap boulders would be stable under ice sheet impact. He does suggest, as a general rule, that the mean diameter of rip rap boulders

should exceed the maximum thickness of the ice sheets that are likely to impact with them. He also comments that in most cases it is likely the armour stone size will be governed by wave attack rather than ice impact criteria.

There is a distinct lack of discussion and detail on modes of ice/structure interaction in the studies mentioned above. However, it is revealed that ice forces need to be considered when designing breakwaters and analyzing failures.

1.3 Scope and Objectives

In establishing the ability of a structure to withstand interaction with ice it is first necessary to document the ice formations surrounding the structure and, if necessary, within the structure. As is the case with rubble mound breakwaters, ice growth within the structure is as important as that surrounding the breakwater. Therefore, a field program devoted to documenting the types of ice interaction with a particular breakwater design is desirable.

The field program provides a practical understanding of the processes of ice interaction with the breakwater. It also provides the basis for developing numerical models to analyse the structure under different scenarios once the field program is complete. Supplementing the field program with literature reviews and analysis of the collected data aid in making an assessment of the reliability and efficiency of the breakwater design in northern environments.

The objectives of this study were to:

- 1) gather data on ice-breakwater interaction using surveying techniques, photography, and other general observations,
- 2) determine the structure and origin of the various ice types present around the breakwater by using crystallographic techniques and relating the results to the meteorological data for the site,
- 3) study the formation of ice and temperature profiles within the breakwater by designing and installing an array of thermocouples to cover both the horizontal and vertical profiles,
- 4) analyse the collected data and develop relationships between the various parameters,
- 5) provide documentation which will identify the factors that need to be incorporated in a mathematical model of ice action in these breakwater structures,
- 6) provide an assessment of the ability of the breakwater design to withstand interaction with ice.

CHAPTER 2

BREAKWATER DESIGN

2.1 Traditional Hudson Armour Design

The majority of breakwaters built to date in North America and Europe were designed using the Hudson formula. The Hudson formula provides a relationship between the design wave height and the weight of armour stone necessary to resist the wave height when placed on a specified breakwater slope. The Hudson formula forms the basis for the breakwater design procedure described in the U.S. Corps of Engineers Shore Protection Manual (1984).

The Hudson Formula used to determine the weight of the armour stone (W) is given by:

$$W = \frac{H^3 w_r}{K_d (S_r - 1)^3 \cot \theta}$$

where: W = weight of armour stone

H = wave height

w_r = unit weight of armour stone or concrete

S_r = specific gravity of the armour unit

$\cot \theta$ = slope of the armour

K_d = damage coefficient

A traditional breakwater cross section based on the Hudson formula is shown in the bottom of Figure 2.1. The stones in the filter layer have weights ranging from $W/10$ to $W/15$ where W is the weight of the main armour stones. Stones in the core range from $W/200$ to $W/6000$.

The damage coefficient (K_d) used in the Hudson formula is the source of many discussions on the effectiveness of this design procedure. It is derived from the results of model studies which are subject to the biases of the observer including what constitutes damage, when has damage occurred and so on. The many limitations of the model studies are discussed in detail by Baird (1985).

It is evident that the Hudson design procedure is in a state of

Berm Design

Conventional Breakwater

(Baird and Hall, 1984)

FIGURE 2.1 COMPARISON OF BREAKWATER CROSS SECTIONS
(for the same design conditions)

development when a comparison of designs for identical situations is made from the two most recent versions of the Shore Protection Manual, 1977 and 1984. The recommended weight of armour stones increases by factors of 1.75 to 2.05 depending on the wave conditions, (Baird 1985).

Removal of armour stone from the outer slope of a traditionally designed breakwater by either wave or ice forces makes the breakwater vulnerable to failure. Therefore, armour stones must be sufficiently large to reduce the frequency of removal. Exposed locations dictate the need for very large armour stones which are both expensive and difficult to obtain. If large stones are not available, many locations require the use of concrete armour units to achieve the necessary weight. This can dramatically increase the cost of a project and the complexity of construction.

Many construction related problems are inherent with traditional armour stone breakwaters. The construction related problems can be categorized as follows (Baird and Hall, 1984a):

- 1) Costly quarry operations are required to blast and sort the various stone sizes needed for each layer.
- 2) Excessive stone wastage will occur at the quarry. The graph on the left side in Figure 2.2 demonstrates the yield of a quarry for a breakwater designed for a 5m significant wave height and a 2:1 front slope for the Hudson design. The graph also shows the quarry yield for each stone layer based on conventional design requirements. It is evident from this plot that there is a substantial amount of blasted material which does not fall into the design requirements.
- 3) The difficulty of construction including scheduling, and equipment requirements are other considerations. Depending on the location it may be necessary to construct the core, filter, and armour layers in close succession to avoid erosion by storms during construction. This requires complex scheduling of material deliveries and inefficient use of the varied construction equipment required for each layer. The accurate construction of slopes and placement of materials under water for each layer can also pose problems. Finally, such construction is further complicated by the necessity of using a land based crane, or a floating crane requiring calm weather, to place the armour stone.

It is evident from the above discussion that there are numerous problems associated with the traditional Hudson breakwater design.

Conventional Breakwater

Berm Design

(Balrd and Hall, 1984)

FIGURE 2.2 COMPARISON OF QUARRY YIELDS AND STONE WEIGHTS

2.2 BERM Design

The breakwater constructed in North Bay during the summer of 1984 incorporates a relatively new design for rubble mound breakwaters termed the BERM design. A typical cross section of the berm design is shown in the top of Figure 2.1 which also provides a traditional breakwater design cross section. The berm design is described in detail in Hall et. al. (1983), Hall and Baird (1983), Baird and Hall (1984b).

The berm design was primarily developed to optimize the use of locally available quarry material. In doing so it avoided many of the problems associated with traditional designs based on the Hudson formula, such as construction problems and availability of sufficiently large armour material.

The berm design is based on the fact that as the width of the armour layer on a breakwater is increased, the stone sizes can be decreased. The berm design is just one of an entire family of breakwater designs which includes the traditional two stone armour design. The dimensions and stone sizes of the berm design are also site specific. Physical hydraulic model studies are used to determine the required berm width and elevations to ensure a stable breakwater profile. The wide armour stone layer in the berm design provides an increased volume of voids to dissipate wave energy. This results in lower velocities in the armour layer which, in turn, produces lower drag forces on the individual stones. A comparison between the flow field through the berm structure and a conventional structure is shown in Figure 2.3.

Each site requires individual attention since the berm design uses locally available quarry material to provide a cost efficient, stable breakwater. To develop the design for a specific site it is first necessary to define the gradation of locally available material. Secondly, depending on the site, it may be necessary to assign the fraction of smaller quarry material to the core of the structure and the larger portion to the armour layer. The next step involves determining the shape and dimensions of the armour protection using physical hydraulic model studies. Finally, the geometry of the armour cross section is reviewed to ensure that it suits simple construction procedures.

The berm design generally requires the construction of a horizontal berm just above the water line as shown in Figure 2.1. This design has the following features: the armour stone can be less than one fifth the size of the armour used in conventional designs (Hall and Baird, 1983), a maximum use of the quarry yield is achieved, and minimal sorting of stone is required at the quarry. In addition, to the above, there are several other advantages of the berm design. It is frequently the case that no toe scour protection or filter layers are required which reduces both the construction and underwater survey costs. The breakwater can be built using land based equipment making it less susceptible to damage from storms during construction. The

FLOW IN A TWO STONE ARMOUR LAYER

(Hall and MacIntosh, 1984)

FLOW IN THE BERM CONCEPT ARMOUR LAYER

FIGURE 2.3 COMPARISON OF FLOW FIELDS IN ARMOUR LAYER

performance of the structure, under wave conditions exceeding the design wave height, is substantially better than conventional designs under the same conditions. Removal of some of the outer armour protection from the berm slope does not cause catastrophic failure as it does once the main armour stone layer is removed from traditional designs. Experience has shown that for some specific locations the berm can be built for 50 to 70 per cent of the cost of a traditional structure (Baird and Hall, 1984a).

For the breakwater at North Bay the design criteria included a design wave height of 1.0m (significant) and available stone sizes which varied from 2 to 250kg. Applying these criteria and allowing for simple construction procedures produced a berm characterized by the following features. The breakwater has a 6.4m wide crest with an elevation of 1.5m above summer water level. The breakwater was constructed using only one stone gradation (2 to 250 kg). This stone gradation was sufficient for wave protection and available in sufficient quantities to construct the entire berm. The side slopes are 1.5 horizontal to 1.0 vertical as shown in Figure 2.4. These side slopes represented the natural angle of repose for the stone gradation used and therefore required only minor reshaping after construction. This structure was constructed using only dumping and pushing operations as shown in Figure 2.5. The berm crest was sufficiently wide to allow dump trucks to back out on the crest, past a bulldozer, and then dump over the edge. The bulldozer then pushed any stone remaining on the crest over the edge allowing the next truck to dump.

The North Bay design is a good example of how each application of the berm design requires special attention. For example, sufficient armour material was available to construct the entire berm without dividing the berm up into a core material and an armour layer. A grizzly (steel grate) was used to sort out the material less than 100mm in diameter. This was required to avoid having the small stones block the pores in the breakwater which are necessary for wave absorption. It was also not necessary to construct the horizontal portion of the berm. The cross section, as built to simplify construction, had sufficient wave absorption capacity without the additional horizontal berm on the lake side. As expected, a horizontal berm has started to form at the water level because of wave action since construction as shown in Figure 2.4.

Consideration was given to how ice would interact with the berm breakwater at North Bay prior to construction. It was anticipated that ice sheets pushed into the structure would fail in bending once the berm profile was developed. The requirement for some minor maintenance of the outer slope and crest were also expected. However, the smaller stone sizes used in the berm design raised several concerns about how the berm would respond to interaction with ice since there is no prototype experience for this type of structure. These concerns included the danger of stones being plucked from the surface by attached ice sheets during water level changes, large stone displacements caused by

FIGURE 2.4 BERM CROSS SECTION — NORTH BAY

FIGURE 2.5 CONSTRUCTION OF NORTH BAY BREAKWATER

moving ice floes driven by wind, and ice rideup and ridges causing scour of the outer slope resulting in downslope slumping. The possibility of ice inclusions being left in the berm after spring breakup created some concern. Ice inclusions in the berm would result in concentrated wave forces possibly causing erosion or failure of the outer slope of the berm.

CHAPTER 3

FIELD STUDY

3.1 Field Trip Summaries

The field study is an essential part of any investigation which attempts to define the response of a structure to interaction with ice. By combining a number of activities it was possible to make a critical assessment of the new breakwater constructed in North Bay. The site investigation included:

- 1) Vertical surveys of the berm,
- 2) Determination of snow and ice profiles,
- 3) Ice thickness measurements,
- 4) Collection of ice samples for crystallographic analyses,
- 5) Measurement of temperature profiles within the berm,
- 6) Measurement of temperature profiles in the water column,
- 7) Visual observations and documentation of modes of ice interaction with the berm. Site observations were documented using field notes, photography, and video recorders.

The vertical surveys were completed using standard surveying techniques and the results are summarized in chapter 3.3. Determination of the snow and ice profiles was completed by surveying the elevation of the snow and ice at 1 m increments out from the breakwater crest. The snow was shovelled from the ice where necessary to provide accurate ice elevations. Ice thicknesses were determined by augering holes through the ice and then inserting the ice depth gauge developed for this study and shown in Figure C.1. Ice samples were collected for crystallographic analyses by carefully cutting and removing the ice surrounding the desired sample. The orientation was marked on each sample before removing it from the surrounding ice sheet. The samples were then packed in plastic bags, surrounded by snow, and placed in coolers for transportation to the ice lab. The results of the ice analyses are provided in chapter 4 and the method of analysis, namely crystallography, is summarized in Appendix D. A summary of the berm temperature readings is provided in chapter 3.2. Water column temperatures were completed by augering holes through the ice and then inserting a chain of thermocouples into the water column as described in Appendix A2. The most significant visual observations are listed in chapter 3.4.

Table 3.1, provided on the next page, reveals the dates of the most significant field trips and a brief description of the ice conditions noted on those dates.

=====

TABLE 3.1 SUMMARY OF FIELD TRIPS

DATE	ICE THICKNESS	
	Marina (cm)	Lake (cm)
Nov 21, 1984	2	no ice
Dec 12, 1984	4	4 pan ice
Dec 28, 1984	27	42
Jan 25, 1985	47	67
Feb 28, 1985	67	84
March 15, 1985	77	92
April 4, 1985	76	84
April 23, 1985	35	50
April 30, 1985	no ice	10
May 1, 1985	no ice	no ice

=====

After each field trip the collected information was summarized and plotted to provide a clear picture of the ice conditions. The plots include the berm and water column isotherms (lines joining places at the same temperature) and the snow and ice conditions surrounding the berm. These plots along with a list of the major observations and some relevant photographs are also provided for each field trip.

For example, Figure 3.1 provides a photograph of the initial spray ice on the breakwater on November 21, 1984 and a list of the major observations. Figure 3.2 provides a summary of the site conditions for December 12, 1984.

FIGURE 3.1 INITIAL SPRAY ICE Nov. 21, 1984

November 21, 1984

- a) No ice existed on the lake; however, as the air temperature dropped late in the day ice crystals were forming on the surface under calm conditions. This indicated that the water column was sufficiently cool to allow ice formation.
 - b) The marina was covered with a thin ice cover approximately 1 to 2 cm thick with the exception of a band of water 0.5 m wide surrounding the breakwater.
 - c) Some spray ice was located on the lake side and crest of the berm as shown in Figure 3.1; the berm was not sealed.
-

Figure 3.2 SITE CONDITIONS December 12, 1984

- a) The breakwater was covered in spray ice approximately 25cm thick, as shown in Figure 3.3, which was a significant increase over the conditions noted in the previous field trip. The spray ice completely covered the surface of the berm however, it could be broken away revealing no ice in the stones directly below the surface.
- b) Figure 3.3 reveals the minimal amount of snow present both along the sides of the breakwater and on the lake ice cover.
- c) Open water existed across the lake with the exception of an area of pan ice adjacent to the breakwater. The pan ice existed from the edge of the berm to 100m offshore of the breakwater. It was approximately 3.5 to 4.0 cm thick and broken into small floes with an average diameter of less than one meter as shown in Figure 3.4.
- d) The marina was covered with approximately 4 cm of ice with the exception of directly adjacent to the breakwater where it was unsafe to walk on.

FIGURE 3.3 SPRAY ICE — Lake Side Dec. 12, 1984

FIGURE 3.4 PAN ICE — Lake Side Dec. 12, 1984

Figure 3.5 SITE CONDITIONS December 28, 1984

- a) Some of the pan ice which had been previously floating in front of the breakwater was pushed up onto the lake side of the berm before complete freeze over occurred.
- b) Considerable growth of both the lake and marina ice sheets had occurred since December 12. The marina ice sheet was 27cm thick and the lake was 42cm thick.
- c) The spray ice previously on the surface of the berm had subsided into the top layer of stone and the ice cover on the crest was increased by ice rain on the day of the field trip. The ice on the surface did not extend below the first layer of stone. This was confirmed by excavation of the ice which revealed the open voids below the top stones.
- d) There was no snow cover in existence on either the lake or marina ice sheets although some snow had piled up on the sides of the berm as shown in Figures 3.6 and 3.7.
- e) The berm isotherms reveal higher temperatures within the berm and significantly depressed temperatures on the lake side.

FIGURE 3.6 LAKE ICE CONDITIONS Dec. 28, 1984

FIGURE 3.7 MARINA ICE CONDITIONS Dec. 28, 1984

Figure 3.8 SITE CONDITIONS January 25, 1985

- a) Figures 3.9 and 3.10 show the increased snow cover adjacent to the breakwater and on the ice sheets.
- b) Spray ice was still present in the top layer of stone and in combination with the surrounding snow formed a seal to the interior of the berm.
- c) The temperatures had dropped both in the water column and within the berm since the last field trip.

FIGURE 3.9 SNOW AND ICE CONDITIONS, BREAKWATER CREST Jan. 25, 1985

FIGURE 3.10 SNOW COVER AROUND BREAKWATER Jan. 25, 1985

Figure 3.11 SITE CONDITIONS February 28, 1985

- a) Steady drops in the water level caused some fracturing of the ice adjacent to the breakwater as shown in Figure 3.11.
- b) The berm was still sealed by the surrounding snow and ice covers as shown in Figures 3.12 and 3.13. The spray ice had subsided into the top layer of stone on the crest yet was still intact.
- c) Ice growth continued to occur with an increase of about 20 cm on both the lake and marina ice sheets since January 25, to thicknesses of 84 cm and 67 cm respectively.

FIGURE 3.12 SNOW COVER — Lake Side Feb. 28, 1985

FIGURE 3.13 SNOW COVER — Marina Side Feb. 28, 1985

Figure 3.14 SITE CONDITIONS March 15, 1985

- a) The water level continued to drop fracturing the ice sheet adjacent to the breakwater even further.
- b) Snow and ice continued to insulate the berm completely. Figures 3.15 and 3.16 show the berm and surrounding snow conditions from the lake and marina sides respectively.
- c) The spray ice completely subsided into the top layer of stone in the berm providing a solid cover of ice and stone.
- d) The thermocouple measurements indicated that there was no ice within the berm at this time which was confirmed by excavating the berm down to water line. Figure 3.17 shows the excavation revealing the top layer of solid spray ice and stone underlain by dry stone and open voids down to the waterline.
- e) The snow cover was also cleared away from the slope on the marina side of the berm as shown in Figure 3.18. Once the ice was broken away from the outer stone it was possible to see that no ice had formed within the voids even at the outer edge of the berm.
- f) Ice growth continued with a total of 77cm in the marina and 92cm existing in the lake at this time.

FIGURE 3.15 OVERALL BREAKWATER CONDITIONS — Lake Side Mar. 15, 1985

FIGURE 3.16 OVERALL BREAKWATER CONDITIONS — Marina Side Mar. 15, 1985

FIGURE 3.17 EXCAVATED BERM

NO ICE IN VOIDS Mar. 15, 1985

FIGURE 3.18 BREAKWATER SLOPE EXCAVATED

Marina Side Mar. 15, 1985

Figure 3.19 SITE CONDITIONS April 3, 1985

- a) Figures 3.20 and 3.21 show the deterioration of the ice immediately surrounding the berm and the fractured ice sheet on the marina side of the berm, respectively. As shown in Figure 3.21, the ice sheet fractured in a vertical plane with a wedge of ice remaining on the breakwater slope. This block was supported by the rockfill. Observations indicated that only three stones were dislodged by this ice action; the movement of less than 0.5m was considered to be insignificant.
- b) Figure 3.22 shows how the ice sheet was cantilevered on the lake side, approximately 0.5m out from the breakwater before fracturing. It appeared that the ice was supported by the flat section of the berm causing the difference between how the lake and marina ice sheets separated from the berm.
- c) Both ice sheets had started to deteriorate as indicated by their slightly lower thicknesses of 76cm in the marina and 84cm in the lake.

FIGURE 3.20 ICE CONDITIONS — Marina Side Apr. 3, 1985

FIGURE 3.21 FRACTURED ICE SHEET — Marina Side Apr. 3, 1985

FIGURE 3.22 CANTILEVERED ICE SHEET — Lake Side Apr. 3, 1985

Figure 3.23 SITE CONDITIONS April 23, 1985

- a) The ice had completely melted away from the sides and crest of the breakwater by this time. Figures 3.24 and 3.25 show the conditions for the lake and marina sides respectively.
- b) Prior to this date the berm temperatures were consistently higher than the surrounding water temperatures at the same elevation. By April 23 the situation had reversed. At this time the temperatures within the berm were lower than those in the water column immediately adjacent to the berm. This was probably due to record air temperatures in the high 20's C warming the water column surrounding the berm and insufficient time had elapsed for the rock in the berm to warm up to the same temperature.
- c) A substantial deterioration of both ice sheets occurred leaving a 35cm thick ice sheet in the marina and a 50 cm thick ice cover in the lake. Although there had been a significant deterioration of the lake ice there were still no open water areas visible.

FIGURE 3.24 LAKE ICE CONDITIONS Apr. 23, 1985

FIGURE 3.25 MARINA ICE CONDITIONS Apr. 23, 1985

April 27, 1985

- a) A rapid movement of the lake ice was witnessed by a local resident on this date. The movement occurred in less than a minute, yet caused stone movement on both the berm and traditional breakwaters. Figure 3.26 identifies the three stones moved on the berm. All three were large stones for the berm design and similar in size to those which were dislodged on the traditionally designed breakwater.
 - b) The lake ice was approximately 0.15m thick at this time but had not deteriorated to the extent that it candled (rotten columnar grained ice fracturing into individual or small groups of crystals) readily.
 - c) In addition to the movement of several stones on the traditional breakwater the ice movement caused some damage to the wooden wall on the government dock as shown in Figure 3.27.
 - d) The steep 1:1 slopes and large rock sizes of the stone protection adjacent to the government dock on the lake side appeared to promote stone movement. For example, one stone in the 700kg range was pushed over the top of the wall which is 2.5 m above the water level.
-

FIGURE 3.26 STONE MOVEMENT ON BERM Apr. 27, 1985

FIGURE 3.27 ICE DAMAGE TO GOVERNMENT WHARF Apr. 27, 1985

April 30, 1985

- a) The ice in the marina had completely melted by this time.
 - b) The lake ice had deteriorated to the point where it was approximately 0.1m thick, honeycombed, brittle, and candled readily. As the ice sheets either struck one another or the breakwater, they candled without causing any damage or stone movement. Figure 3.28 shows the deteriorated ice conditions in the vicinity of the berm. Figure 3.29 reveals the individual ice crystals created by candling of the ice sheet.
 - c) No openings were visible in the lake until late in the day at which time the ice was moving in a SSE direction under the influence of light winds (under 10 km/hr).
-

FIGURE 3.28 LAKE ICE CONDITIONS Apr. 30, 1985

FIGURE 3.29 ICE CANDLING AND CRYSTAL SIZE Apr. 30, 1985

May 1, 1985

- a) By 7 a.m. no ice was present in the vicinity of the breakwater as shown in Figures 3.30 and 3.31.
 - b) The ice was pushed across the lake during the night and piled on the south shoreline however, it had insufficient strength or energy to cause any substantial damage.
 - c) During the night wind velocities never exceeded 10 km/hr even though the ice moved several kilometres.
-

FIGURE 3.30 LAKE CLEAR OF ICE May 1, 1985

FIGURE 3.31 MARINA CLEAR OF ICE May 1, 1985

3.2 Berm Temperature Readings

An array of thermocouples covering both the horizontal and vertical profiles of the berm was used to accurately determine the location of ice inclusions and temperature profiles within the berm. The array consisted of ten separate thermocouple chains with varying numbers of thermocouples in each chain. Each thermocouple chain was designated by a colour code and each thermocouple by a number as shown in Figure 3.32. All the thermocouple measurements made during the winter of 1984-85 within the berm have been plotted using two formats. Plots of both temperature versus time and temperature versus depth are presented in Appendix B for all the thermocouples located in the berm.

The results were plotted to determine the following:

- i) the existence of any significant anomalies in temperature distributions either in space or in time,
- ii) the existence of any specific temperature trends, and
- iii) the identification of any errors in the recording of temperature data.

Several interesting observations can be made from the plots including the identification of specific temperature trends and confirmation of the accuracy of the data. For example, the thermocouples which were above the water line within the berm show cold berm temperatures prior to heavy insulation by overlying snow and ice. A warming trend to above zero degrees Celcius is then noted in mid February which corresponds to the time of maximum insulation by the snow and ice overlying the berm. Figure 3.33 reveals this trend for the thermocouples numbered 1 and 2 even though the air temperatures surrounding the berm did not increase. The same plots also show the berm temperatures cooling again in mid March to early April when the surrounding insulation was deteriorating, allowing the air to penetrate the berm.

A plot of temperature versus time for the thermocouples below the water line, as shown in Figure 3.34, reveals the consistent temperature of the water column but, no freezing since the temperatures are all above zero degrees celcius.

All plots provide a means of evaluating the accuracy of the data in relation to acquiring the desired results and to detect errors quickly. It is considerably more difficult to evaluate the data and to detect errors when reviewing tables of raw data. One example of the accuracy of the measurements is shown in Figure 3.35. These results indicate the inversion of the water column between April 23 and April 30, 1985. This graph confirms the accuracy of the data since the inversion is shown occurring around 4 degrees Celcius.

FIGURE 3.32 THERMOCOUPLE LOCATIONS AND DESIGNATIONS

FIGURE 3.33 BERM TEMPERATURES VS TIME

FIGURE 3.34 BERM TEMPERATURES VS TIME

FIGURE 3.35 BERM TEMPERATURES VS DEPTH

3.3 Vertical Surveys of Berm

Vertical surveys of the external profile of the berm were completed during each field trip. These surveys were intended to determine if there was any noticeable expansion of the berm due to ice inclusions or settlement because of densification of the berm or consolidation of the supporting soil.

Two cross sections of the berm were identified with a series of points marked on individual stones. Figure 3.36 shows some of the points which were surveyed during each field trip. This rather simple method of identifying stones was chosen after analysing several more complicated methods such as placing steel rods down into the berm which extruded through the surface. It was decided that the more difficult methods would not provide sufficient additional information, (if any at all), to justify their high cost of installation and monitoring. Since the main purpose of the vertical surveys was to determine if there were large vertical displacements in the berm due to either ice inclusions or settlement the simple method chosen proved to be very satisfactory.

An average vertical movement of -0.009m was measured with a maximum of -0.022m and a minimum of -0.001m (± 0.005). Although all the points settled, the magnitude of the settlement is considered negligible in terms of the structure's ability to provide protection against wave action. It can also be noted that there was no noticeable expansion of the breakwater during the time of maximum ice formation in the berm. This indicates that the voids within the berm are capable of consuming the ice growth without causing any large expansion forces.

In future years the berm may experience some expansion due to the occurrence of ice inclusions. If no spray ice forms over the surface of the berm, cold air may infiltrate the voids during the winter and ice could form within the berm. This may cause some expansion of the berm. During the measurement period (winter 84-85) there was only a nominal amount of ice formation within the berm so the settlement pattern recorded may not be representative of the most critical situation. During the winter of 1984-85 a substantial amount of spray ice effectively sealed the berm preventing ice growth within the berm.

FIGURE 3.36 POINTS FOR VERTICAL SURVEYS

3.4 Visual Observations

Several interesting observations were made concerning the interaction of ice with the berm. The most important observation was the manner in which moving ice sheets interacted with the berm type breakwater in contrast to the traditional breakwater design.

The North Bay marina now has both types of breakwater designs so that it is possible to compare the behaviour of the two designs under the same ice conditions. On April 27 some ice movement occurred which moved armour stones on both breakwaters. On the berm it was only possible to identify three stones which were displaced up the slope and all three were large stones for the berm design. Several stones in the same size range (500-750kg) were also moved on the traditionally designed breakwater.

It would appear that the ice simply rolls over the smaller stones and up the breakwater slope in the berm design failing in flexure. The stranded ice then melts in place on the breakwater slope. Only the larger stones in both cases have sufficient size to be caught by the moving ice sheet and pushed up the slope. The movement of the larger stones is not expected to create any problems with the berm design since wave action will reshape the berm and they will eventually interlock with other stones on the berm slope.

Wave action on the berm design causes stone movement until a stable profile is developed with a high degree of interlocking between the stones. The process is referred to as nesting and, as discussed in Chapter 2, it eventually creates a relatively smooth surface on the outer slope of the berm.

The flatter slope of the berm near the water line also appears to have an advantage over traditional designs since the ice can ride up the slope more easily. In general no large horizontal pressures are generated on the berm; this results in smaller stone movements. In contrast, the steep slopes and large stones of traditional designs enhance the contact with the vertical face of the incoming ice sheet, resulting in the development of relatively large forces and more frequent stone movement.

Uplift forces and plucking of stones was originally considered to be a potential problem with the berm design. However, the falling water levels which occurred during the time of the majority of ice formation fractured the ice sheet adjacent to the breakwater. This combined with the more rapid deterioration of the ice along the sides of the breakwater eliminated plucking as a potential problem with the berm design.

Thermally generated ice expansion forces were not expected to be a problem with the North Bay breakwater. Therefore, no measurements were made to determine their magnitude although some applicable visual observations were made. During the winter no ice movements were observed adjacent to the breakwater even

during periods of rapid temperature change. The moderating effect of the snow cover on the ice sheet, the lack of boundaries capable of restricting ice motion (sandy beaches surround the marina site) and the relatively large size of the lake all contribute to reducing the forces caused by ice expansion. For all of the above reasons thermally generated ice forces are not considered to be a threat to the breakwater at North Bay.

The final breakup and movement of the lake ice presented no threat to the stability of the berm. The ice sheet deteriorated to the extent that it had very little strength by the time that the majority of movement occurred. By April 30 the lake ice sheet was less than 0.1m thick (columnar ice) and had transformed into 'black' ice. This is caused by preferential melting of the snow ice which occurs in the spring leaving the transparent or 'black' columnar ice.

Once the snow ice melts from the surface of the ice sheet the sun then melts the crystal boundaries between the large columnar crystals. The deterioration of the columnar crystal boundaries is referred to as candling of the ice sheet. Candling had occurred in Lake Nipissing by April 30 at which time the ice had a honeycomb structure and was very brittle. When this ice sheet interacted with the berm or when two ice floes came into contact with one another, the ice broke into individual or small groups of ice crystals. The crystals then floated horizontally and deteriorated rapidly in the relatively warm surface water. No stone movement or ice runup occurred at this stage.

CHAPTER 4

ICE CHARACTERISTICS

4.1 Ice Climatology-Lake Nipissing

Lake Nipissing is located in Northern Ontario at approximately Latitude 46-25 N, Longitude 79-30 W. It has an average yearly surface elevation of 195.50m above sea level, it is 83.3km long and 27.8 km wide at its widest point.

Information on Lake Nipissing ice conditions was obtained from the Ice Climatology Branch, Atmospheric Environment Service, Ottawa and from the Water Resources Branch, North Bay. Table 4.1 provides a summary of the ice related data recorded between 1952 and 1983. It includes dates for the first permanent ice, complete freeze over, ice safe for traffic, maximum ice thickness, ice unsafe for traffic, first deterioration, and water clear of ice.

The lake ice in North Bay generally forms along the shoreline first and rapidly covers the entire lake. Shallow water throughout the lake provides for relatively uniform cooling of the water body creating this pattern of ice growth. The ice climatology during the winter of 1984-85 was consistent with other years, taking less than one week from the time of first permanent ice to complete freezeover in mid December. A maximum ice thickness of 92cm was measured on March 15 adjacent to the breakwater which is above the maximum annual average thickness of 72cm. This discrepancy will be explained in Chapter 4.3 in the discussion of lake ice formations.

The water level which is regulated by control structures on the French River is another important aspect of the ice climatology in Lake Nipissing. The level is increased during the summer months for boating and then gradually lowered in the fall and winter to reduce spring flooding. Water levels have been recorded at the government wharf in North Bay since 1933 on a daily basis. The highest water level recorded over this time was 196.93m (above sea level) in June 1947 and the lowest was 194.31m in April 1975. During the course of this study the highest recorded water level was 195.71 on November 21, 1984 and the lowest was 194.62m recorded on March 26, 1985.

4.2 Marina Ice Samples

Ice samples were collected from the marina ice sheet on January 25 and February 28, 1985. As expected, the samples were predominantly columnar ice superimposed by snow ice. Figure 4.1 provides a typical cross section of the marina ice cores and Figure 4.2 shows the two locations where samples were cut from the marina ice sheet.

Table 4.1 - Summary of Ice Conditions

Ice Year	First Perm Ice	Complete Freeze Over	Ice Safe For Traffic	Other Date Re Freeze Up	Max Ice Thickness (cm)	Ice Unsafe For Traffic	First Deter'n Of Ice	Water Clear Of Ice
1952							Apr 13	
1953							Apr 21	
1954							Apr 19	
1955							May 09	
1956	Nov 23	Dec 05			41(1)	Apr 01(1)	Apr 20	Apr 30
1957	Nov 26	Dec 02	Jan 04(1)		41(1)	Mar 25(1)	Apr 05	Apr 20
1958		Nov 30			46(1)	Apr 06(1)	Apr 18	Apr 29
1959	Nov 17	Nov 26			46(1)	Apr 01(1)	Apr 20	Apr 30
1960	Dec 07	Dec 10			51(1)	Mar 20(1)	May 01	May 03
1961	Dec 09	Dec 15			51(1)		Apr 24	Apr 26
1962	Dec 11	Dec 12				Mar 25(1)	Apr 16	Apr 22
1963	Dec 02	Dec 10		Dec 03(7)			Apr 18	Apr 28
1964	Dec 01	Dec 03		Nov 22(2)			May 01	May 11
1965	Dec 05	Dec 07				Mar 18(1)	Apr 15	Apr 26
1966		Dec 12		Dec 03(7)			Apr 14	Apr 24
1967	Nov 27	Nov 28		Nov 15(2)	76(0)		Apr 14	Apr 19
1968		Nov 30		Nov 26(2)	61(1)	Apr 10(6)	Apr 20	May 01
1969	Nov 27	Dec 01	Dec 17(6)	Nov 15(2)	71(1)	Apr 15(6)	Apr 17	May 03
1970	Dec 06	Dec 07	Jan 14(7)		91(1)		Apr 27	May 09
1971	Dec 04	Dec 16	Dec 24(6)	Nov 23(2)	91(1)		May 03	May 13
1972	Nov 22	Dec 01	Dec 06(6)		76(1)		Apr 16	Apr 22
1973		Dec 14	Dec 19(6)		91(2)	Apr 20(7)	Apr 21	May 04
1974	Dec 01	Dec 04	Jan 01(6)	Nov 21(2)	91(4)	Apr 12(7)	Apr 29	May 10
1975	Dec 02	Dec 11	Dec 24		76(2)	Mar 20	Apr 05	Apr 21
1976	Nov 11	Nov 29	Dec 02		76(1)	Mar 26	Mar 30	Apr 23
1977	Nov 23	Dec 10	Dec 24		99(2)	Apr 03	Apr 30	May 09
1978	Nov 21	Dec 03	Dec 22		90(1)	Mar 20	Apr 01	May 09
1979	Dec 10	Dec 16	Dec 21		95(1)	Mar 27	Mar 20	May 05
1980	Nov 12	Dec 05	Dec 16		78(2)	Feb 15	Mar 20	Apr 13
1981	Nov 23	Dec 16	Dec 19		76(2)	Mar 03	Apr 17	May 07
1982	Dec 08	Dec 14	Dec 12		72	Feb 27	Mar 06	May 01
1983	Nov 13	Dec 14					Mar 14	Apr 28
Early	Nov 17	Nov 26	Dec 06(6)	Nov 15(2)	41(1)	Mar 18(1)	Apr 03	Apr 19
Mean	Dec 01	Dec 06					Apr 25	Apr 30
Latest	Dec 11	Dec 16	Jan 14(7)	Nov 26(2)	91	Apr 20(7)	May 19	May 13

- 3: 0 Break up, ice broke, or broken, or ice gave way
1 Water body open to navigation
2 Partial clearing or melting of ice with subsequent refreezing
4 Water body said to be open
6 Ice said to be moving
7 Date refers to ice "run"

Vertical Thin Section

FIGURE 4.1 MARINA ICE SAMPLE

Lake Nipissing

FIGURE 4.2 LOCATION OF ICE SAMPLES

The ice formations found in the marina are similar to those found in reservoirs and other protected water bodies. The protection from wave action provided by the breakwater reduced the amount of mixing of the water column and allowed the formation of columnar ice with large crystals.

As shown in Figure 4.1, vertical and horizontal thin sections were prepared from the marina ice samples using crystallographic techniques. The following observations were made concerning the formation of the primary ice layer.

- 1) Extra large crystals were present at the snow ice-columnar ice transition zone. Figure 4.1 shows a horizontal thin section prepared from 15mm below the transition level.
- 2) An irregular and angular crystal shape is observed at the transition zone.

The observations noted above generally indicate that the primary ice was formed under calm conditions with a relatively low temperature gradient. This primary ice type is classified as P1 type, (Ramseier, 1985). The instrument used for measuring crystal orientation (a universal stage) was unavailable at the time of this study. However, observation of the horizontal sections cut from the marina ice sample reveal a vertical crystallographic orientation for some of the crystals in the secondary ice layer. For example, it is possible to identify the same crystal in approximately the same position in two of the horizontal sections prepared from the marina ice core. The crystal referred to above is identified in the two horizontal thin sections by a number 1 in each photograph. Secondary ice with the characteristics noted in the marina ice sample, such as preferred vertical c-axis orientation, is classified as S1 type ice.

The marina ice sample also contained several layers of concentrated bubbles as shown in Figure 4.3. Although the concentrated bubble areas are not important for the purposes of this study they need to be analysed in order to properly describe the marina ice structure. An attempt was made to correlate the location of the bubbles with changes in air temperature (average and extremes), water level changes, and rate of ice growth. The most common parameter associated with the bubble layers was the occurrence of low air temperatures (below -20 degrees C) and the resulting rapid ice growth. However, low air temperatures occurred at other times which did not produce bubble layers. It can also be shown that the depth of bubble layers is not consistent with the amount of ice growth expected during the occurrences of low temperatures. It is conjectured that some form of biological activity may be responsible for the bubble layers. A nearby creek which provides a flow of warm water into the marina may be the source of the high air content in the water column that eventually created the bubble layers. Water samples from the creek may provide some insight into whether or not it is another possible source of the air bubbles.

Scattered Light on Thin Section

Field Sample

FIGURE 4.3 CONCENTRATED BUBBLE REGIONS — MARINA

4.3 Lake Ice Samples

In comparison to the formation of ice in the marina, the lake ice formed under more complicated conditions. Substantially more work was required to determine its origin. A multi-layered ice sheet was created adjacent to the breakwater by a combination of cold air temperatures and a variety of wind conditions before the lake was completely frozen over. By combining the results of the crystallographic analyses with the observations made during each field visit it was possible to determine the meteorological conditions responsible for the ice formations.

During the field trip of December 12, 1984, pan ice (ice sheet fractured into small rounded floes) was observed pushed against the breakwater while open water was still present farther offshore. It was obvious that the breakwater influenced the ice regime in its vicinity by preventing the pan ice from being pushed to the shoreline. At this time it was not possible to walk on the ice on the lake side of the breakwater. By December 29 the ice thickness on the lake side was approximately 42cm.

During the field trip of January 25, 1985, ice samples were cut at locations 7m and 14m away from the breakwater. Laboratory analysis of these samples revealed the presence of only frazil ice (S4 ice type) superimposed by a thin layer (35mm) of columnar (S1 ice type) and snow ice (T1 ice type), (Ramseier, 1985). A vertical thin section of this ice is shown under polarized light in Figures 4.4 and 4.5. Due to the sample size it had to be divided into two figures for presentation. Figure 4.4 shows the top half of the sample and a horizontal thin section through the columnar layer. Figure 4.5 shows the bottom half of the sample with a horizontal thin section through the frazil layer.

Since there are no sources such as a river, which can result in the development of frazil ice, it was deduced that the frazil ice was generated in the open water offshore from the breakwater prior to December 12, 1984. By combining the ice core data with the air temperature and wind data it was possible to reconstruct the history of the ice formation on the lake, adjacent to the breakwater. Table 4.2 provides the meteorological conditions which existed prior to December 12 and explains the complex ice formation recorded adjacent to the breakwater.

Snow Ice

Columnar

Horizontal Thin Section

Frazil

Vertical Thin Section

FIGURE 4.4 LAKE ICE SAMPLE (top)

(14m from b.w.)

Vertical Thin Section

Horizontal Thin Section

FIGURE 4.5 LAKE ICE SAMPLE (bottom)

(14m from b.w.)

TABLE 4.2

METEOROLOGICAL DATA ASSOCIATED WITH LAKE ICE GROWTH

Date	Air Temperature		Wind	
	Maximum (C)	Minimum (C)	Direction (10 degrees)	Velocity (knots)
Dec 1/84	4.1	-1.8		
2	1.1	-2.9		
3	2.9	-1.3		
4	0.2	-7.1	calm	
5	-0.2	-8.1	calm (theoretical ice .04m)	
6	-2.1	-16.9	10 to 14	5
7	-1.2	-20.8	11 to 34	3 to 7
8	3.7	0.7	20 to 27	9 to 13
9	4.2	-1.9	calm	
10	4.3	2.0	calm	
11	4.0	2.0		
12	Field Trip			

As predicted using Ashton's (1980) equation (see Appendix C.2) the 35mm thick columnar layer formed during the calm conditions on December 4 and 5, 1984. Ashton's method predicts an ice thickness of 40mm, whereas the actual ice thickness varied between 35mm and 40mm. Considering natural variations in ice thickness and the meteorological conditions on December 4 and 5, these values represent the same event of ice formation.

The high winds and increasingly cold temperatures of December 6th and 7th were responsible for pushing the columnar ice into the breakwater and breaking it into pan ice as observed on December 12. These conditions also created the frazil slush which eventually congealed to become part of the ice sheet. The water column temperatures measured on December 28 and January 25 indicate that the frazil slush cooled the lake water. At the time of frazil formation, the wave energy would have agitated the water causing the frazil crystals to be distributed throughout the water column. This would cool the water column as indicated by the consistent temperature of +0.5 degrees measured throughout the water column. As the waves subsided the frazil crystals would have floated up to the bottom of the ice sheet.

Observations of the vertical thin section also indicate that suspended frazil slush was present in the water column. In Figure 4.4 (top 39cm of sample) the basal plane of the frazil crystals is almost exclusively vertically oriented and parallel to the breakwater. This reveals the fact that the crystals were packed into this area by wave energy and eventually congealed to the bottom of the ice sheet in an orderly fashion. In contrast, Figure 4.5 (bottom 28cm of sample) shows a random orientation of the frazil crystals. The suspended frazil crystals are floating in a random manner until enough heat is lost to congeal them to the bottom of the ice sheet. This creates a random orientation

in the frazil crystal pattern on the bottom portion of the ice sheet.

In order to determine the ice profile on the lake it was necessary to collect samples at locations further offshore from the breakwater than those collected on January 25, 1985. The extent of the frazil ice had to be determined to complete the ice profile. Therefore, on February 28, 1985 ice samples were cut in a line perpendicular to the breakwater until the end of the thin columnar layer (pan ice) and frazil ice were located.

Figure 4.6 provides field photographs of ice samples taken from 60m and 80m offshore from the breakwater. A vertical thin section is also provided for the sample taken at 80m. Figure 4.7 provides a vertical thin section and field photograph of a sample from 90m offshore. This sample reveals the end of the frazil ice with only columnar ice superimposed by snow ice. The total ice column was 67cm thick which is equivalent to the thickness measured in the marina. Note that only the top portion of the actual ice columns are shown since they provide enough information when combined with the ice thickness to determine the overall ice profile. A horizontal thin section from 1cm below the snow ice/columnar ice transition reveals a slightly different crystal pattern from that found in the marina, (S2 ice type). The crystal size varies through a wider range than in the marina indicating that they formed under a larger temperature gradient. This is quite possible since it is known that these two areas of ice formed at different times.

An ice profile was developed for the lake adjacent to the breakwater using the information discussed above and is provided in Figure 4.8. This profile represents the heaviest ice conditions encountered before deterioration of the lake ice, which was initiated by warmer air temperatures and stronger sunlight. Figure 4.8 shows the effect of the breakwater on the local ice regime. The breakwater caused the frazil accumulation and subsequent thicker ice conditions out to 90 m offshore of the breakwater.

Deterioration of the lake ice began in late March and continued until early May, by which time the water surrounding the marina was totally clear of ice. Deterioration proceeded in the following manner: melting of the surface snow ice occurred first; and the transparent columnar ice then deteriorated at its crystal boundaries (referred to as candling) with no major movement occurring until the lake ice sheet was less than 0.1m thick and very brittle. Final breakup and movement of the ice occurred in early May.

Lake Ice (60m from b.w.)

CI = Columnar
SI = Snow Ice
F = Frazil

Lake Ice (80m from b.w.)

Vertical Thin Section

FIGURE 4.6 LAKE ICE SAMPLES

Vertical Thin Section

Field Sample

Horizontal Section

FIGURE 4.7 LAKE ICE SAMPLE

(90m from b.w.)

FIGURE 4.8 LAKE ICE PROFILE

CHAPTER 5

MATHEMATICAL MODELLING

The prediction of freezing patterns within a breakwater requires an understanding of many complex processes. These include temperature variations at the boundaries, relatively complex geometrical shapes, and spatially dependent thermal properties. This makes the solution of the problem too complex for manual calculations, leading to the possible use of finite element or finite difference procedures for predicting the temperature regime of the breakwater.

Heat may be transferred within the breakwater mass and the surrounding materials by several means including conduction, radiation, and mass transfer processes such as convection. During the winter, conduction and convection are the predominant forms of heat transfer. Conduction is the transmission of heat by the passage of energy from one particle to another and is independent of mass transfer processes. Convection is the transmission of heat by mass movement of the heated particles, such as water or air circulation. During the spring, solar radiation becomes important, causing rapid deterioration of snow and ice around the dark, radiation absorbing breakwater. Radiation also melts the crystal boundaries of the columnar ice, eventually leading to candlering of the ice sheets surrounding the breakwater.

Conduction is the principal mechanism for heat transfer in most freeze-thaw situations involving soils. Once a frozen zone is established there is often a restriction on the convection processes, leaving conduction through the frozen zone to predominate. However, convection cannot be ignored in this study. Convection currents in the water column are the most likely source of heat preventing freezing within the berm. Circulation of the water column may be caused by the temperature difference at the water/air interface within the berm. This heat source may have prevented freezing within the berm when combined with the insulation effects of the overlying snow and lack of cold air circulation in the berm.

The development of an accurate numerical model to simulate the freezing patterns around and within a rubblemound breakwater would be beneficial. The model could be used to evaluate whether or not ice related problems are probable before construction begins. This would save a substantial amount of time and money by allowing design modifications to be made before final designs are completed. The implementation of proper designs during the initial construction would also reduce the amount of maintenance required after construction if proper designs can be implemented.

The model could use meteorological data for the site under investigation to predict the ice conditions which will exist around and within the breakwater. Knowing the ice conditions, it would be possible to investigate the stability of the breakwater

using slope stability analysis and other standard forms of engineering analysis.

The complete numerical model would require that sufficient meteorological data be input to allow the prediction of the lake and marina ice thicknesses. This will require a prediction of the amount of frazil formation adjacent to the breakwater based on air temperatures, wind direction and extent of open water areas. The numerical model should also predict whether or not surface ice will form on the breakwater. Once the range of surface conditions has been determined, the numerical model would provide an estimate of the pattern of ice growth within the breakwater. This step is essential, since the ice conditions within the breakwater can influence the stability of the breakwater under both hydrodynamic and static loadings. For example, ice inclusions within the breakwater could create areas of concentrated wave energy if they remained intact after spring breakup.

The model would require the following features to ensure accurate results:

- 1) The capability to step through the flow path outlined in Flowchart 5.1. This would provide an accurate representation of the boundary conditions at all times.
- 2) The model must provide for heat transfer by convection, especially for the region of rock and water within the berm. Convection should also be included for the area of rock and air above the water line to account for years with no seal due to spray icing.
- 3) An attempt to define the relative importance of the various heat transfer processes (convection, conduction, and radiation) over time should be made. For example, the input for radiation needs to be altered as the seasons change.

There are existing finite element models used to predict freezing patterns below pavements and within earth dams. Existing models (Ho et al, 1970) are oriented toward soil heat transfer problems which are not directly applicable to quarried rock berms. Heat transfer within soil masses is often dominated by conduction, whereas heat transfer in the open breakwater mass may be controlled by convection processes. Other models (Jessberger and Makowski, 1981) incorporate either time or phase change dependent values for thermal conductivity and specific heat parameters. Although these models are quite complex they are also directed toward heat transfer processes in soils. Heat transfer by convection within breakwaters and solar radiation at the surface need to be incorporated into FEM models to make them applicable to predicting freezing patterns in breakwaters.

Another major problem with using existing models is the lack of accurate thermal conductivity values for the combinations of rock and water and rock and air. Accurate thermal conductivity values are essential to any numerical modelling of ice growth within a rock berm.

Flowchart 5.1

Numerical Model

Description of Flow Chart Steps:

INPUT A	Meteorological Data prior to lake freezing over (air temperatures, wind speeds and direction).
CALCULATE A	Whether or not spray ice and frazil accumulation are probable.
INPUT B	Meteorological Data after lake freezes for a specific amount of time, such as one week.
CALCULATE B	Ice Thickness surrounding breakwater (distinguish between lake and marina if frazil accumulation was predicted).
INPUT C	The results from the above into the FINITE ELEMENT MODEL for a specific period, such as one week, to represent the boundary conditions for that period.
OUTPUT	Prediction of berm temperature isotherms and therefore prediction of and location of ice lenses.
RESULTS	1) Ability to complete standard engineering analyses such as slope stability calculations by inputting extent and location of ice lenses. 2) Prediction of possible erosion problems if ice still exists in the berm after the lake has cleared of ice in spring.

Figure 5.1 provides an example of a finite element grid which could be used to delineate the various areas of ice, water, rock, and rock and ice combined. The boundary conditions would include: a constant temperature boundary at the lake bottom of four degrees celcius, a varying temperature on either side representing water column temperatures, and a varying upper boundary based on air temperature data.

FIGURE 5.1 FINITE ELEMENT GRID

CHAPTER 6

CONCLUSIONS

A field program and investigation of the effects of ice interaction with a rubble mound breakwater during the winter of 1984-85 led to the following conclusions.

1. It is possible to undertake a successful field monitoring program to evaluate the effects of ice interaction with a rubble mound breakwater. General observations made during regular site visits proved to be essential to understanding and documenting how the structure responded to interaction with ice. The instrumentation system developed for this study, and procedures followed, provided all the necessary information with repeatable and accurate results.
2. Vertical surveys of the external profile of the berm showed no expansion of the berm due to ice inclusions or settlement of the rock mass. The survey results indicated that there were no significant expansion forces created in the voids of the breakwater by ice growth. Therefore there was no need to investigate if ice inclusions reduced the shear strength of the breakwater in this situation.
3. The berm temperature readings supported the above conclusions by indicating that no major ice inclusions formed within the berm. The insulation from the overlying snow and ice, combined with the heat generated by the lake water, prevented the formation of ice inclusions.
4. During the spring thaw, the ice failed in such a manner that the breakwater was not damaged due to either plucking of stones or slope failure due to the weight of the ice overburden. As the water level dropped during the winter the ice sheet sheared relatively close to the breakwater and therefore the rise in water level in the spring did not produce any significant uplift forces on the structure.
5. The relatively smooth and flat slope of the berm design in comparison to traditional designs caused the ice to ride up the structure and fail in flexure with an insignificant amount of stone movement.
6. The majority of lake ice had deteriorated substantially before any significant ice movement occurred in the lake and therefore, posed no threat to the stability of the berm.
7. Overall, it appears that the berm type breakwater is not significantly affected by the interaction of ice with the structure. However, additional monitoring of the performance of the berm design under ice loadings is recommended. Future ice conditions in Lake Nipissing may create situations not covered in this study although the ice conditions of 1984-85

were considered to be above average severity. The interaction of the berm breakwater design with sea ice also deserves special attention. The different properties of sea ice compared to freshwater ice including brine inclusions, depression of the freezing point, and crystallographic structure of sea ice, create the need for a separate investigation.

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APPENDIX A

THERMOCOUPLE DESIGN AND INSTALLATION

1) Berm Temperature Measurements

To achieve the objectives of this study, it was necessary to design some means of measuring the freezing patterns which occurred within the breakwater. Consultation with experts in the field of measuring permafrost areas in soils and earth temperatures under foundations led to the selection of thermocouples as the most appropriate measuring devices.

Thermocouples work on the principle that when two lengths of different metals are joined at both ends, and the junctions subjected to different temperatures, a small electromotive force is set up, causing a current to flow. The magnitude of the electromotive force is dependent on the temperatures at the junctions and on the types of metal used. If the properties of the metals are known, and an ice bath (0°C) is used as a reference junction, it is possible to determine the temperature at the other junction.

A portable potentiometer or multimeter of sufficient accuracy can be used to measure the voltages. A portable Hewlett Packard 3465A digital multimeter, in a protective case complete with an ice bath as a reference junction, was used for this study.

An array of thermocouples covering both the horizontal and vertical profiles of the berm was used to accurately determine the location of ice inclusions and temperature profiles within the berm. The array consisted of ten separate thermocouple chains with varying numbers of thermocouples in each chain. Each thermocouple chain was designated by a colour code and each thermocouple by a number as shown in Figure A.1.

A number of different types of thermocouples and protection for the leads were constructed and tested before the optimum configuration was determined. The thermocouple construction procedure used for this study required several modifications of conventional thermocouple installations in earth (Johnston, 1963). Since the thermocouples were being placed in rock, they required protection from crushing; this was achieved by using a combination of hard flexible plastic and steel pipes as lead protectors. The sensitive thermocouple junctions were protected by small aluminum caps and silicone. The complete sequence involved in the construction of the thermocouple cables is described below.

The first step in the thermocouple cable construction involved measuring and cutting the different lengths of thermocouple wire required for each cable. The thermocouple cables were cut from one continuous length of thermocouple wire in order to minimize inconsistencies within each cable. If any variation occurred

FIGURE A.1 THERMOCOUPLE LOCATIONS AND DESIGNATIONS

along the length of thermocouple wire in the main coil it would be determined by a consistent variation in one cable. Any discrepancies of this nature would be detected during calibration and accounted for by modifying the results with a correction factor.

Once the individual leads were cut they were carefully measured, labelled, properly aligned and tied into bundles. Both ends of each lead were stripped of the plastic covering. The lower end of each lead was prepared for tiggig (the two metals are heated to the point where they fuse together) by twisting the copper and constantan wires together around a small nail. Once tiggig the thermocouples were coated with several layers of liquid plastic, coated with silicone and then placed inside 7 mm diameter, 25mm long aluminum caps. The upper end of each lead was connected to a banana plug switch and properly labelled.

Determining the accuracy of the thermocouples was also necessary for proper interpretation of the results. Therefore, each thermocouple cable was calibrated at the National Research Council (NRC) before installation, to determine their accuracy and to ensure their proper operation in the field.

Each thermocouple bundle was immersed in an ice bath which was kept at a constant temperature of zero degrees Celcius. The thermocouples were allowed time to reach an equilibrium temperature (cooling of metal cap, silicone, etc.) before readings were taken. Constantan switches were then connected to each lead and a voltage reading was taken using a multimeter and ice bath as a reference junction, similar to the procedure used in the field.

The next stage involved placing the thermocouple bundles in a cold room which was kept at a temperature of -10 degrees Celcius. Readings were then taken for each thermocouple at the cold room temperature. By comparing the measured readings with the manufacturer's predicted values it was possible to detect any errors in the cables and to locate malfunctioning thermocouple's.

The copper banana plug switches proposed for use in North Bay were also tested at the National Research Council to ensure that they functioned properly. A number of thermocouples were connected to the switch and then readings were taken under two sets of conditions. First, the switch and thermocouples were taken inside the ice lab so that all of the equipment was at -10 degrees C and measurements were taken. Then the thermocouples were threaded through a porthole into the ice lab (-10°C) while the switch was left outside (22°C). A second set of readings confirmed the fact that the switches worked properly, since the same temperatures were measured even though the switch had undergone a temperature change of 32°C.

Two methods of thermocouple installation were required to provide sufficient coverage of the berm cross section. Originally, all of the thermocouples were to be installed during

construction of the breakwater. However, a problem unrelated to this project required removal of the lake side of the berm which destroyed the thermocouples already in place. To replace the thermocouple's on the lake side it was necessary to drill through the berm and install standpipes. The two installation methods required slightly different protective coverings for the thermocouple leads. Both methods are described below, with the use of boreholes recommended for future work where sufficient financing is available.

The installation of the thermocouples during construction required relatively complex protective coverings and careful placement of the thermocouple cables. A substantial amount of physical labour and careful scheduling with the contractor were required to ensure placement in the proper location and to avoid delaying construction.

Placement during construction required plastic CVPC pipes to protect the thermocouples below the water line. The CVPC pipes were chosen after testing several sizes and types of plastic pipe (plastic was chosen because of its thermal properties). PVC pipe was tested but tended to crimp when hit with large stones. The CVPC was rigid enough to prevent crimping yet flexible enough to bend sufficiently without shattering.

The protected thermocouple cables were placed on the breakwater slope after the contractor had finished work for the day (or weekend). They were then carefully surveyed to determine their location and covered by hand with a layer of rock. When construction resumed, the first load of rock was dumped on top of the berm and then carefully pushed over the cables by a bulldozer. Subsequent loads were normally dumped over the edge of the berm as construction proceeded. This procedure combined with the thermocouple protection described below resulted in very few thermocouples being damaged.

The 3 metre length of the CVPC pipe necessitated the addition of another one meter section to achieve the required length. A 12.7mm inside diameter PVC pipe section was used as a coupler by heating it, spraying the inside with oil and then placing it over the CVPC sections. This provided a strong joint which would not separate or influence the performance of the thermocouples.

Small holes were drilled in the sides of the pipes at the location of each thermocouple and along the length of the covering pipes. This exposed the metal cap as much as possible without endangering the lead wires. Different hole sizes were tested to ensure that the drilled holes were not too large, which would cause the pipes to fracture when hit with large stones, but large enough to optimize the flow of water around the thermocouples. Flow into the pipe by the surrounding water and air is necessary to provide accurate temperatures and to prevent convection currents within the pipe.

Once the covering pipes were assembled and drilled, the proper

thermocouple cables were threaded through each pipe and the pipes clearly labelled to identify the location of each cable. In order to thread the cables through the pipes without damaging them it was necessary to coat the inside of the pipes with oil, carefully tape the ends of each cable and then run the cables through the pipes while the pipes were in a vertical position.

Additional sections of PVC pipe were split and placed over the end of the CVPC pipes to add extra protection at the water line. The split PVC pipes fit snugly but acted as a moveable collar when large stones contacted them during the covering process. The completed cables were then placed as described earlier.

Placement of the thermocouples after construction of the berm was completed required the installation of standpipes in the berm by drilling through the rock. The standpipes were installed before the hollow drill rods were removed, to allow collapse of the borehole and ensure that the thermocouples could be placed at the correct depths. The standpipes consisted of 3/4 inch CPVC pipe with drilled holes to allow circulation of the surrounding water and air into the pipe, and to prevent convection within the pipe.

The thermocouple chains were attached to sections of 1/2 inch CPVC pipe cut in half. In this way the cables were stiffened so that they could be threaded into the standpipes which were already in place. This method also ensured that the cables did not bunch up during installation and were located as intended. The cables were installed in the standpipes in November before any ice had formed on the lake.

2) Water column measurements

Water column measurements were made during each field trip using a thermocouple assembly prepared for this study. A chain of thermocouples with one thermocouple every 0.25m along its length was constructed. This spacing was sufficient to clearly define the temperature profile of the water column. A switch was connected to the upper end of the thermocouple chain and a plumb bob connected to the lower end. The plumb bob, in combination with a CPVC pipe cut in half and attached to the thermocouple chain, prevented the thermocouple chain from diverging from its vertical position once placed in the water. Figure A.2 shows the complete assembly.

During each field trip a series of holes were drilled through the ice, the tc chain was inserted into the water column, and allowed to stabilize thermally. Voltage readings were then taken at each borehole to determine the water temperatures at 0.25m intervals of depth. This method of determining the water column temperature profiles was relatively easy, requiring a minimal amount of equipment and effort.

FIGURE A.2 WATER COLUMN TEMPERATURE GAUGE

APPENDIX B

BERM TEMPERATURE READINGS

PRESENTATION OF RESULTS

All of the thermocouple measurements made during the winter of 1984-1985 are presented below in three different formats.

- 1) Table B-1 provides the actual temperature measurements by date and thermocouple designation. Through the calibration process it was possible to assign an accuracy of plus or minus 0.1 degrees Celcius to the thermocouple measurements.
- 2) Plots of temperature vs time by colour designation and thermocouple number are given for each thermocouple. Figure A.1 shows the thermocouple locations in the berm as designated. The temperature vs time plots are divided into two presentations for each thermocouple chain for clarity and ease of interpretation. They are plotted with the same horizontal and vertical axis to allow the comparison of results from different thermocouple locations. Figures B.1 through B.9 provide the temperature vs time plots.
- 3) Plots of temperature vs depth by date are provided for each thermocouple chain. The results for each thermocouple chain are divided into two plots for clarity; one covering the field trips from November 21, 1984 to February 28, 1985; and the other covering the period from March 15, 1985 to April 30, 1985. Figures B.10 through B.18 provide the temperature vs depth plots.

Table B.1

Berm Temperature Readings °C

THERM DESIGNATION	X COOR	Y COOR	DATE	DATE	DATE	DATE	DATE	DATE	DATE	DATE	DATE
			21-Nov	12-Dec	28-Dec	25-Jan	28-Feb	15-Mar	03-Apr	23-Apr	30-Apr
			TEMP	TEMP	TEMP	TEMP	TEMP	TEMP	TEMP	TEMP	TEMP
BLACK/WH 1	-3.303	196.142	0.5	0.4	-0.5	-1.6	0.5	NA	NA	-0.4	8.6
B/W 2	-4.376	195.279	0.9	0.7	0.9	0.3	-0.3	NA	NA	1.1	6.4
B/W 3	-4.902	194.846	1.0	0.7	0.9	0.4	0.7	NA	NA	1.7	5.7
B/W 4	-5.428	194.416	1.2	0.9	1.0	0.5	1.4	NA	NA	2.2	5.1
B/W 5	-5.954	193.985	1.5	0.9	1.3	0.8	1.4	NA	NA	2.6	5.2
RED/YELL 1	-3.275	196.142	0.5	0.3	-0.7	-1.7	0.5	NA	NA	-0.4	7.9
R/Y 2	-3.918	195.279	0.8	0.6	0.9	0.4	-0.2	NA	NA	1.4	5.9
R/Y 3	-4.239	194.846	1.0	0.8	1.0	0.5	0.9	NA	NA	1.5	5.2
R/Y 4	-4.560	194.416	1.4	1.0	1.5	1.1	1.1	NA	NA	2.5	5.6
R/Y 5	-4.881	193.985	1.6	1.1	1.4	1.2	1.4	NA	NA	2.7	5.7
BLUE/GR 1	-3.200	196.142	0.7	0.2	-0.6	-1.5	0.5	NA	NA	-0.5	7.6
B/G 2	-3.200	195.279	1.0	0.5	0.6	-0.1	-0.2	NA	NA	0.5	5.8
B/G 3	-3.200	194.846	1.1	0.6	0.8	0.3	0.2	NA	NA	0.8	5.0
B/G 4	-3.200	194.416	1.2	0.8	1.0	0.7	1.1	NA	NA	1.8	5.3
B/G 5	-3.200	193.985	1.1	0.8	1.0	0.8	1.3	NA	NA	1.8	5.4
BROWN 1	0.000	196.089	0.5	0.3	-0.2	-1.9	0.6	NA	NA	-0.4	5.8
BR 2	0.000	195.360	0.7	0.6	0.7	0.1	0.7	NA	NA	0.9	5.8
BR 3	0.000	194.996	1.0	0.6	0.8	0.8	0.9	NA	NA	1.2	5.4
BR 4	0.000	194.632	1.2	0.7	1.0	0.8	1.3	NA	NA	1.4	5.6
BR 5	0.000	194.268	1.3	0.7	0.9	0.9	1.7	NA	NA	1.7	5.8
BLACK 1	0.000	196.044	0.4	0.2	-3.3	-1.2	0.4	-0.1	-1.0	0.2	4.1
B 2	0.000	195.544	0.7	0.3	-1.8	-0.5	0.1	0.0	-1.5	0.0	4.2
B 4	0.000	195.044	0.7	0.8	0.6	-0.2	0.2	0.1	-0.9	1.5	4.3
B 6	0.000	194.544	0.9	0.8	0.8	0.4	0.7	0.6	1.0	1.9	4.0
B 8	0.000	194.044	1.1	0.8	0.7	0.5	0.6	0.6	1.3	2.0	3.9
B 9	0.000	193.794	1.4	0.7	1.0	0.6	0.6	0.6	0.9	2.0	3.9
B 10	0.000	193.544	1.7	0.8	1.1	0.7	0.7	0.7	1.3	2.0	3.9
WHITE 1	1.600	195.761	0.3	0.3	-1.8	-0.3	0.4	0.3	-0.8	-0.6	3.0
W 2	1.600	195.261	0.8	0.6	0.6	0.2	0.3	0.3	-2.1	0.3	3.4
W 4	1.600	194.761	1.0	0.6	1.0	0.3	0.2	0.4	0.3	1.3	3.2
W 6	1.600	194.261	1.4	0.6	1.0	0.4	0.6	0.6	1.1	1.4	3.1
W 8	1.600	193.761	1.4	0.6	1.1	0.6	0.5	0.5	1.0	1.6	3.1
W 9	1.600	193.511	1.5	0.7	1.2	0.6	0.6	0.6	1.0	1.9	3.5
W 10	1.600	193.261	1.5	0.7	1.3	0.7	0.8	0.8	1.5	2.1	3.4
RED 2	3.171	195.329	0.5	0.5	-0.5	-0.9	0.3	0.3	-0.1	0.9	3.6
R 4	3.325	194.853	0.8	0.6	0.8	0.2	0.3	0.3	0.0	1.0	3.4
R 6	3.480	194.378	1.1	0.6	0.9	0.3	0.7	0.5	1.0	1.3	3.4
R 8	3.634	193.902	1.2	0.7	0.9	0.5	0.6	0.5	1.0	1.5	3.4
R 9	3.712	193.664	1.3	0.6	1.0	0.5	0.7	0.5	1.2	1.7	3.5
R 10	3.789	193.427	1.3	0.6	1.1	0.6	0.8	0.5	1.1	1.8	3.5
BLUE 1	4.029	195.409	0.6	0.6	-0.4	-1.8	0.2	0.1	0.2	-1.1	3.5
B 2	4.389	194.980	0.7	0.6	0.8	-0.4	0.2	-0.3	0.1	0.9	3.7
B 3	4.582	194.750	0.8	0.5	0.8	0.1	0.3	0.2	0.4	1.1	4.0
B 4	4.762	194.536	0.9	0.6	0.9	0.2	0.6	0.5	1.0	1.1	3.7
B 5	4.942	194.321	1.0	0.7	1.0	0.2	0.7	0.5	1.0	1.2	3.8
B 6	5.128	194.100	0.9	0.6	1.1	0.5	0.6	0.5	1.0	1.2	3.8
B 7	5.315	193.877	1.0	0.6	1.1	0.4	0.6	0.5	1.0	1.3	3.6
B 8	5.501	193.655	1.0	0.6	1.1	0.4	0.8	0.5	1.1	1.3	3.6
B 9	5.688	193.432	1.1	0.5	1.1	0.5	0.6	0.4	1.1	1.5	3.6
B 10	5.868	193.218	1.3	0.6	1.1	0.5	0.7	0.4	1.1	1.6	3.5
YELLOW 1	4.282	195.488	0.6	0.5	-0.7	-2.2	0.2	-0.4	0.2	0.4	3.9
Y 2	4.841	195.067	0.8	0.5	1.0	-0.5	0.3	-0.8	0.2	1.7	4.0
Y 3	5.121	194.856	0.7	0.5	1.2	0.2	0.2	0.1	0.4	1.6	4.5
Y 4	5.400	194.646	1.0	0.5	1.0	0.2	0.3	0.4	0.8	1.7	4.4
Y 5	5.688	194.429	1.0	0.7	1.2	0.6	0.4	0.6	0.8	1.6	4.3
Y 6	5.967	194.218	1.1	0.7	1.2	0.5	0.4	0.5	0.8	1.6	4.0
Y 7	6.247	194.008	1.1	0.6	1.1	0.5	0.5	0.5	0.8	1.7	3.9
Y 8	6.534	193.791	1.3	0.6	1.1	0.5	0.5	0.5	0.9	1.7	3.9
Y 9	6.814	193.581	1.3	0.7	1.3	0.5	0.5	0.6	1.0	1.7	3.8
Y 10	7.093	193.370	1.3	0.6	1.2	0.5	0.5	0.4	1.2	1.7	3.8

2) PLOTS OF TEMPERATURE VS TIME

FIGURE B.1

BLUE TEMPERATURE VS TIME

BLUE TEMPERATURE VS TIME

FIGURE B.4

BLACK TEMPERATURE VS TIME

BLACK TEMPERATURE VS TIME

FIGURE B.6

FIGURE B.7

FIGURE B.8

FIGURE B.9

3) PLOTS OF TEMPERATURE VS DEPTH

FIGURE B.10

FIGURE B.12

FIGURE B.13

BLUE/GREEN

TEMPERATURE VS DEPTH

BLUE/GREEN

TEMPERATURE VS DEPTH

APPENDIX C

METEOROLOGICAL DATA AND ASSOCIATED
ICE THICKNESS PREDICTIONS

All of the meteorological data used in this study was collected by the North Bay office of Environment Canada. They operate one weather station at the government dock adjacent to the marina and another at the North Bay airport. Significant differences in temperature and winds can occur between the two stations. Two factors are responsible for the difference; the moderating effect of the lake, and the fact that the airport is 200m higher in elevation than the marina. It is important to note that all of the data used in this study was collected at the marina weather station, whereas only the airport data is published by Environment Canada. The data from the marina station is not automatically reduced. Therefore, the maximum and minimum air temperatures and wind speeds and directions were manually extracted from the hourly values provided by the weather office.

Once the data was collected it was used to predict ice growth and compared to the actual measurements made during the field trips.

Table C.1 provides the meteorological data and ice thickness predictions using Ashton's equation. Ashton's equation is presented in Section C.2. Field measurements of ice thickness were made using a simple ice thickness gauge designed for this study by the author. The gauge shown in Figure C.1, consisted of a graduated wooden pole with a section of flexible metal tape on the lower end. The design allowed the pole to be easily inserted through the narrow (3/4") boreholes. Bouyancy forces on the pole then pushed it up until the metal tape contacted the bottom of the ice sheet. A reading of ice thickness was then taken directly from the graduated pole. The accuracy of this device was confirmed by measuring the ice thickness before cutting ice samples. The measured thicknesses were identical to the ice sample depth dimensions.

Table C.1

Meteorological Data and Ice Thickness Predictions

	AIR TEMPERATURE			SNOW DEPTH (m)	ICE GROWTH (m)	ICE THICKNESS		WIND CONDITIONS	
	max (°C)	min (°C)	average (°C)			predicted (m)	measured (m)	direction 10	velocity knots
								STA A	STA D
15-Oct-84	22.9	10.3	16.6		-0.094	0.000			
16-Oct-84	22.6	11.0	16.8		-0.095	0.000			
17-Oct-84	16.8	11.3	14.1		-0.079	0.000			
18-Oct-84	12.8	9.4	11.1		-0.063	0.000			
19-Oct-84	14.9	9.7	12.3		-0.069	0.000			
20-Oct-84	13.2	9.8	11.5		-0.065	0.000			
21-Oct-84	10.9	7.1	9.0		-0.051	0.000			
22-Oct-84	13.3	3.6	8.5		-0.048	0.000			
23-Oct-84	10.0	6.6	8.3		-0.047	0.000			
24-Oct-84	9.6	6.5	8.1		-0.045	0.000			
25-Oct-84	11.2	7.3	9.3		-0.052	0.000			
26-Oct-84	9.0	6.2	7.6		-0.043	0.000			
27-Oct-84	16.9	8.6	12.8		-0.072	0.000			
28-Oct-84	17.3	6.7	12.0		-0.068	0.000			
29-Oct-84	9.2	2.6	5.9		-0.033	0.000			
30-Oct-84	14.2	2.3	8.3		-0.047	0.000			
31-Oct-84	4.2	-2.9	0.7		-0.004	0.000			
01-Nov-84 *	13.9	4.2	9.1		-0.051	0.000	0.000	0.000	
02-Nov-84	3.7	-1.4	1.2		-0.006	0.000			
03-Nov-84	5.6	-1.4	2.1		-0.012	0.000			
04-Nov-84	9.7	3.2	6.5		-0.036	0.000			
05-Nov-84	9.9	3.7	6.8		-0.038	0.000			
06-Nov-84	2.7	-4.2	-0.8		0.004	0.004			
07-Nov-84	4.7	-4.6	0.1		.000	0.004			
08-Nov-84	7.3	1.1	4.2		-0.023	0.000			
09-Nov-84	10.4	5.1	7.8		-0.044	0.000			
10-Nov-84	9.5	0.6	5.1		-0.029	0.000			
11-Nov-84	0.5	-3.2	-1.4		0.008	0.008			
12-Nov-84	-0.6	-4.1	-2.4		0.012	0.020			
13-Nov-84	3.8	-6.2	-1.2		0.006	0.026			
14-Nov-84 *	5.7	-5.9	-0.1		.000	0.026	0.000	0.000	
15-Nov-84	6.9	2.5	4.7		-0.022	0.005			
16-Nov-84	5.4	-1.0	2.2		-0.012	0.000			
17-Nov-84	1.1	-5.9	-2.4		0.014	0.014			
18-Nov-84	0.7	-8.3	-3.8		0.019	0.033			
19-Nov-84	-3.4	-9.3	-6.4		0.028	0.060			
20-Nov-84	-3.2	-7.6	-5.4		0.020	0.080			
21-Nov-84 *	-3.3	-8.8	-6.1		0.020	0.100	0.000	0.000	
22-Nov-84	2.4	-8.4	-3.0		0.009	0.109			
23-Nov-84	3.3	1.4	2.4		-0.007	0.102			
24-Nov-84	5.8	2.6	4.2		-0.012	0.090			
25-Nov-84	5.7	1.2	3.5		-0.011	0.079			
26-Nov-84	12.0	2.1	7.1		-0.023	0.056			
27-Nov-84	13.8	8.2	11.0		-0.041	0.014			
28-Nov-84	13.3	4.0	8.7		-0.043	0.000			
29-Nov-84	4.1	3.0	3.6		-0.020	0.000			
30-Nov-84	5.1	3.1	4.1		-0.023	0.000			
01-Dec-84	4.1	-1.8	1.2		-0.006	0.000			
02-Dec-84	1.1	-2.9	-0.9		0.005	0.005			
03-Dec-84	2.9	-1.3	0.8		-0.004	0.001			
04-Dec-84	0.2	-7.1	-3.5		0.019	0.020			calm

Table C.1 (cont)

	AIR TEMPERATURE			SNOW DEPTH (m)	ICE GROWTH (m)	ICE THICKNESS		WIND CONDITIONS	
	max (°C)	min (°C)	average (°C)			predicted (m)	measured (m)	direction 10	velocity knots
							STA A	STA D	
05-Dec-84	-0.2	-8.1	-4.2		0.020	0.040			calm
06-Dec-84	-2.1	-16.9	-9.5		0.040	0.080			10 to 14 5.00
07-Dec-84	-1.2	-20.8	-11.0		0.036	0.116			11 to 34 3 to 7
08-Dec-84	3.7	0.7	2.2		-0.006	0.110			20 to 27 9 to 13
09-Dec-84	4.2	-1.9	1.2		-0.003	0.106			calm
10-Dec-84	4.3	2.0	3.2		-0.009	0.097			calm
11-Dec-84	4.0	2.0	3.0		-0.009	0.088			
12-Dec-84 *	4.2	2.6	3.4	0.005	-0.009	0.080	0.040	NA	
13-Dec-84	3.2	-10.7	-3.8	0.005	0.010	0.090			
14-Dec-84	-5.7	-11.1	-8.4	0.005	0.022	0.111			
15-Dec-84	0.5	-5.9	-2.7	0.005	0.006	0.117			
16-Dec-84	9.4	1.3	5.4	0.005	-0.012	0.105			
17-Dec-84	8.0	-5.2	1.4	0.005	-0.003	0.102			
18-Dec-84	-2.3	-6.5	-4.4	0.005	0.011	0.113			
19-Dec-84	-1.0	-4.7	-2.9	0.005	0.007	0.119			
20-Dec-84	-1.1	-10.3	-5.7	0.005	0.013	0.132			
21-Dec-84	-4.6	-12.4	-8.5	0.005	0.019	0.151			
22-Dec-84	2.7	-6.2	-1.8	0.005	0.004	0.154			
23-Dec-84	-5.3	-9.6	-7.5	0.005	0.015	0.170			
24-Dec-84	-5.4	-15.1	-10.3	0.005	0.020	0.189			
25-Dec-84	-5.6	-23.1	-14.4	0.005	0.026	0.216			
26-Dec-84	-10.1	-20.2	-15.2	0.005	0.026	0.241			
27-Dec-84	-12.2	-17.8	-15.0	0.005	0.024	0.265			
28-Dec-84 *	3.3	-11.9	-4.3	0.005	0.006	0.272	0.267	0.419	
29-Dec-84	4.1	-11.9	-3.9	0.005	0.006	0.277			
30-Dec-84	-9.8	-17.7	-13.8	0.005	0.020	0.297			
31-Dec-84	-8.5	-11.4	-10.0	0.005	0.014	0.311			
01-Jan-85	-16.0	-17.0	-16.5	0.060	0.011	0.322			
02-Jan-85	-10.3	-16.7	-13.5	0.060	0.009	0.331			
03-Jan-85	-10.9	-17.8	-14.4	0.060	0.009	0.340			
04-Jan-85	-5.7	-19.8	-12.8	0.060	0.008	0.348			
05-Jan-85	-1.5	-7.7	-4.6	0.060	0.003	0.351			
06-Jan-85	-9.2	-17.2	-13.2	0.060	0.008	0.360			
07-Jan-85	-10.2	-17.7	-14.0	0.070	0.008	0.368			
08-Jan-85	-12.7	-16.7	-14.7	0.070	0.008	0.376			
09-Jan-85	-15.0	-24.8	-19.9	0.070	0.011	0.387			
10-Jan-85	-11.9	-26.1	-19.0	0.070	0.011	0.398			
11-Jan-85	-14.1	-22.7	-18.4	0.070	0.010	0.408			
12-Jan-85	-8.3	-17.8	-13.1	0.070	0.007	0.415			
13-Jan-85	-1.3	-8.4	-4.9	0.080	0.002	0.418			
14-Jan-85	-1.6	-17.7	-9.7	0.080	0.005	0.423			
15-Jan-85	-19.5	-26.2	-22.9	0.080	0.012	0.434			
16-Jan-85	-12.8	-27.0	-19.9	0.080	0.010	0.444			
17-Jan-85	-10.0	-12.8	-11.4	0.080	0.006	0.450			
18-Jan-85	-7.7	-12.0	-9.9	0.080	0.005	0.455			
19-Jan-85	-13.7	-22.9	-18.3	0.090	0.008	0.463			
20-Jan-85	-20.1	-23.9	-22.0	0.090	0.010	0.473			
21-Jan-85	-11.9	-30.4	-21.2	0.090	0.010	0.483			
22-Jan-85	-7.2	-13.9	-10.6	0.090	0.005	0.488			
23-Jan-85	-7.4	-11.7	-9.6	0.090	0.004	0.492			
24-Jan-85	-4.1	-10.9	-7.5	0.090	0.003	0.495			
25-Jan-85 *	-6.1	-14.1	-10.1	0.100	0.004	0.500	0.470	0.670	
26-Jan-85	-10.8	-23.2	-17.0	0.100	0.007	0.507			
27-Jan-85	-3.4	-11.3	-7.4	0.100	0.003	0.510			
28-Jan-85	-5.9	-23.0	-14.5	0.100	0.006	0.516			
29-Jan-85	-11.3	-28.8	-20.1	0.100	0.008	0.524			

	AIR TEMPERATURE			SNOW DEPTH (m)	ICE GROWTH (m)	ICE THICKNESS		WIND CONDITIONS	
	max	min	average			predicted	measured	direction	velocity
	(°C)	(°C)	(°C)			(m)	(m)	10	knots
								STA A	STA D
30-Jan-85	-3.8	-16.4	-10.1	0.100	0.004	0.528			
31-Jan-85	-7.1	-10.9	-9.0	0.100	0.004	0.532			
01-Feb-85	-6.9	-18.1	-12.5	0.095	0.005	0.537			
02-Feb-85	-15.3	-25.8	-20.6	0.095	0.009	0.546			
03-Feb-85	-7.9	-19.1	-13.5	0.095	0.006	0.552			
04-Feb-85	-7.4	-22.9	-15.2	0.095	0.006	0.558			
05-Feb-85	-9.3	-20.3	-14.8	0.095	0.006	0.564			
06-Feb-85	-8.1	-16.0	-12.1	0.095	0.005	0.569			
07-Feb-85	-13.9	-23.8	-18.9	0.095	0.008	0.577			
08-Feb-85	-13.4	-20.0	-16.7	0.095	0.007	0.584			
09-Feb-85	-7.1	-14.8	-11.0	0.095	0.004	0.588			
10-Feb-85	-3.5	-12.8	-8.2	0.095	0.003	0.592			
11-Feb-85	1.6	-12.8	-5.6	0.095	0.002	0.594			
12-Feb-85	4.2	-2.4	0.9	0.095	.000	0.594			
13-Feb-85	4.1	-2.9	0.6	0.095	.000	0.593			
14-Feb-85	-3.1	-12.7	-7.9	0.095	0.003	0.597			
15-Feb-85	-12.2	-14.0	-13.1	0.095	0.005	0.602			
16-Feb-85	-3.9	-16.5	-10.2	0.095	0.004	0.606			
17-Feb-85	-5.2	-8.6	-6.9	0.095	0.003	0.609			
18-Feb-85	-3.6	-15.9	-9.8	0.095	0.004	0.613			
19-Feb-85	-1.7	-8.4	-5.1	0.095	0.002	0.615			
20-Feb-85	-3.6	-11.4	-7.5	0.095	-0.003	0.618			
21-Feb-85	5.1	-5.1	0.0	0.095	0.000	0.618			
22-Feb-85	4.0	2.3	3.2	0.095	-0.001	0.616			
23-Feb-85	4.5	2.1	3.3	0.095	-0.001	0.615			
24-Feb-85	2.5	-2.8	-0.1	0.095	.000	0.615			
25-Feb-85	-0.4	-11.4	-5.9	0.095	0.002	0.618			
26-Feb-85	2.6	-0.4	1.1	0.095	.000	0.617			
27-Feb-85	1.6	-15.9	-7.2	0.095	0.003	0.620			
28-Feb-85 *	3.1	-16.5	-6.7	0.095	0.003	0.623	0.660	0.840	
01-Mar-85	3.50	1.10	2.3	0.10	-0.001	0.622			
02-Mar-85	1.80	-9.20	-3.7	0.10	0.001	0.623			
03-Mar-85	-8.50	-16.70	-12.6	0.10	0.005	0.628			
04-Mar-85	-11.90	-15.40	-13.7	0.10	0.005	0.633			
05-Mar-85	-8.10	-12.60	-10.4	0.10	0.004	0.637			
06-Mar-85	-2.20	-21.10	-11.7	0.10	0.004	0.642			
07-Mar-85	-0.10	-7.80	-4.0	0.10	0.002	0.643			
08-Mar-85	3.90	-1.10	1.4	0.10	-0.001	0.643			
09-Mar-85	1.70	-11.10	-4.7	0.10	0.002	0.645			
10-Mar-85	8.30	-6.30	1.0	0.10	.000	0.644			
11-Mar-85	6.30	-1.30	2.5	0.10	-0.001	0.643			
12-Mar-85	4.30	-1.20	1.6	0.10	-0.001	0.643			
13-Mar-85	2.60	-5.50	-1.5	0.10	0.001	0.643			
14-Mar-85	3.30	-3.70	-0.2	0.10	.000	0.643			
15-Mar-85 *	-5.60	-12.40	-9.0	0.10	0.003	0.647	0.77	0.88	
16-Mar-85	-4.60	-13.10	-8.9	0.10	0.003	0.650			
17-Mar-85	-6.00	-12.40	-9.2	0.10	0.004	0.654			
18-Mar-85	-7.70	-22.30	-15.0	0.10	0.006	0.659			
19-Mar-85	4.20	-7.90	-1.9	0.10	0.001	0.660			
20-Mar-85	-0.90	-6.90	-3.9	0.10	0.001	0.662			
21-Mar-85	-1.10	-14.60	-7.9	0.10	0.003	0.664			
22-Mar-85	5.80	-8.40	-1.3	0.10	.000	0.665			
23-Mar-85	7.60	-6.20	0.7	0.10	.000	0.665			
24-Mar-85	1.90	-3.20	-0.7	0.10	.000	0.665			
25-Mar-85	0.60	-8.40	-3.9	0.10	0.001	0.666			
26-Mar-85	5.40	-7.50	-1.1	0.10	.000	0.667			

Table C.1 (con't)

	AIR TEMPERATURE			SNOW DEPTH (m)	ICE GROWTH (m)	ICE THICKNESS		WIND CONDITIONS	
	max	min	average			predicted	measured	direction	velocity
	(°C)	(°C)	(°C)			(m)	(m)	10	knots
							STA A	STA D	
27-Mar-85	11.40	3.10	7.3	0.10	-0.003	0.664			
28-Mar-85	6.70	0.80	3.8	0.10	-0.001	0.663			
29-Mar-85	2.10	-1.70	0.2	0.10	.000	0.663			
30-Mar-85	1.90	-5.70	-1.9	0.10	0.001	0.663			
31-Mar-85	1.90	-3.70	-0.9	0.10	.000	0.664			
01-Apr-85	3.30	-2.30	0.5	0.10	.000	0.663			
02-Apr-85	-0.30	-4.70	-2.5	0.10	0.001	0.664			
03-Apr-85 *	2.50	-4.80	-1.2	0.10	.000	0.665	0.76	0.84	
04-Apr-85	7.30	-6.90	0.2	0.10	.000	0.665			
05-Apr-85	3.90	2.40	3.2	0.09	-0.001	0.664			
06-Apr-85	5.90	-3.60	1.2	0.09	.000	0.663			
07-Apr-85	3.20	-4.10	-0.4	0.08	.000	0.663			
08-Apr-85	-0.50	-5.90	-3.2	0.08	0.001	0.665			
09-Apr-85	-2.80	-11.10	-7.0	0.07	0.003	0.668			
10-Apr-85	2.30	-6.20	-2.0	0.07	0.001	0.669			
11-Apr-85	-0.10	-6.20	-3.2	0.06	0.002	0.670			
12-Apr-85	5.10	-7.80	-1.4	0.06	0.001	0.671			
13-Apr-85	1.60	-2.70	-0.6	0.05	.000	0.671			
14-Apr-85	12.40	-1.20	5.6	0.05	-0.003	0.668			
15-Apr-85	10.20	3.40	6.8	0.04	-0.004	0.664			
16-Apr-85	7.80	-3.90	2.0	0.04	-0.001	0.663			
17-Apr-85	2.70	-7.80	-2.6	0.03	0.002	0.665			
18-Apr-85	4.90	1.80	3.4	0.03	-0.002	0.663			
19-Apr-85	9.30	2.30	5.8	0.02	-0.004	0.659			
20-Apr-85	15.70	4.10	9.9	0.02	-0.007	0.652			
21-Apr-85	17.50	5.80	11.7	0.01	-0.009	0.644			
22-Apr-85	21.60	5.60	13.6	0.01	-0.010	0.634			
23-Apr-85 *	27.9	10.0	19.0	0.00	-0.016	0.618	0.35	0.50	
24-Apr-85	22.6	9.9	16.3	0.00	-0.014	0.603			
25-Apr-85	14.1	4.7	9.4	0.00	-0.008	0.595			
26-Apr-85	10.1	1.5	5.8	0.00	-0.005	0.590			
27-Apr-85	5.7	0.1	2.9	0.00	-0.003	0.587			
28-Apr-85	11.8	1.8	6.8	0.00	-0.006	0.581			
29-Apr-85	10.6	1.0	5.8	0.00	-0.005	0.576			
30-Apr-85 *	16.8	4.9	10.9	0.00	-0.010	0.566	0.00	0.10	
01-May-85 *	16.0	4.7	10.4	0.00	-0.010	0.556	0.00	0.00	

* indicates field trip

FIGURE C.1 ICE DEPTH GAUGE

C.2) Ashton's Equation (Prediction of ice thickness)

A method of predicting changes in lake ice thickness was developed by Ashton (1980) using simple heat transfer analyses. Using this method it is possible to predict the change in ice thickness by inputting snow depth, thickness of the ice at the beginning of the time considered, and average air temperature. Several other constants are also used, including the heat of fusion of ice, the density of freshwater ice, and the thermal conductivity of pure ice and snow. A heat transfer coefficient that depends on wind speed can also be used, however, it is generally sufficient to use a constant which is representative of the average heat transfer due to wind over a lake ice sheet. Ashton's equation is presented below:

PREDICTION OF LAKE ICE THICKENING

George D. Ashton

21 January 1980

This describes a method to predict the daily thickening of lake ice, and is based on a simple heat transfer analysis. Calculations are most convenient using the metric system. An example calculation follows.

The formula is

$$\Delta\eta_i = \frac{\Delta t}{\rho_i \lambda} \left[\frac{T_m - T_a}{\frac{\eta_i}{k_i} + \frac{\eta_s}{k_s} + \frac{1}{h_{ia}}} \right]$$

where

$\Delta\eta_i$ is the increment of thickening over an increment of time Δt . For

1 day, $\Delta t = 86,400$ seconds.

ρ_i is the density of fresh water ice. In all calculations $\rho_i = 916 \text{ kg m}^{-3}$.

λ is the heat of fusion of ice. In all calculations, $\lambda = 3.34 \times 10^5 \text{ J kg}^{-1}$.

T_m is the melting point of ice. $T_m = 0^\circ\text{C}$

η_i is the thickness of the ice at the beginning of the time considered.

η_s is the snow thickness.

T_a is the average air temperature. Generally the daily average of maximum and minimum is used, expressed in degrees Celsius.

k_i is the thermal conductivity of pure ice. In all calculations use

$k_i = 2.24 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$.

k_s is the thermal conductivity of the snow which depends on the snow

density. For typical windblown snow use $0.25 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$.

A prediction of the ice thickness for North Bay was completed using the above equation. Figure C.2 reveals an excellent relationship between the theoretical and actual ice thickness for the marina ice. The lake ice shows a consistently higher thickness than predicted. The frazil slush located in the water column from December 6th on would cause this discrepancy. By cooling the water column to near freezing, the frazil slush creates faster ice growth. There is less heat transfer required to cause the frazil to congeal to the bottom of the ice sheet than would be required to create columnar ice from freshwater. Therefore, the lake ice grows faster than predicted theoretically.

FIGURE C.2 LAKE NIPISSING ICE THICKNESS (measured and predicted)

APPENDIX D

CRYSTALLOGRAPHY - METHOD OF SAMPLE PREPARATION AND EQUIPMENT USED

All of the crystallographic work completed for this study was done at the National Research Council of Canada on Montreal Road in Ottawa. The division of Building Research has a cold room facility which contains all of the necessary equipment for preparing thin sections, determining crystal orientations, and for photographing the samples under polarized light.

The ice samples were transported to Ottawa in coolers after being placed in plastic bags and surrounded by snow to prevent their deterioration. Each ice sample was cut into vertical and horizontal sections as required to define the various ice types present and crystal orientations. The sample was then placed on a glass plate (while retaining sample orientation) and microtomed. Microtoming involves gradually shaving the sample until a very smooth and thin sample (approx 1mm) is achieved. All of the crystallographic work was completed in an ice lab at -10 degrees Celcius as recommended by Ramseier (1985) in his description of how to prepare samples and evaluate the results.

A number of horizontal and vertical thin sections were prepared from each ice column. Several thin sections were required to complete each vertical profile due to the limits imposed on the thin section size by the microtome. After each thin section was prepared, it was placed under a combination of polarized and transmitted light to distinguish the individual crystals; the sample was then photographed. The results of the crystallographic analyses are presented in Chapter 4 entitled "Ice Characteristics".

The End