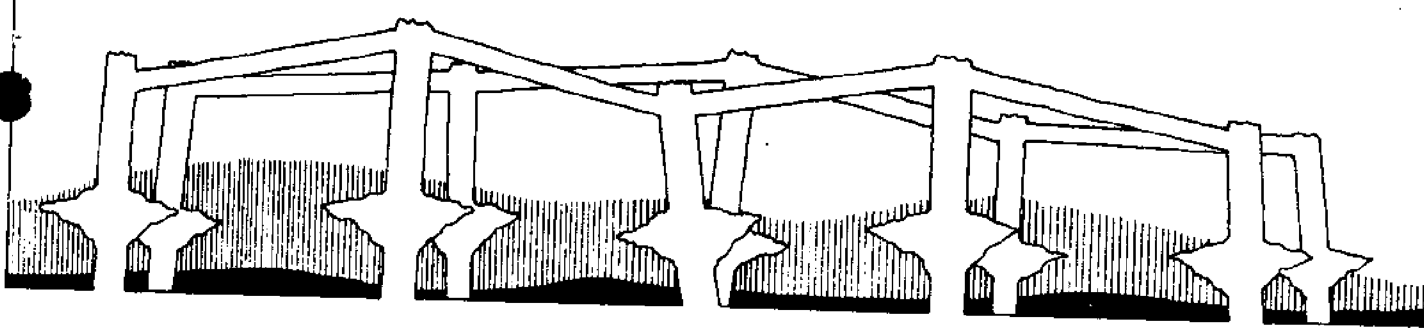
MICHIGAN SEA GRANT PROGRAM - ADVISORY SERVICE -

ICE UPLIFT ON PILES

ON THE UPPER GREAT LAKES



MARCH 1980

MICHU-SG-506

MICHU-SG-80-506
Extension File
Code No. 3636

ICE UPLIFT ON PILES:

PROGRESS REPORT OF WATER TEMPERATURE AND ICE-PILE ADHESION INVESTIGATIONS ON THE UPPER GREAT LAKES

by

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February, 1980

Michigan Sea Grant Program, a Cooperative Effort of
the University of Michigan and Michigan State University

ACKNOWLEDGEMENTS

The information in this report was collected by and under the direction of James E. Muschell, BSCE, PE, F.ASCE, with the field study sponsored by the Michigan Waterways Commission, Michigan Department of Natural Resources. Technical guidance was provided by Raymond G. Lawrence, Chief Planner and Coordinator, Michigan Waterways Commission. The data was analyzed and the report compiled by Techmedia, Inc., sponsored by the Michigan Sea Grant Program, with review by James E. Muschell, Raymond G. Lawrence and Keith E. Wilson, Chief, Michigan Waterways Commission.

The findings reported herein are neither exhaustive nor conclusive but add to the field of knowledge of ice action in small craft harbors. This publication is intended to assist designers, developers and operators in improving the art and science of construction and maintenance of small craft harbors in the upper Great Lakes region.

The printing of these results has been funded by the Marine Advisory Service of the Michigan Sea Grant Program through cooperation of the National Oceanic and Atmospheric Administration, Office of Sea Grant, Grant No. 04-M01-134, and by the Michigan Legislature.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The Michigan Waterways Commission has been concerned for many years with the damage caused by ice in recreational boating harbors in the Michigan Great Lakes area. In an effort to solve some of the annual ice damage problems, the Commission has been conducting field research in several locations to understand more precisely why some structures fail and others do not.

This is an interim report of an ongoing research project. Although much more study must be done, some of the findings are useful now in reducing ice damage. The research project is not complete. A number of problems in marine design, development and operation remain to be explored. This report summarizes information collected through the research effort to date and offers some guidance to developers and operators of small craft harbors in the Great Lakes region.

SUMMARY OF ICE CHARACTERISTICS

In order to better understand the significance of this research and how it may be applied, it is of value to briefly review some of the characteristics of ice as found in recent work by other researchers.

Ice in most small craft harbors is quite stable horizontally once the winter ice cover has been established. It is, however, subject to powerful vertical forces. Reaction to these vertical forces is highly varied because of the variable nature of ice.

Freshwater ice has been classified into three basic forms by Michel and Ramseier (1969): primary ice, secondary ice and snow ice. Each of these classes is then further divided depending on how the ice was formed and the orientation of its individual crystals.

Primary ice is the uppermost layer. It may form on calm water as a thin skim only a few tenths of a millimeter, about a hundredth of an inch, thick and grow horizontally. It may also develop as a result of snow with the snow flakes serving as nuclei for ice growth. The snow slush then congeals to become a part of the primary ice. A third form of primary ice begins as frazil slush which, as with snow slush, congeals to form the ice cover.

Primary ice develops in supercooled water. With the air temperature significantly below freezing, a thin layer of water on the surface will transfer heat to the air faster than the heat can be replaced from water below. The temperature of this water layer may then fall a few hundredths of a degree below the freezing point. A foreign particle such as a snowflake, a suspended solid particle or an air bubble may then trigger the freezing process.

Secondary ice forms below the primary ice and consists of two major forms, columnar and congealed frazil slush. Columnar ice grows downward from the cover of primary ice as heat is transferred from the water to the ice sheet to the air. Turbulent water does not allow this columnar ice growth but creates frazil ice instead. Frazil ice is most simply described as a group of ice crystals formed in supercooled turbulent water; it is a loose agglomerate of crystals which would have formed an ice skim in calm water and it requires more supercooling than does skim ice. Secondary ice may be all columnar, all frazil (congealed) or layers of each.

Snow ice is the third class. It forms on top of the primary ice. Rain, meltwater or water forced up from below the primary ice cover may change the snow layer into snow ice.

Generally, columnar ice is the strongest form but its strength may vary considerably, especially depending on the amount of air trapped in the ice. As water is solidifying, air absorbed in the water is rejected. During slow ice growth, the rejection of air is thorough and the ice will be transparent. When growth is fast, air bubbles will be trapped in the ice. Transparent ice is often called "black ice." Air entrapment results in "white ice." Snow ice is usually white ice but frazil ice may be either "white" or transparent.

Ice below the topmost layer grows more slowly as the ice thickens. Ice serves as a barrier to the transfer of heat from underlying water to the atmosphere. A thin layer of ice allows a fairly rapid flow of heat through it but as the ice thickens the flow is retarded; as ice thickens it becomes a more effective insulator. Snow on top of ice is a very effective insulator and, if of low density and sufficiently deep, can stop ice growth.

Lack of sufficiently correlated information has forced engineers to apply intuition and experience as well as engineering principles in dealing with ice. Ice may be brittle or ductile or both; its internal structure is highly variable; its behavior changes with temperature, type of load, direction of load, strain rate and stress level; and, laboratory test data do not necessarily reflect field conditions.

On the Great Lakes, ice loads usually exert the critical stresses on structures in small craft harbors. Because it is so difficult to predict the type of ice which can be anticipated in a particular harbor, most facilities are either over-designed or are subject to regular damage.

The research of Lavrov (1969) is especially valuable as he worked to meet the needs of engineers in his native Russia. Wortley (1977) summed up Lavrov's description of the nature of ice under load quite nicely: "These peculiarities cause ice to be a material which in its totality appears to consist of plastic hinges ..." Lavrov determined that slip within crystals and between crystals was of essential importance in analyzing how ice behaved under load. So many factors affect the slip characteristics of ice that it becomes necessary to deal with averages within broad ranges and to speak of "similar magnitudes."

When ice is subjected to a load, it immediately responds by deforming, first internally then externally. In designing piles for mooring small craft, the concern is with upward rather than with downward forces. Figure 1 illustrates the general form of ice sheet deformation as a rising water level applies a vertical force to a pile which has been firmly frozen into the ice and at the same time been well-anchored in the foundation soil.

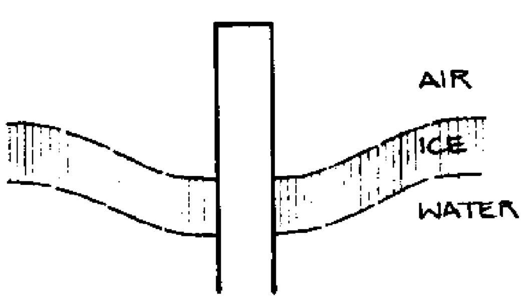

FIGURE 1. - MODEL OF ICE SHEET DEFORMATION AROUND A PILE RESULTING FROM RISING WATER LEVEL.

The first reaction of ice to a load is elastic. A large load applied quickly may cause the ice to rapidly exceed its elastic limits and break. A more moderate load or one applied more slowly will result in creep, a sustained and continuing deformation, which again may end in breakage of the ice. The ice does not break if the load is reduced before strain limits are exceeded. Load reduction commonly occurs from a lowering of the water level or because the pile is pulled out of its foundation.

Expansion and contraction of ice in response to thermal changes also affects the force applied to a pile. Although lateral thrust forces are important in some facilities, in the case of most small craft harbors the force related to the grip of the ice on the pile is usually critical.

As ice is heated it tends to expand. When the ice sheet is fixed so that it cannot expand, stresses within the ice are created. Even if the stress forces were not especially large, they would still develop a "tighter" grip on structures frozen into the ice cover. This affects not only ice-pile uplift tests but also the field application of engineering data.

Compression and tension under load have important effects on ice strength. The crystalline nature of ice allows microscopic cavities filled with air and impurities to exist within what appears to be solid ice. During compression, these physical characteristics change resulting in a more solid structure. The change in physical characteristics of ice under tension weakens the ice structure. On the average, the compressive strength of ice is nine times greater than the tensile strength, with considerable variation according to Lavrov's studies. The difference in these strengths affects the crack development pattern as ice is deflected from a plane by the vertical forces of uplift.

Compressive and tensile strength differences also affect adhesive strength. As ice around a pile is deformed by the vertical force of a rising water level, the upper layer "pinches" more tightly against the pile. This force may be much greater than the relaxation at the lower layer resulting from tension tending to pull the ice away from the pile.

The peculiar nature of ice with its characteristics changing continuously but inconsistently during formation and under load conditions does not allow application of normal engineering principles. The current research is being conducted to add knowledge directly useful in solving ice-damage problems.

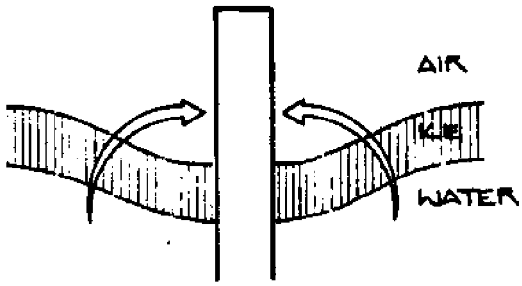

FIGURE 2A. – MODEL OF ICE SHEET DEFORMATION AROUND A PILE RESULTING FROM RISING WATER LEVEL AND CAUSING A COMPRESSIVE "PINCHING" FORCE AT THE UPPER LAYER OF ICE.

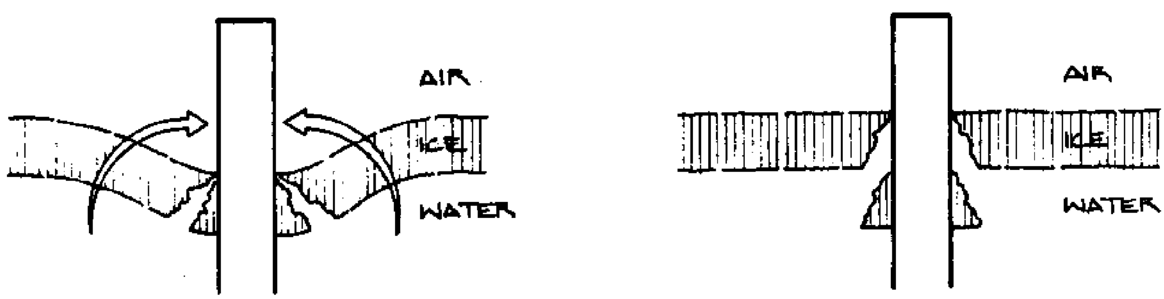

FIGURE 2B. – MODEL OF COMMON BREAKAGE PATTERN RESULTING FROM RISING WATER LEVEL. ICE SHEET DEFORMATION FORCES HAVE EXCEEDED THE COHESIVE FORCE WHICH NORMALLY KEEPS THE ICE SHEET INTACT.

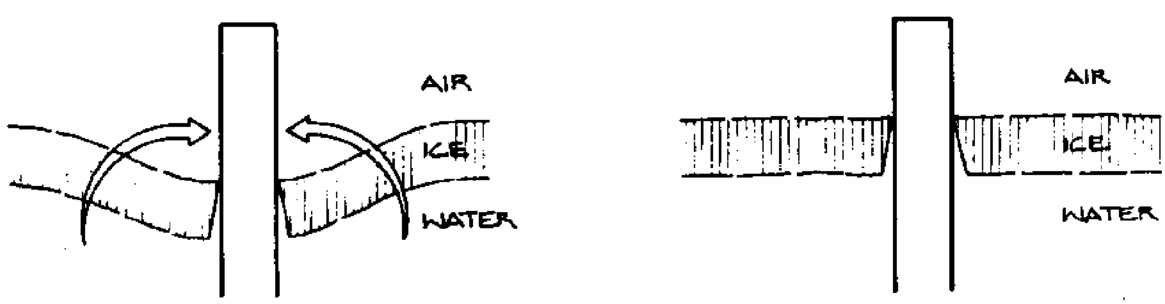

FIGURE 2C. – MODEL OF ASSUMED BREAKAGE PATTERN RESULTING FROM RISING WATER LEVEL WHEN ICE SHEET DEFORMATION FORCES HAVE EXCEEDED THE ADHESIVE FORCE AT THE ICE-PILE INTERFACE.

RESEARCH PROCEDURE

Designers, developers and operators of small craft harbors and marinas in the Great Lakes region have been especially concerned with damage to structures caused by vertical ice forces. Changing levels of water beneath the ice sheet create uplift loads which often cause more damage than lateral forces from expanding or moving ice.

Experience has shown that ice does not act on structures in a consistent way. Neither does it always act as theory suggests it should. It is valuable to examine assumptions which form the basis for ice behavior theory in order to revise the theory to fit the facts. However, it is of more immediate value to determine, through field testing, loading values for design purposes which may contribute to reducing ice damage to harbor structures. Practical need of marina engineers, developers and operators stimulated the current research.

Water temperature, ice thickness, ice density and ice-pile adhesion were the measurements considered of special value in attempting to establish realistic design and construction criteria.

Eight locations were selected to represent typically severe problem facilities in the upper Great Lakes area. Situated between 45^{o} and 48^{o} North Latitude, the locations were:

Straits of Mackinac	Rogers City
Mackinaw City	Cross Village
Duncan Bay	Harbor Springs
Hammond Bay	Whitefish Point

Figure 3 is a map of Michigan showing the selected locations.

Field conditions limited the number of tests which could be conducted, but data collected from 1973 to 1979 have not only provided solid information but have also indicated promising directions for researchers and designers to follow.

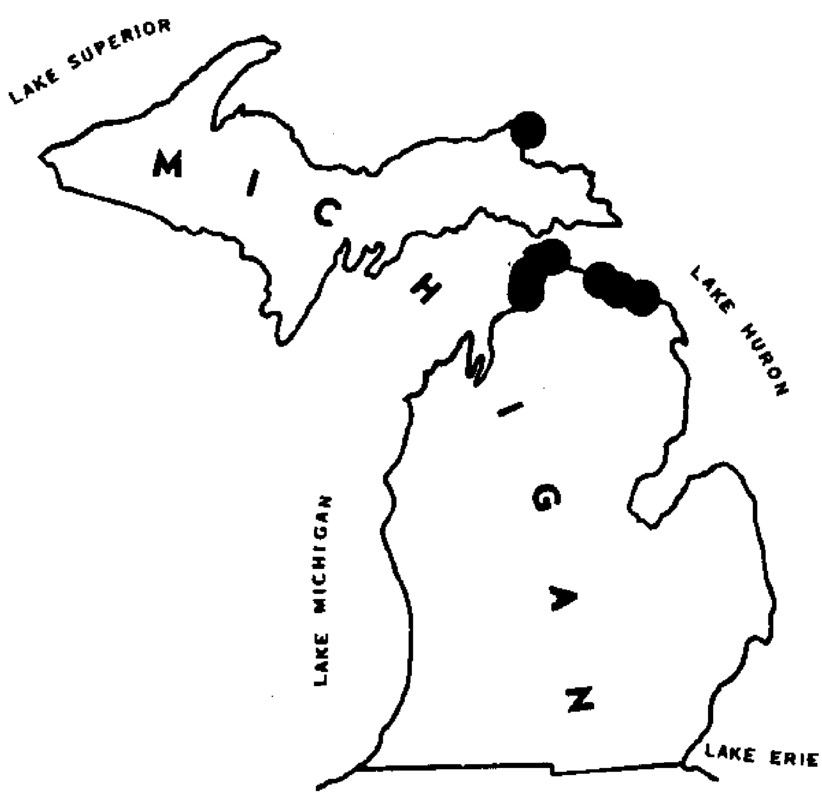

FIGURE 3. LOCATIONS OF TEST SITES.

Experimental Design

Water temperatures have been recorded during this research to depths of 89 feet. A digital temperature indicator and the required heating elements were powered by a portable, gasoline-driven, electrical generator. The digital indicator was calibrated using a mercury calibrating instrument with 0.1°C divisions, traceable to the National Bureau of Standards. The specific equipment used is described in Appendix A. While the recorded temperature values are based on a resolution of 0.1°C, they are relative values which should satisfy most engineering design requirements.

Ice-pile adhesion load failure tests required a specially designed system for load application. Piles were frozen into the ice and subsequently pulled to determine loads and loading rates necessary to free the pile from the ice.

Early tests were performed to measure direct shear load and adhesion values. Hydraulic rams were used to apply loads to the pile and the ice at the interface of the two as shown in Figure 4.

Later and current testing more nearly simulate forces acting on the pile in the field by placing the bearing plates at a distance from the pile as shown in Figure 5. Measurements from both kinds of loading systems are necessary for effective engineering design. The specific equipment used is described in Appendix B.

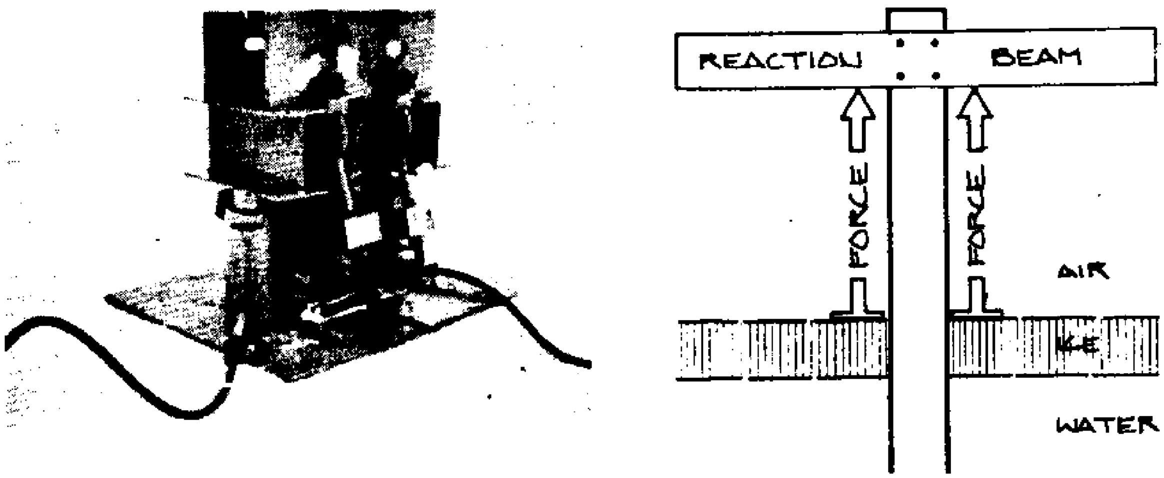

FIGURE 4. – HYDRAULIC LOAD-TEST DEVICE, DIRECT SHEAR TEST CONFIGURATION.

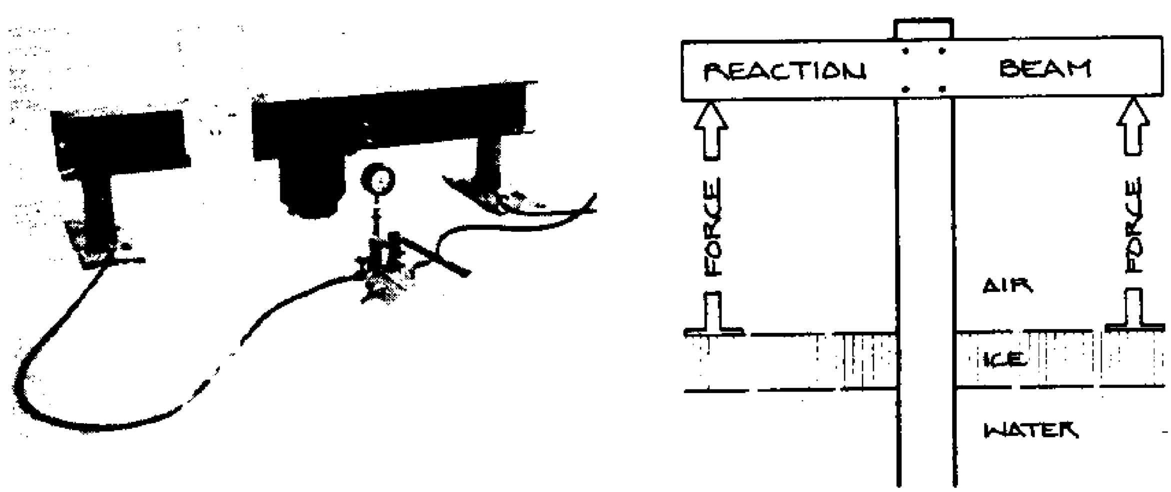

FIGURE 5. – HYDRAULIC LOAD-TEST DEVICE, FLEXIBLE SHEET TEST CONFIGURATION.

Several different piles were used in the pull-out tests:

H-section	HP8x36	HP10x42
Pipe piles	8" O.D.	8.25" O.D.

The pipe piles received several different treatments: top open to the ambient air, air-filled with top sealed from the ambient air, and filled with insulating material such as Zonolite or Vermiculite and sealed. Some of the filled and sealed pipes were painted black, some green and some were left unpainted. In the most recent tests, some of the pipe piles were coated with epoxy resin.

WATER AND ICE TEMPERATURES

A customary assumption is that the temperature at the bottom of large bodies of water will not usually cool below 4°C, the temperature at which water is most dense. Further, it is ordinarily assumed that there will be a decreasing temperature gradient from 4°C at the bottom to 0°C at the interface of the ice cover and the water. Measurements in this research have not supported these assumptions. In fact, there has been a surprising uniformity of temperatures between the ice cover and the lake bottom. Figure 6 is a model of average conditions encountered during the test period, 1973-1979, using the data from 47 samples.

As expected, water at the interface with the bottom was warmest. The highest temperature recorded for bottom water was 1.7°C, at a total water depth of four feet. At harbor depths of eight to nine feet, the bottom water temperature averaged 0.1°C, as shown in Figure 6. Two tests in the Straits of Mackinac found a bottom water temperature of 0.0°C at 45 feet and -0.1°C at 89 feet.

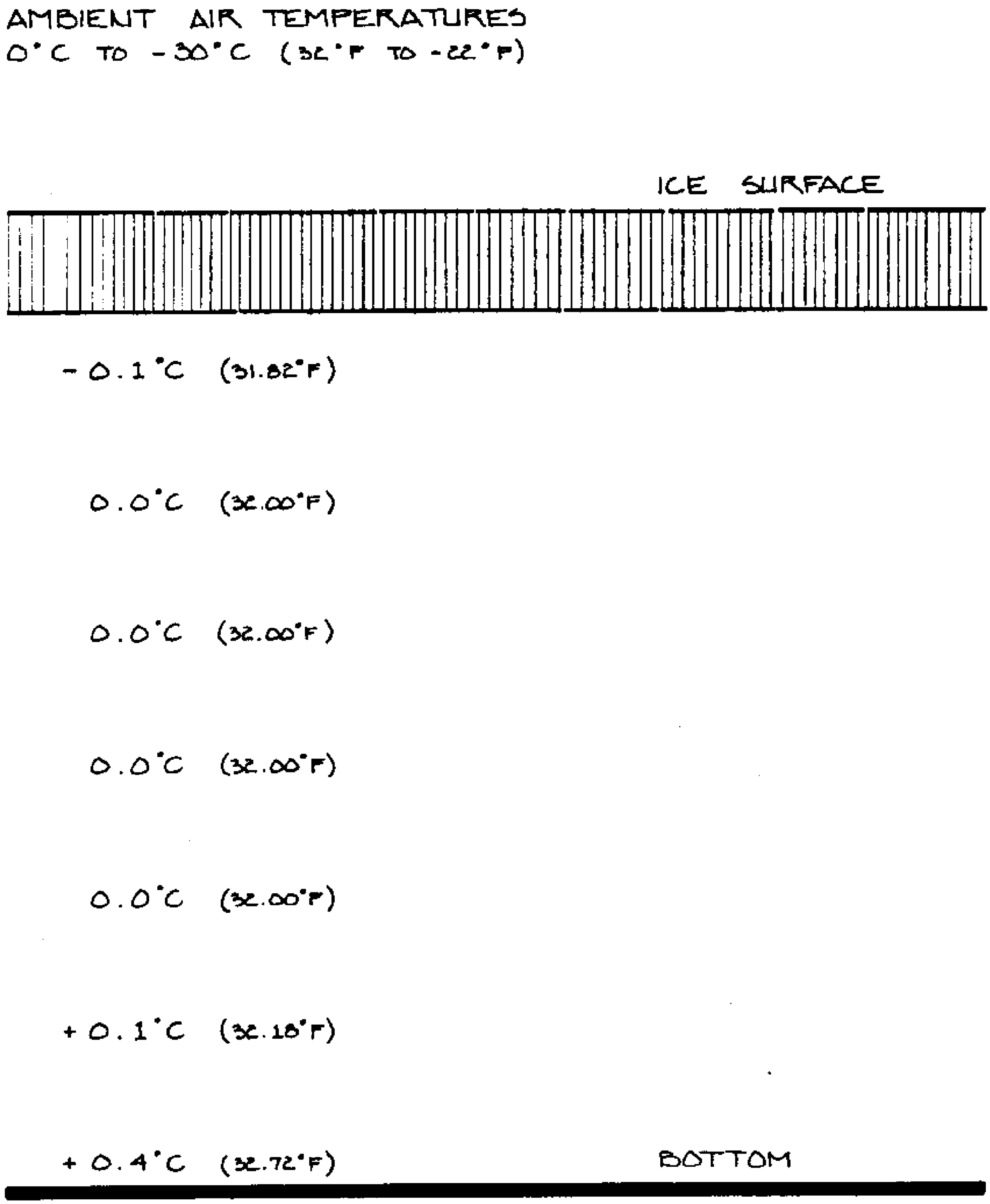

FIGURE 6. – TYPICAL GREAT LAKES WINTER WATER TEMPERATURES FOR HARBOR DEPTHS OF 4 TO 9 FEET - AVERAGE OF 47 SAMPLES

The special significance of this temperature uniformity near $0^{\circ}C$ is that there may be very little or no thermal reserve in the water to help suppress ice formation.

In several instances it was found that water two to four feet below the bottom surface of the ice sheet, in six feet of water, was supercooled to $-0.2^{\circ}C$ to $-0.3^{\circ}C$. This phenomenon was not limited to shallow water. One test in the Straits of Mackinac found a uniform temperature of $-0.1^{\circ}C$ from the ice to the bottom, 89 feet below the surface.

Ice temperatures usually showed a gradient, although not necessarily from water temperature to ambient air temperature. The most severe ice temperature at depth was in a 15 inch thick ice cover with $-6.9^{\circ}C$ at one foot, $-6.5^{\circ}C$ at six inches and an air temperature of $-14.7^{\circ}C$. An adjacent location, measured one hour later in a 16 inch thick sheet, had a gradient from $-4.4^{\circ}C$ near the bottom of the ice to $-3.7^{\circ}C$ three inches from the top. Often the ice temperature varied only a few tenths of a degree from near-top to near-bottom. The total range of ice temperatures recorded was $+0.1^{\circ}C$ to $-7.7^{\circ}C$.

The data table in Appendix C represents water temperatures recorded at various depths. The data table in Appendix D represents ice temperatures.

The collected data suggests that an ice sheet reflects the immediate history of weather conditions, especially ambient air temperatures. Ice temperatures reduce in response to lowered air temperatures, the reduction progressing downward in the sheet. Increasing air temperatures are followed by increasing ice temperatures with the increases gradually affecting the lower levels. Ice temperature gradients may then show the lowest temperature at the top, the bottom, or toward the middle of the sheet.

As expected, weather-induced temperature changes in thick ice occurred more slowly than in thin ice. Further detailed studies should enable ice temperature predictions from weather data, including temperature gradients, for ice sheets of different thicknesses, with enough accuracy to be helpful for engineering design and operational purposes.

Although Wortley (1977, p. 20) indicates that "attenuation of temperature variation in the interior of an ice sheet is very rapid," the data acquired here suggests that "very rapid" may be too strong a description.

Measured water temperatures of -0.1°C and -0.2°C were common below the ice cover and often extended downward for several feet.

Appendix E shows field-recorded ice temperature ranges for ice of different thicknesses, measured near the top and near the bottom, and includes the ambient temperatures above and below the sheet. The statistical summary of Table 1 shows that, although the ice thickness sampling approaches a normal distribution, the temperatures deviate considerably from the mean. This points up the need for designers to consider the range of conditions which might be encountered rather than relying on averages, even for thick ice covers.

The 1979 data are summarized separately in Table 2 because of the unusual frequency of cone formation along the pile underneath the ice sheet during that season.

Analysis of ice temperatures as they might affect the uplift forces on piles indicated no direct correlation between the two. Three dimensional plotting of ice temperatures, ice thicknesses and ice uplift forces confirm that ice temperature alone is of little value in predicting the uplift force tending to pull a pile out of the harbor bottom. Ice temperature is only a small factor in the grip of ice on the pile.

Table 1. ICE TEMPERATURE RANGE, °C, 1975-1978

Number of Samples = 43	Ice Depth inches	Air Temperature	Ice Temperature		Water Temperature Below Ice
			Near Top	Near Bottom	
Range	7.5 to 29	+21 to -16.4	0.0 to -7.7	+0.1 to -6.7	+0.3 to -0.3
Mean	18.1	- 4.8	- 2.28	- 1.62	- 0.09
Standard Deviation	5.95	5.63	2.07	1.46	0.134

Table 2. ICE TEMPERATURE RANGE, °C, 1979

Number of Samples = 8	Ice Depth inches	Air Temperature	Ice Temperature		Water Temperature Below Ice
			Near Top	Near Bottom	
Range	10 to 18.5	+1.0 to -15.2	-0.1 to -5.9	-0.1 to -6.2	+0.2 to -0.3
Mean	15.0	- 8.7	- 2.0	- 2.6	- 0.12
Standard Deviation	2.46	4.86	1.96	2.22	0.147

ICE DENSITY

Density measurements in this research show dramatically the highly variable structure of an ice sheet. Clear, columnar ice ranged in density from 0.664 gm/ml to 0.998 gm/ml. Dissolved materials, suspended particles and fine air bubbles as well as the crystalline structure contribute to this range of densities, even for ice samples which appear to be the same.

The density of an ice sheet may affect heat transfer rate, thermal expansion and contraction, cracking characteristics, load-bearing capacity, rate of growth and other factors. However, data collected here indicate that density alone has little or no direct effect on ice-pile adhesion or direct-shear strength.

A summary of sample ice densities is presented in Table 3 and shown in Figure 7.

Table 3. SAMPLE ICE DENSITY RANGE (gm/ml)

Number of Samples = 19	Clear Columnar "Black" Ice
Range	0.664 - 0.998
Mean	0.883
Standard Deviation	0.105

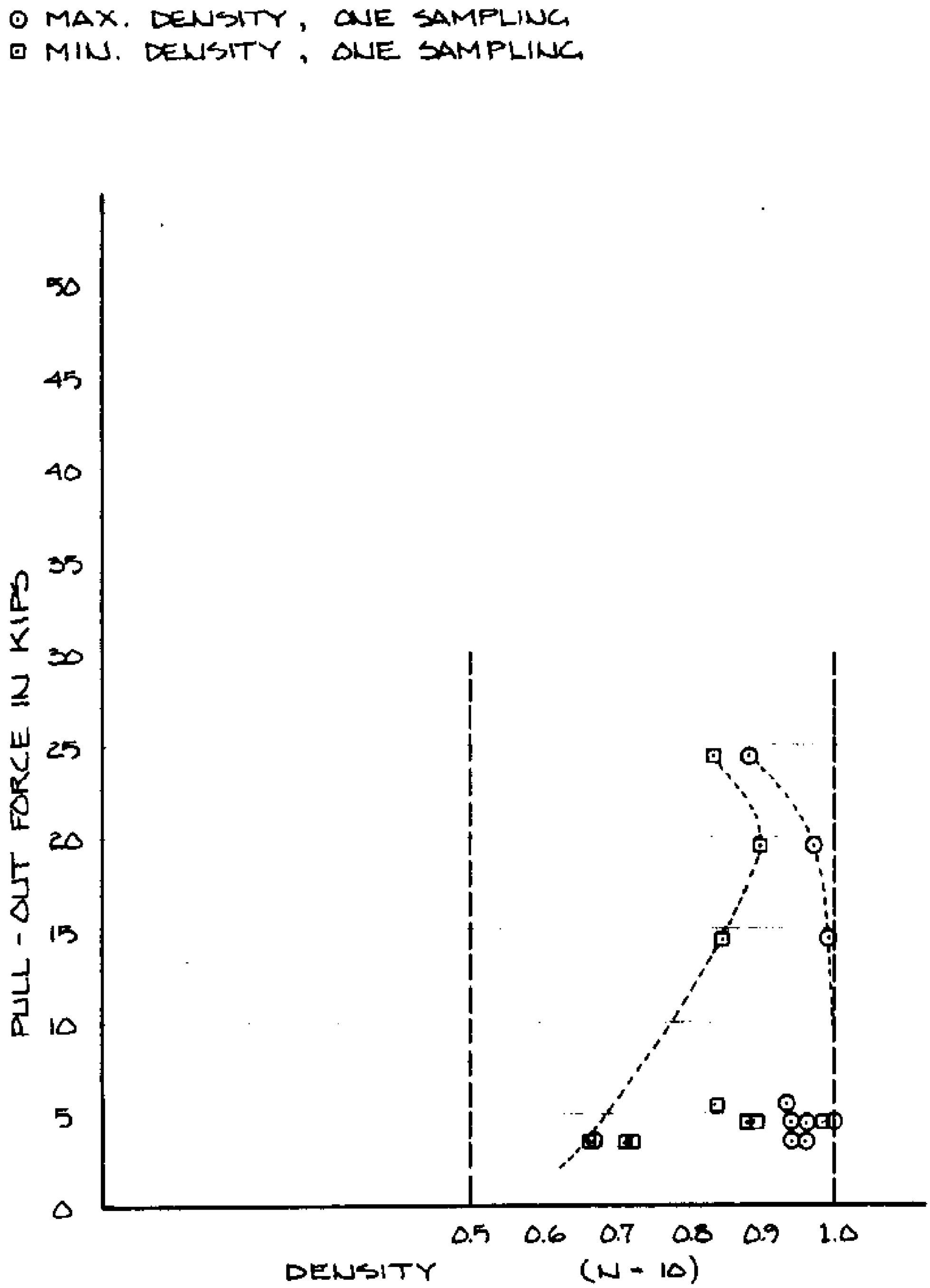

FIGURE 7. – ICE DENSITY AND PULL-OUT FORCE

CONE FORMATION

The ice cover of a lake or harbor does not have the same thickness over its entire surface. Early season freezing along a shore may be offset by melting from solar radiation and from thermal reserve in the soil at the bottom. Wave wash and spray may add to the thickness of the shoreline ice cover. Changing water levels and wave action may drastically alter the shoreline ice.

At varying distances from these boundary effects and after the ice cover has become established for the winter, there is some consistency in harbor-ice thickness. Engineering decisions are often made based on records or assumptions of maximum nominal ice depth and assumptions of consistency in ice thickness. The term "nominal depth" as used in this report refers to the ice thickness in the vicinity of the tests but beyond the ice thickness influence of the piles.

Design decisions may prove to be inaccurate if some consideration is not given to the phenomenon of cone formation around steel piles. Steel piles act to carry heat above the ice, from the water to the air, where the heat is dissipated. This cools the water in contact with the pile, reducing the caloric content and promoting the change of state from water to ice. The result may be the formation of a cone of ice extending downward, along the pile surface, below the bottom of the ice sheet. The cone effectively increases the ice-pile adhesion area. A model subsurface ice cone is illustrated in Figure 8.

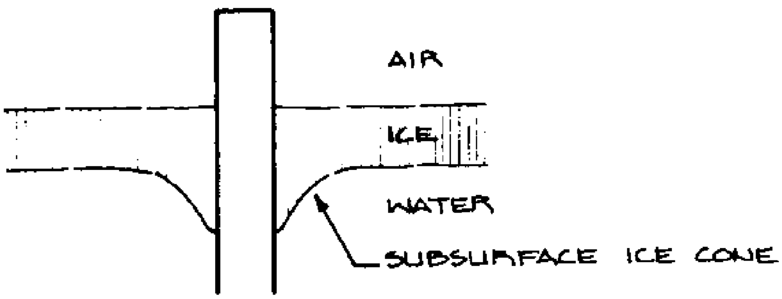

FIGURE 8. – MODEL OF A SUBSURFACE ICE CONE ALONG THE SURFACE OF A STEEL PILE.

Ice-pile adhesion force is usually expressed in psi, pounds per square inch. Using only the nominal ice depth and ignoring the subsurface cone of ice in computations inflates the psi values. Cone formation is, however, difficult to detect or measure before pull-out and unpredictable in its occurrence. As an example of unpredictability, during the 1979 testing season 56 percent of the piles pulled had cones whereas in previous years only 36 percent of the piles had cones, occurring with approximately the same frequency each year.

The effects of additional adhesive strength due to cone formation fall within the range of ice-pile adhesion values without cone formation, as will be seen later. As it is the total force which causes pile uplift, the data tabulated and analyzed in this report combines the adhesive forces into a single expression, pull-out force. This expression is measured in thousands of pounds or KIPS.

ICE-PILE ADHESION

Direct-Shear Load Failure, H Piles

The first stage of field test research used H section piles and measured the direct-shear force required to pull the piles out of the ice. The general configuration of the pull-out device was illustrated in Figure 4, page 12. The bearing plates conformed closely to the H section.

Data summaries are shown in Table 4 for 8 inch piles and in Table 5 for 10 inch piles. The average or mean values showed the ice-pile adhesion to be twice as great for a 10 inch H pile as it was for an 8 inch H pile whether measured in terms of psi or total pull-out force. The range of load failure values was very wide as shown by the standard deviation.

From this data, correlations between ice depth and load failure were found to be of little value for predictive purposes. This was in marked contrast to pipe piles, to be discussed next. Figures 9 and 10 illustrate the relationships between ice depth and pull-out forces from this data. Much more data, including specific comparisons, needs to be collected over a number of winter seasons. The quality of the ice varies considerably from one year to another.

Table 4. LOAD FAILURE MEASUREMENTS, 8" H PILE

Number of Samples = 6	Nominal Depth, inches	Pull-out Force KIPS	Pull-out Force psi
Range	8.5 to 18.5	3.3 to 15.5	3.64 to 21.57
Mean	13.83	6.98	9.18
Standard Deviation	3.01	4.18	6.20

Table 5. LOAD FAILURE MEASUREMENTS, 10" H PILE

Number of Samples = 9	Nominal Depth, inches	Pull-out Force KIPS	Pull-out Force psi
Range	7.5 to 18.0	3.3 to 28.7	5.36 to 49.20
Mean	12.44	15.17	21.30
Standard Deviation	4.01	9.47	15.78

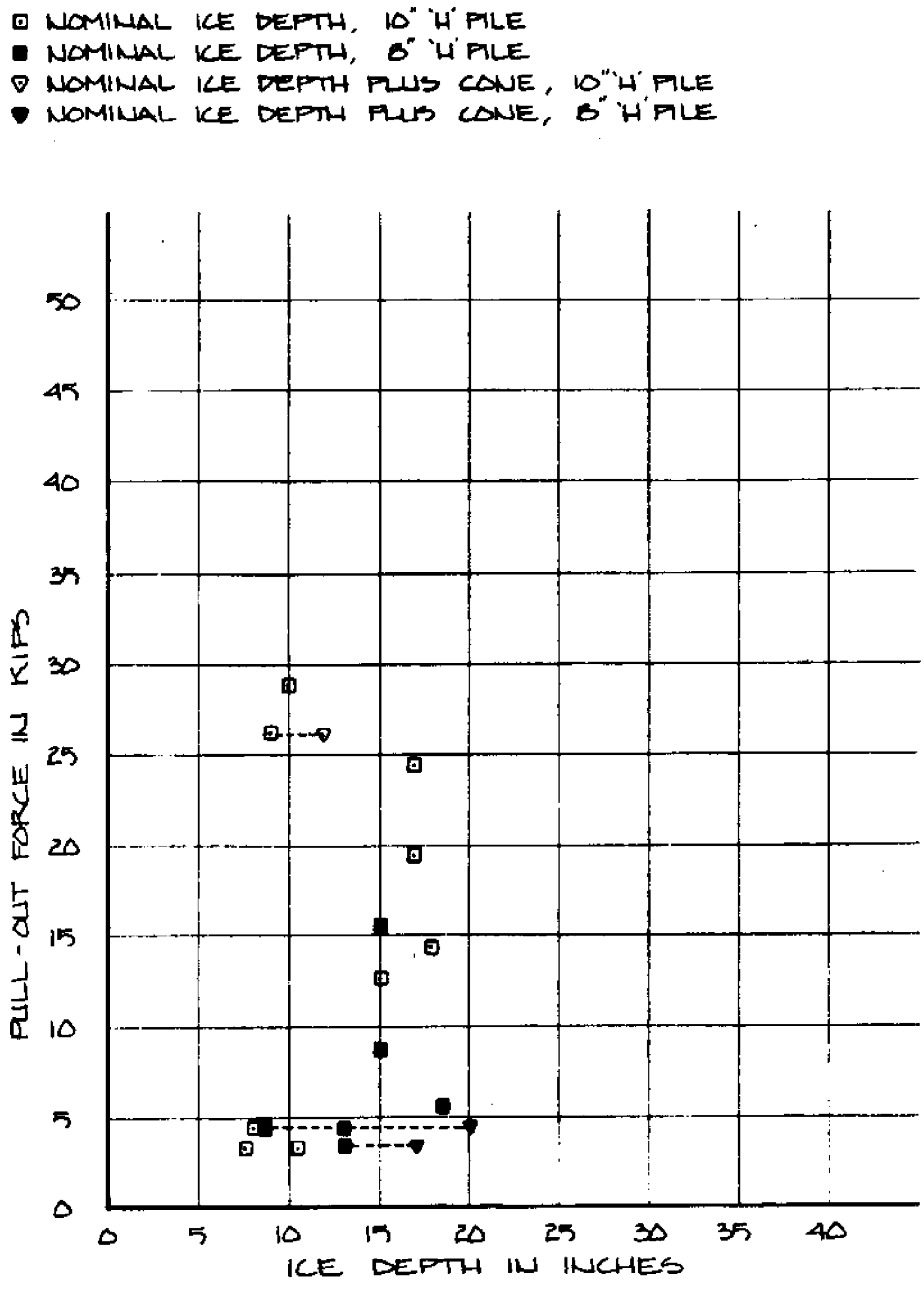

FIGURE 9. – ICE DEPTH AND PULL-OUT FORCE, 'H' PILES – KIPS

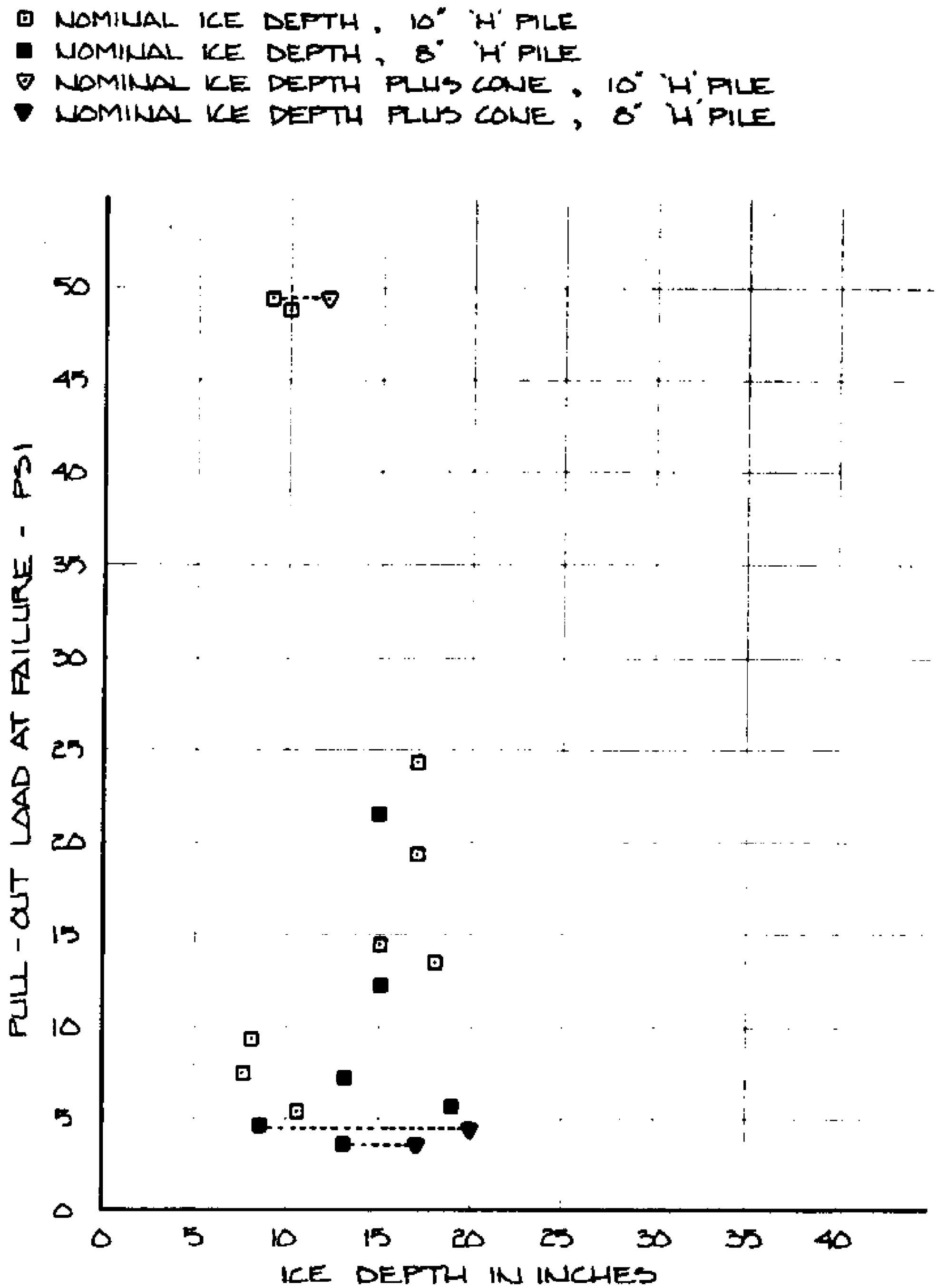

FIGURE 10. - ICE DEPTH AND PULL-OUT FORCE, 'H' PILES - PSI

Direct-Shear Load Failure, Pipe Piles

Second stage testing used pipe piles. It became evident early in the testing procedure that a pipe pile filled with nothing but air was quite different in behavior from a solid pile, such as the H-section, or one filled with some form of insulating material. The air-filled pile acted as a thermo-pile. The free movement of air within the pile permitted a much more rapid transfer of heat between the water surrounding the pile and the ambient air than a solid pile or one filled with insulation. Fillers were used to reduce the thermo-pile effect of open or air-filled-and-sealed pipe piles; the testing procedure was conducted nearly simultaneously on both air-filled and insulation-filled piles.

Again, direct-shear pull-out testing was used with the piles allowed to freeze into the ice cover naturally. Data acquired in this stage suggested that the theoretical calculations previously used in harbor design did not in fact represent real conditions encountered in the field.

The wide range of uplift forces actually measured is represented by specific data points in Figure 11 and Appendix H. It can be seen here that cone formation causes a significant shift in recorded force values with nominal depths resisting pull-out as if they were greater depths. However, the shifts still fall within the tolerances of upper range values of piles without cone formation so that the practical effect is minimal.

Plotting and evaluating statistically the upper and lower values acquired in the testing of air-filled piles, Figure 12, indicated a wide range of values. The lower values for piles filled with insulating material and sealed are shown in Figure 13. (There is insufficient data to determine upper values for the insulated piles.)

The theoretically predicted upper and lower values are plotted in Figure 14. Combining these graphs into Figure 15 suggests fundamental difficulties in applying theoretical principles to actual field conditions for ice sheets. With such major departures from predicted upper values, it is not surprising that ice-jacking has remained a serious problem.

Limited data at this point suggests that insulation-filled pipe piles may offer some distinct advantages over air-filled piles. The filling does not appear to affect cone formation as expected. In the data recorded, 37½ percent of insulation-filled piles formed cones (1975-78) while 35 percent of the air-filled piles formed cones. With both groups, the cones were of comparable depth. 1979 data showed a notable increase in the frequency of cone formation with 56 percent of all piles (N=18) showing cones extending below the nominal ice sheet.

Insulation-filled piles do, on the other hand, show a decided tendency for uplift forces to fall within the lower part of the ice depth versus uplift force value range. Whatever the effect on cone formation, the insulation filling does appear to reduce the ice-pile adhesive strength.

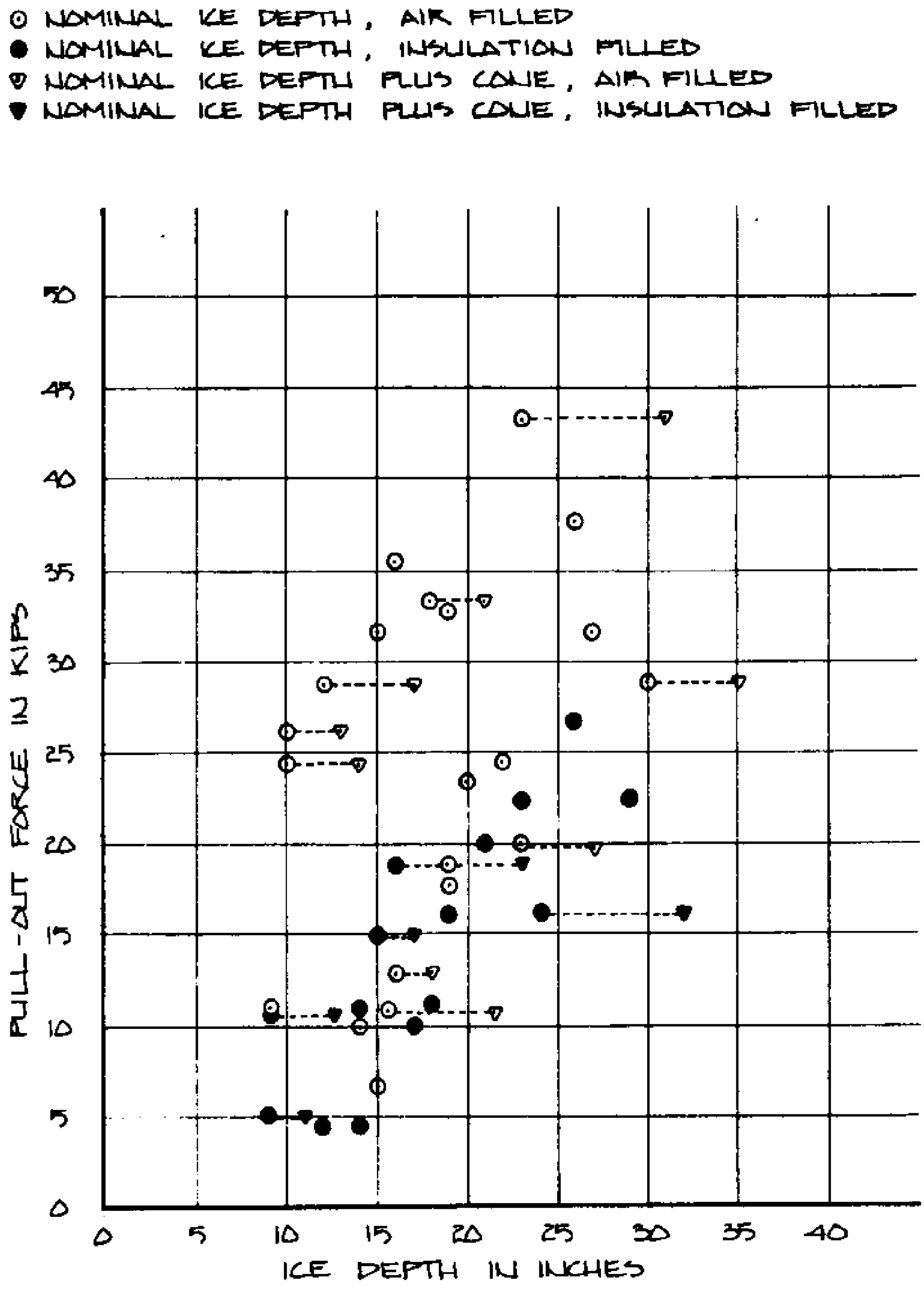

FIGURE 11. – ICE DEPTH AND PULL-OUT FORCE, 8" DIA. PILES

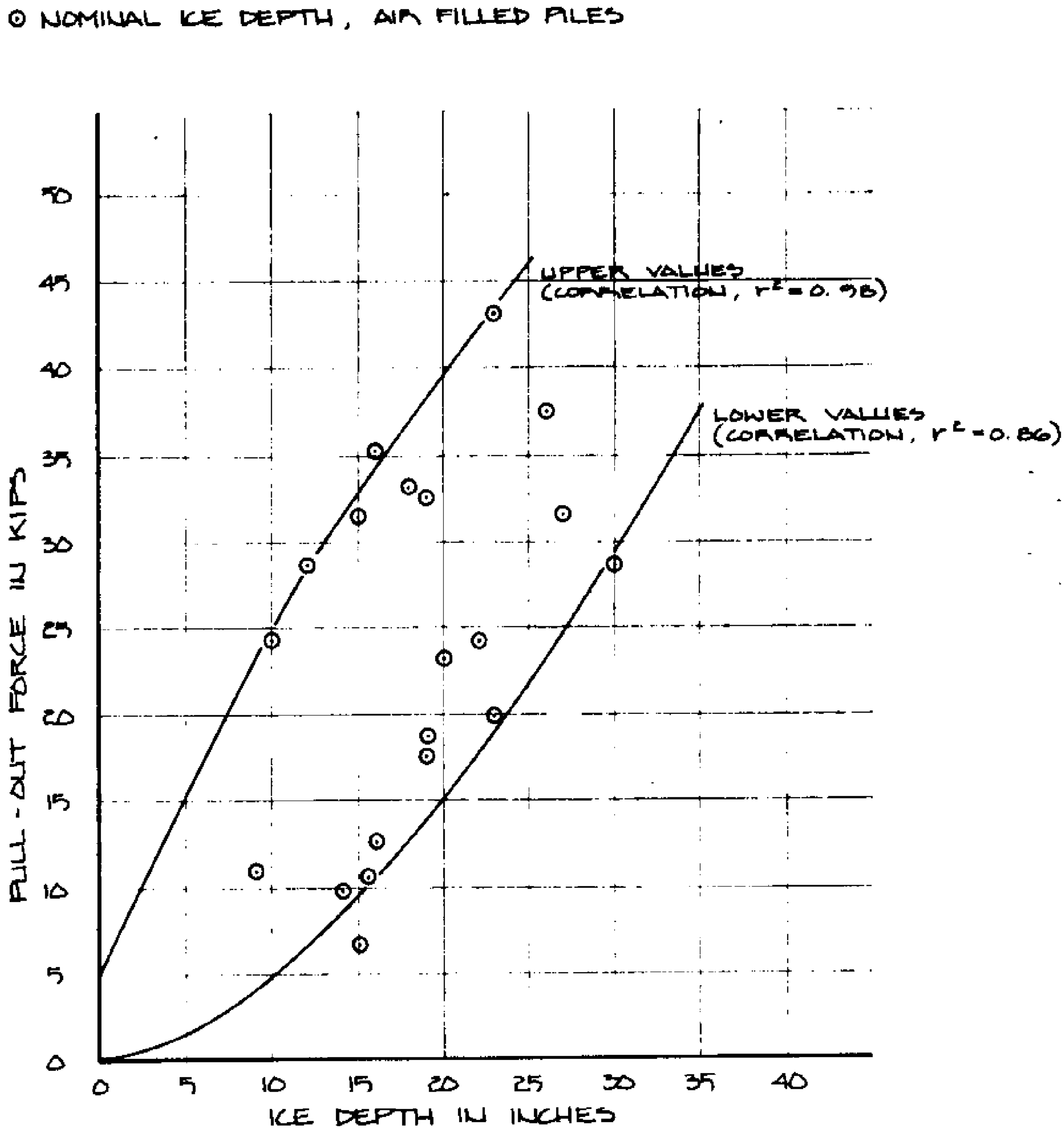

FIGURE 12. - ICE DEPTH AND PULL-OUT FORCE, FIELD RECORDED UPPER AND LOWER VALUES - 8" DIA. PILES, AIR FILLED

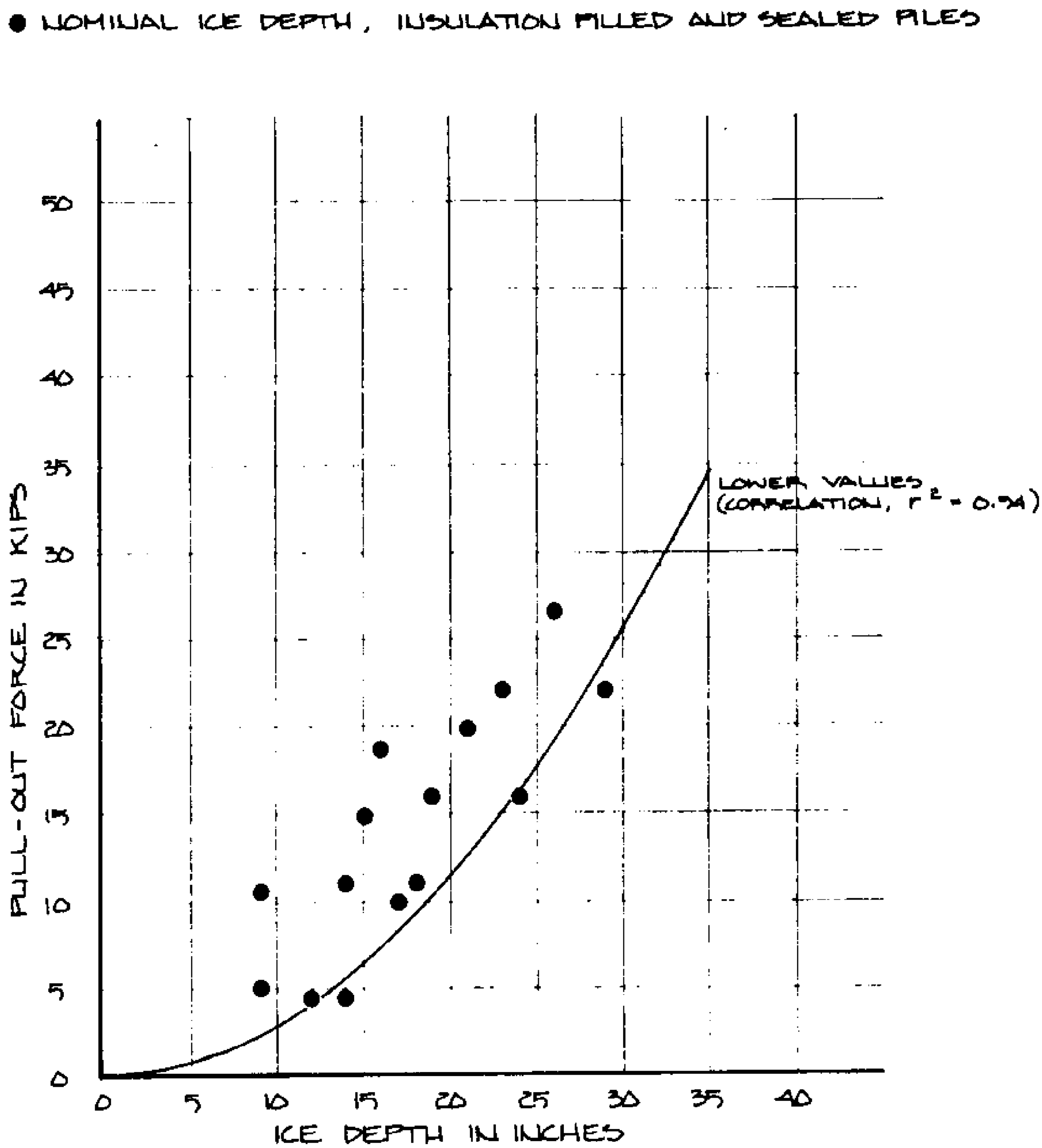

FIGURE 13. – ICE DEPTH AND PULL-OUT FORCE, FIELD RECORDED LOWER VALUES – 8" DIA. PILES, INSULATION FILLED AND SEALED

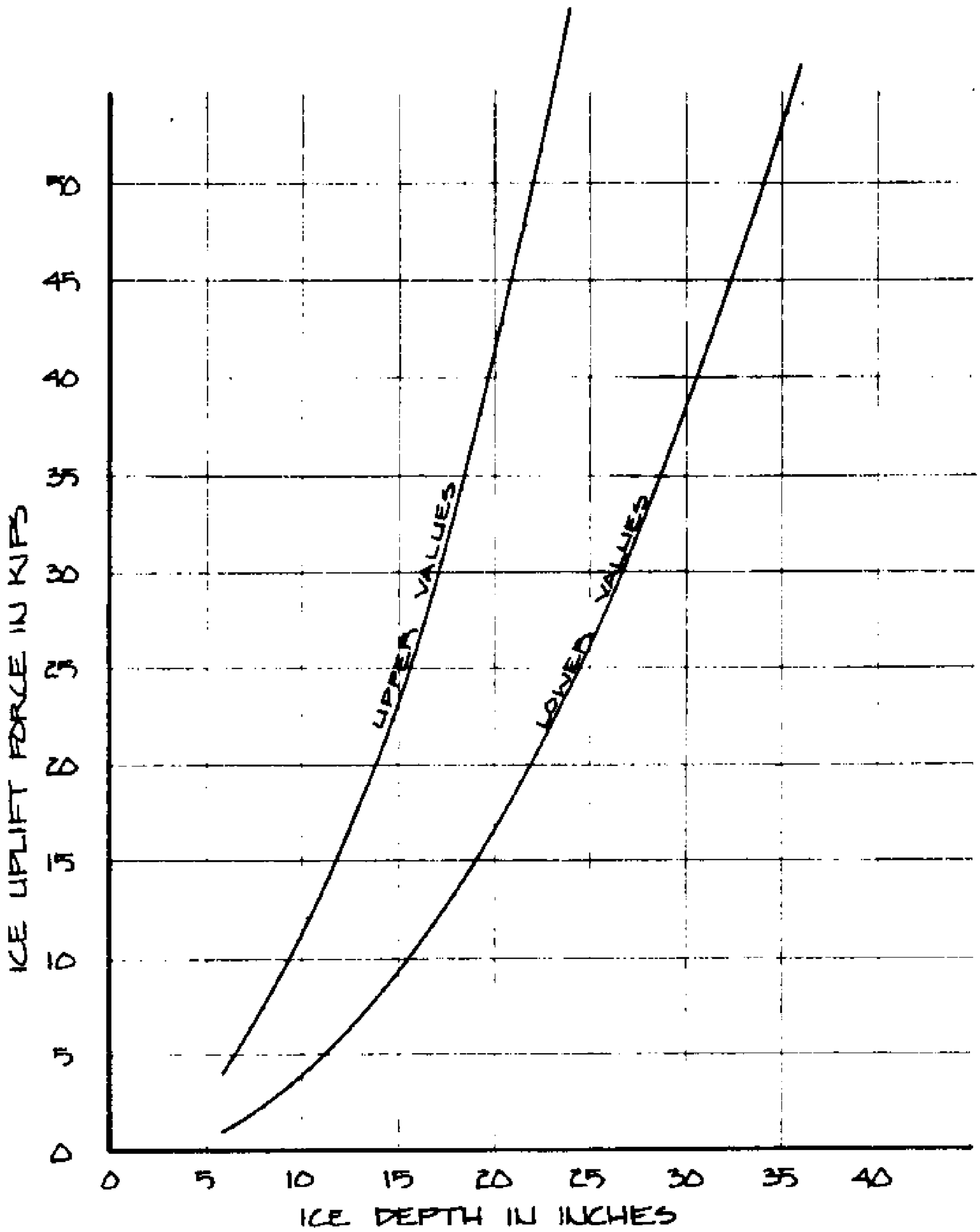

FIGURE 14. - ICE DEPTH AND ICE UPLIFT FORCE, 8.25" DIA. PILES - PREDICTED UPPER AND LOWER VALUES (MUSCHELL, 1976)

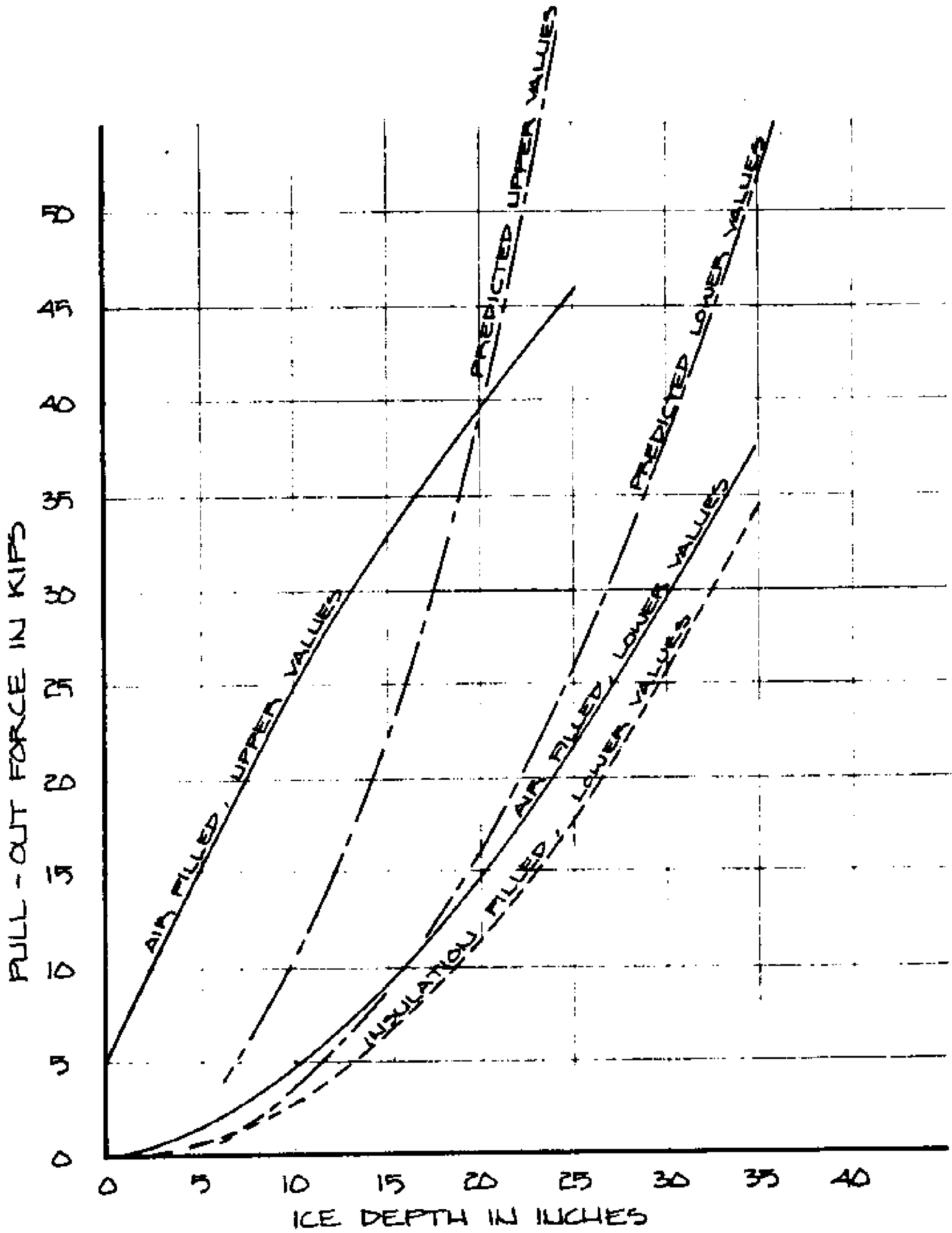

FIGURE 15. - ICE DEPTH AND PULL-OUT FORCE, PREDICTED *versus* FIELD RECORDED VALUES

Flexible Sheet Load Failure, Pipe Piles

The third stage of testing, a flexible sheet configuration as illustrated in Figure 5, page 12, is currently underway. It is obvious that a large quantity of data will be necessary to adequately test the engineering theories and assumptions used in the past.

The field data collected during the 1979 season indicated some important changes in practical effects when test procedures simulated actual field conditions of flexible ice sheets. The most visible change was the ice fracture during pull-out resulting in an ice collar around the pile. This phenomenon is common in most harbor situations.

Lowered water levels may leave the ice sheet in a harbor suspended from piles or other structures. The weight of the ice may be sufficient to overcome the force causing the ice to adhere to the structure resulting in failure at the ice-pile interface--the ice sheet then slides down the pile, following the water surface. Cohesion forces within the ice sheet may not be as strong as the grip of the ice on the pile. In this case, the ice may break before the grip on the pile is overcome. The result is a cone-shaped collar clinging to the pile some distance above the ice sheet. Figure 16 shows typical collar formation occurring as a result of rising and falling water levels.

There may be several of these collars on a pile, especially if ice-jacking has occurred, lifting the pile

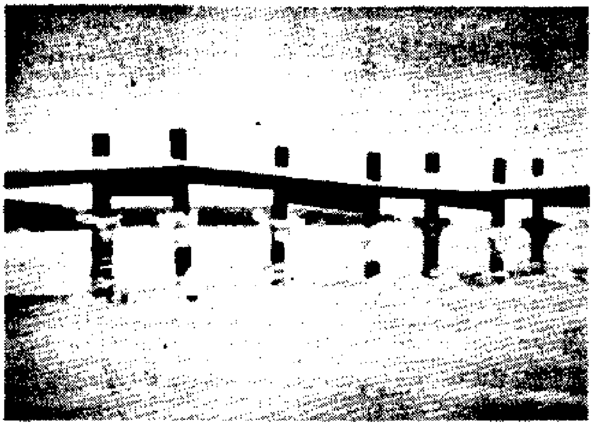

FIGURE 16. - TYPICAL ICE COLLAR FORMATION IN A GREAT LAKES HARBOR RESULTING FROM FALLING WATER LEVELS.

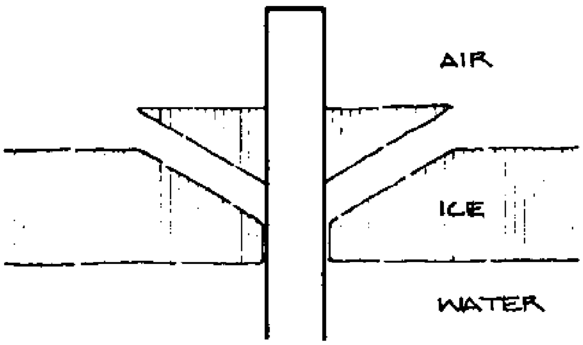

FIGURE 17. - MODEL OF BREAKAGE PATTERN AND COLLAR RESULTING FROM FALLING WATER LEVELS.

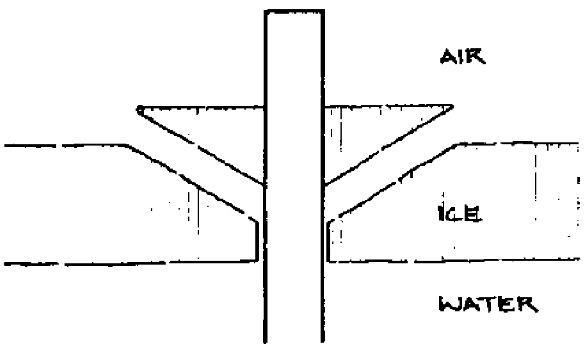

FIGURE 18. - MODEL OF BREAKAGE PATTERN AND COLLAR RESULTING FROM TEST PROCEDURES.

out of the bottom in several successive changes in water level.

Figure 17 shows the model breakage pattern resulting in collar formation from natural fluctuations in water level. Figure 18 is a model of the collar resulting from the test procedures. The similarity in actual forms observed in the field supports the validity of the testing procedure.

Most previous testing of the bending strength of ice has been performed in the laboratory using cantilever beams. As Lavrov points out, "there is no sense in talking about the bending strength of ice without reference to the sample dimensions." (Lavrov, 1971, p. 130) This research uses the ice sheet surrounding the pile as its sample.

The field testing reported here may be modelled as "a (large) floating ice plate of uniform thickness on a liquid water base assumed to have a uniform load symmetrically distributed with respect to the center." (Muschell, 1976, p. 11) While the symmetrical distribution of the testing procedure may be questioned because the uplift force is applied at only two points on the ice sheet, the nearly symmetrical configuration of the ice collars indicates that the two-point bearing on the ice has minimal practical effect on the validity of the procedure. The pull-out force on the pile itself is symmetrical and is the dominant force. Perfect-model departures from the field-collected data are expected to be minor; the bearing radius is expected to be more important than the number of bearing points.

Radial cracking of the ice was commonly experienced during pile uplift. These tension cracks developed up to the point of complete failure. H-section piles offered a great variety of starting points for "radial" tension cracks and field observations confirmed the efficacy of corners in "seeding" cracks. Pipe piles offered no starting points themselves so that the tension fracturing around pipe piles may be assumed to be a function of the ice structure. Field conditions made it difficult to collect accurate data on radial crack formation with any consistency.

The diameter of the "test collar" is probably influenced by the distance between the bearing plates of the pull-out device, a diameter of six feet. The length of radial cracks occurring during testing ranged from 3.5 feet to 8.7 feet. The load failures ranged from a low of 12.7 KIPS to a high of 39.8 KIPS for eight samples. Statistical tests with this limited data indicate no correlation between the size of the collar and the failure load. The deflection wave form of a loaded ice sheet may contribute more to the diameter of the collar than the load itself.

Nor does there appear to be a correlation between the depth of the collar or the remaining direct-shear thickness and the failure load. Five of the eight collars had a thickness of 12 or 13 inches; the other three were from 7 to 10 inches thick. This suggests that there may be a maximum collar thickness. In all but one instance the ice sheet was thicker than the collar. The exception was a 10 inch sheet where the collar fracture occurred at the top of the under-ice cone. Again, thickness of the ice sheet appears to be the single factor having the most influence on the load failure. The 1979 data for uncoated piles are displayed in Figure 19.

It has been "common practice to count only half the thickness of infiltrated snow ice when bearing capacity calculations are made." (Weeks and Assur, 1969, p. 52) Tests here support the findings of Frankenstein (1959, 1961, 1968) that dense snow ice has a strength similar to clear lake ice. Since the cohesion strength of the ice sheet would appear to be the critical factor in load failure, snow ice should be considered to have the same practical strength as clear ice in design decisions.

Midrange values of ice uplift forces are presented in Figure 20. Data limits require that these curves be considered tentative. They are, however, indicative of some important tendencies. While the values tend to fall near or within the range of predicted values, Figure 21 (Muschell, 1976), the comparison shown in Figure 22 is of special interest.

Uplift forces on a pile are different when the natural flexing of the ice sheet is permitted. Explanation of the increased force required for pull-out is based on the "pinching" effect described on page 7 and pictured in Figure 2. The ice grips the pile more firmly.

Formation of one or more collars around a pile suggests that the cohesion forces holding an ice sheet intact are frequently less than the adhesion forces holding ice to piles.

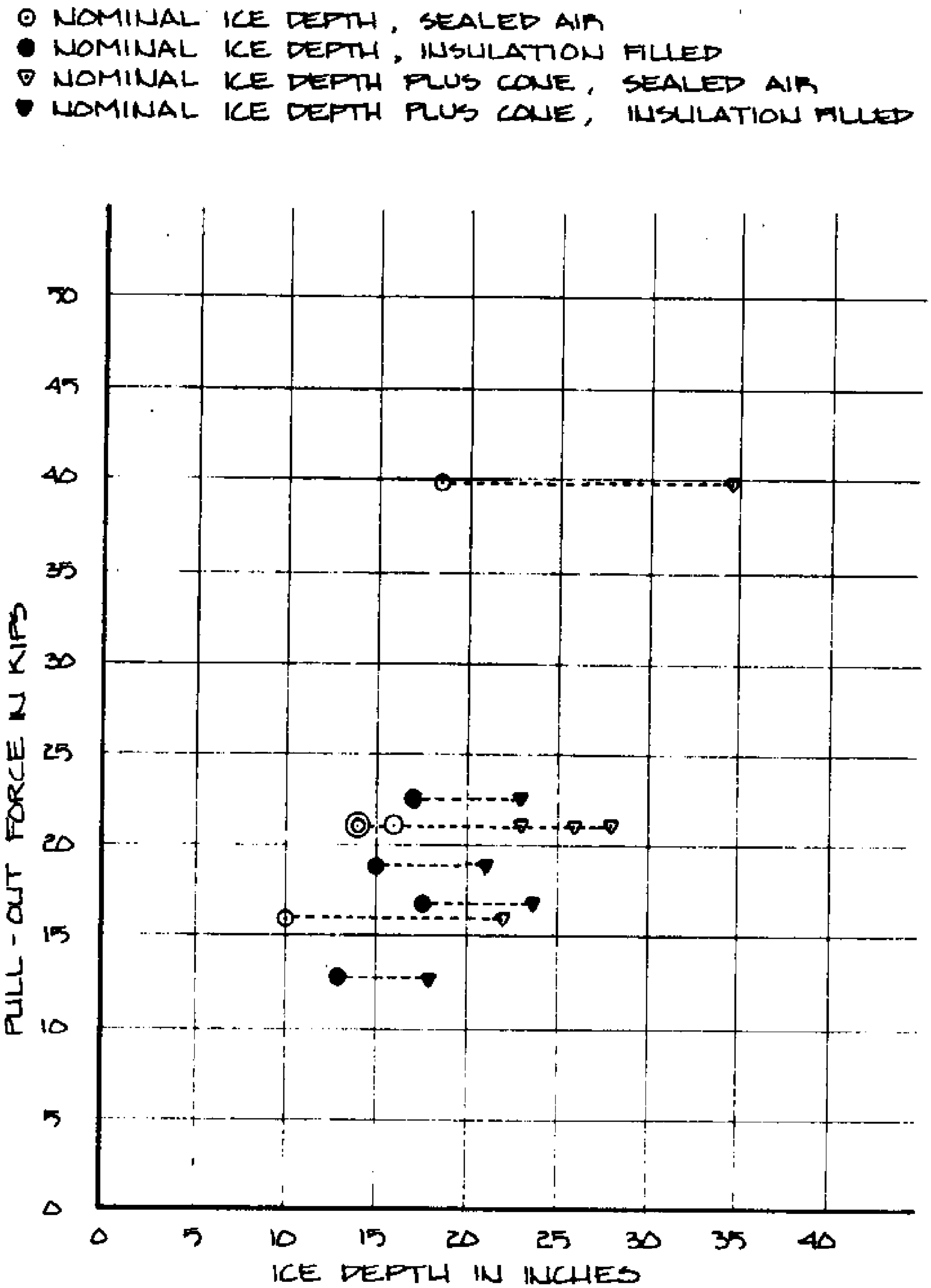

FIGURE 19. – ICE DEPTH AND PULL-OUT FORCE, 8" DIA. PILES – FLEXIBLE SHEET FIELD DATA, 1979

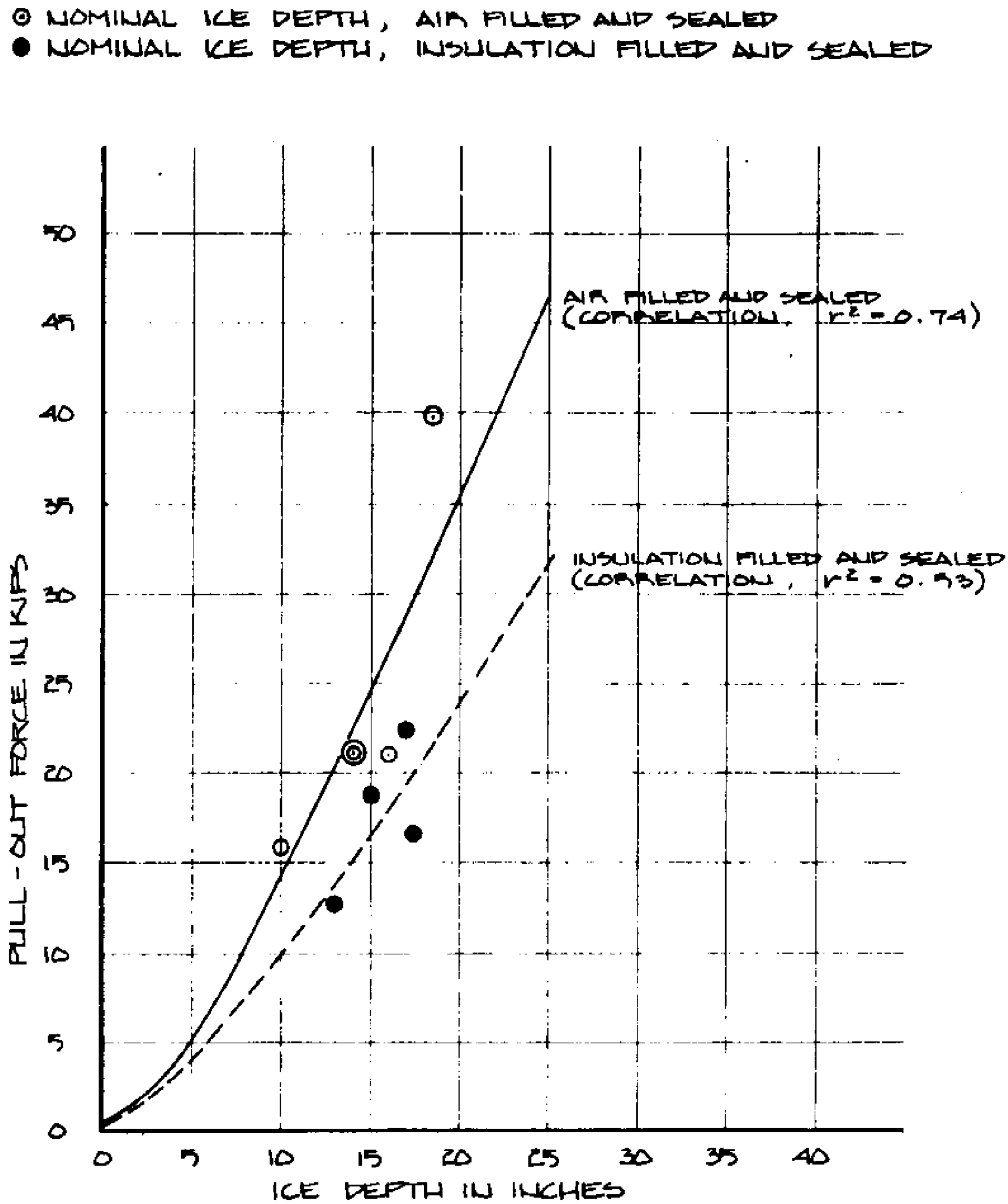

FIGURE 20. - ICE DEPTH AND PULL-OUT FORCE, MIDRANGE VALUES - FLEXIBLE SHEET FIELD DATA, 1979

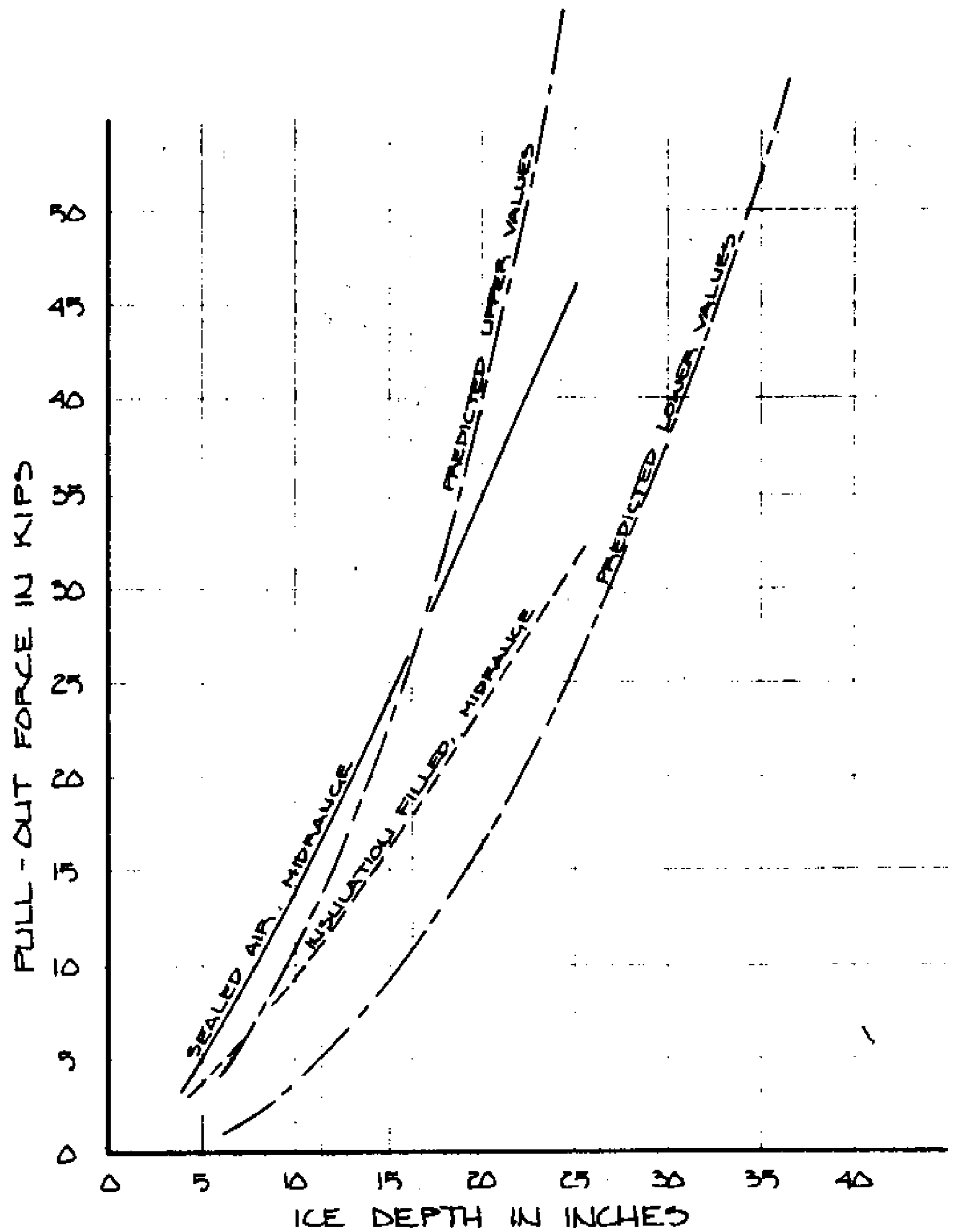

FIGURE 21. - ICE DEPTH AND PULL-OUT FORCE, PREDICTED *versus* FIELD RECORDED VALUES - FLEXIBLE SHEET DATA, 1979

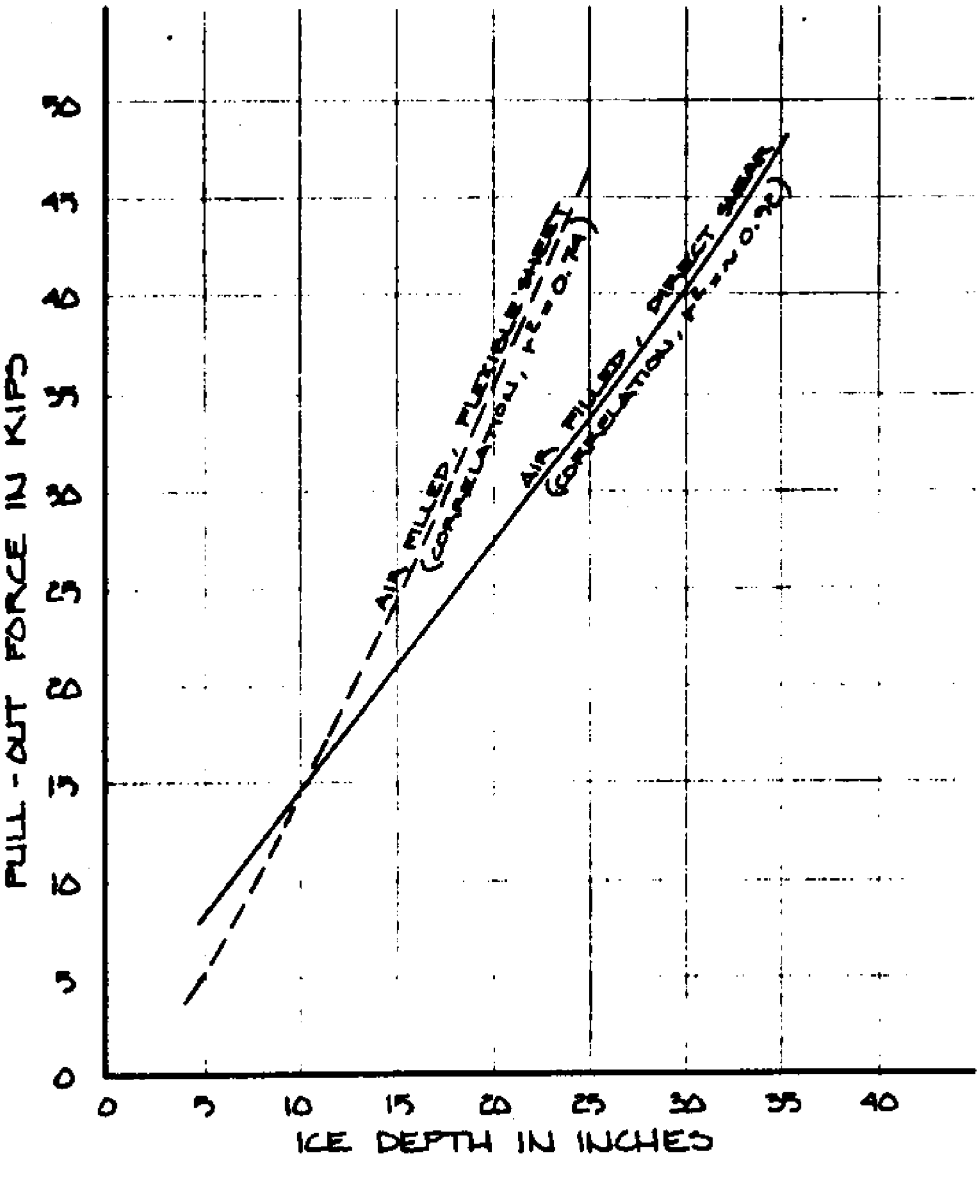

FIGURE 22. – ICE DEPTH AND PULL-OUT FORCE, MIDRANGE VALUES - DIRECT SHEAR. VERSUS FLEXIBLE SHEET (SEE PG. 12 FOR CONFIGURATION ILLUSTRATIONS)

Pile Coatings

Past experience with various coatings applied to piles in attempts to weaken the adhesive forces has been, for the most part, unsatisfactory. Recent developments in epoxy coatings show some promise. Experiments are being conducted in this research with epoxy-coated piles, both air-filled and insulation-filled types. The epoxy based coating used in this test series with the flexible sheet pull-out configuration is described in Appendix J.

Of the nine coated piles, only one exhibited collar fracturing. Eight of the nine uncoated piles pulled from adjacent locations on the same day showed collar fracturing. This suggests that the coatings reduce the ice-pile adhesive strength to or below the cohesion strength of the ice sheet. The three lowest failure load values may have been especially influenced by snow cover which drifted in or fell before the cold weather existing at test time. Water under the snow cover at the lowest-value pile suggests discarding this value in computations. The distribution of depths and uplift forces is depicted in Figure 23. Further testing of this coating is needed to determine its effectiveness and its durability.

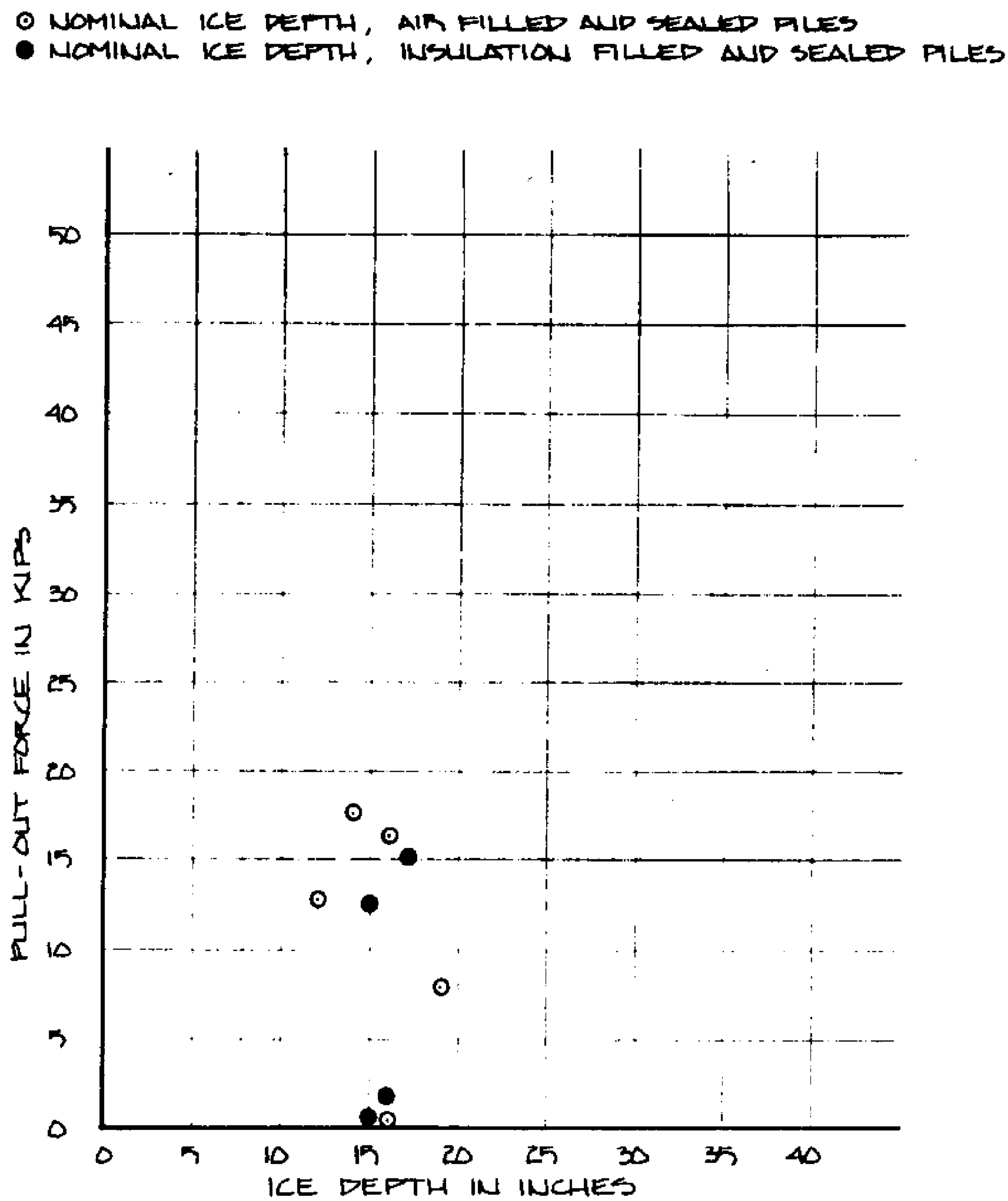

FIGURE 23. – ICE DEPTH AND PULL-OUT FORCE, 8" DIA. PILES, EPOXY COATED

DATA SUMMARY

Water Level Changes in the Great Lakes

Fluctuations in water levels of the Great Lakes are nearly continuous, even in winter. Hodek and Doud (1975) recorded rather high frequency oscillations under an ice cover with the water rising and falling as much as 3 inches in 10 minutes in the southern Lake Superior harbor of Ontonagon, Michigan.

Wind storms over water may cause severe changes; an eight foot increase over general water levels has been recorded at Buffalo, New York. Strong winds may pile up water in one part of a lake basin to heights of several feet with corresponding depressions of water levels in other parts of the basin.

The phenomenon known as a seiche (pronounced saysh) plays an important role in water level changes on the Great Lakes. A seiche is an oscillation of water level which is somewhat irregular and which may be mild, only two or three inches, or severe. One major seiche recorded accurately by the Canadian Hydrographic Service (1948, pp. xxviii-xxix) showed a rise of 18½ inches in 30 minutes, a fall of 46 inches in 105 minutes and a rise of 36 inches in 42 minutes, followed by undulations of 18, 6 and 12 inches over the following two days. Historical commentaries have suggested even more severe seiches such as one in 1904 of 10 feet or more (Jenks, 1945).

Storms and changes in barometric pressure cause this "standing wave" oscillation, consisting of a primary flow along the long axis of a large lake and a secondary oscillation of shorter duration running across the axis. When these influences are coincident, enormous uplift forces can occur in an ice-locked harbor.

Ice Thickness in the Great Lakes

The 50 year maximum ice thickness records, 1899 through 1951, shown by Aune, et al., (1957), indicate maximums from 17 inches at 41° North Latitude to 41 inches at 48° North Latitude. The National Oceanic and Atmospheric Administration (Muschell, 1976, p. 9) shows the same general range for the period 1967-74. This does not, however, demonstrate a consistent increase with latitude or even with average daily temperature. Saginaw Bay at 43° North Latitude recorded a maximum of 35 inches as did Escanaba, Michigan, at 46° North Latitude (Aune, et al., 1957).

It is reasonable to assume that three feet of ice or more will occur frequently in the northern regions of the Great Lakes. In the southern regions, records should be scanned carefully to determine maximum expectations for a specific harbor.

Minimum Water Temperatures

Data acquired in this research indicates strongly that water temperatures under a mid-winter ice cover in a small craft harbor seldom are warmer than 0.5°C throughout the water depth. This supports the observations of Wortley (1977, p. 34). Moreover, a general supercooling may be expected, not only at the ice-water interface but to significant depths.

Tabulating recorded temperature measurements from this research reveals that water under the ice cover in shallow (4 to 6 feet deep) basins is warmer than water in deeper (7 to 9 feet deep) basins. The actual thermal reserve, however, will usually be higher in the deeper harbors because of the greater volume of water. Transfer of heat from the bottom soil to the water may occur but be rapidly dissipated through vertical currents from water density instability or through lateral currents resulting perhaps from the continual seiche effects.

Ice Uplift Forces

It was fully expected that ice temperature and ice density would have decided effects on the adhesive forces between an ice sheet and a pile. In fact, these two characteristics showed no correlation with the force required to pull a pile out of the ice. It must nevertheless be assumed that they do make some kind of contribution but that any effect is so small as to be lost in the larger influence of ice thickness.

The formation of an under-ice cone around a pile does affect the withdrawal force required to free a pile from the ice. It appears, however, that the effect is not of particular field-application importance since the maximum values of direct-shear pull-out for piles without cones equals or exceeds the values for piles with cones.

Other researchers have assumed that cone formation contributes importantly to the load-failure which results in an ice collar. (Wortley refers to the under-ice cone as a collar (1977, p. 59) but a distinction between the two, cone and collar, now requires separate terms.) Although current data are limited, there is a strong suggestion that the cone is not especially important in determining collar formation. A tentative hypothesis is that there is a maximum collar thickness dependent on the cohesive force values within the ice sheet and that the diameter of the collar is a function of the deflection wave form of a loaded ice sheet. There may be other contributing factors to this hypothesis.

Reducing the thermo-pile effect by filling a pipe pile with insulation does not seem to reduce the incidence or severity of cone formation appreciably. However, insulation-filled piles do exhibit reduced ice-pile adhesive forces. This indicates that heat transfer through the steel does affect adhesion, probably by influencing ice temperature and density too close to the interface to have been measured by customary means.

Of all the factors studied in this research, the one which has overwhelming value as a predictor of ice uplift force is that of ice depth or thickness. There are two findings which should be emphasized.

First, the upper values determined in the field do not correspond with the predicted upper values ordinarily accepted. At ice thicknesses of 10 inches or less, the upper values for direct-shear pull-out of air-filled piles may exceed predictions by two and one-half times. (See page 35.) At the same time, at thicknesses of 20 inches or more the field recorded values were below those predicted.

Secondly, the flexible ice sheet has an increasingly strong "grip" on a pile resulting from the pinching effect of the compression-tension force couple when the ice sheet is flexed, increasing with ice thickness.

Much more data must be accumulated but there is a suggestion that there may be a maximum uplift force at some fairly specific ice thickness. This maximum force may prove to be considerably greater for a naturally encountered flexible ice sheet than for a direct-shear test force.

CONCLUSIONS AND RECOMMENDATIONS

Small craft harbors in the Michigan Great Lakes area are subject to considerable damage annually from ice uplift forces. While compression piles may provide high point bearing-capacity values, they may not develop sufficient skin friction to prevent withdrawal by ice uplift and water buoyancy forces. There is enough information available so that engineers, with proper soil investigation, can determine skin friction resistance. A major weakness in design decisions has been the lack of adequately accurate information about vertical forces ice can exert on piles. Findings in this research may help designers, developers and operators of marinas by supplying some of the missing knowledge.

Ice uplift forces on pipe piles have been found to be very different from those expected when using traditional and laboratory concepts. Also, adhesive forces are not necessarily critical in establishing the force tending to pull a pile from its foundation. Furthermore, attempts to adapt field data to useful engineering formulas may be complicated by the frequent operation of seiches of varying magnitude which, through their continual flexing of the ice sheet, change the characteristics of the ice. Conclusions in this report are thus limited to practical recommendations.

The force acting on a pile is much greater than generally anticipated and may thus suggest a design concept using a crib or floating system rather than a pile supported structure where foundation soil skin friction is marginal or insufficient. Pipe piles with flat-plate point closures have been found to be less satisfactory than those with conical points. During the pile driving operation, the conical point disturbs the surrounding soil less. The result is better skin friction and greater resistance to ice uplift.

Filling a pipe pile with insulating material reduces the thermo-pile effect. While it does not appreciably affect under-ice cone formation, it does have some effect on ice-pile adhesive values.

Although not directly studied in this research, spacing between piles is worth reconsidering. There may be some optimum spacing related to the stability of piles under ice load.

Special coatings, too, need much more study. The epoxy resin coating tested here shows considerable promise in reducing ice-pile adhesive forces.

APPENDICES

APPENDIX A

Temperature Indicating Equipment

APPENDIX A

Temperature Indicating Equipment

Digital thermocouple temperature indicator	Model 410 TC; $0.1^{\circ}C$ resolution; TC type material: Copper-Constantan; Range $-200^{\circ}C$ to $+400^{\circ}C$; Maximum linearization error $0.07^{\circ}C < 0^{\circ} < 0.06^{\circ}C$; Mfr: Omega Engineering, Inc. Box 4047, Stamford, CT 06907
Stainless steel probe	SK-5623195; 3/16" O.D. by 5" long; waterproofed and attached to 220 ft. of TT-T-20 thermocouple wire (Teflon on each conductor, Teflon overall sheath); Mfr: Omega Engineering, Inc. Box 4047, Stamford, CT 06907
Stainless steel probe	SK-5623195; 3/16" O.D. by 5" long; waterproofed and attached to 20 ft. of TT-T-20 thermocouple wire (Teflon on each conductor, Teflon overall sheath); Mfr: Omega Engineering, Inc.
Mercury calibrating	Serial No. T4664, Celsius No. 63-C; Range $-8^{\circ}C$ to $32^{\circ}C$; divisions $0.1^{\circ}C$; Certified in accordance with ASTM 63-C 0.1° Divisions; Corrections traceable to National Bureau of Standards; Mfr: H-B Instrument Co., American and Bristol Sts., Philadelphia, PA 19140

Electrical generator	1500 watt, 4 HP, 4 cycle; gasoline driven electrical generator; Mfr: Milwaukee Electric Tool Corp., Brookfield, WI 53005

APPENDIX B

Load Test Equipment

APPENDIX B

Load Test Equipment

Hydraulic cylinder rams	Enerpac Model No. RC-506; 55 ton capacity, 6.25" stroke, effective cylinder area 11.045 sq. in.; Mfr: Enerpac, Butler, WI 53007
Hydraulic pump	TK Force Pak, Model No. 180-8-4 with gauge and two high pressure hydraulic lines, 10,000 psi capacity; Mfr: Templeton, Kinley & Co., Broadview, IL 60153
Steel pile clamping device	2 @ 30"x18"x1/2"; total bearing area: 968 sq. in.; Mfr: J.B. Lund's Sons, 707 Cleveland Ave., Cheboygan, MI 49721
Reaction beams	W8x28
Drive sockets	"Proto" Heavy Duty 3/4" drive with hinged handle; Mfr: Ingersoll Rand, P.O. Box 255, Columbus, OH 43216
Electrically heated and insulated equipment carrier	Protective container for the digital thermometer and density measuring equipment; Mfr: United Marine Associates, Inc., 111 North Main St., Cheboygan, MI 49721

Stop watch	0.20 second divisions Mfr: Industrial Time Corporation, 597 Fifth Avenue, New York, NY 10(
Steel test pile sections	HP 8x36, HP 10x42, 8.25" O.D. x 8'; Mfr: U.S. Steel
Weighing scales and balances	Capacity 20kg - 45 lb.; Mfr: Ohaus Scale Corporation, Florham Park, NJ

Miscellaneous tools and materials

Wire rope, 0.375"
McCulloch chain saw
Electric hand drill
Hand saw
Ice spud
Sounding weight with measuring tape
Ice tongs
Glass beakers

APPENDIX C

Water Temperature
Test Data

APPENDIX C

Water Temperature Test Data

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	13"	12"	8.5"	13"	15"	13"	27"
Water Depth feet	Water Temperature °C						
0	-0.1	-0.1	-0.1	-0.1 -0.2	0.0	+0.1 -0.1	0.0
1			-0.1 -0.2	-0.1 -0.2	0.0	0.0	0.0
2			-0.1	-0.1 -0.2	0.0	0.0 -0.1	0.0
3			-0.1	-0.1	0.0	0.0 -0.1	0.0
4			-0.1	-0.1	0.0	-0.1 +0.1	0.0 -0.1
5		-0.1	-0.1	-0.1	0.0	-0.1 +0.1	0.0 -0.1
6	-0.1		-0.1	-0.1	+0.1	-0.1 +0.1	0.0 -0.1
7			-0.1	-0.1	+0.1	0.0	0.0
8			+0.1	-0.2	+0.1	0.0	0.0
9						+0.1	+0.1
10	-0.1	0.0 -0.1					
45		0.0					
89	-0.1						

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	30"	13"	9"	9"	10.5"	18"	17"
Water Depth feet	Water Temperature °C						
0	+0.1 -0.1	0.0	+0.2	0.0	0.0	0.0	-0.1
1	+0.1 -0.1	+0.1 0.0	+0.3	+0.3	0.0	+0.1 0.0	-0.1
2	+0.1 -0.1	+0.1 0.0	+0.7	+0.4	+0.3	+0.1 0.0	-0.1
3	0.0 -0.2	+0.1 0.0	+1.0	+0.8	+1.4	+0.7	-0.2
4	0.0 -0.2	+0.1 0.0	+0.9	+1.3	+1.7	+1.0 +1.2	-0.2
5	0.0 -0.2	+0.1					
6	-0.1	+0.1					
7	-0.1	+0.1					
8	-0.1	+0.3					
9	-0.2						
10							

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	8"	17"	7.5"	18"	18"	8"	18"
Water Depth feet	Water Temperature °C						
0	-0.1	-0.1	-0.1 -0.2	-0.1	-0.1	-0.1	+0.1 0.0
1	-0.1	-0.1	-0.1 -0.2	-0.1	-0.1	-0.1	+0.1
2	-0.1	-0.1	-0.1 -0.2	-0.1	-0.1	-0.1	+0.1
3	-0.1	-0.1 -0.2	-0.1 -0.2	-0.1	-0.1	-0.1	+0.1
4	-0.2	-0.1 -0.2	-0.1 -0.2	-0.1	-0.1	-0.1	+0.1 0.0
5			-0.1 -0.2	-0.1	-0.1	-0.1	+0.1 0.0
6			-0.1 -0.2	-0.1	-0.1	-0.1	+0.1 0.0
7			-0.1 -0.2	-0.1	-0.1	-0.1	+0.1
8			-0.1	0.0 -0.1	0.0 -0.1	+0.1	+0.1
9			0.0	0.0	0.0 -0.1	+0.1	+1.1
10							

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	Starting	None	14"	15"	14"	18"	20"
Water Depth feet	Water Temperature ^{o}C						
0	+0.1 0.0	+0.5					
1	+0.1 0.0	+0.8					
2	+0.1 0.0	+0.8	-0.1	-0.1 -0.2	-0.2	-0.2	-0.2 -0.3
3	+0.1 0.0	+0.8	0.0	-0.1 -0.2	-0.2	0.0 -0.1	-0.2
4	+0.1 0.0	+0.8	0.0	-0.1 -0.2	-0.1 -0.2	0.0 -0.1	-0.2
5	+0.1 0.0	+0.9	0.0 +0.1	-0.1 -0.2	-0.1 -0.2	-0.1 -0.2	-0.1 -0.2
6	+0.1 0.0	+0.9	0.0 +0.1	0.0 -0.1	0.0 +0.1	-0.2	0.0 +0.1
7	0.0	+0.9					
8	+0.3	+1.0					
9							
10							

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	17"	23"	26"	29"	9"	9"	15"
Water Depth feet	Water Temperature °C						
0							
1					+0.2	-0.1 -0.2	
2	-0.3	-0.2 -0.3			+0.2	+0.1	+0.2
3	-0.2 -0.3	-0.2 -0.3	0.0	-0.1	+0.2	+0.2	+0.2
4	-0.2	-0.2 -0.3	0.0	0.0	+0.2	+0.2	+0.2
5	-0.1 -0.2	-0.2 -0.3	+0.1 +0.2	0.0	+0.2	+0.2	+0.2
6	0.0 -0.1	-0.1 -0.2	+0.2	+0.1	+0.7	+0.9	+0.2
7							
8							
9							
10							

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	16"	19"	21"	22"	23"	24"	25"
Water Depth feet	Water Temperature °C						
0							
1							
2	+0.1	0.0	-0.3	-0.3	-0.2	-0.2	
3		0.0	-0.2	-0.2	-0.1	-0.1	-0.1
4	+0.1	0.0	-0.2	-0.2	0.0	0.0	0.0
5	+0.8	+0.8	+0.9	+0.2	+0.5	+0.4	+0.5
6							
7							
8							
9							
10							

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	27"	10"	17"	19"	17.5"	14"	25"
Water Depth feet	Water Temperature °C						
0							
1		-0.2					
2			-0.2	-0.2	-0.2	-0.3	
3	0.0	-0.2		-0.1	-0.1	-0.3	-0.1
4	-0.1		-0.2	0.0	0.0	-0.3	+0.2
5	+0.3	-0.2	+0.2	+0.2	+0.1	-0.3	+0.8
6		+1.2	+0.8	+1.1	+1.0	+1.0	+1.2
7							
8							
9							
10							

SAMPLE WATER TEMPERATURE TEST DATA

Ice Depth	26"	29"					
Water Depth feet	Water Temperature °C						
0							
1							
2							
3	0.0	-0.2					
4	0.0	-0.1					
5	+0.6	+0.5					
6	+1.3	+0.7					
7							
8							
9							
10							

APPENDIX D

Ice Temperature
Test Data

APPENDIX D

Ice Temperature Test Data

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	13"	8.5"	15"	13"	27"	10.5"	18"
Ice Depth inches*	Ice Temperature °C						
Air	-10.4	-0.8	-16.4	-2.0	-0.4	-10.2	-7.4
0							
3	-2.9	-0.2	0.0	-0.2	0.0	-1.2	-0.1
6	-2.3	-0.2	0.0			-1.7	-0.1
9	-1.4		-0.1	-0.2		-1.7	-1.1
12	-0.7		-0.1		0.0		-1.3
15					0.0		-0.9
18					0.0		
21					0.0		
24							
27					-0.1		
30							
	-0.1	-0.1 -0.2	0.0	0.0 -0.1	0.0 -0.1	+0.3	+0.1 0.0
	Water Temperature Below Ice °C						

*Temperatures at nearest 3" interval depth

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	17"	17"	7.5"	18"	8"	18"	14"
Ice Depth inches*	Ice Temperature °C						
Air	-7.0	-9.1	-0.6	-0.5	-7.2	-8.6	-9.2
0							
3	-2.7	-0.7	-0.2	-0.2	-2.0		-3.8
6		-0.7	-0.2		-2.3	-0.6	-3.1
9	-2.4	-0.8		-0.1 -0.2		-0.1	
12	-2.3	-0.2		-0.2		0.0	-3.1
15		-0.1		-0.2		+0.1	
18							
21							
24							
27							
30							
	-0.1	-0.1	-0.1 -0.2	-0.1	-0.1	+0.1	-0.1
	Water Temperature Below Ice °C						

*Temperatures at nearest 3" interval depth

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	15"	15.5"	15"	16"	14"	14"	18"
Ice Depth inches*	Ice Temperature °C						
Air	-9.2	-9.2	-14.7	-14.7	-5.6	-5.6	-6.3
0							
3		-4.3			-1.4	-1.6	-1.6
6	-1.7	-4.0	-6.5	-3.7		-1.4	-2.5
9			-6.9	-3.8			
12	-1.8	-4.0		-4.4	-1.4	-1.0	-3.5
15							-4.6
18							
21							
24							
27							
30							
	-0.1	-0.1	-0.1 -0.2	-0.1 -0.2	-0.2	-0.2	-0.2
	Water Temperature Below Ice °C						

*Temperatures at nearest 3" interval depth

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	19"	20"	23"	23"	22"	26"	27"
Ice Depth inches*	Ice Temperature °C						
Air	-6.3	-4.9	-5.0	-5.0	-5.0	-4.4	-4.4
0							
3						-7.3	-7.6
6	-5.2		-2.5	-3.2			
9	-5.4	-2.2			-2.2	-6.5	
12			-1.9	-2.4		-4.7	-4.6
15	-3.6						
18		-0.9	-1.0	-1.6	-1.4	-4.7	
21			-0.6	-1.4	-1.2		
24						-1.3	-1.8
27							
30							
Water Temperature Below Ice °C	-0.2	-0.2 -0.3	-0.2 -0.3	-0.2 -0.3	-0.2 -0.3	0.0	0.0

*Temperatures at nearest 3" interval depth

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	26"	29"	29"	9"	9"	15"	12"
Ice Depth inches*	Ice Temperature °C						
Air	-4.4	-0.3	-0.3	-4.5	-1.0	-3.5	-3.0
0					0.0	-2.6	-3.3
3	-7.7	-3.2	-3.5	-3.7	0.0		-2.5
6				-2.5	0.0	-3.0	-2.5
9					0.0	-2.6	
12						-1.1	-1.0
15		-2.4	-2.6				
18	-5.2						
21			-1.8				
24	-1.8	-1.4					
27							
30							
	0.0	-0.1	-0.1	+0.2	-0.1	+0.2	
	Water Temperature Below Ice °C						

*Temperatures at nearest 3" interval depth

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	16"	19"	21"	22"	23"	24"	25"
Ice Depth inches*	Ice Temperature °C						
Air	-6.8	+21.0	-1.2	-2.0	-4.0	-4.5	-3.0
0		0.0	-1.2	-1.2	-0.9	-1.0	-1.1
3	-1.7				-1.2		
6	-2.2	-0.3	-1.0			-1.3	-1.2
9					-1.1		
12	-2.8	-0.1	-1.2	-1.3		-1.3	-1.5
15	-3.9				-1.3		
18		-0.1	-1.2	-1.3	-1.7	-1.5	-1.8
21						-1.7	
24							-1.6
27							
30							
Water Temperature Below Ice °C	+0.1	0.0	-0.3	-0.3	-0.2	-0.2	-0.2

*Temperatures at nearest 3" interval depth

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	27"	10"	17"	19"	16"	14"	25"
Ice Depth inches*	Ice Temperature °C						
Air	+0.1	-14.6	-9.8	-9.9	-5.2	-8.8	-7.0
0	-1.1			-1.6		-2.2	-0.3
3		-5.9	-4.2		-1.2	-2.5	-1.1
6	-1.2	-5.9	-3.7	-2.4			
9		-6.2		-2.2	-1.8	-2.7	-0.7
12	-1.3		-3.6	-2.1	-2.1	-2.5	-0.2
15			-5.5	-2.8	-2.6		-0.7
18	-1.5			-3.4			-0.8
21							-2.0
24	-1.5						-0.2
27							
30							
	0.0	-0.2	+0.2	-0.2	-0.2	-0.4	-0.1
	Water Temperature Below Ice °C						

*Temperatures at nearest 3" interval depth

SAMPLE ICE TEMPERATURE TEST DATA

Nominal Thickness	26"	29"					
Ice Depth inches*	Ice Temperature °C						
Air	-15.2	+1.0					
0							
3	-0.1	-0.2					
6							
9		-0.4					
12	-0.1	-0.4					
15		-0.4					
18							
21							
24	-0.1	-0.3					
27							
30							
Water Temperature Below Ice °C	0.0	-0.2					

*Temperatures at nearest 3" interval depth

APPENDIX E

Ice Temperature Range

APPENDIX E

ICE TEMPERATURE RANGE, ^{o}C

Ice Depth, Inches	Air Temperature	Ice Temperature		Water Temperature Below Ice
		Near Top	Near Bottom	
7.5	- 0.6	-0.2	-0.2	-0.1 -0.2
8	- 7.2	-2.0	-2.3	-0.1
8.5	- 0.8	-0.2	-0.2	-0.1 -0.2
9	- 4.5	-3.7	-2.5	+0.2
9	- 1.0	0.0	0.0	-0.1
10.5	-10.2	-1.2	-1.7	+0.3
12	- 3.0	-3.3	-1.0	
13	-10.4	-2.9	-0.7	-0.1
13	- 2.0	-0.2	-0.2	0.0 -0.1
14	- 9.2	-3.8	-3.1	-0.1
14	- 5.6	-1.4	-1.4	-0.2
14	- 5.6	-1.6	-1.0	-0.2
15	-16.4	0.0	-0.1	0.0
15	- 9.2	-1.7	-1.8	-0.1
15	-14.7	-6.5	-6.9	-0.1 -0.2
15	- 3.5	-2.6	-1.1	+0.2
15.5	- 9.2	-4.3	-4.0	-0.1
16	-14.7	-3.7	-4.4	-0.1 -0.2
16	- 6.8	-1.7	-3.9	+0.1
17	- 7.0	-2.7	-2.3	-0.1
17	- 9.1	-0.7	-0.1	-0.1
18	- 7.4	-0.1	-0.9	+0.1 0.0
18	- 0.5	-0.2	-0.2	-0.1
18	- 8.6	-0.6	+0.1	+0.1
18	- 6.3	-1.6	-4.6	-0.2
19	- 6.3	-5.2	-3.6	-0.2
19	+21.0	0.0	-0.1	0.0
20	- 4.9	-2.2	-0.9	-0.2 -0.3
21	- 1.2	-1.2	-1.2	-0.3
22	- 5.0	-2.2	-1.2	-0.2 -0.3
22	- 2.0	-1.2	-1.3	-0.3
23	- 5.0	-2.5	-0.6	-0.2 -0.3
23	- 5.0	-3.2	-1.4	-0.2 -0.3
23	- 4.0	-0.9	-1.7	-0.2
24	- 4.5	-1.0	-1.7	-0.2
25	- 3.0	-1.1	-1.6	-0.2
26	- 4.4	-7.3	-1.3	0.0
26	- 4.4	-7.7	-1.8	0.0
27	- 0.4	0.0	-0.1	0.0 -0.1
27	- 4.4	-7.6	-1.8	0.0
27	+ 0.1	-1.1	-1.5	0.0
29	- 0.3	-3.2	-1.4	-0.1
29	- 0.3	-3.5	-1.8	-0.1

APPENDIX F

Ice Density,
Sample Measurements

APPENDIX F

Ice Density, Sample Measurements

SAMPLE ICE TEMPERATURE AND DENSITY DATA

Water Depth feet	Ice Depth inches	Air Temp. °C	Water Temp. Below Ice °C	Ice Temp. Min. °C	Ice Temp. Max. °C	Ice Density Min. gm/ml	Ice Density Max. gm/ml	Total Failure Load KIPS
8.7	18	-8.6	+0.1	-0.6	+0.1	0.798	0.970	
3.5	18	-7.4	+0.1 0.0	-1.3	-0.1	0.800	0.983	
8.7	8	-7.2	-0.1	-2.3	-1.7	0.880	0.960	4.4
8.0	15	-16.4	0.0	-0.1	0.0	0.714	0.960	3.3
3.5	10.5	-10.2	+0.3	-1.7	-1.2	0.719	0.944	3.3
4.0	17	-0.1	-0.1	-0.8	-0.1	0.831	0.881	24.3
89.0	13	-10.4	-0.1	-2.9	-0.7	0.942	0.972	
8.7	18	-0.5	-0.1	-0.2	-0.15	0.845	0.993	14.4
9.0	27	-0.4	0.0 -0.1	-0.1	0.0	0.833	0.932	5.5
4.0	17	-7.0	-0.1	-2.7	-2.3	0.898	0.969	19.3
8.0	8.5	-0.8	-0.1 -0.2	-0.2	-0.2	0.980	0.998	4.4
8.7	7.5	-0.6	-0.1 -0.2	-0.2	-0.2	0.664	0.669	3.3
9.0	13	-2.0	0.0 -0.1	-0.2	-0.2	0.884	0.938	4.4

APPENDIX G

Load Failure Measurements, H Pile, Direct Shear

APPENDIX G

Load Failure Measurements, H Pile, Direct Shear

Nominal Ice Depth, inches	Cone, inches	Total Ice Depth, inches	Adhesion Failure Load, KIPS	Adhesion Failure Load, p.s.i.	Pile Size
15		15	8.8	12.32	HP 8x36
15		15	15.5	21.57	
13	4	17	3.3	3.64	
8.5	13.5	20	4.4	4.63	
18.5		18.5	5.5	5.78	
13		13	4.4	7.11	
10.5		10.5	3.3	5.36	HP 10x42
17		17	24.3	24.26	
17		17	19.3	19.30	
8		8	4.4	9.37	
18		18	14.4	13.54	
7.5		7.5	3.3	7.50	
15		15	12.7	14.40	
10		10	28.7	48.76	
9		9	26.1	49.20	

APPENDIX H

Load Failure Measurements, Pipe Pile, 8", Direct Shear

APPENDIX H

Load Failure Measurements, Pipe Pile, 8", Direct Shear

Nominal Ice Depth, inches	Cone, inches	Total Ice Depth, inches	Adhesion Failure Load, KIPS
14		14	4.4
15		15	6.6
15.5	6	21.5	10.7
15	2	17	14.9
16	2	18	12.8
14		14	11.0
14		14	9.9
18		18	11.0
19		19	18.8
19		19	32.6
20		20	23.2
17		17	9.9
19		19	17.7
23		23	22.1
23		23	19.9
22		22	24.3
26		26	26.5
27		27	31.5
26		26	37.6
29		29	22.1
30	5	35	28.7
9	2	11	5.0
9		9	11.0
9	3.5	12.5	10.5
12	5	17	28.7
15		15	31.5
12		12	4.3
16		16	35.3
16	7	23	18.8
18	3	21	33.1
10	4	14	24.3
19		19	16
21	6	27	19.9
23	8	31	43.1
24	8	32	16.0

APPENDIX I

Load Failure Measurements, Pipe Pile, 8",
Flexible Sheet

APPENDIX I

Load Failure Measurements, Pipe Pile, 8", Flexible Sheet

Nominal Ice Depth, inches	Cone, inches	Total Ice Depth, inches	Failure Load, KIPS	Fill
10	12	22	15.9	air
17	6	23	22.3	insulation
18.5	16	34.5	39.8	air
17.5	6	23.5	16.6	insulation
14	9	23	21.0	air
13	5	18	12.7	insulation
14	12	26	21.0	air
15	6	21	18.8	insulation
16	12	28	21.0	air

APPENDIX J

Epoxy Based Coating
as Used in the Cited Tests

APPENDIX J

Epoxy Based Coating As Used In The Cited Tests

This epoxy coating was previously tested by CRREL. It is known as CITAL AQUACOAT 28.05 as manufactured by Citosan (Canada) Limited, 9569 Cote de Liesse Road, Dorval 760, Quebec (514-636-4116). It is described by Citosan as:

> Cital Aquacoat 28.05 is a protective coating for use on dry, moist or wet surfaces in air or under water.
>
> It creates a tough, highly adhesive, abrasion and corrosion resistant coating on steel, concrete and wood surfaces.
>
> Cital Aquacoat 28.05 is a solvent-free, two-part, epoxy-based coating of low viscosity, that may be applied with a paint brush or paint roller, or sprayed with an airless gun, depending on the application.
>
> It is nontoxic when cured and is approved for use as a coating material for the interior of drinking water tanks and pipes. It is available in many standard colors as well as grey and white.
>
> Cital Aquacoat 28.05 is supplied as two components, Part A and Part B, that have to be mixed uniformly prior to use. Part A and Part B are packaged to exact weights for mixing.
>
> Work or potlife: About 30 to 60 minutes at 78°F after the two components have been mixed together.
>
> Curing time: Dry to the touch after about 4-5 hours at a temperature of 78°F and after 12-18 hours at a temperature of 40°F. Under water at all temperatures down to 36°F after about 14 hours.
>
> A second coat can be applied when the first coat is dry to the touch. DO NOT USE below 38°F without obtaining further information.
>
> Coverage: Theoretical coverage amounts to 1685 sq. ft./gal./mil. Two coatings of 6 mil each are recommended in order to insure a complete, nonporous surface.

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