Laboratory tests on downdrag loads developed by floating ice covers on vertical piles

Frederking, R. M. W.

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.BORATORY TESTS ON DOWNDRAG LOADS DEVELOPED BY FLOATING ICE COVERS ON VERTICAL PILES

by R.M.W. Frederking

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SOMMAIRE

L'auteur effectue des essais systématiques en laboratoire afin de déterminer les effets de la vitesse de fléchissement, de l'épaisseur de la glace et du diamètre des pieux sur les charges verticales de la glace sur ces pieux. L'auteur utilise des pieux de bois d'un diamètre de 50 à 145 mm dans des épaisseurs de glace de 25 à 200 mm. Les essais sont effectués à des vitesses de fléchissement nominales constantes. L'auteur constate une augmentation de la charge sur le pieu à mesure que s'accroît la vitesse de fléchissement. La charge unitaire sur les pieux augmente avec l'accroissement de l'épaisseur de la glace et diminue avec l'accroissement du diamètre du pieu.

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At the Norwegian Institute og Technology.

LABORATORY TESTS ON DOWNDRAG LOADS DEVELOPED BY FLOATING ICE COVERS ON VERTICAL PILES

R.M.W. Frederking,
Research Officer,
Division of Building Research

National Research
Council of Canada

Canada

ABSTRACT

Systematic laboratory tests were carried out to determine the effects of deflection rate, ice thickness and pile diameter on vertically acting ice loads on piles. Wooden piles with diameters ranging from 50 to 145 mm were used in ice thicknesses from 25 to 200 mm. Tests were done at constant nominal deflection rates. Pile load was observed to increase with increasing deflection rate. Unit pile load increased with increasing ice thickness and decreased with increasing pile diameter.

Contents

Introduction

A floating ice cover can develop substantial vertical loads on a structure to which it is frozen as a result of changes in water level. For example, drawdown of a reservoir would generate downward loads while the water level increase resulting from a winter rainfall can generate upward-acting loads. Seiches in large lakes and storm tides in coastal waters may also lead to vertical ice loads. Isolated piles, pile groups, and long structures such as retaining walls and wharves are all susceptible to this sort of loading.

In the analysis of vertical ice loads on piles by Lofquist [1] he assumed that ice has a viscoplastic behaviour with deformation proportional to the cube root of time. A means for predicting vertical load was given, but no direct field or laboratory measurements were available to confirm the predictions. Stehle [2] has reported measurements of short- and long-term holding strength of wood piles in ice. Short-term tangential adfreeze strengths of about 2 MPa were reported for piles 70 mm in diameter. Measurements of vertical ice loads developed on instrumented piles have been reported by Doud [3]. A maximum load of 80 kN on a 356 mm diameter steel pile was developed by a 350 mm thick ice cover. Recently Parameswaran [4] carried out a laboratory study of the adfreeze bond between various pile materials and frozen ground. An adfreeze strength of 1 MPa was obtained at a displacement rate of 10^{-5} mm•s for British Columbia fir piles 75 mm in diameter. This brief review indicates that although there are some useful data in the literature there is a need for further systematic investigation of vertical ice loads on piles.

Some field tests with cylindrical piles were undertaken by the author several years ago [5], but weather conditions were so variable that uniform test conditions were difficult to obtain and it was impossible to repeat tests. It was decided, therefore, to simulate the field loading condition in the laboratory. Working in the laboratory, systematic investigations of pile diameter, ice thickness, loading rate, pile material, etc., could be undertaken.

In nature a water level change is usually the independent variable so in these experiments the relative rate of movement between the pile and the ice cover was made the controlled variable. This relative movement is comprised of bending of the ice cover and shear in the ice adjacent to the pile. At low loading rates, however, shear predominates. It is therefore possible to model interaction between a pile and the ice in a tank of relatively small diameter. A circular tank was designed in which a pile could be frozen into a uniform ice cover. A temperature gradient was maintained in the ice cover during a test. A loading frame placed over the tank contained a mechanism for drawing the pile up at a constant rate. This paper reports the results of laboratory tests on the effect of ice thickness, pile diameter and displacement rate on downdrag loads developed on a vertical wood pile.

Description of apparatus

The tank, which had a liner of galvanized steel, was 660 mm in diameter and 610 mm deep. Heating tapes (electrical resistance type) were coiled around the bottom and sides of the tank (Figure 1). Three separate tapes, each 18 m long and rated at at 420 W, were used. Thermocouple temperature sensors fixed directly to the bottom and lower side heating tapes allowed the temperature of each to be independently controlled. The bottom and sides of the tank were insulated to a thickness of about 100 mm with foamed-in-place urethane. A pressure relief tube, containing an electrical heating element, was connected to the bottom of the tank to ensure that excess pressure did not build up under the ice during the freezing process.

A load frame set up over the tank pulled the pile upwards relative to the ice by reacting against the liner. The outer perimeter of the ice cover was fixed to the tank by adhesion to the liner. Vertical motion was applied to the pile through a 50 kN capacity screw jack actuator. A variable speed DC motor drove the screw jack

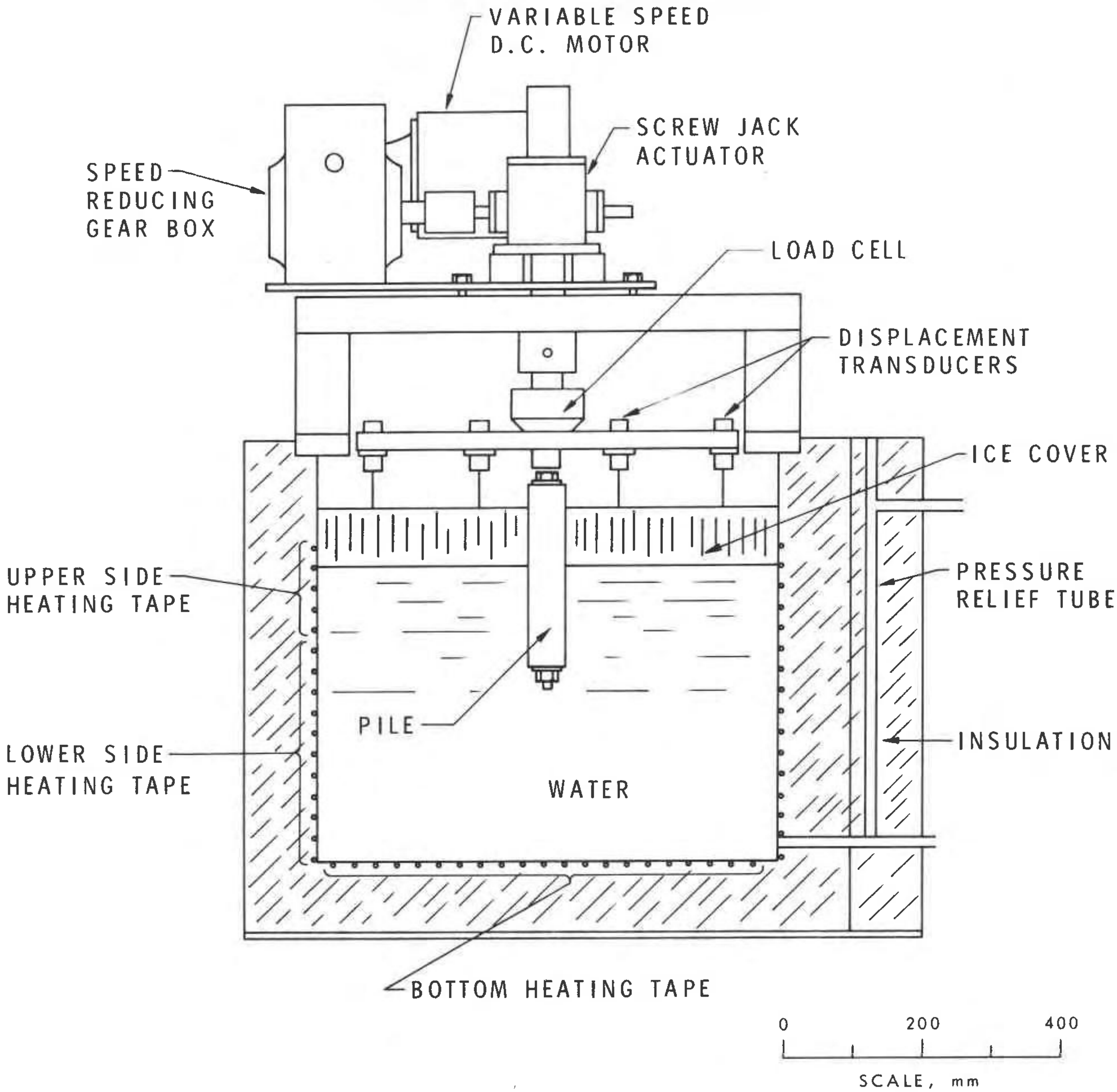

Fig. 1 Schematic of ice growing tank and pile loading apparatus

through one of two double-reduction speed-reducing gear boxes. With the low speed gear box, actuator speed could be varied infinitely over the range 7×10^{-5} mm·s^{-1} to 4×10^{-3} mm·s^{-1}. With the high speed gear box the range was 1.35×10^{-3} mm·s^{-1} to 3.5×10^{-2} mm·s^{-1}. Calibration tests confirmed these rates under both no-load and load conditions. Because of friction in the screw jack actuator a torque was imposed on the pile. At a load of 10 kN the torque was 45 N·m which corresponds to 2 kN at the pile radius of 25 mm. To reduce this effect a torque rod was used to restrain rotation of the pile.

Loads were measured by means of a load cell placed between the pile and the screw jack actuator (Figure 1). Four displacement transducers (linear variable differential transformers), placed on a cross arm at radii of 100 mm and 250 mm, measured relative displacement between the pile and the top surface of the ice cover. Load and displacement signals were recorded on analogue strip chart recorders and also fed into a digital data acquisition system for reduction and plotting of the results. Ice growth and ice temperature during the test were monitored via a thermocouple probe. Ice thicknesses during growth were checked with a resistance wire thickness gauge [6].

The piles were made of dry B.C. fir turned to a uniform diameter on a lathe. They were not treated in any way and had a surface roughness of ±0.1 mm. A threaded rod through the centre of the pile connected it to a coupler on the bottom of the load cell.

Test procedure

The ice growth and subsequent testing were carried out in a cold room which was maintained at -10°C. To model nature the pile was set in the tank and the ice grown around it. Before initiating ice growth the pile was fixed to the loading frame and carefully aligned vertically.

For ease of reproduction a type S-2 [7] columnar-grained ice cover was grown for all the tests. This type of ice is representative of the natural ice cover which generally forms on a lake. Satisfactory reproduction of the same ice for each test required careful attention to growth conditions. The procedure followed was as follows:

> The water in the tank was mixed until it had cooled to a uniform temperature of 4°C, the temperature of maximum density of water. With cooling below 4°C, water becomes less dense so that a temperature gradient develops. When the water temperature 10 mm below the surface reached 1°C the tank was seeded. Seeding was done by sieving (0.8 mm opening) fine-grained snow at -10°C onto the water surface. This initiated the formation of a fine-grain randomly-oriented surface layer of ice which within a couple of centimetres was transformed into a columnar structure in which the crystallographic symmetry axes were randomly oriented tending to be in the horizontal plane. The ice cover grew at a rate of about 25 mm per day. To maintain a continuous columnar structure, heat was applied through the heating tapes to keep the water temperature at the bottom of the tank at between 3.5 and 4°C. Ice of reproducible characteristics could be formed in this fashion.

At 15 mm depth the average grain size was 1.5 mm and at 80 mm, 4 mm. The ice thickness in the tank was quite uniform with no thickening adjacent to the pile. The cold room used for the tests had a fairly low humidity so several millimetres of ice sublimated off the surface during the ice-growing period. The normal ice thickness for the majority of the tests was 80 mm so about two tests could be run each week.

Before running a test the displacement transducers, load cell and electronics were set up and allowed to stabilize for at least an hour. Tests were run at a nominal constant rate.

Test results

Over 20 tests were carried out to investigate effects of deflection rate, ice thickness and pile diameter on vertical pile loads. Continuous records of load and deflections versus time were made for all tests. Temperature profiles of the ice cover were also measured in each case. All the test conditions and results are presented in Table I. Details of the information in the table will be discussed later in this paper.

To illustrate the load- and displacement-time behaviour the results from test No. 7 are plotted in Figure 2. The first point evident from these results is that the actual displacement rate of the pile with respect to the ice cover is not constant. In the example illustrated in Figure 2 the displacement rate increased continuously reaching a value of 1.43×10^{-3} mm$\cdot$s^{-1} at yield and only approached the nominal rate of 2.4×10^{-3} mm$\cdot$s^{-1} in the post yield region. Characterizing the test with a single displacement rate is questionable. Examining the load-time curve in

TABLE I: RESULTS OF LABORATORY TESTS WITH WOODEN PILES

Test No.	Nominal Deflection Rate, $mm \cdot s^{-1}$	Pile Diameter, mm	Ice Thickness, mm	Maximum Load, kN	Time to Maximum Load, s	Load Rate, $N \cdot s^{-1}$
1	2.4×10^{-3}	50	165	c 16.8 y	240	8.9
2	2.4×10^{-3}	50	152	16.4 c	2000	12.2
3	2.4×10^{-3}	50	102	12.9 c	1550	12.9
4	4.3×10^{-3}	50	146	16.7 c'	1100	24.8
5	2.1×10^{-4}	50	172	10.7 y	18500	0.82
6	4.3×10^{-4}	50	216	16.1 y	9050	2.9
7	2.4×10^{-3}	50	70	c 6.2 y	1650	6.3
8	2.4×10^{-3}	50	93	c 8.5 y	1500	9.8
9	2.4×10^{-3}	50	67	c 5.2 y	1500	6.4
10	2.4×10^{-3}	50	150	c 15.2 y	1750	13.0
11	2.4×10^{-3}	50	60	4.7 c	1150	4.5
12	2.4×10^{-3}	50	25	c 1.04 y	930	2.6
13	9.3×10^{-4}	50	98	c 6.9 y	4700	2.16
14	4.3×10^{-4}	50	80	c 5.0 y	8100	0.92
15	4.3×10^{-3}	50	89	c 8.9 y	730	1.13
16	2.4×10^{-3}	100	67	*	-	-
17	2.4×10^{-3}	100	70	c 6.5 c	1450	6.2
18	2.4×10^{-3}	145	83	c 10.0 y	800	1.48
19	1.0×10^{-2}	50	90	c 9.3 c'	290	38
20	2.0×10^{-2}	50	86	c 9.2 c'	142	77
21	1.4×10^{-2}	50	75	c 7.4 c'	195	42
22	3.5×10^{-2}	50	86	c 8.2 c'	85	139

*Test aborted due to ice slippage on tank wall.

Figure 2 suggests that the test condition could be reasonably approximated as a constant loading rate. The displacement- and load-time behaviour of test No. 7 was generally typical of all tests in the series.

Ice subjected to uniaxial compressive loading at constant nominal cross-head rates on a conventional test machine shows load- and displacement-time behaviour [8] similar to that exhibited in this series. This behaviour is controlled by the relative stiffness of the test machine and the ice specimen and is the subject of another paper to be presented at this conference [9].

Figure 2 also serves to illustrate the failure process of the ice sheet and the maximum ice load developed on the pile. As the pile is displaced upward with respect to the ice the load increased monotonically and tensile radial and circumferential stresses are set up in the upper part of the ice cover. The ice is

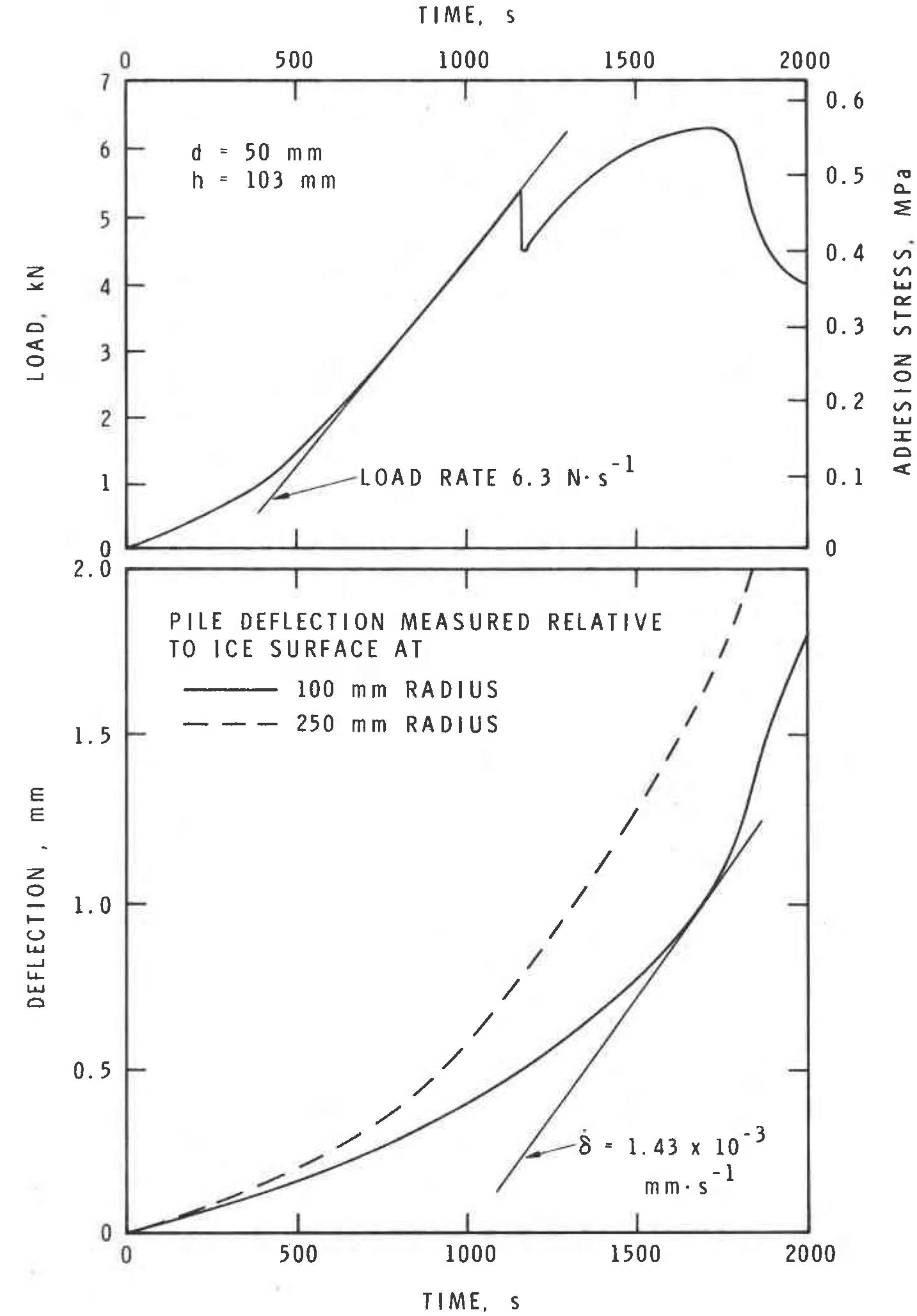

Fig. 2 Results of test No. 7. Nominal deflection rate: 2.4×10^{-3} mm$\cdot$s^{-1}; pile diameter: 50 mm; ice thickness: 103 mm

observed to gradually separate from the top of the wood pile. At a load level of about 1 kN the first vertical micro cracks (1 mm or smaller) appeared within 10 to 20 mm of the pile. They tend to be vertically aligned, i.e., parallel to the columnar grains. Between a load of 3 and 4 kN small "plate" cracks, oriented parallel to the ice surface began to develop on a plane midway through the ice cover adjacent to the pile. The separation of the ice from the pile at this time extended down about 10 mm. The next event in the failure process was the abrupt development of radial cracks which extend through the full depth of the ice and ran from the pile out to the tank wall. An abrupt drop in pile load was associated with the formation of these radial cracks. There is, however, no corresponding inflection in the deflection-time curve. As the pile continues to move the load again increases while at the same time the "plate" cracks gradually coalesce into a conical failure surface. A characteristics yield-type maximum load occurs with the extensive development of the conical failure surface. A cross-section of the conical failure surface is shown in Figure 3. In the case of test No. 7 the

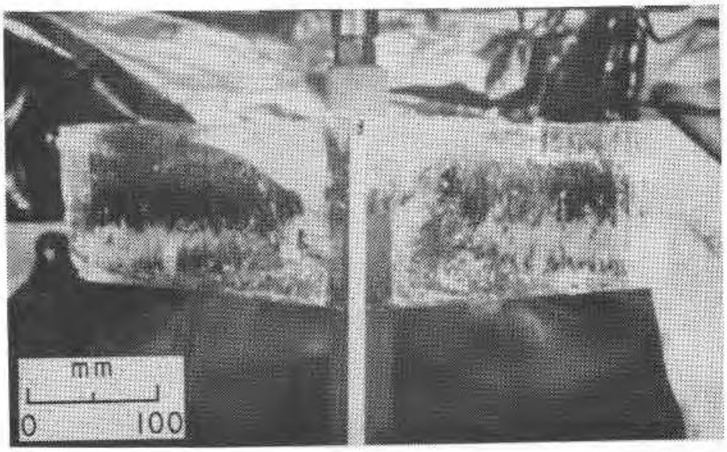

Fig. 3 Cross-section of conical failure surface

maximum pile load was associated with yield; in some tests, however, the subsequent yield load was lower than the initial crack load.

The failure process in each test is indicated by the prefix and suffix codes in the Maximum Load column of Table I. The prefix c indicates that radial cracks occurred before the maximum load was reached. The suffix y indicates that maximum load was associated with yield behaviour; the suffix c indicates maximum load corresponded to radial crack occurrence. The prime on the suffix c indicates that the load drops abruptly to near zero after the crack at maximum load occurs.

Typical results for the ice temperature profiles from test No. 13 are shown in Figure 4. The initial average ice temperature was -2.0°C and it increased to -1.7°C over the 5000 s interval of the test. In most cases the test time was shorter and the temperature increase was less.

Analysis of results

The test results have been analysed in terms of deflection rate, ice thickness and pile diameter effects.

(i) Deflection rate effects

In considering the effect of deflection rate on vertical pile loads the load results have been reduced in terms of an adhesion strength, τ, defined as

$$\tau = \frac{P}{\pi dh} \tag{1}$$

where P is maximum vertical ice load on the pile, d is pile diameter and h is ice thickness. The adhesion strengths measured in the laboratory tests at constant nominal deflection rate, $\dot{\delta}$, are plotted in Figure 5. Also shown in the figure are the results of field tests [5] carried out under a state of constant load. The test conditions of these data cover quite a broad range; ice thickness 25 to 500 mm and pile diameter 50 to 150 mm; but a general trend of increasing strength with increasing nominal deflection rate is clearly exhibited. A regression analysis gave the following best fit equation to the laboratory test data

$$\tau = 0.51 \left(\frac{\dot{\delta}}{10^{-3}}\right)^{0.175} \tag{2}$$

where τ is in MPa and $\dot{\delta}$ is in $mm \cdot s^{-1}$

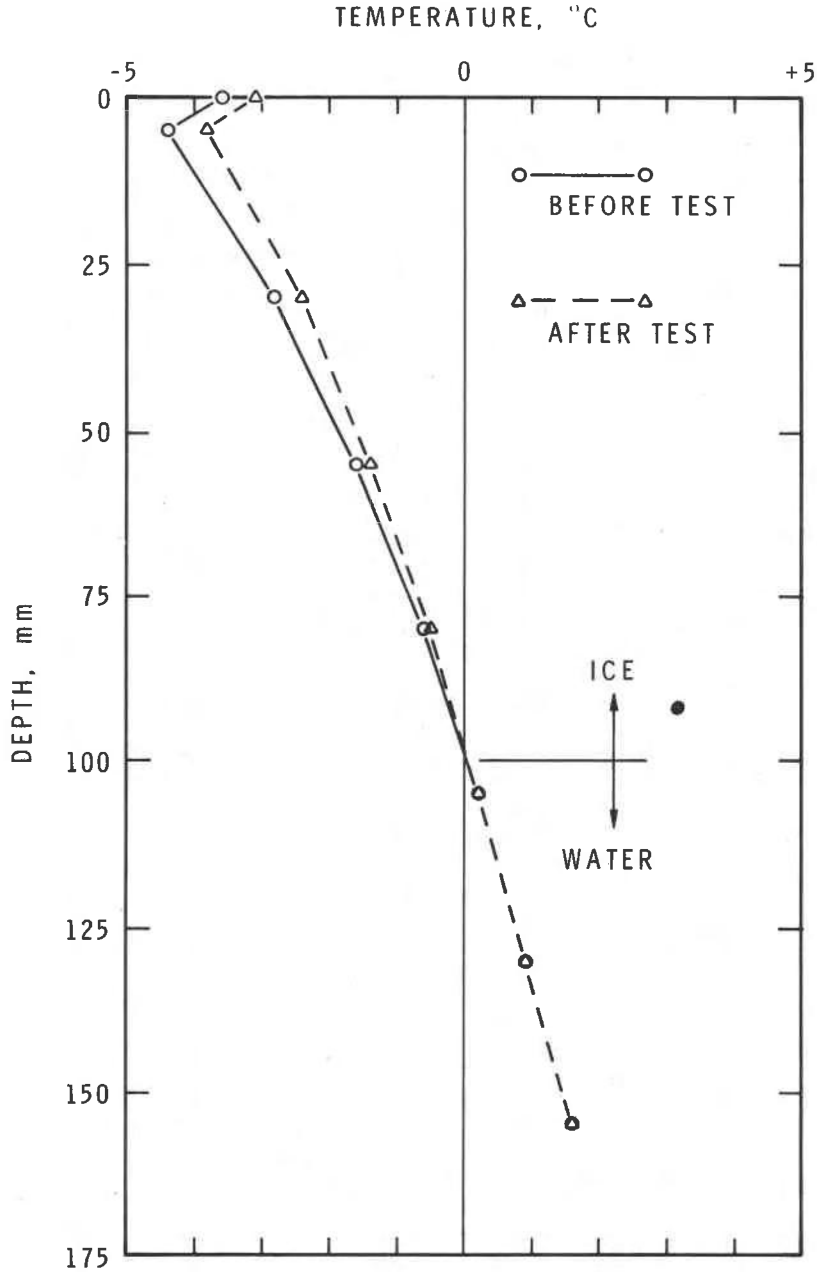

Fig. 4 Ice temperature profile, test No. 13

(ii) Ice thickness effects

The next stage of the analysis of the data was to examine the laboratory test results in terms of ice thickness. The adhesion strengths for a 50 mm diameter pile have been classified into two groups by ice thickness and plotted versus nominal deflection rate in Figure 6. A line is drawn through each group of results to help clarify the difference between them. It is seen that in addition to a deflection rate effect there is an increase in adhesion strength with increasing ice thickness.

A specific series of tests to examine ice thickness effects was carried out at a constant nominal deflection rate of 2.4×10^{-3} mm$\cdot$s^{-1} with a 50 mm diameter pile. The results of this series, given in Figure 7 show that the adhesion strength increases with approximately the square root of the ice thickness. A regression analysis gave the following best fit to the data

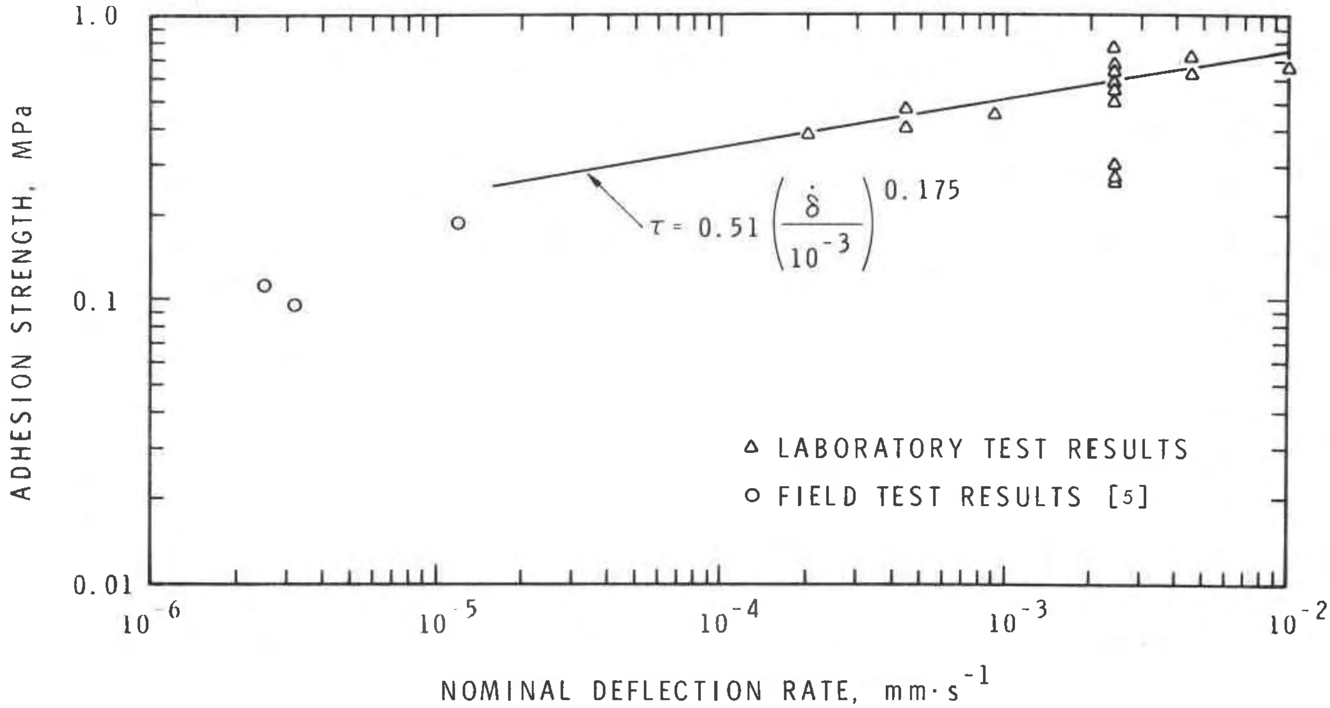

Fig. 5 Adhesion strength vs nominal deflection rate for laboratory and field tests with wooden piles

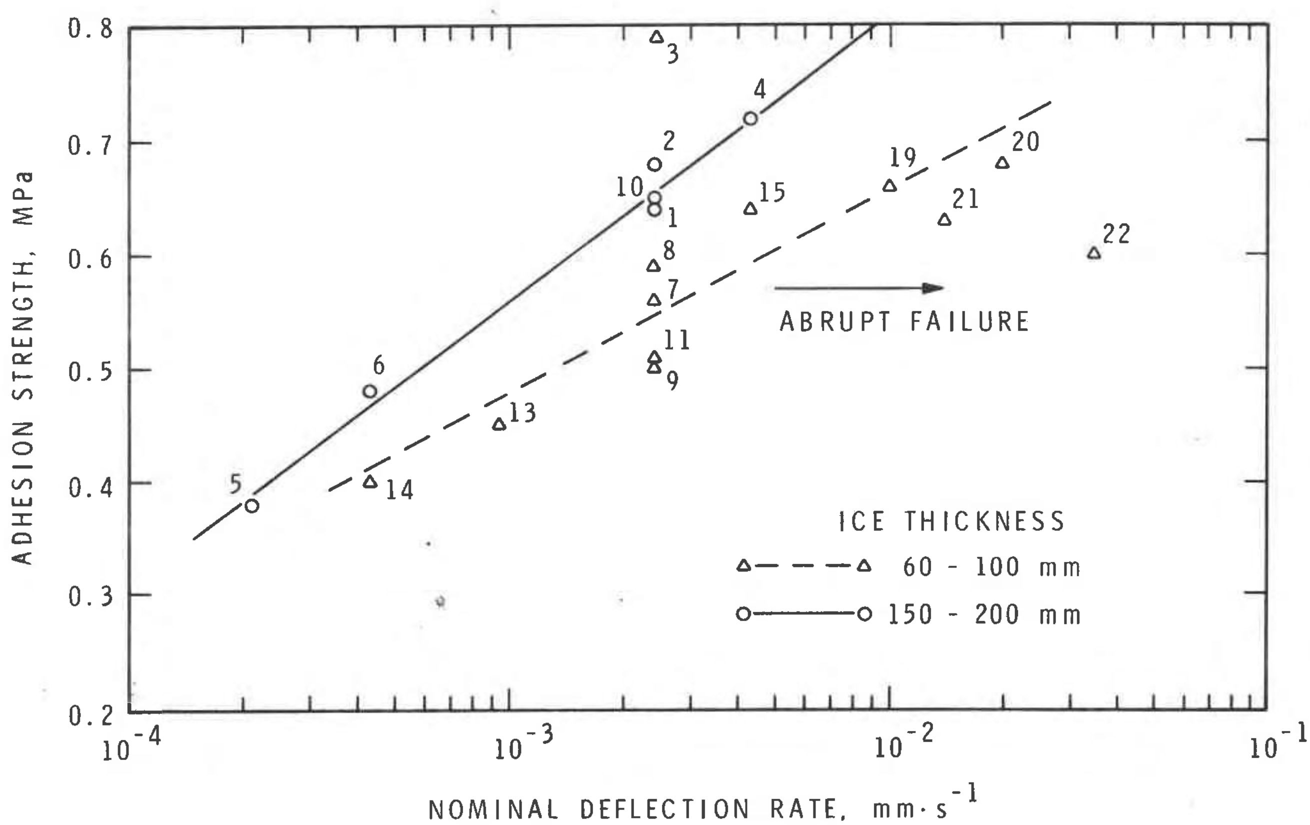

Fig. 6 Deflection rate dependence of adhesion strength of 50 mm diameter wood pile in ice. (Note: numbers adjacent to data points refer to test number of Table I.)

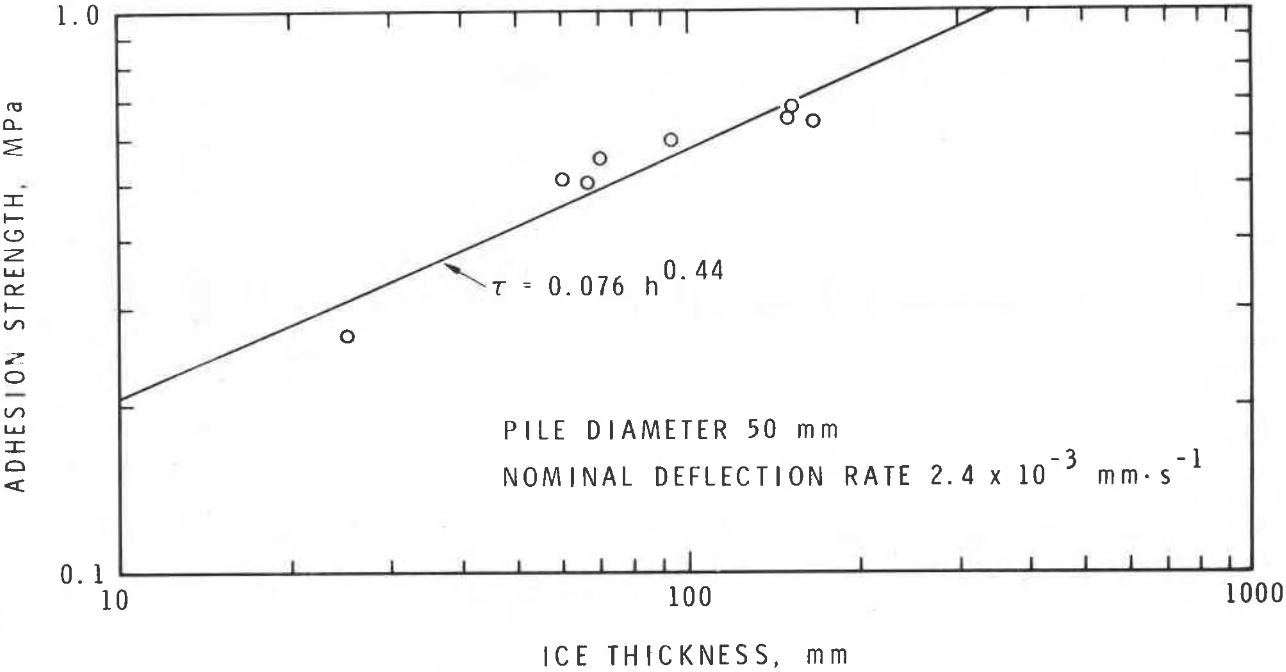

Fig. 7 Effect of ice thickness on adhesion strength

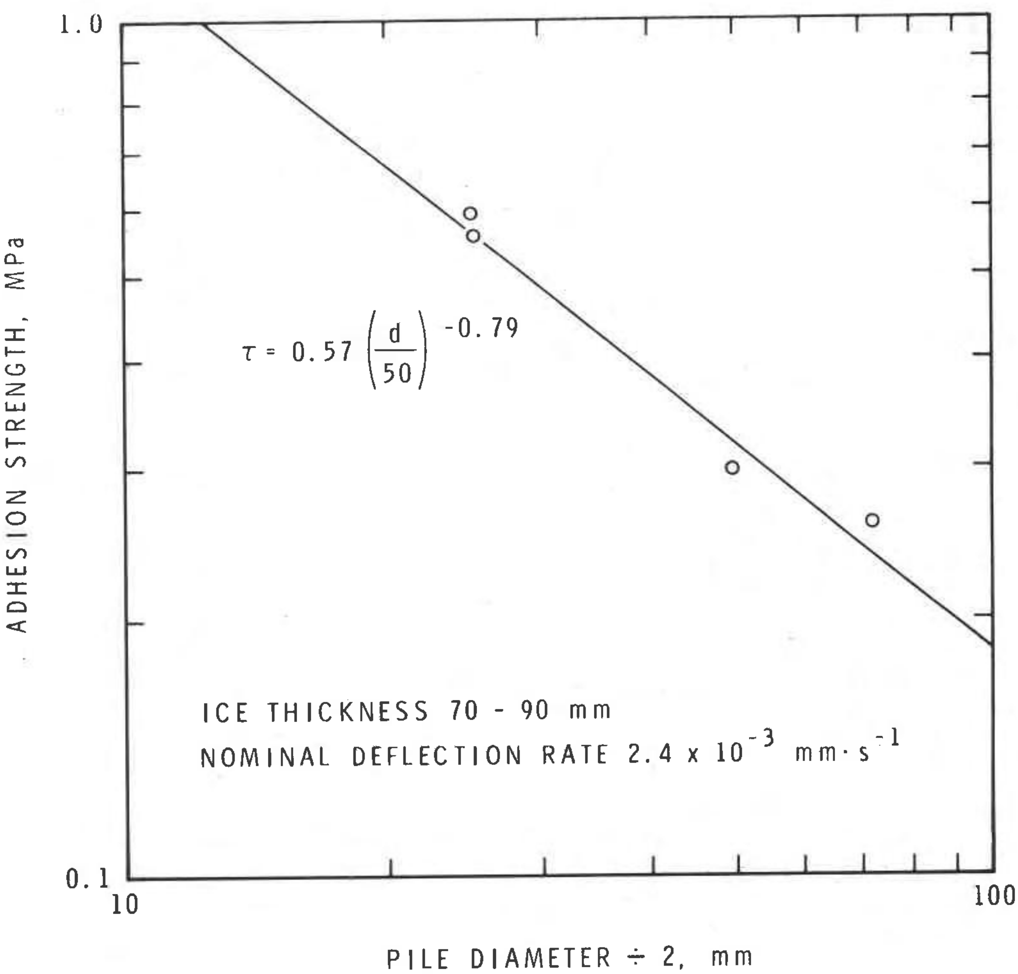

Fig. 8 Effect of pile diameter on adhesion strength

$$\tau = 0.52 \left(\frac{h}{80}\right)^{0.44} \tag{3}$$

where h is in mm and τ is in MPa.

(iii) Pile diameter effects

A very limited number of tests were carried out to investigate the nature of the pile diameter influence on adhesion strength. They were done at a nominal deflection rate of 2.4×10^{-3} mm$\cdot$s^{-1} and an average ice thickness of 80 mm. These results show that the adhesion strength decreases with increasing pile diameter (Figure 8). A regression analysis gave the following best fit to the data

$$\tau = 0.57 \left(\frac{d}{50}\right)^{-0.79} \tag{4}$$

where d is in mm and τ is in MPa.

(iv) Stress rate

As already pointed out, the laboratory tests could probably be described more accurately as constant loading rate tests. With this in mind the results for the 50 mm diameter pile were replotted in terms of the loading stress rate in Figure 9. A straight line has been drawn through each of two ice thickness groups.

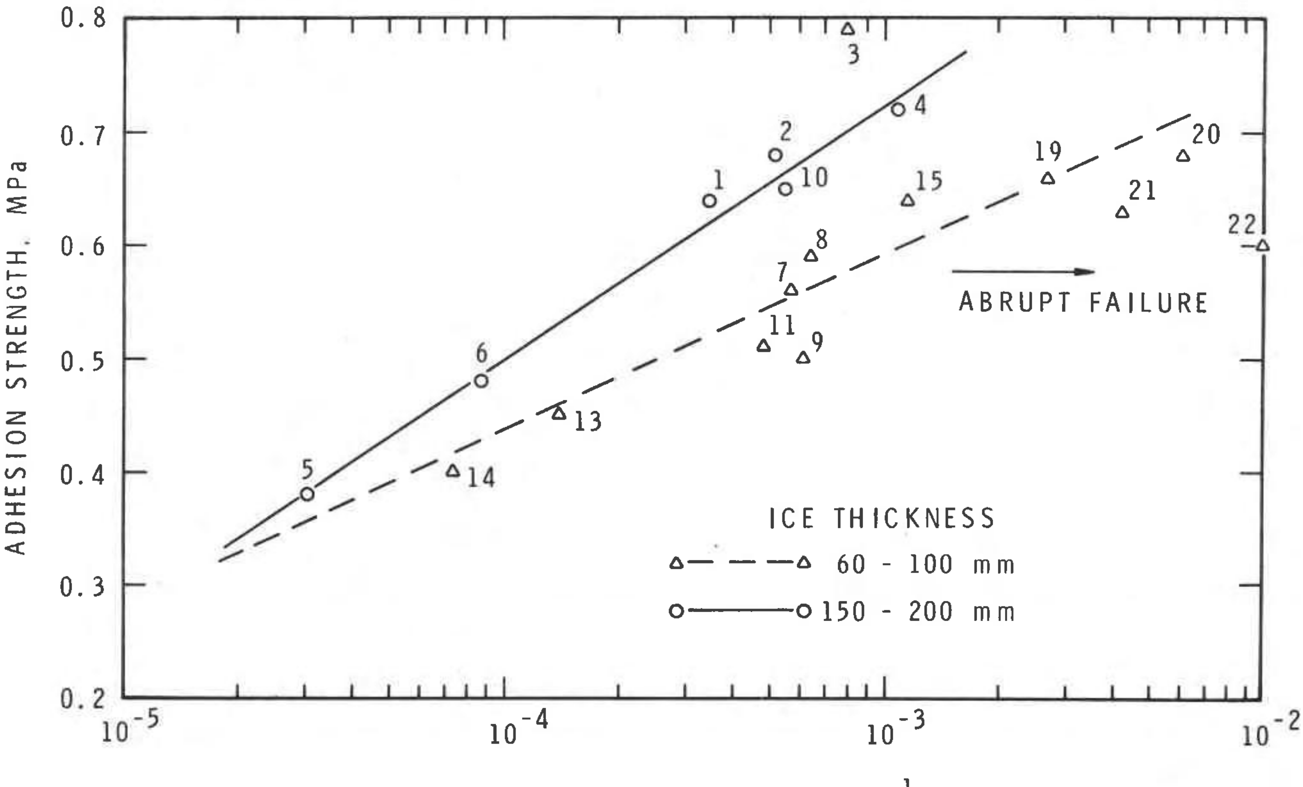

Fig. 9 Stress rate dependence of adhesion strength of 50 mm diameter wood pile in ice. (Note: numbers adjacent to data points refer to test number of Table I.)

Discussion of results

The results of the laboratory tests show a very definite deflection rate effect on adhesion strength. There is a general increase in strength with increasing rate up to about 5×10^{-3} mm•s^{-1}. Parameswaran [4] has observed similar behaviour with 75 mm diameter B.C. fir piles in frozen sand. Over a deformation rate range similar to that of this study he found the exponent of the power law relation to be 0.22 compared with the value of 0.175 found in this study. For deformation rates greater than 5×10^{-3} mm•s^{-1}, in the region of abrupt failure, the adhesion strength appears to remain constant. This is similar to the strength behaviour of ice subjected to uniaxial compressive loading [8].

A general trend of decreasing adhesive strength with decreasing ice thickness has been observed. This is to be expected since for thin ice the flexural stress, which varies with $1/h^2$, is relatively greater than the adhesion stress, which varies with $1/h$. Therefore with the thinner ice flexural failure would predominate and the associated adhesion strength would be relatively lower. The theoretical work of Mohaghegh and Coon [10] also supports this trend of decreasing adhesive strength with decreasing ice thickness for the case of thick circular plates.

Adhesion strength was observed to decrease with increasing pile diameter. This same trend was predicted theoretically by Lofquist [1] for piles frozen into infinite ice sheets and by Mohaghegh and Coon [10] for circular plates.

Combining deflection rate, ice thickness and pile diameter effects of the current tests, i.e., Equations (2), (3) and (4), the following composite empirical equation can be formulated

$$\tau = 0.67 \left(\frac{\dot{\delta}}{5 \times 10^{-3}\ \mathrm{mm \cdot s^{-1}}}\right)^{0.175} \left(\frac{d}{50\ \mathrm{mm}}\right)^{-0.79} \left(\frac{h}{150\ \mathrm{mm}}\right)^{0.44} \quad [\mathrm{MPa}] \qquad (5)$$

for the following ranges

$$10^{-4}\ \mathrm{mm \cdot s^{-1}} \leq \dot{\delta} \leq 5 \times 10^{-3}\ \mathrm{mm \cdot s^{-1}}$$

$$50\ \mathrm{mm} \leq d \leq 150\ \mathrm{mm}$$

$$25\ \mathrm{mm} \leq h \leq 150\ \mathrm{mm}$$

Extrapolating beyond these ranges should only be done with great caution. The test data suggest that for deflection rates greater than 5×10^{-3} mm•s^{-1} there is no further increase in adhesion strength. It should also be pointed out that the adhesion strengths given by Equation (5) are maximum or upper bound values which are only achieved when sufficient deflection has occurred.

Observations of the failure process for this test series showed that a combination of flexural and shear behaviour was present in all cases. The relative contributions varied with test conditions, flexure predominating for the thinner ice sheets and shear for the thicker ice. In the 150 mm thick ice sheets the conical failure surface started to develop before any radial cracks formed. Radial cracks were observed to be a part of the failure process except for deflection rates less than 4×10^{-4} mm•s^{-1}, in which case shear predominated. In the region of abrupt failure, $\dot{\delta} > 5 \times 10^{-3}$ mm•s^{-1}, radial cracking preceded the peak load, but final failure was associated with instantaneous development of the conical failure surface.

It is useful to compare the predictions of Equation (5) with information in the literature. Lofquist's [1] theory indicates a maximum adhesive strength of 0.24 MPa for a 200 mm diameter pile and a 200 mm ice thickness. For similar conditions Equation (5) predicts an adhesion strength of 0.25 MPa. Stehle [2] measured rapid loading adhesion strength of 1.7 MPa for 75 mm diameter piles frozen into fresh water ice of 250 mm thickness whereas Equation (5) predicts an adhesion strength of 0.61 MPa. It should be noted however that Stehle's loading was pure shear with no bending so her adhesion strengths would be expected to be higher.

Conclusions

1. Adhesion strength increases with deflection rate up to a point and then appears to remain constant.

2. Adhesion strength decreases with decreasing ice thickness.

3. Adhesion strength decreases with increasing pile diameter.

4. The downdrag loads developed on wood piles by a floating ice cover are a function of both flexural and shear failure in the ice.

Acknowledgements

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