CRREL REPORT 77-10

Ice forces on vertical piles

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Cover: Four-inch-wide round pile in natural ice.
(Photograph by CRREL Photo Service.)

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The amount of force that an ice sheet can apply to a vertical pile was tested by lowering a hydraulic ram device into a hole cut in an existing ice sheet. The device had a large base and shoved a relatively narrow vertical pile in a horizontal direction. Test variables were: pile widths – 1.5 in. to 36.7 in.; pile shapes – flat, round, 45° and 90° wedges; ice thickness – 2.6 in. to 8.8 in.; and ram speed – 0.07 in./sec to 18.75 in./sec; but not all shapes and sizes were tested at all speeds. Air temperature was 20°F (-6.7°C). Forces and displacements were measured electronically. The findings are presented as a table of test results and as bar graphs of the resultant ice pressures versus the pile width-to-ice-thickness ratio, pile width and shape combination and pile velocity. The types of failures in the

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ice sheet were classified as crushing, splitting, buckling, bending, and creeping. The ice sheet generally withstood a high initial load followed by several lower peak load levels. The maximum ice pressure measured was 610 psi for a 12.6-in.-diam round pile in 8.4-in.-thick ice.

PREFACE

This report was prepared by Dr. Donald E. Nevel, Research Physical Scientist, Applied Research Branch, Roscoe E. Perham, Mechanical Engineer, Northern Engineering Research Branch, and Gary B. Hogue, Specialist 5, Applied Research Branch, of the Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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This report was technically reviewed by Dr. George D. Ashton and Guenther Frankenstein of CRREL.

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	0.0254*	meter
foot	0.3048*	meter
$inch^2$	0.00064516*	$meter^2$
gallon	0.003785412	$meter^3$
gallon/minute	0.00006309020	$meter^3$/second
psi	6894.757	pascal
ton	8896.444	newton

* Exact.

ICE FORCES ON VERTICAL PILES

by

D.E. Nevel, R.E. Perham and G.B. Hogue

INTRODUCTION

The forces that floating ice sheets exert on vertical piles are important to the design of both military and civilian structures. Present design codes call for 400 psi as the crushing strength of ice without regard to the influencing factors and their variations. The forces which drive the ice into a structure are due to water currents, wind, or thermal expansion. These driving forces may be large enough to cause the ice to fail at or near the structure. The purpose of this research was to define this limiting force level and to gain a better understanding of the failure process in the ice.

LITERATURE REVIEW

In the winter of 1932-33, Hill[4] measured the ice forces at Hastings lock and dam on the Mississippi River about 20 miles below St. Paul, Minnesota. For these measurements, he sensed the strain in a taintor gate at the dam and the deflection of a 12-ft horizontal beam supported on the lock wall. From 1947 to 1951, Monfore[8] measured the ice forces on a number of Colorado reservoirs. He used indentor gages and electrical resistance gages of 2½-in. diameter. In both cases, three gages were embedded in thin mortar panels 12½ by 22½ in. During the winter of 1951-52, Willmot[16] measured ice forces at the Des Joachims Dam, on the Ottawa River in Canada, by means of load cells placed behind a 10 by 10-ft panel which was set flush with the dam.

From 1962 to 1969, Peyton[12, 13] and Blenkarn[2] measured the forces of sea ice under strong tidal action in the Cook Inlet near Anchorage, Alaska. The measurements were obtained from a strain-gaged cantilever pile, strain-gaged offshore oil drilling platforms, and a simple beam vertical pile whose reaction was measured by a load cell. In the winters of 1967-68 and 1968-69, Schwarz[14] measured the pressure distribution on a pile in a tidal estuary of the Eider River in Germany. The pile was covered with a shield consisting of 50 load cells.

Since 1967, Neill[9] and Neill et al.[10] have measured the ice forces on a vertical and on a sloping bridge pier near Edmonton, Alberta, during the spring breakup. These forces have been measured by recording the reaction of a simple beam shield on the upstream side of the piers. In 1970, Croasdale[3] measured the ice strength in Tuktoyaktuk Harbor near the Mackenzie Delta. He used four nutcracker-like structures, with 30-in.-diam legs which floated vertically, with the hinges deeply submerged. After freezeup, the tops of the legs were pushed apart, causing the ice to fail. These tests measured the ultimate resistance of the ice rather than the driving forces of nature. Recently, Afanasev et al.[1] moved piles mounted on an overhead carriage through model sea ice up to 1.4 in. thick that was grown in a model test basin.

This literature review has considered only ice force measurements and not theories. Further references can be obtained in the review papers by Michel[7] and Korzhavin.[5, 6]

TEST EQUIPMENT AND PROCEDURE

In order to meet the research objective, a test had to be chosen that would simulate the ice pushing against piles as closely as possible. Unconfined compression tests were ruled out because the results of

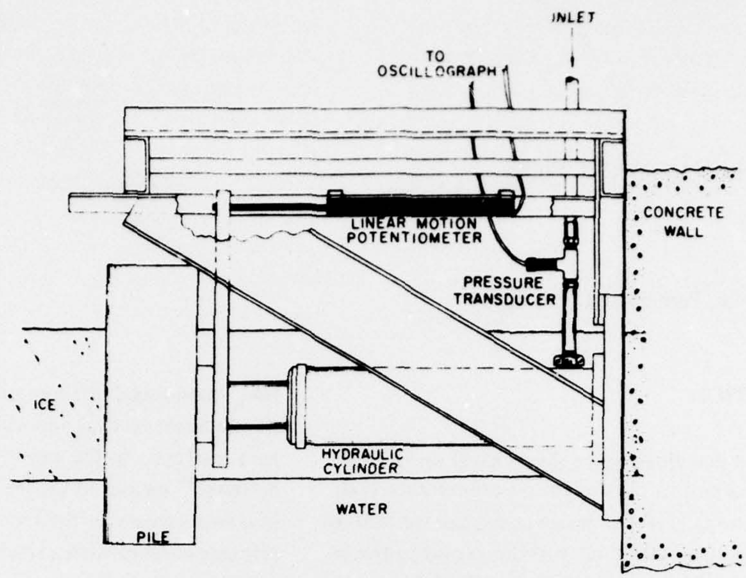

Figure 1. Testing apparatus.

these tests cannot be directly related to field results. Shadrin and Panfilov[15] and Nuttall and Gold[11] ran penetration tests on the edges of small ice sheets in conventional testing machines. This type of testing was also discarded, however, because of sample size limitation and the difficulty of preparing samples and obtaining realistic temperature profiles through the ice thickness. Instead, an ice cover was grown on water similar to natural conditions and tested in place.

To do this, a 21-x 21-ft refrigerated room that had originally been designed to hold snow was converted to hold water. This pit-like room was flooded with about 4 ft of sea water and a working platform was constructed about 1 ft above the water surface. The planking on the platform was movable to provide uniform cooling of the water below. The ice was grown at an air temperature of -20°F. The temperature was raised to +20°F a day before testing to maintain a more constant ice thickness during the test period. Temperature and salinity profiles were measured during each test day to define the state of the ice. Just before freezing ice sheet 5, a swimming pool pump was used to filter the water, vacuum the bottom of the pool, and skim the water surface. This procedure was used for the remainder of the ice sheets.

Instead of the ice sheet being pushed into the pile, the pile was pushed into the ice sheet by means of a 50-ton hydraulic cylinder. A 14-x 16-in. aluminum plate was attached to the base of the cylinder and the simulated pile was located on the rod end as shown in Figure 1. A hole was cut into the ice next to the concrete bearing wall. The outer edge of this hole was cut to conform to the shape of the pile. The apparatus was lowered into the hole and centered on the ice thickness by adjustable cables. The slack between the wall and the ice was taken up by applying oil pressure to the cylinder.

An electric pump was used to store hydraulic oil in a 2½-gal accumulator at pressures up to 6000 psi. This energy was released manually, and quickly, by opening a shutoff valve. The flow passed through adjustable, constant-flow control valves on its way to the hydraulic cylinder. Two control valves assembled in parallel provided a flow range from ½ to 70 gal/min. These flow rates, coupled with the cylinder piston area of 11.05 in.^{2} and a stroke of 13 in., provided tests lasting from about ½ sec to 1 min.

A linear motion potentiometer was mounted parallel to the cylinder and well above it to prevent it from getting wet. The potentiometer directly indicated the pile's displacement and provided a check for uniformity of velocity. A pressure transducer measured the hydraulic oil pressure near the cylinder inlet. Both displacement and pressure were recorded on an oscillograph. Also, the recorder had an automatic, accurate timing marker and an event marker that an observer could operate.

The cylinder rod was found to need an antirotation guide to prevent the tops of the piles from rotating side to side as they moved through the ice. Round piles were provided in diameters of 1.5, 3.0, 4.5, 7.5, 12.6, 18.0 and 36.7 in. Flat piles were provided in widths of 1.5, 3.0, 4.6, 5.5, 8.0, 12.0, 18.0 and 35.9 in. Piles with a 90° angle were provided in widths of 1.5, 3.5 and 4.7 in., while piles with a 45° angle were provided in widths of 1.5, 2.9 and 4.8 in. All piles whose widths were less than 4.5 in. were mounted on an extension plate to prevent the cylinder rod from scraping against the ice. Most of these piles were tested.

TEST RESULTS

The results of the testing for each ice sheet will be discussed separately, since significant differences in the ice sheets were observed. In Table I the results are given for each test except for the peak nominal ice pressures, which are given in Figures 2-8. The nominal ice pressure is defined as the force divided by the ice thickness times the pile width. In some cases, a line on the bar graph represents more than one peak. The extra heavy line for each test represents the initial peak. For these tests, the first digit of the test number is the number of the ice sheet.

The objective of ice sheet 1 tests was to investigate the effect of speed for a 4.5-in. round pile on the strength of the ice. The results from tests 101 to 107 indicate that the speed had no effect within the speed range tested. All these tests, except 106, showed that the initial peak was the maximum peak. The tests that followed were run in an attempt to explain this. Test 108 was started and stopped a number of times, and test 109 was run using the ice sheet as the reaction rather than the concrete wall. In both tests, the initial peak was still the maximum. In test 110, the ice was cut flat rather than conforming to the shape of the circular pile, and test 112 was run with 6 in. of open water followed by 6 in. of ice. Both these tests showed a low initial peak because the piles did not make full contact with the ice initially. Test 111 was run in open water and showed no appreciable force level. The only reasonable explanation for the high initial peak is that the pile was initially in full contact with the ice and broke out a larger piece of ice than any of the succeeding pieces.

In all the tests on ice sheet 1, the failure is best described as *crushing*. Internal cracks developed in front of the pile, and the broken ice pieces were pushed either up or down from the center of the ice sheet thickness. Observations at the end of each test showed that the pile was in full contact with the ice near the center section of the sheet and that the upper and lower sections were composed of completely broken-up pieces of ice. Usually, at the beginning of the test, radial cracks would propagate from the pile in the direction of push and at 45° from this direction. By using the event marker, it was verified that these cracks occurred before the initial peak load. These results are shown in Figure 2.

The objective of ice sheet 2 tests was to determine the effects of pile shape and pile width on ice strength. Round piles were used for these tests. The results are shown in Figure 3 (tests 201 to 208). In test 203, the ice crushed on one face of the 90° pile, while sliding along the other face. Then the faces reversed their action a number of times, causing a zigzag movement of the pile through the ice sheet. This indicated a high horizontal force on the pile perpendicular to the direction of push.

In test 204 the ice split and moved into a previous test area. This *splitting* type of failure is common in nature, but only occurred once during these tests because the concrete walls confined the ice sheet. The force level was not obtained. In test 205, a crushed lobe-shaped area developed initially from each face of the 45° pile, but this was not repeated after the pile motion began. Test 208 was started one day, then stopped and completed the next day to see if the ice rubble around the pile would freeze together. Results indicated that this did not happen.

In test 209, the electric pump was used directly to produce a very slow test. Internal cracking occurred and these cracks became connected along the lines of the maximum shear stress. This type of failure has been labeled *creep*. For test 210, the temperature of the room was lowered to 0°F one day before the test. For this colder, thicker ice, the loading system did not have sufficient load capacity and a creep failure occurred.

The objective of ice sheet 3 tests was to study further the effect of round pile sizes on ice strength. A thinner sheet was used so that tests of larger piles could be run. The results are shown in Figure 4. Tests 301, 302 and 303 failed because the ice sheet buckled up along a circumferential line about 2 to 3 ft from the pile. There was no vertical movement of the ice at the pile. Test 304 was a crushing failure; in test 305, the ice sheet jumped up as if buckling had started, but the pile crushed its way through the ice.

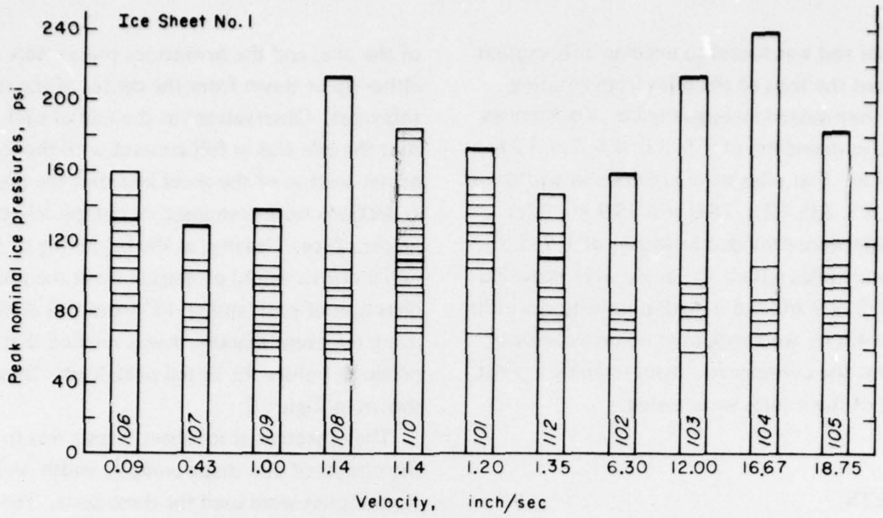

Figure 2. Effect of pile velocity on strength of ice sheet 1. Numbers on bar graphs are test numbers.

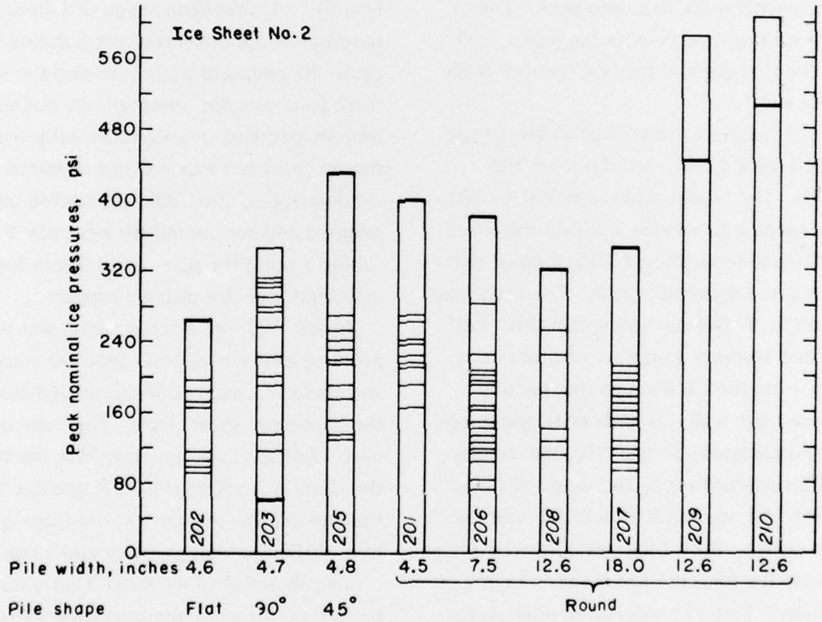

Figure 3. Effect of pile shape and width on strength of ice sheet 2.

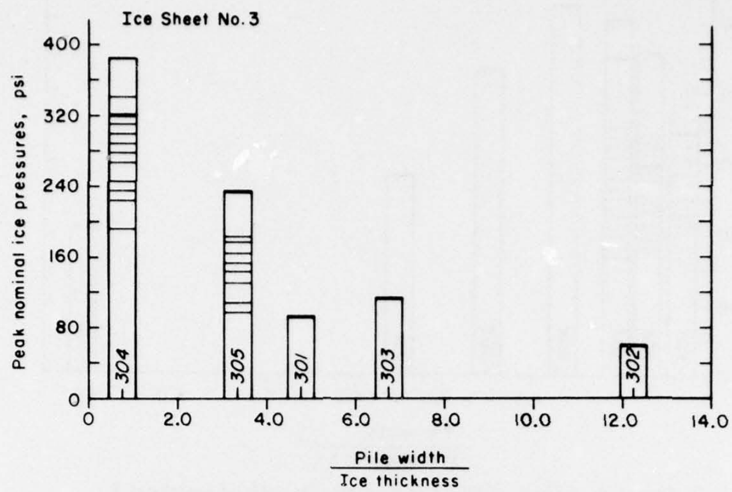

Figure 4. Effect of round pile size on strength of ice sheet 3.

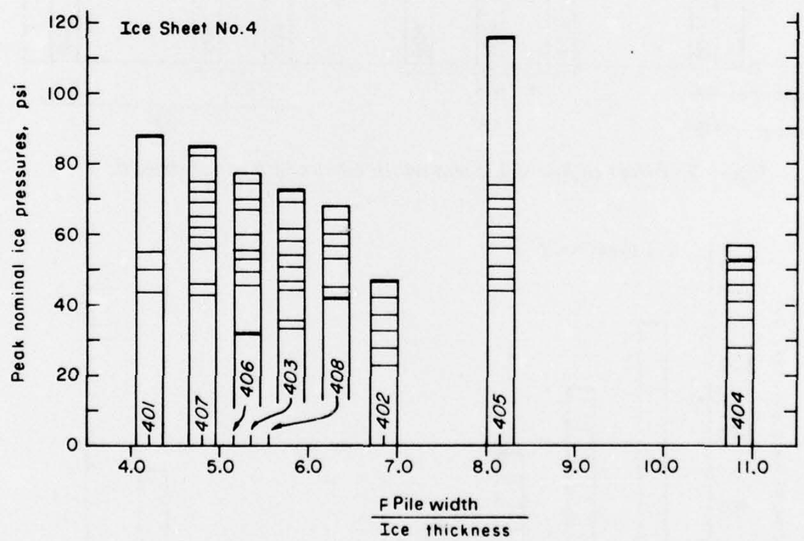

Figure 5. Effect of round pile size on strength of ice sheet 4.

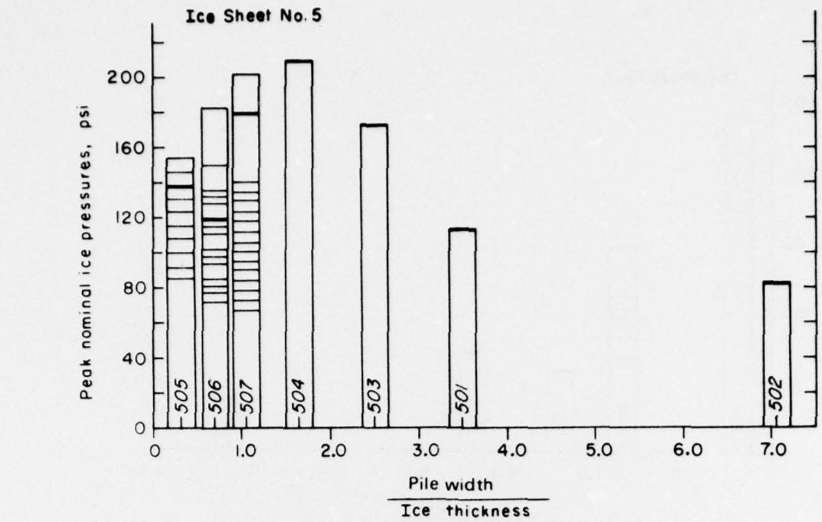

Figure 6. Effect of flat pile size on strength of ice sheet 5.

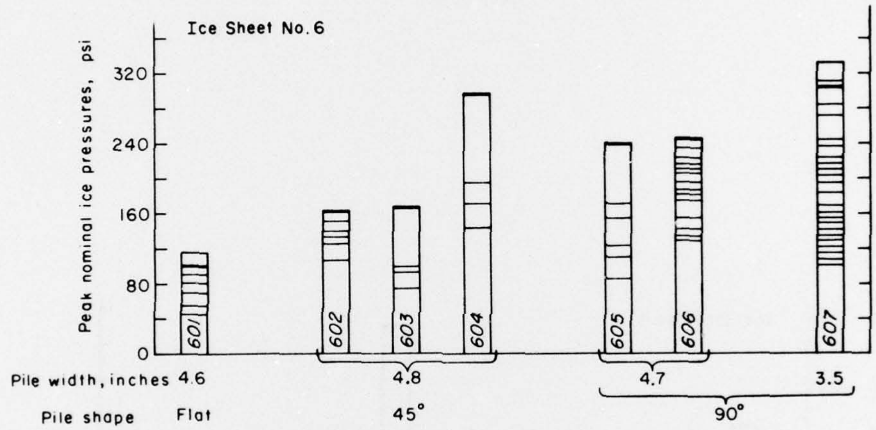

Figure 7. Effect of pile shape and width on strength of ice sheet 6.

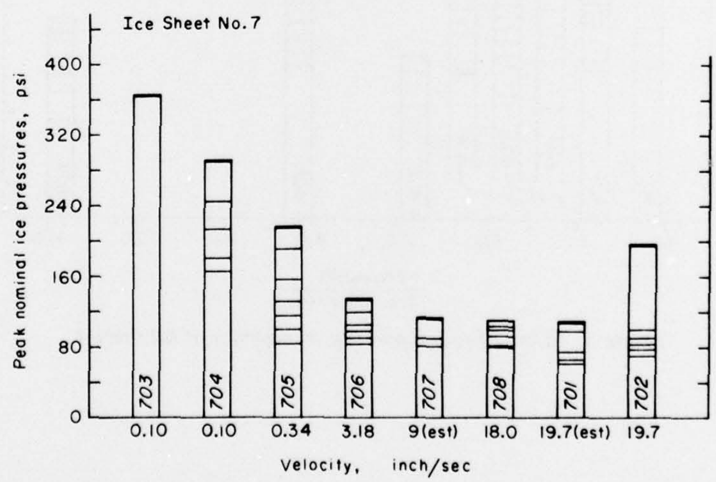

Figure 8. Effect of flat pile velocity on strength of ice sheet 7.

Table I. Test results.

Test no.	Date	Pile width (in.)	Pile shape	Ice thickness (in.)	Speed (in./sec)	Avg ice temp (°C)	Avg salinity (‰)	Failure mode	Movie available
101	8 Oct 70	4.5	Round	4.7	1.20	-3.0	7	Crushing	No
102	8 Oct 70	4.5	Round	4.5	6.30	-3.0	7	Crushing	No
103	8 Oct 70	4.5	Round	3.8	12.00	-3.0	7	Crushing	No
104	9 Oct 70	4.5	Round	3.9	16.67	-2.6	7	Crushing	No
105	9 Oct 70	4.5	Round	3.6	18.75	-2.6	7	Crushing	No
106	9 Oct 70	4.5	Round	3.5	0.09	-2.6	7	Crushing	No
107	9 Oct 70	4.5	Round	3.8	0.43	-2.6	7	Crushing	No
108	12 Oct 70	4.5	Round	5.0	1.14	-2.5	7	Crushing	No
109	12 Oct 70	4.5	Round	5.4	1.00	-2.5	7	Crushing	No
110	12 Oct 70	4.5	Round	5.4	1.14	-2.5	7	Crushing	No
112	12 Oct 70	4.5	Round	5.5	1.35	-2.5	7	Crushing	No
201	1 Feb 71	4.5	Round	7.5	0.90	-2.5	7	Crushing	Yes
202	1 Feb 71	4.6	Flat	7.9	0.82	-2.5	7	Crushing	Yes
203	2 Feb 71	4.7	90°	8.5	0.86	-2.5	6	Crushing	Yes
204	2 Feb 71	4.8	45°	8.8		-2.5	6	Splitting	Yes
205	2 Feb 71	4.8	45°	8.2	1.00	-2.5	6	Crushing	Yes
206	3 Feb 71	7.5	Round	7.8		-2.5	6	Crushing	Yes
207	4 Feb 71	18.0	Round	7.2	0.86			Crushing	Yes
208	8 Feb 71	12.6	Round	6.2	0.82	-2.5	6	Crushing	Yes
209	19 Feb 71	12.6	Round	7.5				Creeping	No
210	24 Feb 71	12.6	Round	8.4				Creeping	Yes
301	6 Apr 71	12.6	Round	2.6	0.07	-4.0	10	Buckling	Yes
302	6 Apr 71	36.7	Round	3.0	0.77	-4.0	10	Buckling	Yes
303	7 Apr 71	36.7	Round	4.8	0.30	-4.0	11	Buckling	Yes
304	8 Apr 71	4.5	Round	5.8	0.68	-4.0	10	Crushing	Yes
305	8 Apr 71	18.0	Round	5.4	0.80	-4.0	10	Crushing	Yes
401	19 Apr 71	12.6	Round	3.0	0.75	-3.3	8	Crushing	Yes
402	19 Apr 71	18.0	Round	2.6	0.68	-3.3	8	Crushing	Yes
403	20 Apr 71	18.0	Round	3.4	0.64	-2.7	8	Crushing	Yes
404	20 Apr 71	36.7	Round	3.4	0.68	-2.7	8	Bending	Yes
405	21 Apr 71	36.7	Round	4.5	0.72	-2.6	8	Bending	Yes
406	21 Apr 71	18.0	Round	3.5	0.68	[illegible]	8	Crushing	Yes
407	22 Apr 71	18.0	Round	3.8	0.65	[illegible]	NA	Crushing	Yes
408	22 Apr 71	18.0	Round	3.2	1.13	NA	NA	Crushing	Yes
501	1 July 71	18.0	Flat	5.2	0.44	-4.3	9	Buckling	Yes
502	1 July 71	35.9	Flat	5.2	0.36	-4.3	9	Buckling	Yes
503	1 July 71	12.0	Flat	4.8	0.35	-4.3	9	Buckling	Yes
504	1 July 71	8.0	Flat	4.8	0.37	-4.3	9	Buckling	Yes
505	1 July 71	1.5	Flat	4.8	0.38	-4.3	9	Crushing	Yes
506	2 July 71	3.0	Flat	4.3	0.38	-3.2	9	Crushing	Yes
507	2 July 71	4.6	Flat	4.3	0.38	-3.2	9	Crushing	Yes
601	22 July 71	4.6	Flat	3.31	0.39	-2.7	9.3	Crushing	Yes
602	22 July 71	4.8	45°	3.13	0.38	-2.7	9.3	Crushing	Yes
603	22 July 71	4.8	45°	3.75	0.38	-2.7	9.3	Crushing	Yes
604	23 July 71	4.8	45°	4.63	0.38	-3.1	9.1	Crushing	No

Table I (cont'd). Test results

Test no.	Date	Pile width (in.)	Pile shape	Ice thickness (in.)	Speed (in./sec)	Avg ice temp (°C)	Avg salinity (‰)	Failure mode	Movie available
605	23 July 71	4.7	90°	4.13	0.38	-3.1	9.1	Crushing	No
606	23 July 71	4.7	90°	4.50	0.36	-3.1	9.1	Crushing	No
607	23 July 71	3.5	90°	4.63	0.38	-3.1	9.1	Crushing	No
701	14 Sept 71	5.5	Flat	5.63	19.7*	-2.7	9.7	Crushing	No
702	14 Sept 71	5.5	Flat	5.50	19.7	-2.7	9.7	Crushing	No
703	14 Sept 71	5.5	Flat	5.38	0.10	-2.7	9.7	Buckling	No
704	14 Sept 71	5.5	Flat	5.13	0.10	-2.7	9.7	Crushing	Yes
705	15 Sept 71	5.5	Flat	4.88	0.34	-2.7	9.7	Crushing	Yes
706	15 Sept 71	5.5	Flat	5.38	3.18	-2.7	9.7	Crushing	Yes
707	15 Sept 71	5.5	Flat	5.00	9.00*	-2.7	9.7	Crushing	Yes
708	15 Sept 71	5.5	Flat	5.55	18.00	-2.7	9.7	Crushing	Yes

* Estimated.

The objective of ice sheet 4 tests was to repeat the results of ice sheet 3 tests. But ice sheet 4 was warmer and softer, and nearly all the failures were crushing. However, in tests 404 and 405, after some crushing had occurred, the ice slid up and over the top of the pile, creating a *bending* type of failure. When this bending failure occurred, many radial cracks developed and the load dropped significantly. The results are shown in Figure 5.

The objective of ice sheet 5 tests was to study the effect of flat pile sizes on ice strength. The piles in tests 501, 502, 503 and 504 failed by buckling, and the piles in tests 505, 506 and 507 failed by crushing. The buckling failures for flat piles were different from those for round piles. For flat piles, a crack propagated from each corner of the piles in the direction of push, and after traveling a foot or so, they turned outward at 45° angles. This formed a funnel-shaped piece of ice which buckled down in the wider part. Ice sheet 5 had a ¼-in. surface layer which split off, making it difficult to see the ice cracks underneath. Test results are shown in Figure 6.

The objective of ice sheet 6 tests was to test 45° and 90° piles and to determine how consistent the results were. The results are shown in Figure 7. For the 90° pile the same zigzag failure pattern noted in test 203 occurred. To a lesser extent, it also occurred for the 45° piles. The ¼-in. surface layer also appeared in ice sheet 6.

The objective of ice sheet 7 tests was to determine the effect of speed on ice strength of the 5.5-in. flat pile. In tests 701 and 707, the linear potentiometer cable became disconnected; therefore, the speed was estimated from the flow control valve settings. All the tests were crushing failures except test 703, which was a buckling failure.

CONCLUSION

The most important result of these tests is the identification of the different modes of ice failure. The failure mode has a pronounced influence on the peak nominal stress. Although the general trends observed should extend to full scale, the specific peak nominal stresses may not.

The authors hope to extend this test program to include vertical piles in freshwater ice and sloping piles. At the same time, theories are being developed that will help explain the observed data.

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