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ICE FORCE MEASUREMENTS ON THE PEMBINA RIVER, ALBERTA, CANADA

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PREFACE

This report was prepared by F.D. Haynes, Materials Research Engineer, D.E. Nevel, Research Physical Scientist, of the Applied Research Branch, and D.R. Farrell, Mechanical Engineer, of the Construction Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

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ICE FORCE MEASUREMENTS ON THE PEMBINA RIVER, ALBERTA, CANADA

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INTRODUCTION

Laboratory work and field work have been conducted at the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) to determine the force that a floating ice sheet exerts on a structure. An active testing system has been developed whereby a vertical pile section is pushed against a stationary ice sheet. This simulation of the impingement of an ice sheet on a structure yields force measurements applicable to determination of structural design criteria.

Peyton (1968) and Blenkarn (1970) measured ice forces on drilling platforms in the Cook Inlet during four winters, between 1963 and 1969. Since 1967, Neill and Schultz (1973) have measured ice forces on bridge piers located on the Pembina and Athabasca Rivers in Alberta, Canada. The forces were measured during spring ice breakup by recording the reaction of a simple ice beam shield on the upstream side of the piers. A laboratory investigation of ice forces made by pushing a vertical pile section against a sea ice sheet was conducted by Nevel et al. (1972). Schwarz (1970) measured ice forces in 1968-1969 by instrumenting a pile located in the Eider River, Germany. In 1970, Croasdale (1970) used a nutcracker device to measure ice forces near the Mackenzie Delta in Canada. Comprehensive reviews of ice force work were prepared by Michel (1970) and Korzhavin (1968).

The purpose of this study was to compare the force measurements of Neill and Schultz (1973) at the bridge pier with those of CRREL in situ results using the active test system. Just before spring ice breakup on the Pembina River, 23 tests were conducted from 29 March to 12 April 1972. The test site was about 400 yards (366 m) upstream from the bridge where Neill and Schultz (1973) measured ice forces and was approximately 60 miles (96 km) northwest of Edmonton, Alberta, Canada.

TEST APPARATUS AND PROCEDURE

The apparatus used for the Pembina River tests was the same as that used by Nevel et al. (1972) for laboratory tests, as shown in Figure 1. A 30-ton (2.7×10^5 N) hydraulic cylinder was used to push the pile against the ice. Both round and flat piles were used for the tests and they were mounted on the rod end of the cylinder. All piles were 5½ in. (14 cm) wide except the round pile used in one test which was 3 in. (7.62 cm) wide. The base of the cylinder reacted against the ice sheet via a 14 × 16-in. (35.6 × 40.6-cm) aluminum plate. A hole was cut through the ice sheet, and the apparatus was lowered into the hole and centered on the ice sheet. In some tests the pile was seated by applying oil pressure to the cylinder.

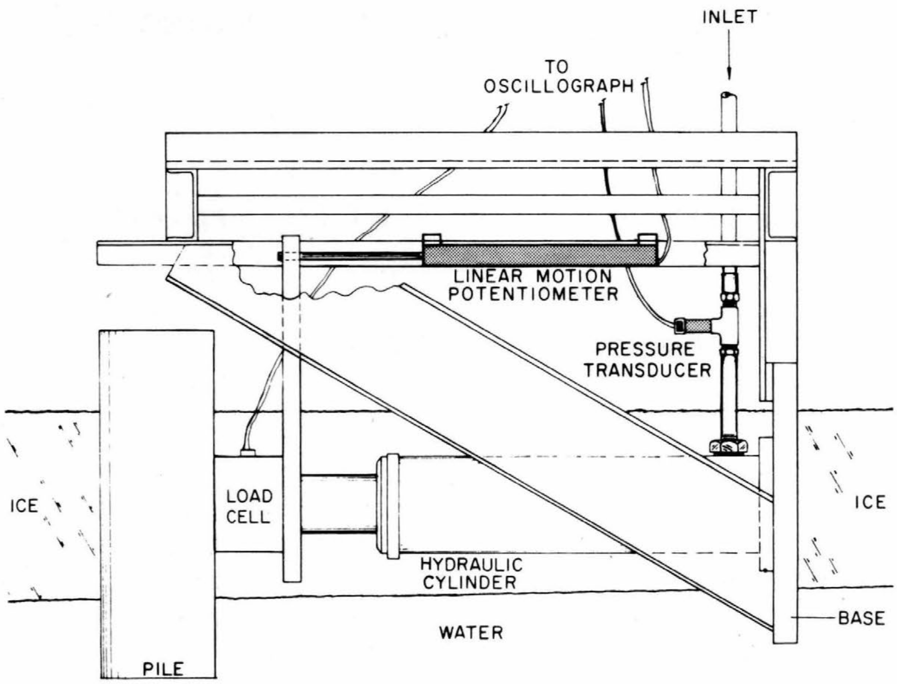

Figure 1. Testing apparatus.

A 2½-gal (9470-cm^3) accumulator was filled with oil and pressurized up to 6000 psi (4.1×10^7 N/m^2) by using an electric pump. A manual shutoff valve permitted a rapid release of this stored energy. Two adjustable flow control valves, mounted in parallel, provided for flow rates from ½ to 70 gal/min (63 to 4433 cm^3/sec). A piston area of 11.05 in.^{2} (71.3 cm^2) and a stroke of 13 in. (33 cm) enabled tests to be conducted with pile velocities from 0.07 to 21.2 in./sec (0.178 to 53.3 cm/sec). Figures 2 and 3 show tests being conducted.

A linear motion potentiometer was used to measure the displacement of the pile. A special load cell, made at USA CRREL, was designed so that the direct thrust, horizontal moment, and vertical moment could be measured. Both the displacement and the load cell output signals were recorded on an oscillograph. The recorder had a timing mark signal and was equipped with an event marker which an observer could operate.

TEST RESULTS

The results will be discussed by considering the effects of several variables: pile shape, pile/ice contact area, pile velocity and the weather. The nominal ice pressure is defined as the measured force divided by the product of the ice thickness and pile width.

The results of the 23 tests are shown in Table I. Nominal ice pressure peaks were taken from the oscillograph record. The sequential peaks were chronological for each test run. The initial peak was highest for 12 out of 19 tests with multiple peaks. The vertical and horizontal moments were measured by the load cell during a test. Dividing the measured vertical moment by the force at any

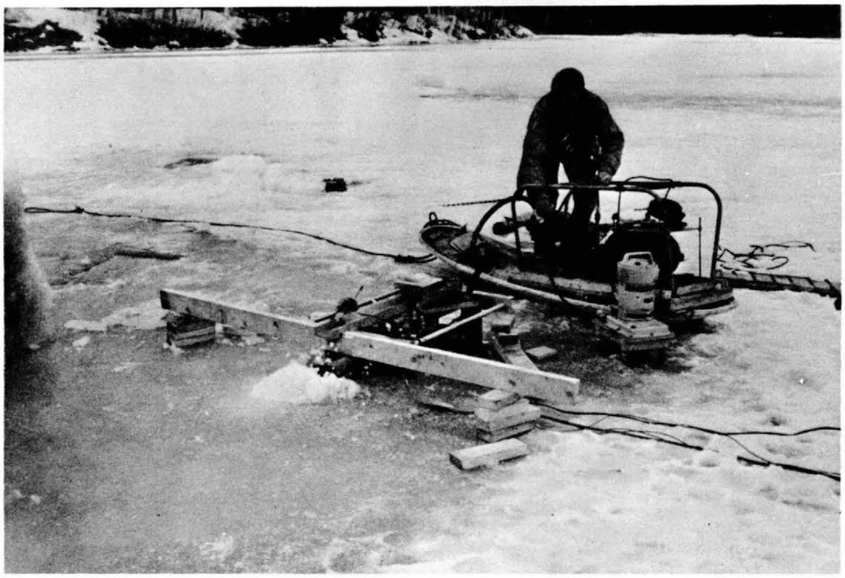

Figure 2. Pile being pushed through the ice as pressure is released to the hydraulic cylinder. (Photograph by C. Neill.)

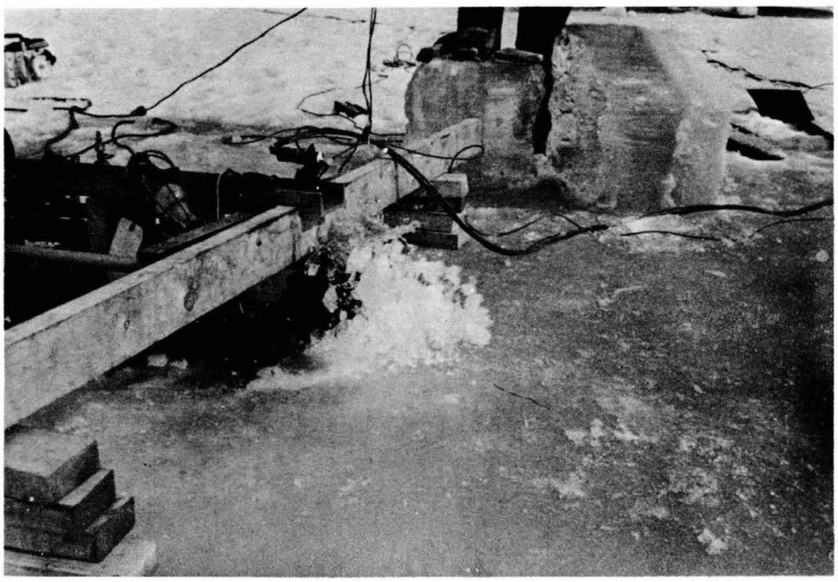

Figure 3. Failure and spalling of the ice during test 14. (Photograph by C. Neill.)

instant gives an eccentricity from the midpoint of the pile if the vertical force on the pile is assumed to be zero. Chronological vertical peak eccentricities e_1, e_2 and e_3, are given in Table II. Positive and negative eccentricities represent distances above and below the pile midpoint, respectively. The eccentricities were less than ±5.74 in. (±14.56 cm) and well within one-half the ice thickness except for test 13. For test 13, the ice faces were not parallel, resulting in the test apparatus being forced out of the hole in the ice. Horizontal eccentricities were found to be negligible for all tests.

Table I. Ice pressure data from the Pembina River, 29 March 1972 - 12 April 1972.

Test	Date (1972)	Local time (hr)	Pile width (cm)	Distance pile to ice (cm)	Shape of cut in ice	Pile velocity (cm/sec)	Ice thickness (cm)	Nominal ice pressure ($N/m^2 \times 10^6$) Sequential peaks 1	2	3	4	5	6	Remarks
1	29 Mar	1:05 p.m.	14	0	Round	1.27 (est.)	49.5	2.48						Ice did not break.
2	30 Mar	3:00 p.m.	7.6	0	Round	2.54	48.3	3.52	3.58	3.53	3.56			
3	30 Mar	4:00 p.m.	14	0	Round	10.2	33.0	3.96	0.29	0.24	0.87	1.1	0.97	
4	4 Apr	12:15 p.m.	14	0	Round	0.97	45.7	4.45						Ice did not break.
5	4 Apr		14	0	Round	–	45.7	4.6						In same hold used for test 4. Ice did not break.
6	4 Apr		14	0	Flat	33.0	29.2	0.5	0.43	0.45	0.94	1.03	0.9	Question values. Scale on record in question.
7	5 Apr	10:00 a.m.	14	0	Round	53.6	30.5	4.7	1.7	2.5	1.77			Two radial cracks at 75°.
8	5 Apr	12:00 p.m.	14	0	Round	51.6	38.1	3.03	1.84	1.3	1.05			Possible horizontal crack.
9	5 Apr	2:00 p.m.	14	4.5	Flat	48.8	35.6	2.24	1.67	2.13				Radial crack at 0°. Possible horizontal crack.
10	5 Apr	3:30 p.m.	14	8.9	Flat	49.3	35.6	1.2	1.13	0.75	0.72	0.88		Possible horizontal crack.
11	6 Apr	11:45 a.m.	14	5.7	Flat	53.1	35.6	3.24	2.64	2.21	2.64	2.36	2.66	Noisy record.
12	6 Apr	2:00 p.m.	14	5.08	Flat	46.9	36.8	2.82	0.51	0.81	1.43	1.30	1.01	
13	6 Apr	3:30 p.m.	14	0	Flat	53.3	40.6	3.07	1.53	1.36	1.06			Apparatus lifted out of hole.
14	7 Apr	11:30 a.m.	14	0	Round	51.3	39.4	3.08	1.22	0.63	1.26			
15	7 Apr	1:00 p.m.	14	0	Round	48.5	40.6	2.82	1.33	1.03	1.29	1.25	1.06	It snowed.
16	7 Apr	1:45 p.m.	14	7.62	Flat	45.5	40.6	1.5	1.57	1.03				
17	11 Apr	11:30 a.m.	14	0	Round	50.3	45.7	1.77	2.47	2.38	2.03	1.82	1.68	Horizontal crack, spalled 1 m.
18	11 Apr	1:15 p.m.	14	0	Round	3.3	38.1	2.76	0.45	0.63	0.73			Radial crack at 0°. Horizontal crack.
19	11 Apr	2:45 p.m.	14	0	Round	15.5	40.6	2.35	1.83	0.92	1.01			Radial cracks at 0° and 80°.
20	11 Apr	3:30 p.m.	14	0	Round	0.18	48.3	2.97						1 peak; ice did not break.
21	12 Apr	12:00 p.m.	14	12.1	Flat	3.05	39.4	2.24	2.79	2.5				
22	12 Apr	1:45 p.m.	14	5.08	Flat	16.5	39.4	0.58	1.28	1.22	0.53			Apparatus shifted sideways.
23	12 Apr	2:45 p.m.	14	7.62	Flat	31.3	45.7	0.57	0.69	1.18	1.4	1.77		Melt holes in plane of ice sheet.

NOTE: Pile shape for tests 12 and 13 was flat; for all others, round.

Figure 4. Clear bottom ice used for unconfined compression tests 10 and 11 of 12 April. Bottom roughness due to differential melting. (Photograph by C. Neill.)

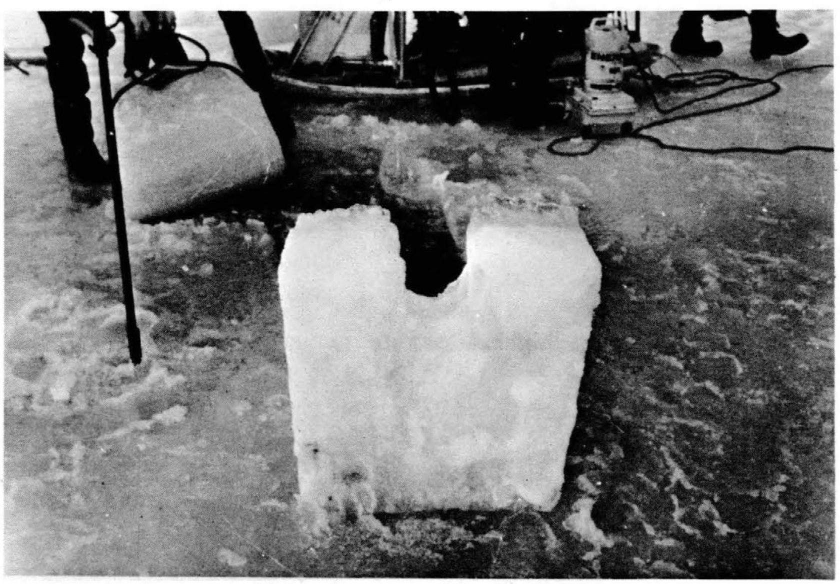

Figure 5. Ice block cut out after in situ test 10. (Photograph by C. Neill.)

Figure 4 shows the bottom roughness of the ice sheet due to differential melting. An ice block cut out after in situ test 10 is shown in Figure 5. The ice tested was typically 3-4 in. (7.6-10.2 cm) of clear ice on the bottom, with 12-13 in. (30.5-33 cm) of snow-ice on the top. For all the tests, the principal failure mode was crushing. Radial cracks were observed for tests 7, 9, 18, and 19. Possible horizontal cracks were observed for tests 8, 9, 10, 17, and 18. A horizontal crack is a tensile crack generally near the middle plane of the ice sheet. Horizontal cracks were also observed by Zabilansky et al. (1975).

Table II. Vertical peak eccentricities, Pembina River, Spring 1972.

e_1, e_2, and e_3 were chronological eccentricities.
Plus means above center of pile; negative means below center of pile.

Test	Ice thickness (cm)	e_1 (cm)	e_2 (cm)	e_3 (cm)
1	49.5	+1.88	+1.68	+1.37
2	48.3	+1.88	+1.68	+1.37
3	33.0	+1.88	−1.78	−4.78
4	45.7	−2.77	3.35	2.46
5*†	45.7			
6	29.2	+8.05	7.1	5.92
7	30.5	+7.3	−4.52	−5.89
8	38.1	−5.3	−3.38	−3.45
9	35.6	11.0	3.56	−0.74
10	35.6	9.8	−7.34	−7.49
11	35.6	−4.4	−0.6	−4.6
12	36.8	3.58	4.5	
13	40.6	−4.7	−15.6	−22.3
14	39.4	7.34	−2.6	−3.35
15	40.6	6.27	−2.24	−6.25
16	40.6	6.78	4.52	6.7
17	45.7	9.58	6.5	7.82
18	38.1	7.19	10.3	11.2
19	40.6	±2.0	−5.72	−4.04
20	48.3	−1.45	1.8	
21	39.4	1.45	4.47	6.27
22	39.4	11.7	2.67	7.47
23	45.7	−3.43	−4.24	−4.83

* Same pile used for test 4.
† No data collected.

The pile shape used for all tests was round, except for 12 and 13, in which the pile shape was flat. The peak ice pressures found for tests 12 and 13 were about average, indicating that the test pile shapes had little influence on the ice pressure results. However, the five highest ice peak pressures found, those for tests 2, 3, 4, and 11, were all obtained with round piles. Similar results were found by Nevel et al. (1972).

The effect of the initial pile/ice contact area on the nominal ice pressure appears to be significant. The four highest pressures found, those for tests 3, 4, 5, and 7, were made with round piles fitting into a round cut in the ice to allow maximum initial contact area. The five lowest pressures found, those for tests 6, 10, 16, 22, and 23, were made with round piles impinging upon a flat cut in the ice which allowed minimum initial contact area. Also, for tests 10, 16, 22, and 23, the round pile was 2-3 in. (5.08-7.6 cm) from the flat edge of the ice sheet when the tests began. The probable explanation for the low pressures found is that failure occurred before the pile was fully embedded. The test results show that, for tests 6, 16, 22 and 23, the highest ice pressure was not the first peak found, indicating that as the pile penetrated the ice sheet, it established a larger pile/ice contact area. However, the peak ice pressure found for these tests was still low, probably because spalling of the ice occurred in front of the pile, reducing the thickness. This reduced thickness area was not determined or used for the ice pressure calculations.

Figure 6 gives a plot of the peak nominal ice pressure versus pile velocity. The velocity was taken from the displacement time signal recorded on the oscillograph. The heavy line for each test represents the initial peak. Velocities measured ranged from 0.07 to 21.1 in./sec (0.178 to 53.3 cm/sec). As Figure 6 shows, there is no definite effect of pile velocity on the peak pressure. Similar results were found by Nevel et al. (1972).

A plot of the ice pressure, air temperature and total incoming solar radiation as a function of time is given in Figure 7. The meteorological information was obtained from *Meteorological Observations*

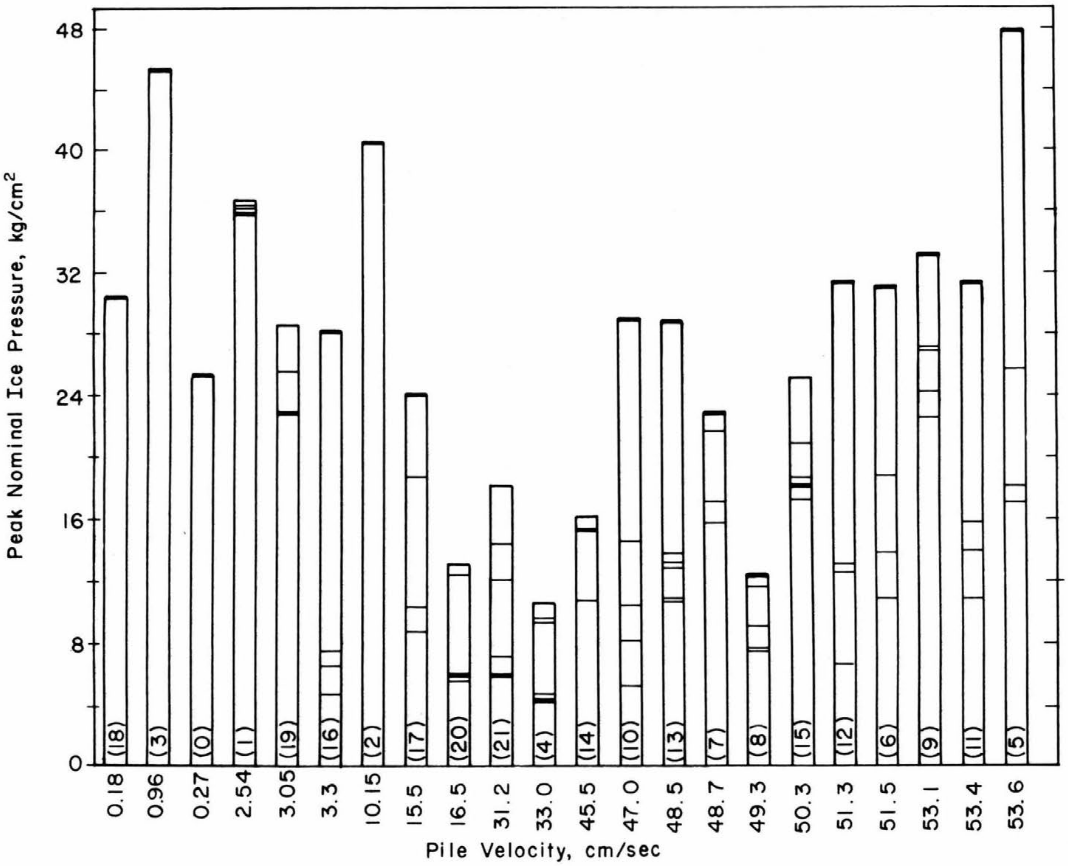

Figure 6. Peak nominal ice pressure versus pile velocity. The abscissa is not to scale. Heavy line indicates initial peak for each test. Test numbers are in parentheses.

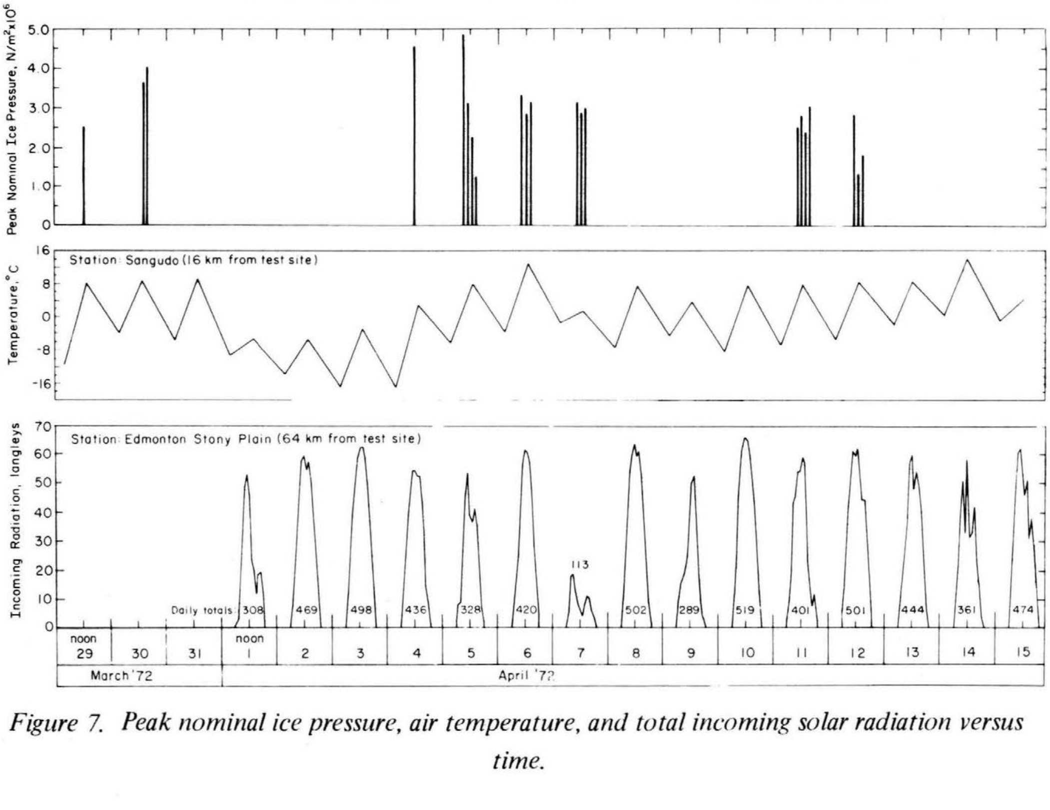

Figure 7. Peak nominal ice pressure, air temperature, and total incoming solar radiation versus time.

in Canada (Department of Transport 1972a and b). The daily minimum and maximum temperatures were arbitrarily plotted at 4:00 a.m. and 2:00 p.m., respectively, since exact times were not available. The hourly radiation values were plotted for each test day in April. Insolation data for March were not available. It snowed on 7 April, and this was reflected in the low radiation values for that day.

Tests 1, 3, and 4 were run with 3 in. (7.6 cm) of water on the surface of the ice. The air temperature dropped below freezing for three days prior to running test 5, during which time the water on the ice was frozen to form a single ice sheet. Tests 5 and 7 produced the highest air pressures. This was probably due to the subfreezing air temperatures just prior to these tests and to the formation of 3 in. (7.6 cm) of new ice on top of the ice sheet. This new ice, together with the original clear ice on the bottom of the ice sheet, sandwiched the old snow ice. The result was that the new ice had a high resistance to crushing for the initial peak. Test 5 had only one peak pressure and test 7 had a second peak which was about one-half of the initial peak pressure.

Frankenstein (1961) found that the flexural strength for lake ice decreased as the air temperature increased during the day. The present data indicate a similar effect for tests 7, 8, 9, and 10, on 5 April. However, round cuts in the ice were used for tests 7 and 8 and flat cuts for tests 9 and 10. In addition, the distances between the pile and the ice sheet were 1.75 and 3.5 in. (4.45 and 8.9 cm) for tests 9 and 10, respectively. This further complicates the analysis because of the effect of impact loading. Therefore, the effect that Frankenstein found cannot be verified from the present data.

COMPARISON WITH BRIDGE DATA AND COMPRESSION TESTS

Data collected by Neill and Schultz (1973), using a simple beam mounted on a bridge near the CRREL in situ test site, are given in Table III. The average ice pressure measured by Neill on 7 events was 189 psi (1.3×10^6 N/m^2) with a high of 304 psi (2.1×10^6 N/m^2) and a low of 71 psi (4.9×10^5 N/m^2). This is considerably lower than the average of 424 psi (2.9×10^6 N/m^2) for the 22 in situ tests. It is more reasonable to compare the results of the in situ tests for the last day, 12 April, with Neill's results of 15 April, the ice breakup date. Using this comparison, the in situ average of 283 psi (1.95×10^6 N/m^2) is 50% higher than Neill's average value of 189 psi (1.3×10^6 N/m^2).

The higher values found for the in situ tests are probably due to three factors. The first factor is D/T, the ratio of the diameter or width of the pile to the ice thickness. The average D/T ratio for the in situ tests was 0.34, while for the bridge pile the average ratio was 1.94. Based on the results of Nevel et al. (1972) and Zabilansky et al. (1975), a 50% higher strength can be expected with the lower ratio.

The second factor is the method of ice thickness measurement. The ice thickness was obtained by direct measurement for the in situ tests, while it was estimated from 38.1 to 45.7 cm for the bridge pile data. For example, a difference of 1 in. (2.54 cm) in the estimated ice thickness at the bridge gives a 6% change in the calculated ice pressure. It was observed that the downstream edge of the ice sheet used for the in situ tests was about one-third as thick as the center of the sheet. Based on this concept, the initial crushing strength from the bridge pile may be too low. In some cases, the ice sheet split after some crushing and each half passed around the bridge pier. This failure of the ice sheet by splitting, which was not observed in the in situ tests, could have produced lower pressures than the crushing-type failures observed in the in situ tests. Zabilansky et al. (1975) found in laboratory tests that splitting of the ice occurred at lower pressures than crushing of the ice.

The third factor is the deterioration of the ice during the three-day interval between tests. Figure 7 shows that there was a definite warming trend during the three days between the last in situ test and

Table III. Ice forces and pressures from the bridge pier at Pembridge, Alberta, Canada, 15 April 1972 (from Neill and Schultz 1973).

Water surface elevation about 650 m.

Event	*Time (p.m.)*	*Peak instantaneous force ($N \times 10^5$)*	*Estimated ice thickness (cm)*	*Corresponding unit pressure ($N/m^2 \times 10^6$)*	*Maximum of sustained force ($N \times 10^5$)*	*Event description*
1	1:29:02	3.73	38.1	1.15	1.01	15-sec sequence of crushing and splitting; ice sheet used for CRREL tests and strength samples.
2	4:59:30	8.23	45.7	2.1	–	Single instantaneous load "spike" on chart during soft crushing episode; may represent isolated piece of hard thicker ice.
3	5:00:03	6.13	45.7	1.57	3.0	Instantaneous "spike" followed by 1-sec sustained force.
4	5:00:58	3.4	45.7	0.87	–	½-sec duration for significant force; continuous crushing observed.
5	5:04:45	7.34	45.7	1.87	2.03	Continued passage of same sheet as in event 4; 8-sec sustained force.
6	6:55:11	1.93	45.7	0.49	1.37	15-sec sustained force; slow crushing.
7	7:00:48	4.25	45.7	1.08	–	Same sheet as event 6; single high "spike" on chart.

Avg = 1.3.

the breakup on 15 April. The above freezing temperatures should have weakened the ice to partially account for the lower ice pressures found at the bridge pier.

Table IV shows the results of uniaxial unconfined compression tests conducted by Neill and Schultz (1973). The specimens were cut out of the same ice sheet used with the CRREL in situ test apparatus. A comparison of these tests with the in situ tests is given in Table V. The two types of tests, unconfined compression and in situ, are basically different, and the results are expected to be different. Nevertheless, it is useful to observe that the tests with the greatest similarity, a flat pile on a flat cut, had the lowest ratio.

CONCLUSIONS AND RECOMMENDATIONS

An examination of the several variables identified and their effects upon the ice pressure for the CRREL in situ tests produced the following conclusions:

1) The pile shape and pile velocity had little effect upon the ice pressure.

2) The weather had an expected effect; e.g. cold air temperatures before testing produced higher pressures and vice versa.

3) The initial pile/ice contact area had a definite effect. The ice pressure was greatly increased (up to three times), when the initial pile/ice contact area was maximized, for a round pile in a round cut. When the area was minimized, for a round pile in a flat cut, stress concentrations produced lower ice pressures. Further work which addresses the pile/ice contact area effect is recommended, particularly as it applies to bridge abutment design criteria.

Table IV. Uniaxial unconfined compression strengths, Pembina River ice (from Neill and Schultz 1973).

Average rate of strain about 1.5 × 10^{-3}/sec, ice temperature close to 0°C.

Date	*Time*	*Specimen*	*Dimensions (compressed along long axis) (cm)*	*Original orientation of long axis*	*Description of ice*	*Location in sheet*	*Description of failure*	*Maximum stress ($N/m^2 \times 10^6$)*
5 April	3:00 p.m.	1	10.2 × 10.2 × 20.3	Horizontal	Mainly clear	Not recorded	Cracking/shear	1.18
(Sunny	3:20 p.m.	2	10.2 × 10.2 × 20.3	Horizontal	Snow-ice	Not recorded	Creep, flat peak	1.73
all day)	4:30 p.m.	3	10.2 × 10.2 × 20.3	Horizontal	Snow-ice	Not recorded	No peak	1.38
	4:35 p.m.	4	10.2 × 10.2 × 20.3	Horizontal	2/3 clear	Bottom	Diagonal shear	0.69
7 April	10:45 a.m.	1	7.3 diam × 14.6	Vertical	Clear	Bottom	Conical shattering	4.28
(Cloudy	10:45 a.m.	2	7.3 diam × 14.6	Vertical	Top 30% snow-ice	Middle	Not recorded	2.89
all day)	11:45 a.m.	3	7.3 diam × 14.6	Horizontal	Snow-ice	Middle	No peak	(>1.38)
	11:50 a.m.	4	7.3 diam × 14.6	Horizontal	Snow-ice	Middle	Flat peak	3.17
	11:50 a.m.	5	7.3 diam × 14.6	Vertical	Snow-ice	Middle	Plateau maximum	1.93
	11:50 a.m.	6	7.3 diam × 14.6	Vertical	Snow-ice	Middle	Flat peak	2.21
	1:00 p.m.	7	8.9 × 8.9 × 17.8	Horizontal	Mainly clear	Bottom	Diagonal shear	1.11
	1:30 p.m.	8	10.2 × 10.2 × 20.3	Horizontal	Clear	Bottom	Multiple cracking	1.11
	1:40 p.m.	9	10.2 × 10.2 × 20.3	Horizontal	Clear	Bottom	Multiple cracking	1.11
	1:45 p.m.	10	10.2 × 10.2 × 20.3	Horizontal	Opaque	Bottom	Creep, ultimate failure	2.55
	2:10 p.m.	11	10.2 × 10.2 × 20.3	Horizontal	Mainly clear	Bottom	Multiple cracking	0.9
	2:15 p.m.	12	10.2 × 10.2 × 20.3	Horizontal	Mainly clear	Bottom	Multiple cracking	0.28
	2:25 p.m.	13	10.2 × 10.2 × 17.8	Vertical	Clear	Bottom	Vertical splitting	2.0
	2:35 p.m.	14	10.2 × 10.2 × 16.5	Vertical	Clear	Bottom	Vertical splitting	1.66
	2:45 p.m.	15	8.3 × 8.3 × 16.5	Vertical	Clear	Bottom	Vertical splitting	1.66
12 April	1:20 p.m.	1	10.2 × 10.2 × 20.3	Horizontal	25% snow-ice	Top	Flat peak	0.97
	1:30 p.m.	2	10.2 × 10.2 × 20.3	Horizontal	20% snow-ice	Top	Double peak	1.25
	1:45 p.m.	3	7.6 × 7.6 × 15.2	Horizontal	Mainly snow-ice	Bottom	Gradual	0.48
	1:45 p.m.	4	7.6 × 7.6 × 15.2	Horizontal	Mainly snow-ice	Bottom	Gradual	0.62
	2:20 p.m.	5	10.2 × 10.2 × 20.3	Horizontal	Snow-ice	Middle	Flat peak	1.79
	2:25 p.m.	6	10.2 × 10.2 × 20.3	Horizontal	Snow-ice	Middle	No peak	(>2.55)
	2:30 p.m.	7	10.2 × 10.2 × 20.3	Horizontal	Snow-ice	Middle	Flat peak	1.73
	3:20 p.m.	8	10.2 × 10.2 × 20.3	Horizontal	Clear	Bottom	Diagonal shear	0.76
	3:25 p.m.	9	10.2 × 10.2 × 20.3	Horizontal	Clear	Bottom	Diagonal shear	0.76

Table V. Comparison of Neill and Schultz (1973) unconfined compression strengths and CRREL in situ test strengths.

	Unconfined compression tests in horizontal direction (Neill and Schultz 1973)		*CRREL in situ strength tests*			*Ratio*
Date	*No. of tests*	*Average strength ($N/m^2 \times 10^6$)*	*No. of tests*	*Shape of cut*	*Average strength ($N/m^2 \times 10^6$)*	*CRREL/UCC strengths*
5 April p.m.	4	1.24	2	Flat pile, flat cut	1.72	1.4
7 April all day	7	1.46	2 1	Round pile, round cut Round pile, flat cut	2.49	1.7
12 April p.m.	9	1.21	3	Round pile, flat cut	1.95	1.6

The in situ tests produced ice pressures about 50% higher than the Neill and Schultz (1973) bridge pier results. One explanation for this difference is the smaller pile diameter or width-to-ice thickness ratio obtained with the in situ tests. It has been found from other tests that the ice pressure varies inversely with this ratio. It is recommended that additional work be done to clearly identify this effect, especially considering the instantaneous pile/ice contact area at peak pressure. Another explanation for the difference in the test results is the deterioration of the ice caused by the above freezing air temperatures during the three-day lapse between the in situ tests and the ice breakup.

The ratio of 1.4 found by comparing the in situ results with the Neill and Schultz (1973) unconfined compression strengths is not conclusive. Many variables germane to the compression tests, such as test temperatures, platen temperatures, strain rate, and specimen geometry, demand that comparisons of compression strengths with in situ results be scrutinized.

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Just before spring breakup in 1972, 23 in situ tests were conducted on the Pembina River, in Alberta, Canada, to measure ice forces. These tests simulated an ice sheet pushing against a bridge pier. The apparatus utilized a hydraulic ram to push a 5½-in. (14.0-cm)-wide vertical pile section horizontally against the ice sheet, which varied from 11.5 to 19.5 in. (29.2 to 49.5 cm) in thickness. The velocity of the pile was varied from 0.07 to 21 in./sec (0.18 to 53.3 cm/sec) by hydraulic flow control valves. Both flat and round piles were used to represent the pier. Some tests began with the piles a few inches away from the ice sheet, whose edge was cut flat. Other tests began with the pile in contact with the ice sheet. For some of the round pile tests, augered holes were used to provide

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SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*) better initial contact. These in situ test results were compared with the ice force measurements made by other workers on a nearby bridge pier during ice breakup. The in situ test ice forces were about 50% higher than the bridge pier test results. This disagreement was caused by a difference between the sizes of the piles and the size of the pier and a three-day warming of the ice before the ice impacted against the pier.