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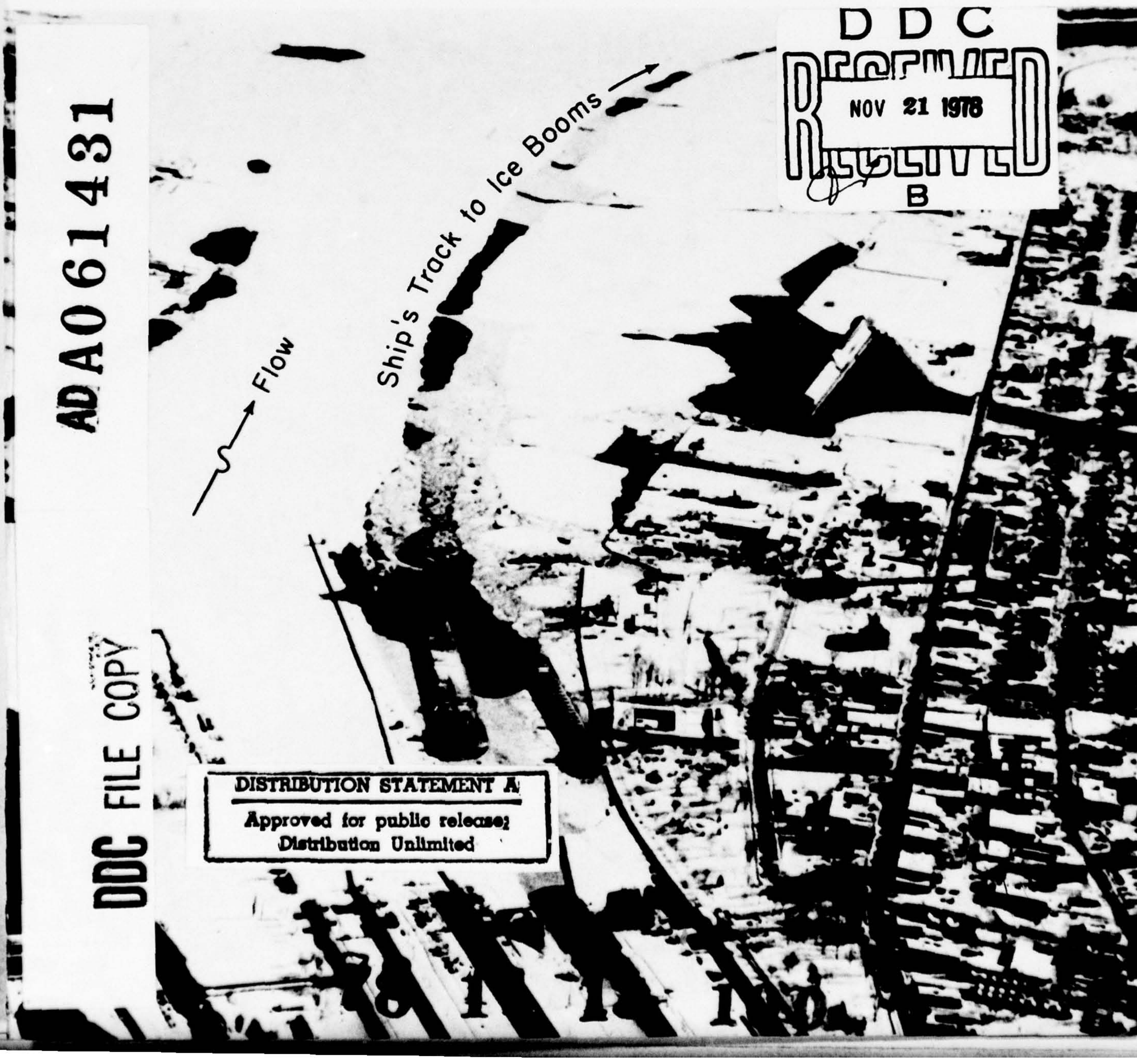
REPORT 78-24

Performance of the St. Marys River ice booms, 1976-1977



Cover: *Broken ice cover in Sault Ste. Marie Harbor (Michigan, right; Ontario, left) on 21 January 1977. The Little Rapids Cut and the ice booms are at the upper right, i.e., the dark, open water area. The ships immediately downstream of the Soo Locks are the Doan Transport, the Roger Clarke, and the Cason Calloway. The broken ice to the right of the 2½-mile-long ship track is upstream of the west ice boom. (Photo, Detroit District, Corps of Engineers.)*

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(10) Roscoe E. Perham

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The ice booms on the St. Marys River at Sault Ste.Marie, Michigan and Ontario, were operated a second winter, 1976-77, under colder conditions, with less water flow, lower water levels, and 25% fewer ships in the river than during the previous year. The ice cover behind the booms remained frozen to shore for longer periods, and the loads registered in the booms were relatively unaffected by ship passages compared with the previous year's activity. As in the previous year, most structural load changes took place in the west ice boom and were due to movements of the ice cover immediately upstream of the boom. The cover broke free from shore on three occasions: the first and third occasions were minor events, but on the second occasion the cover cracked free, the timbers remained frozen

Cont

20. Abstract (cont'd)

CONT → to it, and the boom structure became damaged by the subsequent ice activity. Three anchor line assemblies broke over a period of about 4 hours; the two latter breaks occurred while a ship was operating in the ice. The first break was in an instrumented line and the measured load was unexpectedly low. The most important break was in the main shore anchor and this opened the boom. The maximum force at this anchor was estimated as less than 115 tons (1,023 kN). Some ice moved downstream without serious consequence and the boom was reconnected in two days. These events point out several factors to be considered in ice booms, such as designing the booms to withstand the action of the solid ice cover as well as the fragmented ice cover, keeping the structures and their assembly simple, and inspecting components and assemblies carefully.

PREFACE

This study was conducted and this report was prepared by Roscoe E. Perham, Mechanical Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The work described in this report was funded by the U.S. Army Engineer District, Detroit, Michigan, under FY 77, USAED, Detroit Order No. NCE-AI-77-116, *St. Marys Ice Boom Monitor (Ice Forces)*. CRREL is responsible for the ice engineering portion of this program.

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INTRODUCTION

The St. Marys River ice booms were designed and installed at the head of the Little Rapids Cut in Sault Ste. Marie (Soo), Michigan. The location and general dimensions of the two ice booms used were determined through hydraulic model tests using a model ship and a model ice cover. The boom details are presented in CRREL Report 77-4, *St. Marys River ice booms, Design force estimate and field measurements* (Perham 1977).

The main function of the ice booms was to stabilize and help retain the ice cover upstream in the broad Soo Harbor as an aid to winter navigation. For this purpose, the two booms provided a 250-ft-wide navigation opening. Figure 1 is an aerial photograph of the timber booms, taken looking downstream into the cut.

This report describes the two most important aspects of the operation of the St. Marys River ice booms during the winter of 1976-77 (the second year's operation of the booms). These are: a substantially diminished sensitivity of boom forces to the passage of ships compared with the first year's operation, and the sequential breaking of the structure on one occasion. This report also presents a comparison of several factors, such as the ice cover, water levels and flows, and degree days of freezing, between the first and second years' operation of the booms.

The ice behind the east ice boom remained stable and fixed during both winters; therefore, the descriptions of ice, ship and boom interactions refer only to the west ice boom. The comparison of winters applies to both booms.

COMPARISON OF WINTERS

River flow

Waterflow in the river averaged 60,900 ft^3/s (1720 m^3/s) in 1976-77, whereas it averaged 70,000 ft^3/s (1982 m^3/s) the year before. This made the water level noticeably lower, with more rocks and land showing in shallow areas beside the channel.

Because the water level varies considerably during any one winter, it is a little difficult to select a comparable time for each winter. Fortunately, however, the water level records showed that the same *types* of events occurred during each winter even though the dates of the events and the periods between them were different. The time selected for comparison was a two-day period that followed a note made on these records of a second "influx of frazil ice into the federal and the privately owned hydroelectric powerplants." The water level during this two-day period was fairly constant; the average level for 1975-76 was 581.35 ft (177.3 m) and, for 1976-77 was 580.33 ft (176 m) or 1.02 ft (0.31 m) less.

Coldness

The freezing index is probably the best reference for comparing winter coldness. This index is the number of degree days (above and below 32°F) between the highest and lowest points on the cumulative degree-days time curve for one freezing season (Huschke 1959). It can be calculated from the National Oceanic and Atmospheric Administration (NOAA) climatology

Figure 1. Ice booms at head of Little Rapids Cut, Sault Ste. Marie, Michigan, 23 December 1975. The west boom is in the right foreground. (Photograph: courtesy of Detroit District, Corps of Engineers.)

Table I. Comparison of ice covers behind the ice booms for the winters of 1975-76 and 1976-77.

Parameter	*Winter* 1975-76	1976-77
Start of ice cover (estimated date)	9 Jan 76	9 Dec 76
Time to achieve maximum thickness, days	65	48
Maximum thickness, in. (m)	12 (0.3)	16 (0.41)
Duration of thick condition, days	5	15
Duration of ice cover, weeks	11½	14½
Thermal effluents effects*	0.86	0.56

*Rough estimate only. The numbers are thought to indicate the weakening effect of thermal effluents on the ice cover. They represent the portions of ice condition drawings that show melt areas and holes. A larger value indicates more holes and apparently a weaker ice cover.

reports. For the months of November through March, the freezing index was 2101 degree F days (1167 degree C days) in 1976-77, and 1696 degree F days (937 degree C days) in 1975-76, which shows that the winter of 1976-77 was substantially colder than the previous one. Another important factor in coldness is the windspeed, and the NOAA data showed that the average was slightly greater in the winter 1976-77.

Ice cover

In response to the coldness, the ice cover above the booms formed earlier; it became thicker, lasted longer, and generally stayed frozen to shore. There were only two days when ice passed over the booms, and the quantities lost were small. Table I summarizes several items of comparison for the ice covers of the two winters.

The upstream progression of the ice cover in the Little Rapids Cut was studied as part of the model study for this area by Acres American, Inc. (1975). The fast current in the cut ensures that the cover forms mainly as a collection of ice floes and fragments coming from farther upstream. Acres American, Inc. estimated from aerial photos that it takes on the average from 1½ to 2 weeks for the upstream edge of the ice cover to progress from Lake Nicolet up through the cut to the ferry crossing.

The same phenomenon was studied for the two subject winters using Corps of Engineers' ice data for the area. The data are not precise and have to be plotted, averaged and studied carefully; at the same time the physical events that took place in the cut and upstream of the cut must be considered.

For the winter of 1975-76, it is estimated that the ice cover progression took approximately 2½ weeks and that the cover remained in the vicinity of the ferry crossing for about 2 months. For the following winter (1976-77), the cover progression took over 5 weeks and the cover remained near the ferry crossing for the same 2-month period.

It is difficult to say how much the criterion of ice progression duration should be emphasized in evaluating the performance of the booms. During the first winter, the booms seemed to be of some benefit, but not very much. Yet it is impossible to project how severe the situation might have become without them. Basically, the data indicate that the boom timbers were not holding the ice back as well as they should have.

During the winter of 1976-77, the ice booms worked more as expected and maintained a stable ice cover. But as Cousineau (1959) concludes, it is usually easier for an ice cover to form and stabilize under conditions of severe coldness than under more moderate conditions. This factor may have made the ice booms appear to have overcome their ice restraint weakness during the winter of 1976-77, whereas they still need improving.

Shipping

The number of ships passing through the Soo Locks in 1976-77 was about three-fourths that of the previous year; i.e., from 1 December through 30 April, there were 1784 ship lockages in 1975-76 and, in 1976-77, 1280 ship lockages, or 28% fewer. The winter navigation season was officially closed on 20 January 1977, but in effect this was only a partial closing because there were 45 lockages during February and March. The severe winter conditions seem to have reduced the traffic because, even during the normal navigation period of December, part of January, and April, there were 24% fewer passages than in the previous year.

The speeds of 27 ships passing through the booms were measured and their average speed was 5.6 knots (3.0 m/s). (A knot is a nautical mile per hour.) The average speed for the 3 fastest passages was 8.7 knots (4.5 m/s) and for the 3 slowest, 3.4 knots (1.8 m/s).

SHIP EFFECTS

Noticeable events

Passing ships upset the equilibrium of the ice cover above the booms very few times. All noticeable effects were limited to the west ice boom and its ice cover, which lie between the ship track and the southerly shore of Soo Harbor. Most of the force changes that registered on the recorder charts were very small and were probably due to ship induced waves.

On 4 January 77 and 10 March 77, passing ships probably contributed to the breaking free from shore of the ice cover. The forces generated in the boom structure on these dates, however, were not high. The maximum measured force in cable C1W was 33,000 lbf (147 kN) on the date of the first event and 19,500 lbf (87 kN) on the date of the second event. The main cause of the difference in forces was probably the wind, which was westerly at 12 knots (6.2 m/s) in the first case and easterly at 8 knots (4.2 m/s) in the second.

The ice broke free from shore a third time, apparently from natural causes; and because of a sequence of events involving a ship and other factors described in the following text, the ice boom broke.

Discussion

Little can be said about the effects of ships on the ice cover and ice booms during the winter of 1976-77. The good bond that the ice cover had with the shoreline and the strength of the ice cover allowed it to protect the ice boom most of the time. The addition of sensors for measuring water level changes, flow velocity changes, and

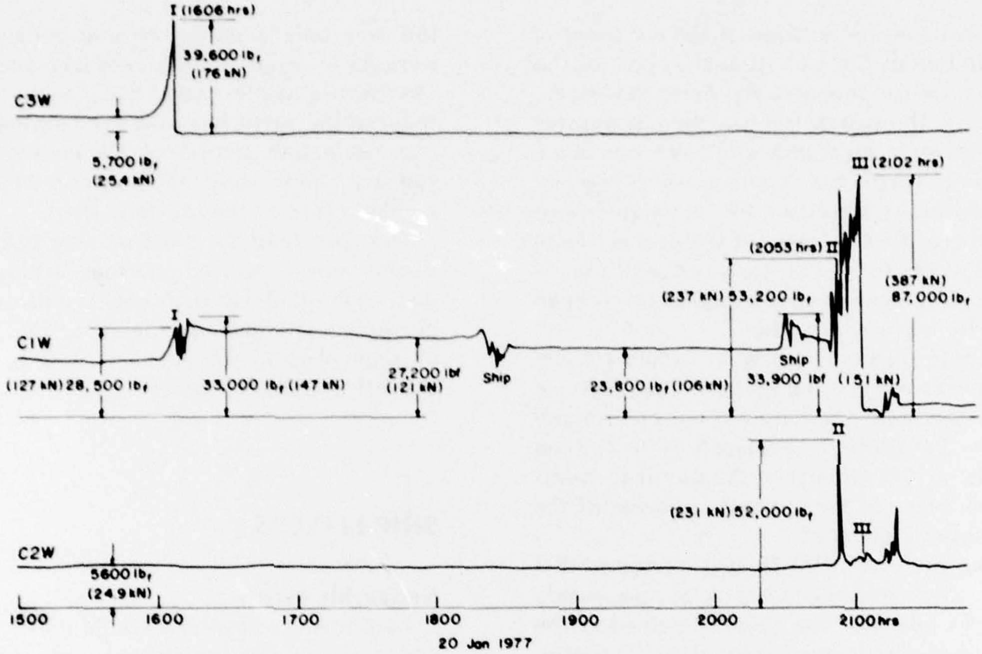

Figure 2. Copy of signal traces, 20 January 1977.

Table II. Average forces in the west ice boom in early winter 1976-77 for selected periods.

Anchor line	*9-11 Dec (lbf)*	*9-11 Dec (kN)*	*13-15 Dec (lbf)*	*13-15 Dec (kN)*	*23-25 Dec (lbf)*	*23-25 Dec (kN)*
C1W	5300	24	4900	22	7800	35
C2W	0	0	2900	11	0	0
C3W	1800	8.0	1200	5.3	3100	14

vertical movements in the ice would help to provide data each year on several of the changes that take place when ships pass and would make this aspect of the study more meaningful.

MEASURED FORCES

Method

The measurement system is described in last year's report by Perham (1977) and in a previous report by Perham (1974). Anchor cable forces were recorded on strip chart recorders. Copies of some signal traces for the T1W, T3W, and T2W systems are given in Figure 2. T1W measures forces in anchor line C1W, T2W measures forces in C2W, and T3W measures forces in C3W.

Early winter

Representative values of forces measured in the west ice boom early this winter are given in Table II. During this period the ice cover is normally unconsolidated or fragmented. The values are averages for three different three-day periods; they are much smaller than the estimated design forces.

A factor of greater significance than the force level may be the relative values of forces between structural members. The values in anchor line C2W were expected to be nearly the same as those in C1W but they were much lower and even zero during two periods. The values in C3W were expected to be a small fraction, approximately one-sixth, of those in C1W, but the average fraction turned out to be one-third or about twice as much as expected. Apparently the ice cover was solid or nearly so most of time. The mechanisms whereby the above differences can develop are described later in the discussion.

Remainder of winter

Most of the remaining noteworthy or representative force activity in the west boom took place during the event of 20 January 1977. The forces measured on this date are given in Appendix A. It should be noted that early in the

Figure 3. Head of Little Rapids Cut showing ice cover behind west boom (upper left arrow) cracked free from shore. Right arrow indicates east boom.

afternoon of that day the relationships between forces in anchor lines C1W, C2W, and C3W were similar to those described above.

SEQUENTIAL BREAKING OF THE STRUCTURE

Brief description of event

Late in the afternoon of 20 January the ice behind the west ice boom cracked away from shore in a manner almost identical to that shown in the upper left of Figure 3, a photo taken last year. That night, at about 2050 hours, while a large ore carrier was moving downstream in the ship track well above the bend, also shown, the shore anchor chain of the west boom broke with a loud noise and approximately 500 ft of ice cover passed through the boom location. The line of timbers remained connected to the upstream anchor but it moved out into midstream, partially blocking the opening. The ship stopped, backed up, and tied up near the Soo locks at 2310 hours. The Soo Area Office personnel and equipment repaired the ice boom, completing most of the work by the evening of 22 January. That night the last four ships — the Callaway, Blough, Clarke and Doan Transport — went downstream without incident.

Boom component identification

Figure 4 is a plan view of the west ice boom; it shows the locations of parts of the structure that are discussed. Each component is identified by function, number and general location; for example, the set of symbols A4W identifies anchor point number 4, on shore, of the west boom. The numbers used in the report are shown in Figure 2. The letter C refers to anchor lines, B refers to boom sections, and T refers to tension links.

Previous conditions

During the previous week, the ice cover behind the west ice boom was solid, about 12 in. (0.3 m) thick, and frozen fast to shore. Only a few ships passed through the ice boom and none had any noticeable effect on the ice cover. Two elevation sighting poles were set into the ice on 19 January to observe ice elevation changes caused by the last ship passages of the navigation season.

The temperature was relatively warm on 20 January, about 20°F (−5°C). A thorough check of the condition of the force sensing and recording systems was completed that morning. All measuring units in the west ice boom structure were found to be properly adjusted and in good operating condition.

At approximately 1630 hours on 20 January, the ice upstream of the west boom cracked along the shoreline. It pulled away from shore, creating an open water gap about 20 ft (6.1 m) wide. There was no apparent reason for the crack. About 1600 hours the U.S. Corps of Engineers Hydrograph located upstream indicated that the water level was dropping, but the total change was a little over an inch in two hours. However, similar changes had taken place the previous week without a noticeable effect on the ice cover. Wind records show that the wind was calm, or nearly so, in the morning and increased to an average of about 8½ knots (4.4 m/s) from a northwesterly direction later in the afternoon.

Recorded force changes

The measurement systems indicated that forces started to increase at about 1555 hours on 20 January in both the C1W and the C3W anchor lines. Figure 2 shows the signal traces for the west boom at that time and later. The force increased rapidly in the C3W cable from 5,700 lbf (25 kN) until it reached a level of 39,000 lbf (173 kN) at about 1606 hours. The signal level in C3W then plummeted to zero, which indicated that some part of the line broke at that time. However, the measuring circuit was still intact and operating.

During the same period, the signal from the C1W cable showed that its force increased from 17,000 lbf (76 kN) to 28,500 lbf (127 kN) at the time of C3W cable separation. The force dropped almost to the previous level and then increased to a peak of 33,000 lbf (147 kN) at 1611 hours. This peak was followed by a gradual force reduction to 27,200 lbf (121 kN) over the next two hours.

Forces in the C2W cable were almost unaffected by the above activity. They remained at a level of about 5,000 lbf (22 kN) except for a period of approximately one-quarter of an hour before and after the T3W signal drop when it was 5600 lbf (24.9 kN). An ice condition sketch for 1730 hours showed lateral cracks in the ice cover upstream 300-400 ft (91-122 m) from the west boom. The force level gradually increased about 1,200 lbf (106 kN) at 1830 hours. The accompanying note found on the recorder chart was "Mackinaw downbound 18:33."

After the Mackinaw went downstream, the force systems gave constant level readings for about 2 hours.

At 1941 hours the ore carrier Roger Blough left the Poe lock downbound. The wind conditions had been calm all day but at about 2000 hours a gentle wind arose from the northwest.

At 2027 hours the force level in the C1W cable started to increase. It rose to 33,900 lbf (151 kN), then dropped and varied somewhat, and seemed to stabilize at 26,000 lbf (116 kN). A note on the recorder chart at approximately 2030 hours read: "Ice movement ahead of the Roger Blough downbound."

At 2050 hours larger forces and force fluctuations were applied to C1W. Less than 2 minutes after this the force level in C2W increased very rapidly. The C2W force went up to 52,000 lbf (231 kN) and then dropped to 7300 lbf (32 kN). At the same time the force in C1W dropped momentarily to 15,500 lbf (69 kN).

The force level in cable C1W varied appreciably and rapidly after 2053 hours but generally increased to 87,000 lbf (387 kN) at 2102 hours. The force level in C2W remained low and increased a little to 10,000 lbf (44.5 kN) at 2102 hours. At this time the force in C1W dropped rapidly to about 2,300 lbf (9.8 kN). The effect on cable C2W was slight but noticeable.

After this occurrence, the forces still varied in C1W and C2W for approximately one-half hour. These variations were probably due to ice moving over remaining parts of the boom. The maximum force in C1W during this period was 11,000 lbf (49 kN); the force level stabilized at 4,800 lbf (21 kN). The maximum force in C2W was 27,000 lbf (120 kN); the force level stabilized at 7,500 lbf (33 kN).

The measurement systems functioned correctly during the period of failure.

Broken elements

While repairing the ice boom, the work crew found several steel structural items broken. These items and the specified load-carrying capacity of each are listed in Table III, but the condition of each just prior to its breaking is not known and careful evaluation of the metal and the resultant fracture patterns has not been made. For comparison, the sizes and strengths of the wire ropes used in series with these items are also shown in the table.

C3W broke at the oval link near the junction plate at the water surface. The link split in the smaller radius at one end.

At the A4W anchor point the load is carried by a stud link chain of 1¾-in. (4.4-cm)-diam stock. One of the links broke in two places. The larger remaining section was found to have a slight lateral bend of about $^3/_{16}$ in. (0.5 cm).

Table III. Selected component strengths of three anchor line assemblies.

Anchor line assembly	Broken part: Name	Broken part: Size (in.)	Broken part: Size (cm)	Minimum breaking strength (lbf)	Minimum breaking strength (kN)	Connected wire rope: Size (in.)	Connected wire rope: Size (cm)	Connected wire rope: Breaking strength (lbf)	Connected wire rope: Breaking strength (kN)
C3W	Oval link	1½	3.8	100,000	445	1	2.5	89,800	399
C3W'	Chain shackle screw pin	1½	3.8	118,000	525	1	2.5	89,800	399
A4W-B2W	Stud link	1¾	4.4	380,000	1,690	1⅝	4.1	230,000	1,023

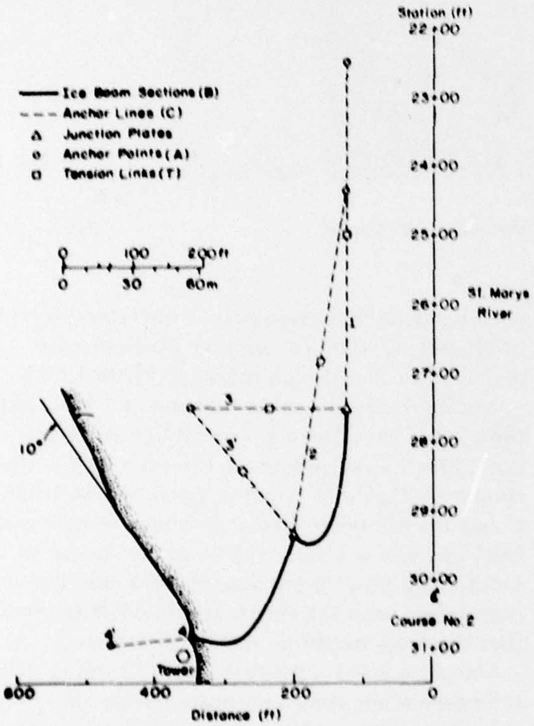

Figure 4. Plan of west ice boom.

The fourth item found broken was a minor connector, an attachment plate on the timber nearest shore. The plate was torn off laterally probably by the B2W ice boom cable undergoing load release movements after the anchor's chain broke.

DISCUSSION

Significance of maximum forces

The first anchor line break occurred in C3W, which was connected to the same junction plate as C1W (Fig. 4). There was a pronounced change in the force level of C1W as a result of this event. Since the other two anchor line assemblies that broke were not instrumented, it is difficult to say when they failed. However, one of them, C3W', shared a junction plate with the instrumented line C2W and, if the force in C3W' changed substantially, it could be expected that this would affect the signal level in C2W.

The peak force level of 52,000 lb (231 kN) in C2W at 2053 hours seems to indicate the time that C3W' broke. However, a similar peak of 87,000 lb (387 kN) that developed in C1W at 2102 hours could have been related to the shore anchor break except that it happened at a different time. The log book gives the time for "a loud noise" associated with the breaking of the structure as 2050 hours. Assuming that the shore anchor broke at 2050 hours, the ice could start moving and cause C3W' to break at 2053 hours as indicated by C2W forces. This indicates, therefore, that the anchor chain was the second item to break.

An alternative possibility for the C2W force peak is that the peak was due to the ice acting only on the floats attached to the junction plate connecting C2W and C3W'. Possibly the C3W' assembly broke earlier and the occurrence went unnoticed because the C2W assembly seemed quite insensitive to force changes in the rest of the structure until 2050 hours. The reason for this insensitivity is believed to be due to the way the ice cover, the shoreline and the ice boom interacted at a much earlier date; this interaction will be discussed in the next section.

The forces in C1W after 2050 hours were probably due to ice acting on the large float supporting C1W at the surface. The ship was still moving through the ice at that time and its activity probably also affected the readings of the forces. When the ship stopped is uncertain. The peak load of 87,000 lb (387 kN) in C1W at 2102 hours

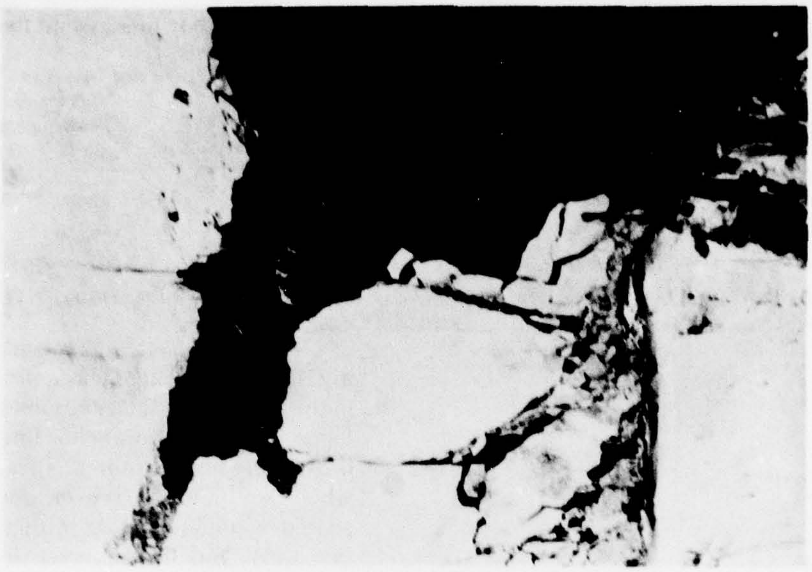

Figure 5. Broken ice behind the west ice boom.

and the rapid drop that followed are thought to be due to ice pushing on the float until it submerged, whereupon the ice could easily slide over it.

Ice, shore, and boom interaction

The interaction between the ice, the shoreline and the ice boom can best be characterized as complex. The data obtained and observations made thus far in this limited study are not sufficient to fully explain what was going on. The original design report (Perham 1977) should be referred to for an understanding of how the unconsolidated ice cover was expected to interact with the ice boom.

The force levels measured in the west ice boom were within expected values as mentioned earlier, but they were often not distributed in the structure as expected; that is, the force level in C3W was often higher than expected in relation to the force level in C1W at corresponding times. Also, the force then in C2W was often lower than expected.

A strong factor in this distribution may be the location of the boom. The original calculations ignored the presence of the shoreline because the harbor was very wide and the ice floes were not expected to arch across the harbor at any point near the boom. However, the orientation and location of the west boom probably give it some of the characteristics of a shoreline. At least it seems to receive part of the lateral forces produced by the ice arching phenomenon, as discussed in the design report (Perham 1977).

Another reason for the unexpected load patterns may have been the presence of large, irregularly shaped pieces of ice such as the one shown in Figure 5. Such a piece could rotate about the shoreline like a mechanical cam and load up only a small section of the boom or a junction float. A point loading like this has no correlation with the theory used which assumed that the load would be evenly distributed.

Should a solid ice cover begin to move over the boom while simultaneously sliding along the shoreline, it may encounter a protrusion which causes it to move sideways. Such a protrusion is shown at the left center of Figure 5. Ice seems to collect naturally and solidify at the bend in the shoreline, and when the photo was taken, it presented a ramp angle of about 20° to the moving ice. An evaluation of the structural forces under these circumstances could indicate that the forces were originating on land.

Another factor making the situation less than ideal is also related to the same bend (see Fig. 3 and 4). The bend would tend to protect the shore end of the boom section B2W from ice pressure and change the direction of tension at the anchor point. The change would probably not be great, but field measurements have not been made to evaluate it.

Table IV. Estimated loads in the anchor lines of an ice boom structure resulting from the movement of an ice cover frozen to its timbers.

	Anchor line characteristics				*Forces in the combinations of anchor lines shown*[4]							
	Spring[1] *rate*		*Elongation*[2]	*Included*[3] *angle*	*Case 1*		*Case 2*		*Case 3*		*Case 4*	
Anchor line assembly	*(lbf/in.)*	*(kN/m)*	*ratio*	*(arc deg)*	*(lbf)*	*(kN)*	*(lbf)*	*(kN)*	*(lbf)*	*(kN)*	*(lbf)*	*(kN)*
C1W	3,750	657	0.79	37	22,200	98.6	23,600	105.0	26,300	117.0	58,400	260.0
C2W	3,750	657	0.72	45	20,200	89.9	21,500	95.8			53,200	237.0
C3W	2,490	611	0.59	53	15,400	68.5						
C3W'	3,340	585	1.00	0	25,000	111.0	26,600	118.0	29,600	132.0	65,800	293.0
A4W-B2W	25,000	4,378	0.67	48	125,000	557.0	134,000	594.0	149,000	661.0		
Displacement in. (m)[5]					7.5	(0.19)	8.0	(0.20)	8.9	(0.23)	19.7	(0.5)

[1]Force required to produce a unit elongation in the anchor assembly.
[2]The ratio of the elongation of the anchor line assembly to the displacement of the ice sheet.
[3]The angle between the anchor line and the direction of travel (116°) of the ice sheet.
[4]The force level in the ice cover, assumed to be 150,000 lbf (667 kN).
[5]Displacement of the ice sheet needed to devel·p the forces shown in the structure.

Lastly, a large ice sheet breaking free from shore (Fig. 2) would tend to rotate about the shoreline at or near the boom and increase the load in C3W in particular.

A rough estimate of the movement possible in the direction of C3W can be made from the ratio of lengths as in leverage calculations. C3W is about 300 ft (90.3 m) upstream of the bend in the shoreline and the ice cover can reach upstream over, say, 7000 ft (2110 m). If the ship track is clear and 110 ft (33.1 m) wide when the cover breaks free, the ice at C3W could tend to move out 4.7 ft (1.42 m). This is actually more stretch than is needed to break the line. Calculations indicate further that the breaking level of force can be developed by this ice cover lever.

Force estimate

Two of the anchor line assemblies that broke were not instrumented, and it seemed advisable to try to estimate the levels of force present in them when the breaks occurred. The ice cover was assumed to be solid at the time of the breaks and frozen firmly to the ice boom timbers even though it had cracked away from shore. Also, the ice cover was assumed to move in the same general direction as the upstream shoreline in the vicinity of the boom, or 116°. The ice boom plans gave the location and orientation of each ice boom component and the shoreline (Fig. 4). The individual components were also well described by the plans and their load deflection characteristics were calculated.

The most difficult part was estimating the elongation characteristics of the anchor assembly at the shore anchor point A4W. The main anchor was located about 220 ft (67 m) on shore and was connected to the ice boom by lengths of 2.0 in. (5.1 cm) and 1¾-in. (4.4 cm) stud-link anchor chain in series. The chain was buried and some of the fill material may have become frozen. In any case, the chain is much stiffer than the anchor lines in other locations.

In addition, the force comes to the chain through a 1⁵⁄₁₆-in. (3.3-cm)-diam wire rope, boom section B2W. The wire rope usually follows the curve of the ice boom and can be pulled into a straighter line under load. Its displacement would then be greater than its tensile properties would indicate.

In the analysis, several possible values for shore anchor stiffness were tried until a combination of forces was found that was fairly consistent with the forces that were measured. Table IV summarizes the structural characteristics and the calculated forces. The force of 150,000 lbf (667 kN) on the ice cover is a rough estimate; the flow conditions were very mild on 20 January, but the size of the solid ice cover was much greater than originally expected. The analysis also assumed that the structure had no loads in it when the conditions were applied. The very stiff spring rate (force-elongation ratio) indicated for A4W produced the most consistent results.

Explanation of cases

In case 1 (Table IV) all of the anchor assemblies are intact. The force levels are roughly the same for each assembly except for A4W where they are much greater. The unexpected condition here is the forces in the C1W and C2W lines, which are roughly at the same level as those in C3W and C3W'. These first two lines are over twice as strong as the latter (see Table III); thus they are capable of supporting a much larger portion of the loads. This force level, however, is controlled by the stiffness of the lines and their direction or orientation with respect to ice movement. If the direction of force from the ice cover should change and be closely aligned with C1W and C2W, the force levels would then be more proportional to the strength of each assembly.

In case 2, C3W is broken. The shore anchor force has increased and the load in the remaining lines has increased similarly. The load calculated for C1W is lower than that measured after the break, but the calculated load for C2W is much higher than its measured value. The latter measurement remained at about 5,200 lbf (23 kN) most of the time.

The constancy of the force on C2W seems to indicate that, for some reason or other, this line was not supporting the boom. Therefore, it was decided to calculate the forces for case 3, which assumed that somehow the C2W line was made ineffective in addition to the C3W lines being broken. This case gave a better correlation with the measured forces than the previous case.

The moving, broken ice seems to interact with the shoreline and the boom to make C2W ineffective for small ice cover movements. It would probably do this in one or more of the ways described earlier under the subject of interactions. For example,a large ice floe could push upon the floats at the junction of C2W and C3W' and move them farther out into the channel. The junction point would move in an arc controlled by C3W' (see Fig. 3), and relieve the load in C2W. The ice could then freeze solid and at the same time freeze to the timbers, thus fixing this combination of positions in place.

Two other items should be pointed out in case 3. The first is the load in A4W. Its magnitude is nearly the same as the load from the ice sheet; yet the other two lines also carry appreciable loads. The main reason for this apparent anomaly is that, because the lines are not oriented to carry this particular load most efficiently, only a portion of their tension restrains the ice. Their vector sum, however, equals the ice load. The second item is the estimated ice sheet movement of 8.9 in. (0.23 m). Although this seems to be a rather small displacement, it is all that is needed to develop the force combination shown under these idealized circumstances.

Case 4 assumes that the shore anchor has broken and that the ice is being restrained by C3W', C2W and C1W. The combination of forces shown is in fair agreement with those measured shortly after the shore anchor break was heard. The breaking of both anchor connections must have agitated the boom structure and probably caused several timbers to crack free from the ice sheet. More cases could be calculated, but the various mechanisms and situations that influenced the breaking of the boom seem to have been pointed out and evaluated sufficiently.

Effect of ship passage

As mentioned earlier, a note on the recorder chart read: "Mackinaw downbound 18:33," meaning that it passed through the ice booms at 1833 hours. The Soo Lock data show that the Mackinaw locked out, downbound, at 1810 hours. The ship must have proceeded directly downstream from the locks and through the ice boom opening at a speed averaging 6 knots (3.1 m/s) or more.

The total fluctuation in force caused by the ship was not great, about 13,000 lbf. The important factor, however, is that the Mackinaw's passage through the Soo Harbor ice cover was sensed by the ice boom force instruments for a period of about 15 minutes before the Mackinaw emerged through the boom opening. This is roughly analogous to travelling two-thirds of the distance between the two points at the above average speed, or approximately the distance between the Edison Sault Electric Plant and the ice boom. In other words, a ship that came closer to the ice boom than this could affect the loading on the boom under these conditions.

Effects of ship, ice and shore

The cracks noticed in the ice cover at 1730 hours make it difficult to estimate the mechanism whereby the ice cover could develop the forces causing failure in the anchor chain. It must be assumed that the ice forces cause the sheet to act as a unit even when cracked. The most plausible mechanism seems to be that some ice slid down the gap previously mentioned between the shoreline and the ice cover to the vicinity of the anchor A4W.

When the Roger Blough started to move down the ship track made by the much narrower Mackinaw, it may have caused the ice sheet at the boom to rotate counterclockwise in plan view about this recently jammed ice. The intruding ice would act like a block stuck between the hinges of a door that makes it rather easy to push on the door and break the hinges. Large forces could be developed with little ice movement. This mechanism is another factor in favor of keeping the ice sheet against shore.

Tension link check

The loads measured by T3W during the two breaks in the C3W anchor line (one in 1975-76 and one in 1976-77) were lower than the expected capacity of the line. Because of this, the data and the tension link were carefully inspected. There was no indication that the tension link and measurement system had changed their characteristics.

CONCLUSIONS

1. The west ice booms showed a substantial *improvement* in reducing harbor ice losses over those of the previous year. The ice behind the east boom was stable both winters.

2. The failure process in the west ice boom was initiated by lateral movement in the solid ice cover upstream, which resulted in loading the C3W anchor cable to failure at 39,600 lbf (176 kN).

3. The failure of the oval link at 39,600 lbf (176 kN) is puzzling because cable C3W had been loaded to at least 53,000 lbf (236 kN) the previous year. Not enough information is available to say why the link broke.

4. The anchor chain at A4W was probably the second item to fail. It was certainly the most important failure and the breaking force is unknown, although it may have been as low as 150,000 lbf (667 kN). The boom cable that is attached to it has a nominal breaking strength of 230,000 lbf (1,023 kN) and this value can be considered as an upper limit for this force. It is thought that the rebounding boom cable caused the connection plate that was broken to be torn from its timber at this time.

5. The C3W' anchor line was probably the third item to fail; but because the line was not instrumented, the force at the time of failure is not known.

6. The breaking forces generated in the boom structure were the result mainly of natural forces acting on a very large ice cover that was frozen to the floating elements. The force levels for various parts of the structure may be calculated reasonably well by treating it as a statically indeterminate structure. For this structure, the forces calculated in this manner were substantially different from the earlier calculations which were based upon unconsolidated, or fragmented, ice cover loading.

7. An evaluation of the measured forces shows that the west ice boom receives some lateral forces, as if it were a shoreline. Also, when the ice cover is broken or partly broken, it can interact between the shore and the boom, or the boom floats, to make the C2W anchor rope ineffective; i.e., C3'W must carry the load of C2W as well as its own.

8. The ore carrier Roger Blough contributed to the load on the boom at the time of failure but its full effect cannot be evaluated.

9. The warming trend probably exaggerated a weakened condition between the ice cover and shoreline and let the cover break loose. The flow forces under the ice cover and the ice boom forces formed a force couple that made the ice swing out away from shore once it had broken free.

10. The St. Marys River ice booms use a much greater quantity of stud link anchor chain and related shackles and links than any other ice boom structures known.

RECOMMENDATIONS

1. Simplify the anchor line assemblies; use no more components than are necessary and use them in the best possible way. For instance, if a wire rope is to be connected to an anchor and a shackle is required, use an anchor shackle, not a chain shackle, on the anchor point and a closed fitting, not an open fitting, on the wire rope. As a general rule, wire ropes should be used for the anchor lines and boom lines.

2. Check the present anchor points for C3W and C3W' to determine if the strength of both anchor ropes can be increased.

3. Check parts carefully for weakening due to wearing, fatigue, or sharp indentations. Replace all broken parts and components of questionable strength before reinstalling them.

4. Investigate installing a structure of some sort that would prevent the large southwest ice cover from rotating out into midstream. Another "rock pile" located due south of the present one, about 300 ft (91 m) south of course 1, might do. A second one, roughly half way between there and the west ice boom at the edge of the navigation improvement, would also help.

5. Add two new sections, complete with independent anchors and cable structure, to the west ice boom; this would help to reduce the load concentration on the boom. If the structure in item 4 is installed, however, these would probably not be needed.

6. Lastly, and most importantly, if the ice booms will be used continuously during the winter after the winter of 1977-78, redesign them using the knowledge gained to date. Originally, they were a prototype structure intended only for temporary use. Several parts of the structure should be changed to make them more reliable and easier to install, remove, and maintain. The ice restraint capacity of the timbers should also be improved.

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APPENDIX A. FORCE LEVEL FLUCTUATIONS IN WEST ICE BOOM, 20 JANUARY 1977.

Anchor line	Time (hr)	Force (lbf)	Force (kN)	Notes on forces
C3W	1405	5,300	24	Small step increase about 1406 hours
(Tension	1407	5,400	24	
link	1555	5,700	25	
T3W)	1556	6,300	28	Small increase
	1606 +	39,600	176	I. Rapid increase to breaking load
	1607	0	0	Dropped to zero and remained there
C2W	1030	5,400	24	Start of slight variation
(Tension	1036	5,600	25	High point
link	1100	5,400	24	
T2W)	1400	5,100	23	
	1540	5,600	25	Center of second slight variation
	1900	5,100	23	
	2051	5,300	24	Start of rapid increase
	2053	52,000	231	II. Peak load followed by rapid decrease
	2054	7,300	32	Maximum following peak
	2102	6,400	28	*III.* Brief force drop of about 3,600 lbf (76 kN)
	2118	27,200	121	Maximum subsequent level
	2120	6,400	28	Decrease
	2220	6,900	31	Gradual rise
	Midnight	7,300	32	Stable level
C1W	1210	16,700	74	Slight gradual increase
(Tension	1555	17,000	76	
link	1556	17,600	78	Small step increase
T1W)	1606	28,500	127	I. Maximum before break of C3W
	1607	20,000	89	Minimum immediately after break
	1615	33,000	147	
	1816	27,200	121	Varying level had stabilized here
	1819	29,000	129	Sequence: small increase
	1825	16,000	71	followed by drop to this level;
	1831	23,800	106	and a rebound to this level where it was nearly constant
	2027	23,500	105	Start of increase
	2031	34,100	152	Maximum followed by fluctuations and
	2049	26,000	116	reduction to this level
	2050	26,000	116	Start of quite large fluctuations
	2052	53,200	237	
	2053	15,600	69	II. Suspect C3W' anchor broke
	2102	87,000	387	III. Maximum load
	2102 +	2,300	10	
	2117	11,000	49	
	2122	4,900	22	Stable level reached

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