SR 222

Special Report 222

ARCHING OF FRAGMENTED ICE COVERS

Darryl J. Calkins and George D. Ashton

April 1975

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Special Report 222	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ARCHING OF FRAGMENTED ICE COVERS		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Darryl J. Calkins and George D. Ashton		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		12. REPORT DATE April 1975
		13. NUMBER OF PAGES 20
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Floating ice Ice Ice boom concept Waterways (transportation)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A study of arching by fragmented ice floes across a gap in a surface obstacle is reported. The study included several series of experiments in a hydraulic flume in which simulated ice was released upstream of the surface obstacle at controlled rates and the occurrence or non-occurrence of the formation of a stable arch was observed. The threshold of arching was found to correlate well as a function of the supply rate of surface area of ice, the exit ice surface discharge at the gap, and the ratio of individual floe size to gap dimension. In a series of corollary experiments an arch, once formed, was subjected to a disturbance in the form of a vertical rod traversed longitudinally through the accumulation in the upstream direction. The quantity of ice released and the rate of release prior to another arch re-forming was determined.		

PREFACE

This report was prepared by Darryl J. Calkins, Research Hydraulic Engineer, of the Applied Research Branch, Experimental Engineering Division; and Dr. George D. Ashton, Hydrologist, Snow and Ice Branch, Research Division. The work was performed as part of the In-house Laboratory Independent Research (ILIR) Program.

Acknowledgment is expressed for helpful advice, assistance and discussions with Kevin Carey, William Hibler and John Stubstad. Technical review of the report was performed by Roscoe E. Perham and Guenther Frankenstein of USA CRREL.

CONTENTS

	Page
Abstract	i
Preface	ii
List of symbols.....	iv
Introduction and background.....	1
Experiments.....	2
Flume facility	2
Simulated ice	2
Experimental procedures	2
Results	6
Uniform size blocks	6
Mixed blocks	10
Funnel geometry	10
Disturbed arch experiments	12
Discussion and conclusions	16

ILLUSTRATIONS

Figure	
1. Hydraulic flume facility	2
2. Cross sectional views of various sections along the flume	3
3. Simulated boom and supports	4
4. Simulated boom and working section of flume	5
5. Feed system upstream of boom	5
6. Q_i vs a/b , uniformly sized blocks (linear scales)	9
7. Q_i vs a/b , uniformly sized blocks (logarithmic scales)	9
8. Definition sketch	10
9. Q_i/Vb vs $\bar{a}/b$, mixed blocks (average block dimension criterion).....	11
10. Q_i/Vb vs a_L/b , mixed blocks (larger block dimension criterion)	11
11. Funnel geometry	11
12. Q_i/Vb vs a/b and a_L/b , funnel geometry	11
13. Exit ice surface discharge rates after disturbance of arch.....	12
14. Area of ice released after disturbance of arch	13
15. Distribution of area of ice released after disturbance of arch.....	15
16. Area of open water between stable arch and gap.....	16

TABLES

Table	
I. Summary of initial arching experiments	7
II. Summary of disturbed arch experiments.....	14

LIST OF SYMBOLS

A_r	Total surface area of blocks released after a disturbance (m^2)
B	Flume width (m)
D	Depth of flow (m)
Q_i	Supply surface discharge of ice ($m^2\ s^{-1}$)
$Q_{i,e}$	Exit surface discharge of ice through gap ($m^2\ s^{-1}$)
S	Length of surface accumulation (m)
V	Mean flow velocity ($m\ s^{-1}$)
a	Side dimension of simulated ice fragment (m)
$\bar{a}$	Average side dimension of mix of block sizes (m)
a_1, a_2	Side dimension of components of mix of blocks (m)
a_L	Side dimension of largest block of mix of blocks (m)
b	Dimension of gap in boom (m)
c	Surface concentration of blocks (dimensionless)
n_1, n_2	Number of blocks of each component size in mix of blocks
t	Block thickness (m)
τ	Time (s)

ARCHING OF FRAGMENTED ICE COVERS

A Laboratory Study

by

Darryl J. Calkins and George D. Ashton

INTRODUCTION AND BACKGROUND

Floating, fragmented ice pieces are often retained at river channel constrictions, or at gaps in floating barriers, by the phenomenon of arching, i.e. a bridging of the gap by the floating fragments. Examples of natural arching occur on the Niagara River at the outlet of Lake Erie and on the St. Clair River at the outlet of Lake Huron. On a smaller scale, ice often arches across the openings between bridge piers, sometimes resulting in an ice jam and sometimes merely in an accumulation of ice upstream from the obstacle.

In recent years, floating ice booms have been used to contribute to the stability of natural ice arches as, for example, in the upper and lower reaches of the St. Lawrence River and at the outlet of Lake Erie. They have also been used simply to retain ice to prevent downstream accumulation and jamming or to insulate the flow against heat loss to the atmosphere and the consequent formation of frazil ice.

Generally ice booms are installed in the form of a complete obstacle across the flow surface. Recently there has been increasing consideration of the possibility of opening navigable waterways for extended periods during the winter season. Clearly, some way must be found for ships to pass through such booms without significantly decreasing their ice retention capability. This passage requirement might be met simply by leaving a gap in the boom and taking advantage of the natural ice arching phenomenon.

In a more general sense, the arching phenomenon is an important factor in determining the point along a waterway at which the accumulation of floating ice should be initiated. Finally, arching is involved, in a reverse sense, in determining the ice passing capability of an opening or openings, as at a multiple-span bridge. The purpose of this investigation is to briefly explore the arching phenomenon via hydraulic modeling.

The study was primarily experimental. Using simulated ice (square polyethylene blocks), the relationship between flow velocity, surface discharge of ice, gap geometry and fragment parameters was explored by conducting several series of experiments in a hydraulic flume in which gap geometry and ice supply rate could be controlled. The result was a simple relationship delineating the arching tendencies between the ice supply rate Q_i ($\text{m}^2 \text{s}^{-1}$), normalized by the product of the surface velocity V (m s^{-1}) and the gap width b (m), and the ratio of the fragment length to the gap width.

A limited attempt was also made to analyze the phenomenon following the general lines of attack previously used in studies of the flow of granular material, most notably studies of gravityflow of bulk materials from storage bins and hoppers. This attempt has not as yet yielded significant results and is not reported here.

Figure 1. Hydraulic flume facility.

EXPERIMENTS

Flume facility

The experiments were conducted in the CRREL hydraulic flume facility (Fig. 1, 2). The flume is a fixed-slope recirculating water flume with a cross section $0.92 \text{ m} \times 0.92 \text{ m}$ and is 7.3 m long between inlet and outlet. The flow is driven by a variable speed pump through a 0.3-m-diameter return line equipped with a Venturi meter for discharge measurement. Additional details of the flume facility are described by Calkins (1974).*

Simulated ice

Ice fragments were simulated by square pieces of low-density polyethylene sheet plastic. Most of the experiments were conducted with 74-mm-square and 37-mm-square pieces with a thickness of 6.5 mm, used either separately or in combination. The square shape was chosen for ease in fabrication and handling in the feed system. A few experiments were conducted with fragments of other sizes, both thicker and larger. The polyethylene fragments have a specific gravity of about 0.92, very close to the specific gravity of pure ice. The pieces were cut from 1.1- $\times$ -2.2-m sheets on a bandsaw. No attempt was made to roughen or smooth the edges. The plastic was translucent and white, and resembled natural ice in appearance.

Experimental procedures

The basic procedure followed in most experiments was as follows. A flow depth of about 0.58 m was established and a simulated boom with a gap of predetermined width was positioned at the water surface. No attempt was made to model or scale the ice boom; information was desired only for the area near the gap. It was assumed that the model barrier would have nearly the same retention characteristics as a full size boom, since submergence and overturning of the blocks was not permitted. Simulated ice fragments were then released about 4 m upstream at a uniform rate and floated downstream to the boom. The behavior of the pieces near the boom was observed visually and also recorded by time-lapse movie photography.

* Calkins, D.J. (1974) A research hydraulic flume for modeling drifting snow: Design, construction and calibration. U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) Technical Report 251.

a. Vertical cross section of bottom of flume structure.

b. Elevation view of structural tee placement along sides of flume.

c. Vertical cross section between glass supports at lower edge of sidewalls.

d. Vertical cross section of carriage rail and the bracket holding the top edges of the glass panels.

Figure 2. Cross sectional views of various sections along the flume.

ARCHING OF FRAGMENTED ICE COVERS

Figure 3. Simulated boom and supports.

by a camera mounted slightly upstream of the boom and approximately 1.5 m above the water surface. The primary information sought was whether or not a stable arch would form across the boom opening. Flow velocities were kept low enough so that the ice fragments accumulated by juxtaposition only, i.e. there was no underturning or submergence of individual pieces. When a stable arch did form, it was disturbed by manually moving a vertical rod upstream through the accumulation (thus crudely simulating the passage of a vessel), and the subsequent behavior of the pieces was observed and photographed.

The boom was made of 25- x 25- x 76-mm wood blocks, painted black for photographic purposes and strung on a nylon line with a 25-mm space between blocks. Both ends of each half of the boom adjacent to the gap were held in place by 9.5-mm-diameter aluminum rods (Fig. 3, 4). The gap in the boom was varied in different experimental runs by repositioning both the vertical rods in the support frame and the number of blocks in the boom, while keeping the gap centered in the flume. In all but one series of experiments the boom elements were aligned perpendicular to the longitudinal axis of the flume. In one series the boom was arranged in a funnel shape; 25-m-square by 0.61-m-long wood strips extended from the endpoints of the gap to the walls of the flume upstream.

Water depth was determined using a point gage mounted on the flume rails. Water discharge was determined using a calibrated venturi meter with the pressure differential sensed by a transducer and the output traced by a strip chart recorder. In any one run the discharge was kept constant. The mean velocity was determined by dividing the water discharge by the area of the flow cross section. Occasionally the velocity calculation was checked by comparison with float measurements; agreement was within 5%. Accordingly, the mean velocity is assumed equal to the surface velocity in the results that follow even though it is recognized that the surface velocity is actually a few percent higher due to boundary layer effects. Similarly the surface velocity through the gap was taken equal to the mean velocity even though it is recognized that the local obstructions near the gap may cause the surface velocity to be different than the mean velocity.

Several methods were used to feed the simulated ice fragments to the water surface. At low ice surface discharges (the surface area of blocks passing a given point per unit of time) blocks were fed individually by hand to the water surface. At intermediate ice surface discharges this method became unwieldy because the number that could be released by hand at a uniform rate was limited and because undesirable waves were created when the blocks hit the water surface.

At higher ice surface discharges two methods were used. The most successful method consisted of arranging the block supply on a sloping board in a regular manner and then, with the aid of a "rake," pushing the blocks off at a constant rate (Fig. 5). The sloping platform was positioned close to the water surface to minimize waves. The platform was constructed by placing 9.5- x 37-mm slats 80 mm apart on a sheet of plywood. The rake was built to fit the grooves, and allowed a uniform distribution of blocks across the flume width to fall to the water surface.

Figure 4. Simulated boom and working section of flume.

Figure 5. Feed system upstream of boom.

The other method consisted of arranging the blocks in a regular manner directly on the water surface upstream of a floating obstacle which extended across the full width of the flume about 4 m upstream of the boom. The obstacle was then removed and the ice pieces allowed to float downstream to the boom. Upon release, the fragments diffused longitudinally somewhat and the initial regular pattern became more random. With this method the ice surface discharge rate at the boom location was determined from the photographic record.

Three major series of experiments were conducted: one using small blocks, one using large blocks, and one using a combination of the two sizes. When the combination of sizes was used, the ratio of large blocks to small blocks was 1:2.26, which yielded a corresponding ratio of area of large blocks to area of small blocks of about 1.76:1. Blocks were fed continually, either until a stable arch formed or until the block supply was exhausted. In the latter case the supply consisted of at least 120 of the large blocks or 385 of the small blocks except in a few early experiments as indicated in Table I. In the combination block runs the supply was 170 large blocks and 385 small blocks. Upon completion of each run the blocks were retrieved from the vicinity of the boom or from the downstream end of the flume with a dip net.

The photography system consisted of a 16 mm movie camera mounted above the flume (see Fig. 2), with a remote start/stop control. The camera was run at selected time-lapse increments down to 1 frame/second and at a continual 8 frames/second rate for several experiments. Black-and-white film provided an excellent record of the behavior of the blocks in the vicinity of the boom for later observation and analysis. Prior to each run a placard with the run description and data was filmed to provide positive identification of each run.

RESULTS

A summary of the experimental runs made to determine the conditions for formation of an initial stable arch is presented in Table I, where the side dimension of a fragment is denoted by a , the thickness by t , the gap dimension by b , the flow depth by D , the mean velocity by V and the ice surface discharge by Q_i . The table also shows whether or not a stable arch formed and gives the ratios a/b and Q_i/Vb . By a "stable" arch is meant an arching across the gap such that no further discharge of blocks occurred through the gap. In some cases, which are discussed in more detail below, the supply ice surface discharge exceeded the exit ice surface discharge, and the outflow of blocks continued until an arch formed or until the supply of blocks behind the barrier was exhausted. In a few cases, a temporary arch formed but released after a short time; these cases were treated as non-arching.

Uniform size blocks

The data for the runs using blocks of uniform size are plotted in Figures 6 and 7 on linear and logarithmic plots, respectively. The line drawn on each of the two plots represents approximately the threshold between the occurrence or non-occurrence of arching and is described by

$$\frac{Q_i}{Vb} = 0.01 \left(\frac{a}{b} \right)^{-2.56} \quad (1)$$

No theoretical significance is attached to the form of eq 1; it separates the arching and non-arching data adequately within the range of the experiments ($0.14 < a/b < 0.5$). In fact, it may well be argued that eq 1 is not of correct form, particularly at high values of a/b , since clearly a/b cannot exceed 1 (or, for that matter, 0.707 if it is hypothesized that eventually a block will position itself diagonally across the gap). At low values of a/b (large opening to block size ratio) there is also considerable uncertainty.

Before examining this point it is useful to discuss the choice of non-dimensional groups used to present the data, i.e. a/b and Q_i/Vb . The ratio of block size to gap dimension is rather obvious; it is expected that

Table I. Summary of initial arching experiments.

 a = Side dimension of block D = Flow depth t = Block thickness V = Mean velocity b = Gap width Q_i = Ice surface discharge

Run	a (mm)	t (mm)	b (m)	D (m)	V (m s ⁻¹)	Q_i (m ² s ⁻¹)	Blocks rtd	Blocks passed	a/b	Q_i/Vb	Stable arch	Remarks
101	74	20	0.127	0.51	0.080	0.0056	52	11	0.582	0.537	Yes	
102						0.0056	52	8	0.582	0.537	Yes	
103				0.56	0.076	0.0056	50	4	0.582	0.566	Yes	
104						0.0056	50	7	0.582	0.566	Yes	
105						0.0093	50	11	0.582	0.961	Yes	
106						0.0093	50	11	0.582	0.961	Yes	
107			0.178	0.58	0.075	0.0137	52	11	0.415	1.023	Yes	
108						0.0191	52	20	0.415	1.432	Yes	
109						0.0191	52	10	0.415	1.432	Yes	
110						0.0191	52	30	0.415	1.432	Yes	
111			0.216		0.065	0.0191	136	32	0.342	1.458	Yes	
112						0.0191	186	20	0.342	1.361	Yes	
113			0.267			0.0191	184	47	0.277	1.101	Yes	
114						0.0191	184	35	0.277	1.101	Yes	
115			0.363			0.0120	120	all (2)	0.204	0.509	No	
116						0.0109	120	all	0.204	0.463	No	
117						0.0300	120	47	0.204	1.273	Yes	
118						0.0344	120	48	0.204	1.458	Yes	
119						(1)	120	9	0.204	(1)	Yes	
120						0.0344	120	17	0.204	1.458	Yes	
121					0.091	0.0328	180	20	0.204	0.992	Yes	
122						0.0137	120	60	0.204	0.204	Yes	
123						(1)	192	7	0.204	(1)	Yes	
124			0.266			(1)	192	2	0.278	(1)	Yes	
125	74	6.4		0.57		0.046	192	9	0.278	1.90	Yes	
126						0.036	192	13	0.278	1.50	Yes	
127	148	6.4	0.363			0.059	60	2	0.408	1.80	Yes	
128			0.540			0.054	60	4	0.274	1.10	Yes	
129	74	6.4	0.343	0.58		0.031	192	12	0.216	1.01	Yes	Funnel geometry
130			0.285	0.59	0.074	0.033	180	20	0.259	1.564	Yes	
131						0.029	180	26	0.259	1.373	Yes	
1			0.240		0.077	0.0055	180	45	0.308	0.296	Yes	
2						0.0037	180	43	0.308	0.197	Yes	
3			0.310			0.0055	180	all	0.238	0.229	No	
4						0.0055	180	all	0.238	0.229	No	
5						0.0070	180	109	0.238	0.295	Yes	
6						0.0072	180	all	0.238	0.300	No	
7						0.0082	180	133	0.238	0.343	Yes	
8						0.0109	180	140	0.238	0.458	Yes	
9						0.0118	180	34	0.238	0.496	Yes	
10						0.0149	180	19	0.238	0.625	Yes	
11			0.440			0.0153	180	all	0.168	0.453	No	
12						0.0164	180	all	0.168	0.484	No	
13						0.037	180	all	0.168	1.093	No	Arch formed temporarily
14						0.026	180	all	0.168	0.774	No	
15			0.198			0.0055	120	10	0.373	0.358	Yes	
16						0.0027	180	106	0.373	0.179	Yes	
17						0.0018	180	all	0.373	0.119	No	
18						0.0027	180	all	0.373	0.179	No	
19			0.267			0.0068	180	107	0.276	0.329	Yes	
20			0.153		0.078	0.0011	180	13	0.483	0.092	Yes	
21							180	8	0.483	0.092	Yes	
22						0.00055	40	all	0.483	0.046	No	
23						0.00082	180	35	0.483	0.069	Yes	
24			0.488			0.034	180	all	0.151	0.904	No	
25						0.032	180	30	0.151	0.841	Yes	
26						0.034	180	all	0.151	0.884	No	

Table I (cont'd). Summary of initial arching experiments.

a = Side dimension of block D = Flow depth
 t = Block thickness V = Mean velocity
 b = Gap width Q_i = Ice surface discharge

Run	a (mm)	t (mm)	b (m)	D (m)	V (m s ⁻¹)	Q_i (m ² s ⁻¹)	Blocks rlsd	Blocks passed	a/b	Q_i/Vb	Stable arch	Remarks
27						0.030	180	52	0.151	0.788	Yes	
29	37	6.4	0.129	0.57	0.080	0.0023	300	all	0.286	0.221	No	
30						0.034	720	3	0.286	3.30	Yes	
31						0.034	720	5	0.286	3.30	Yes	
32						0.0096	150	32	0.286	0.929	Yes	
33						0.0027	264	226	0.286	0.265	Yes	
34				0.56	0.082	0.0030	264	131	0.286	0.285	Yes	
35						0.0020	374	all	0.286	0.189	No	
36			0.175			0.0030	385	all	0.211	0.210	No	
37						0.0060	385	246	0.211	0.420	Yes	
38			0.222			0.0060	385	all	0.167	0.331	No	
39						0.0075	385	all	0.167	0.414	No	
40						0.0160	385	all	0.167	0.877	No	
41						0.0176	385	250	0.167	0.965	Yes	
42			0.268	0.55		0.0527	385	all	0.138	2.398	No	Arch formed, then released
43						0.0146	385	all	0.138	0.666	No	
44						0.0240	385	all	0.138	1.090	No	
45						0.0310	385	all	0.138	1.411	No	Arch formed, then released
46						0.0315	391	120	0.138	1.433	Yes	
47						0.0310	385	all	0.138	1.411	No	
48	74	20	0.222		0.083	0.0055	180	69	0.333	0.296	Yes	
49						0.0027	180	all	0.333	0.148	No	
50						0.0036	180	74	0.333	0.198	Yes	
51	mix (3)	6.4	0.268			0.0172	555	21/69	0.276	0.770	Yes	
52						0.0012	555	29/60	0.276	0.503	Yes	
53						0.0057	555	all	0.276	0.257	No	
54						0.0086	555	41/83	0.276	0.385	Yes	
55			0.327			0.0086	555	all	0.226	0.315	No	
56			0.326			0.0112	555	76/186	0.226	0.414	Yes	
57			0.356			0.0172	555	55/128	0.208	0.580	Yes	
58						0.0112	555	all	0.208	0.379	No	
59			0.425			0.0172	555	93/166	0.174	0.485	Yes	
60						0.0172	555	all	0.174	0.485	No	
61						0.0214	555	all	0.174	0.607	No	
62						0.0286	555	all	0.174	0.809	No	
63						0.0286	555	95/209	0.174	0.809	Yes	
64			0.154			0.0042	555	8/18	0.480	0.331	Yes	
65						0.0027	555	20/31	0.480	0.214	Yes	
67						0.0016	555	47/86	0.480	0.128	Yes	
68	37	6.4	0.293			0.035	385	58	0.126	1.445	Yes	Funnel geometry
69						0.020	385	220	0.126	0.834	Yes	Funnel geometry
70						0.016	385	all	0.126	0.637	No	Funnel geometry
71						0.019	385	all	0.126	0.774	No	Funnel geometry
72						0.025	385	all	0.126	1.032	No	Funnel geometry
73						0.028	385	all	0.126	1.141	No	Funnel geometry
74						0.031	385	all	0.126	1.275	Yes	Funnel geometry
75						0.038	385	all	0.126	1.548	No	Funnel geometry
76	mix (3)	6.4				0.017	555	16/25	0.252	0.704	Yes	Funnel geometry
77						0.0057	555	all	0.252	0.235	No	Funnel geometry
78						0.0086	555	55/125	0.252	0.352	Yes	Funnel geometry

Note (1) Blocks accumulated at boom and temporary barrier removed to start run.

(2) "All" means all blocks passed through the gap except possibly a few that were retained in the corners between the boom ends and the flume wall.

(3) A mixture of 170 large blocks (0.074 m square) and 385 small blocks (0.037 m square) was used. For purposes of the table the large block dimension (0.074 m) was used for "a". The two numbers under "total blocks passed" refer to large and small blocks, respectively.

Figure 6. Q_i vs a/b , uniformly sized blocks (linear scales).

Figure 7. Q_i vs a/b , uniformly sized blocks (logarithmic scales).

larger blocks will more easily bridge a gap than smaller blocks. The ratio Q_i/Vb is the ratio of the arriving surface area of ice per unit time to the exiting water surface discharge through the gap. Without stacking of the fragments (and the experiments were conducted at sufficiently low velocities that fragments accumulated only by juxtaposition) the exiting ice surface discharge cannot exceed the exiting water surface discharge. That is,

$$Q_{i,e} < Vb \quad (2)$$

where $Q_{i,e}$ denotes the exiting surface discharge of ice. Early in the experimental program it was thought that Q_i associated with non-arching would also be subject to the same constraint. Later experiments at lower values of a/b showed this not to be the case. The arriving ice surface discharge Q_i may exceed the exiting ice surface discharge $Q_{i,e}$ without a stable arch forming. The result of such a condition is an upstream progression of the ice-covered surface. Denoting the location of the upstream limit of surface coverage by S and the surface concentration by c , simple continuity yields

$$\frac{ds}{d\tau} = \frac{Q_i - Q_{i,e}}{cB} \quad (3)$$

Figure 8. Definition sketch.

where τ denotes time and B is the channel width (see Fig. 8). The longest potential accumulation upstream of the boom was about 2 m. With a larger supply and hence longer accumulation the increase in forces on the accumulation might cause arching at a lower supply rate Q_i . In three experiments (runs 119, 123, 124) a temporary barrier was placed across the gap and the ice blocks were allowed to accumulate upstream of the barrier. The barrier was then carefully removed and in all three cases arching occurred after

only a small number of blocks had exited through the gap. While these data are very limited they suggest that arching occurs more easily in an initially static ice field than in one in which the field has not yet come to rest in its entirety. Other experiments described later in which an established arch was disturbed support this suggestion.

Finally, the threshold of arching as described by eq 1 did not appear to be influenced by the size or thickness of the blocks although the range of these parameters was limited.

Mixed blocks

The experiments with blocks of uniform size were deliberately of an idealized nature. A natural ice field is seldom composed of uniformly sized fragments but usually contains a range of sizes. In an effort to examine the more natural case of varied fragment sizes, a number of runs were conducted with a mix of the small and large blocks, both with thicknesses of 6.4 mm. The ratio of blocks by number was held at 1:2.26 (large to small), yielding an area ratio of 1.76:1 (area of large blocks to area of small blocks). Immediately a difficulty is presented in choosing a representative block dimension a for use in comparing the results to the results of the uniformly sized block experiments. In Figures 9 and 10 the data have been plotted using two choices for the characteristic block dimension. In Figure 9 the characteristic dimension has been taken as the average side dimension defined by

$$\bar{a} \equiv \frac{n_1 a_1 + n_2 a_2}{n_1 + n_2} \quad (4)$$

where n_1 is the number of blocks with side dimension a_1 and n_2 is the number of blocks with side dimension a_2 . In Figure 10 the dimension of the larger blocks a_L has been used. In both plots Q_i is the ice surface supply rate of the mix. Equation 1 is also presented for comparison with the results of the uniformly sized block experiments. If the average side dimension is used to characterize the fragment size (Fig. 9) it is clear that eq 1 does not describe the threshold of arching well; i.e. the threshold of arching occurs at a lower value of Q_i/Vb than is predicted by eq 1. If the larger block dimension is used to characterize the fragment size (Fig. 10) then eq 1 is a reasonable description of the threshold, with Q_i calculated on the basis of the total area of large and small blocks. In this latter sense the mix of blocks is more conducive to arching than the uniformly sized blocks.

Funnel geometry

A number of runs were conducted with the sides of the boom elements arranged at an angle of 29° with the channel axis (Fig. 11) and with a gap width of 0.293 m. The "funnel" was constructed of single pieces of relatively smooth wood, painted black. Eight runs were conducted using only the 0.037-m-square blocks and three runs with the mix of block sizes (see Table I, runs 68-78). One run was conducted using 0.074-m-square blocks and a gap width of 0.343 m (run 129). The results are plotted in Figure 12 following the same format used earlier. Again, eq 1 is given for comparison with the experiments described earlier. The data are too limited to allow any conclusions to be drawn except to note that the results do not appear to

Figure 9. Q_i/Vb vs $\bar{a}/b$, mixed blocks (average block dimension criterion).

Figure 10. Q_i/Vb vs a_L/b , mixed blocks (larger block dimension criterion).

Figure 11. Funnel geometry.

Figure 12. Q_i/Vb vs a/b and a_L/b , funnel geometry.

ARCHING OF FRAGMENTED ICE COVERS

Figure 13. Exit ice surface discharge rates after disturbance of arch.

be significantly different from the earlier results with more conventional boom geometry. However, the smooth surface of the boom legs allowed blocks to slide along them with ease. It is possible that a rougher surface on the boom would allow arching to occur more easily. Future tests will explore the effects of a roughened boom surface.

Disturbed arch experiments

In many of the runs in which a stable arch was formed, the accumulation behind the arch was deliberately disturbed by passing a vertical rod upstream through the accumulation, thus crudely simulating passage of a vessel upstream through the gap. It was assumed this direction would release the same or more ice than passage downstream. The rod, an ordinary 11-mm-diameter wood dowel, was traversed at approximately 0.2 to 0.3 m s⁻¹. When disturbed, the accumulation generally released a number of ice pieces before a new arch formed. The main results of these experiments are given in Table II in which the numerical part of the run designation corresponds to the initial arching experiment (see Table I) and the alphabetical part to the particular disturbance run. In some experiments the accumulation was disturbed a number of times. In Table II, "blocks released" refers to the total number of blocks used in the parent experiment, and "blocks passed" to the number released as a result of the disturbance. $Q_{i,e}$ is the exit surface discharge of ice determined from the photographic record by counting the number of blocks, multiplying by the appropriate area, and dividing by elapsed time required to pass the gap. The total area of blocks released by each disturbance A_r is also tabulated as are the parameters a/b , $Q_{i,e}/Vb$ and the area of blocks released A_r normalized by the square of the gap dimension.

Several observations are appropriate. In Figure 13 the data of the normalized ice surface discharge rate $Q_{i,e}/Vb$ following the disturbance are presented. It was anticipated that $Q_{i,e}/Vb$ might be as high as 0.7, corresponding to the surface concentration of the accumulated blocks (compare eq 2). However, nearly all cases were less than about 0.35 and the average was about 0.2. The only significance attached to this observation is that the fragments are not released *en masse* by a disturbance but rather are released individually or in small groups as observed in time-lapse photography.

In Figure 14 the total surface ice discharge for each disturbance is presented, normalized by the square of the gap dimension and plotted against the ratio a/b of the block size to gap dimension. Wide scatter exists.

Figure 14. Area of ice released after disturbance of arch.

To gain a better idea of the surface area released by the disturbance the data sets of uniformly sized blocks, mixed blocks, and the funnel experiments have been analyzed (disregarding the possible effects of a/b) to determine the distribution by percentage of occurrences. The results of the analyses are presented in Figure 15 as a plot of cumulative percent of occurrences. Thus, in 50% of the disturbance runs the normalized area of blocks released by the disturbance was about 0.9. Little difference is found between the data sets.

For four gap widths, 0.178, 0.216, 0.267 and 0.36 m, the area of open water between the arch and barrier gap was measured from the photography. Scatter in the data was widespread, with a general trend of more open water area as the size of the gap increased (Fig. 16). The wide scatter in the data was evident on the remaining photography, and at this time the extraction of the remainder of the data is not warranted. For whatever significance it might have, if the area of the open water is compared to the square of gap opening (b^2), only 4 of 38 measurements were greater than b^2 . Then as a rough measure of stable arches 89% of the runs measured for this section had open water areas less than the square of the gap width.

Table II. Summary of disturbed arch experiments.

Run	a (mm)	b (m)	V (m s ⁻¹)	Blocks rlsd	Blocks passed	A_r (m ²)	Elapsed time (s)	$Q_{i,e}$ (m ² s ⁻¹)	a/b	$Q_{i,e}/Vb$	A_r/b^2	Remarks
121A	74	0.363	0.091	180	70	0.382	43.8	0.0087	0.204	0.264	2.90	
123A	74	0.363	0.091	192	54	0.295	42.2	0.0070	0.204	0.212	2.24	
B					120	0.655	85.9	0.0076	0.204	0.231	4.97	
124A	74	0.363	0.091	192	1	0.0055	3.24	0.0017	0.278	0.070	0.08	
B					11	0.060	17.8	0.0034	0.278	0.139	0.85	
C					14	0.076	30.8	0.0025	0.278	0.103	3.76	
D					0	0	—	0	0.278	—	0	
E					8	0.044	14.6	0.0030	0.278	0.124	0.62	
F					25	0.137	38.9	0.0035	0.278	0.145	1.93	
G					25	0.137	34.1	0.0040	0.278	0.165	1.93	
H					2	0.011	3.24	0.0034	0.278	0.139	0.15	
I					15	0.082	9.73	0.0084	0.278	0.348	1.16	
J					20	0.109	22.7	0.0048	0.278	0.199	1.54	
125A	74	0.266	0.091	192	3	0.0164	4.86	0.0034	0.278	0.139	0.23	
B					23	0.126	16.2	0.0078	0.278	0.320	1.78	
C					21	0.115	21.1	0.0054	0.278	0.225	1.62	
126A	74	0.266	0.091	192	7	0.038	6.88	0.0056	0.278	0.230	0.54	
B					75	0.410	40.6	0.0101	0.278	0.417	5.79	
127A	148	0.363	0.091	60	3	0.066	9.73	0.0068	0.408	0.204	0.50	
128A	148	0.540	0.091	60	15	0.482	35.7	0.0135	0.274	0.275	1.13	
129A	74	0.343	0.091	192	10	0.055	8.25	0.0066	0.215	0.212	0.46	Funnel geometry
B					47	0.257	35.4	0.0073	0.215	0.232	2.18	Funnel geometry
C					21	0.115	14.9	0.0077	0.215	0.247	0.97	Funnel geometry
D					8	0.044	8.0	0.0055	0.215	0.175	0.37	Funnel geometry
E					19	0.104	13.5	0.0077	0.215	0.246	0.88	Funnel geometry
F					14	0.076	10.25	0.0075	0.215	0.239	0.65	Funnel geometry
130A	74	0.285	0.074	180	26	0.142	32.4	0.0044	0.259	0.208	1.75	
B					23	0.126	24.3	0.0052	0.259	0.245	1.55	
131A	74	0.285	0.074	180	2	0.011	3.24	0.0034	0.259	0.160	0.13	
B					5	0.027	8.11	0.0034	0.259	0.160	0.34	
C					17	0.093	14.6	0.0064	0.259	0.302	1.14	
9A	74	0.310	0.077	180	7	0.038	9.73	0.0039	0.238	0.165	0.40	
B					88	0.481	71.4	0.0067	0.238	0.282	5.00	
C					18	0.098	16.2	0.0061	0.238	0.254	1.02	
10A	74	0.310	0.077	180	3	0.016	4.86	0.0034	0.238	0.141	0.17	
B					25	0.137	19.5	0.0070	0.238	0.293	3.23	
C					36	0.197	34.1	0.0058	0.238	0.242	2.05	
15A	74	0.198	0.077	120	4	0.022	4.86	0.0045	0.373	0.295	0.56	
19A	74	0.267	0.077	180	12	0.066	13.0	0.0050	0.276	0.245	0.92	
20A	74	0.153	0.078	180	3	0.016	6.0	0.0027	0.483	0.229	0.70	
B					3	0.016	6.0	0.0027	0.483	0.229	0.70	
C					1	0.0055	2.0	0.0027	0.483	0.229	0.23	
25A	74	0.488	0.078	180	107	0.584	55.8	0.0105	0.151	0.275	2.45	
27A	74	0.488	0.078	180	84	0.459	39.0	0.0118	0.151	0.309	1.93	
30A	37	0.129	0.080	720	10	0.014	10.0	0.00137	0.286	0.133	0.82	
B					3	0.0042	4.0	0.0010	0.286	0.099	0.25	
33A	37	0.129	0.080	264	4	0.0055	8.0	0.0007	0.286	0.066	0.33	
B					19	0.026	23.0	0.0011	0.286	0.110	1.56	
C					5	0.0068	5.0	0.0014	0.286	0.133	0.41	
D					32	0.044	27.0	0.0016	0.286	0.157	2.63	
E					9	0.0123	7.0	0.0018	0.286	0.171	0.74	
34A	37	0.129	0.082	264	113	0.155	109.0	0.0014	0.286	0.134	9.30	
B					4	0.0055	7.0	0.0008	0.286	0.074	0.33	
C					11	0.015	9.0	0.0017	0.286	0.158	0.90	
D					7	0.010	5.0	0.0019	0.286	0.181	0.58	
E					10	0.014	10.0	0.0014	0.286	0.129	0.82	
F					1	0.0014	3.0	0.0005	0.286	0.043	0.08	
G					10	0.014	16.0	0.0009	0.286	0.081	0.82	
H					2	0.0027	2.0	0.0014	0.286	0.129	0.16	
I					8	0.0110	14.0	0.0008	0.286	0.074	0.66	
J					10	0.014	10.0	0.0014	0.286	0.129	0.82	
46A	37	0.268	0.082	510	420	0.575	124.0	0.0046	0.138	0.211	8.01	
48A	74	0.222	0.083	180	9	0.049	28.0	0.0018	0.333	0.095	0.17	
51A	mix (1)	0.268	0.083	555	4/9	0.0342	9.0	0.0038	0.276	0.171	0.48	
B					4/2	0.0246	3.0	0.0082	0.276	0.368	0.34	
C					3/4	0.0219	10.0	0.0022	0.276	0.098	0.30	

Table II (cont'd). Summary of disturbed arch experiments.

Run	a (mm)	b (m)	V ($m\ s^{-1}$)	Blocks rslsd	Blocks passed	A_r (m^2)	Elapsed time (s)	$Q_{i,e}$ ($m^2\ s^{-1}$)	a/b	$Q_{i,e}/Vb$	A_r/b^2	Remarks
52A		0.268	0.083	555	2/6	0.0191	9.0	0.0021	0.276	0.096	0.27	
B					7/16	0.0601	21.0	0.0029	0.276	0.129	0.84	
C					20/51	0.179	77.0	0.0023	0.276	0.105	2.49	
D					12/21	0.094	26.0	0.0036	0.276	0.163	1.31	
54A		0.268	0.083	555	3/15	0.037	12.0	0.0031	0.276	0.138	0.52	
B					9/19	0.0752	41.0	0.0018	0.276	0.082	1.05	
C					8/16	0.0656	19.0	0.0035	0.276	0.155	0.91	
56A		0.326	0.083	555	14/11	0.0915	19.0	0.0048	0.226	0.178	0.86	
B					10/31	0.0971	21.0	0.0046	0.226	0.171	0.91	
C					7/17	0.0615	14.0	0.0044	0.226	0.162	0.58	
E					2/9	0.0232	6.0	0.0039	0.226	0.143	0.22	
57A	mix	0.356	0.083	555	39/73	0.313	55.0	0.0057	0.226	0.210	2.95	
B					63/126	0.517	100.0	0.0052	0.208	0.175	4.08	
59A	mix	0.425	0.083	555	16/28	0.126	23.0	0.0055	0.174	0.155	0.70	
B					55/126	0.473	59.0	0.0080	0.174	0.227	2.35	
63A	mix	0.425	0.083	555	50/85	0.389	43.0	0.0091	0.174	0.257	2.15	
67A	mix	0.154	0.083	555	10/23	0.0861	35.0	0.0025	0.480	0.192	3.63	
68A	37	0.293	0.083	385	315	0.527	80.0	0.0066	0.126	0.271	6.14	Funnel geometry
76A	mix	0.293	0.083	555	2/22	0.0410	20.0	0.0021	0.252	0.084	0.48	Funnel geometry
B					12/37	0.116	23.0	0.0051	0.252	0.208	1.35	Funnel geometry
C					3/7	0.0260	7.0	0.0037	0.252	0.153	0.30	Funnel geometry
78A	mix	0.293	0.083	555	10/19	0.0806	16.0	0.0050	0.252	0.207	0.94	Funnel geometry
B					3/0	0.0164	3.0	0.0055	0.252	0.225	0.19	Funnel geometry
C					18/47	0.163	26.0	0.0063	0.252	0.257	1.90	Funnel geometry
D					11/40	0.115	32.0	0.0036	0.252	0.148	1.34	Funnel geometry

Note (1) A mixture of 170 large blocks (0.074 m square) and 385 small blocks (0.037 m square) were used in the initial release of blocks. The tabulation of blocks released upon disturbance lists large/small number released. For "a" the large block dimension was used.

Figure 15. Distribution of area of ice released after disturbance of arch.

Figure adjacent to point indicates number of test points.

Figure 16. Area of open water between stable arch and gap.

DISCUSSION AND CONCLUSIONS

The experiments reported here have yielded two main results. First, a relationship has been established (eq 1) which separates arching events from non-arching events. Second, the quantity of ice released upon disturbance of the accumulation has been documented. While it is recognized that the experiments were idealized representations of actual ice behavior at a boom gap, the results suggest that the ice passing capability is heavily dependent on the ratio of fragment size to gap dimension, with greater difficulty in arching associated with small, uniform fragments and large gaps. Thus, if a boom with a gap is to function effectively in retaining ice, the gap should be as small as possible consonant with other requirements. In addition, if an arch has formed and is subsequently disturbed, it reforms after only a relatively small amount of ice has been discharged through the gap. The rate at which this ice is discharged is low, below about $0.35 Vb$. The amount of ice released following a disturbance varies between wide limits but has a well-defined statistical distribution which seems to be unaffected by piece size or size distribution. Finally, all the results reported here are for ice simulated by plastic fragments. Real ice has certain properties, primarily cohesion and surface roughness characteristics, which the simulated ice does not possess and which are expected to contribute to arching tendencies. Because of this, the results obtained here are considered conservative.