SPECIAL REPORT 96-17

Effects of Ice Boom Geometry on Ice Capture Efficiency

Gordon Gooch

September 1996

Abstract: An ice boom's geometry is critical to the collection and retention of ice in small, fast-moving streams and rivers. Ice booms are designed to quickly form a solid ice cover much earlier than the ice cover would form naturally. Once formed, the ice cover insulates the river, eliminating the production of frazil ice locally. Frazil leads to thick ice deposits, which reduce the river's available flow area and contribute to midwinter and spring flooding. Model experiments, conducted at the Ice Engineering Facility at the Cold Regions Research and Engineering Laboratory, have varied the ice boom geometry to speed up the process of ice cover formation. Model simulations have used floating plastic beads to simulate real ice particles to determine what ice boom design works best. Under controlled laboratory conditions, boom geometry clearly affects the boom's ability to captured more beads. Comparison of field and laboratory tests indicates similar results.

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Cold Regions Research & Engineering Laboratory

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Gordon Gooch

September 1996

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Gordon Gooch, Civil Engineering Technician of the Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Office of the Chief of Engineers under the Civil Works program, Work Unit CWIS 32587, *Ice Jam Characterization.*

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Effects of Ice Boom Geometry on Ice Capture Efficiency

GORDON GOOCH

INTRODUCTION

An ice boom is a series of floating timbers joined together with a cable and anchored to shore or riverbed anchors. The purpose of an ice boom may be to divert floating ice away from problem areas or to collect it to encourage the formation of a solid ice sheet on a river. The sheet will insulate the water beneath, eliminating ice production in those locations. A reduction in ice volume can significantly reduce water levels and prevent ice jam flooding. Researchers have been testing low-cost solutions to encourage ice sheet formation on small, fast-moving, frazil-producing streams using ice booms. Frazil ice has been found to be the leading cause of ice jam flooding. Frazil ice begins as small ice particles and quickly forms into larger ice pans, which can restrict the flow capacity of rivers and streams.

In this report, laboratory and field tests of ice boom geometries are discussed, along with their ability to capture floating ice and form a solid ice cover. How well this can be done is referred to as the "ice capture efficiency." In laboratory tests the ice capture efficiency is dramatically improved when the incoming ice is first directed to the shore, where it becomes stationary and thickens.

Model tests using synthetic plastic beads can compare the ice retention capabilities of ice booms under controlled laboratory conditions. Model and prototype ice boom behaviors are compared in this report to emphasize the similarities between field and laboratory results.

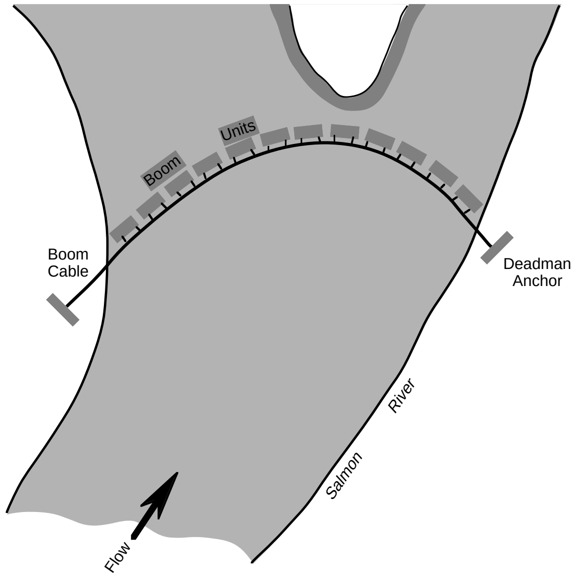
BACKGROUND

Site assessment criteria for ice cover formation

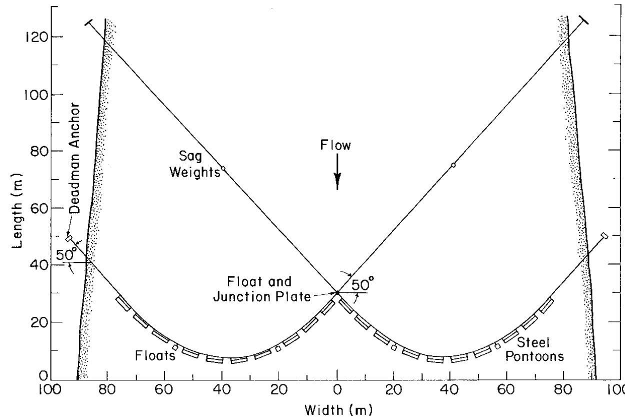
The criteria for a properly designed and functioning ice boom include many of the same general principles as debris booms (Perham 1987, 1988). Froude number, flow velocity, ice forces and site layout must all be within acceptable limits. The Froude number is the ratio of the velocity divided by the square root of gravity times the flow depth. It is very useful, along with pool length, in determining if a location will meet minimum requirements for an ice control structure (ICS). Based on flow depth, an upper Froude number limit of 0.10 is commonly used in selecting a site. The river pool length in open-water conditions should be greater than two river widths (Table 1). Experience has shown that without these two minimum requirements, a conventional ice formation boom may not

Table 1. River hydraulics at ICS sites.

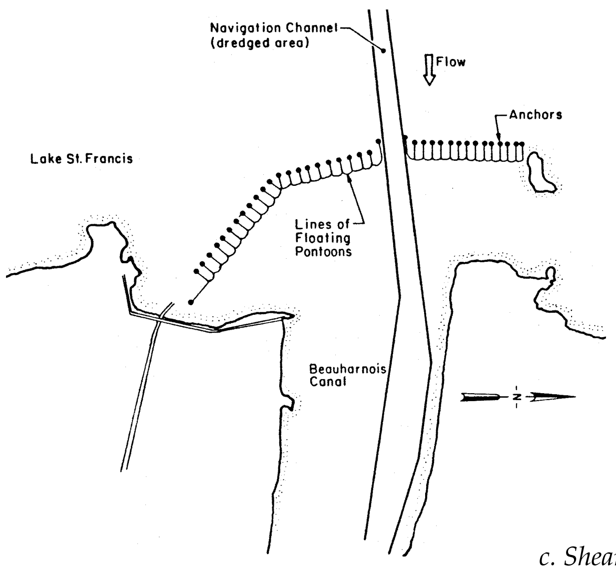
	Oil Creek boom (1981–82)	*Oil Creek boom (1982–83)*	*Oil Creek weir (1988)*	*Allegheny R. boom (1982–83)*	*Salmon River boom (1989–91)*
Average depth					
(ft)	2	2.80	5	4.2	3
(m)	0.60	0.85	1.52	1.28	0.91
Flow velocity					
(ft/s)	1.4	1.2	0.5	0.94	2.0
(m/s)	0.42	0.36	0.15	0.28	0.6
Froude number	0.17	0.13	0.04	0.08	0.21
Discharge					
(cfs)	538	460	900	1870	900
(cms)	15	3	25	52	25
Channel width					
(ft)	190	151	351	540	230
(m)	57	46	106	164	70
Pool length					
(ft)	323	250	2431	600–900	1478
(m)	98	76	740	182–274	450
Length/width ratio	1.7	1.6	6.9	1.6	6.4



a. Single-sag boom on the Salmon River.



b. Multiple-sag boom on the Allegheny River.



c. Shear boom on Lake St. Francis.

Figure 1. Ice boom designs.

work. To be successful an ice boom must cause an ice cover to progress beyond the natural change in water surface slope upstream of the structure. Further constraints on ice boom design include project cost, benefits and environmental impact.

Boom shapes

The three ice boom shapes discussed in this report are single-sag, multiple-sag and shear booms (Fig. 1). The purpose of a sag boom is to collect the maximum amount of floating ice and form a stable solid ice sheet behind the boom as quickly as possible. This ice sheet then thickens, allowing an ice cover to progress upstream, insulating the water beneath and eliminating additional frazil ice production in the process. Frazil ice forms in supercooled, turbulent water and is composed of fine disc-shaped particles of ice. These small particles are suspended in the full depth of the river flow because they have very little buoyancy. When these suspended ice particles reach a region of slower water, they clump together to form a frazil floc, which floats along the water surface until it becomes incorporated into a solid ice sheet. Large volumes of frazil can accumulate, contributing to flooding problems. Since sag booms prevent frazil from forming, the lower ice volume will reduce or eliminate spring or midwinter ice jam flooding.

Single-sag booms are often used on small creeks and rivers because of ease of installation and low cost. Multiple-sag booms are used primarily on large rivers. These rivers typically have much lower flow velocities and greater flow depths, resulting in more favorable river hydraulics for ice cover formation. These booms help stabilize the ice, preventing large ice sheets from floating into a navigation channel. Multiple shore and bed anchors distribute the loads the boom will experience and also help maintain the desired geometry. Each boom design may require a specific shore anchor design to allow boat passage or to span a large river.

Shear booms are designed to direct incoming ice and floating debris away from problem areas, typically navigation channels and flow intakes at power dams, but they can also be used as ice formation booms in high-velocity areas in fast-moving streams and rivers.

Ice arching

When ice floes pass through a constriction in a river, they can arch across, forming a stable ice bridge across the opening. Calkins et al. (1982) found a relationship in laboratory tests between the open-water width between two structures, *b*, and the size of the solid ice floes, *a*, passing through that opening indicating when a stable ice arch would form. The minimum *a/b* ratio for establishing a stable arch for rafted floes was approximately 0.8. Calkins et al. found in laboratory tests, using plastic blocks to simulate ice, that when the *a/b* ratio was greater than 0.3, ice arching was more frequent. Conversely if the gap opening increases and the ice floe size remains approximately constant, formation of an ice cover would be unlikely. Calkins et al. also found that an increase in the *a/b* ratio from 0.1 to 0.2 decreased the amount of ice passing through the opening by tenfold. Although solid plastic blocks were used in the model study, similar limits seem to apply to frazil ice pans. If the estimated floe size, for example, is 5 ft (1.5 m), then the open-water width should be no more than 20 ft (6.1 m) (5.0/20.0 = 0.25) for an arch to form (Fig. 2). As the gap decreases, the *a/b* value increases until it reaches the value of one, or 100% ice cover.

A single-sag boom on Oil Creek in Oil City, Pennsylvania, created an open-water gap between two shore ice covers (Fig. 3) The gap opening increases with distance upstream of the structure and therefore could not meet the arching criteria. The Allegheny River ICS, in comparison, had large 20-ft- (6.1-m-) diameter frazil pans and parallel ice shear walls in the open-water approach to the ice boom (Fig. 4). The *a/b* value was within accept-

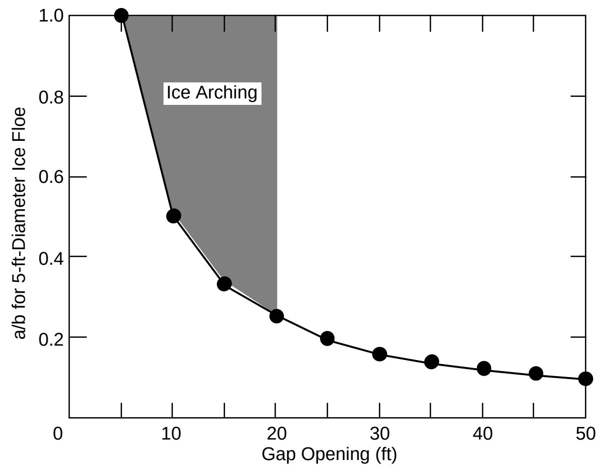


Figure 2. Gap opening vs. a/b *value for a floe 5.0 ft (1.5 m) in diameter. The opening must be 20.0 ft (6.1 m) or less for an arch to form.*

Figure 3. Funnel-shaped ice formation at Oil Creek, Pennsylvania.

Figure 4. Parallel ice shear walls at the Allegheny River ice boom.

able limits for an arch to form, joining the intact ice sheets from both riverbanks and allowing the incoming floating ice to be incorporated into this newly formed ice sheet.

When frazil flocs are present, the situation is more complicated. Although a 100% ice cover with solid ice blocks would indicate a definite arching condition, frazil floes can be compressed, even though the surface concentration may be considered 100%. This means that cohesion and strength must also be considered when calculating arching probability. The compacting of the frazil discs increases in proportion to the force exerted on it. If there is little compression of the frazil before it reaches a structure, the ice floe may separate easily. Frazil floes may also develop strength due to the freezing of the surface layer exposed to the air. The combination of compression and freezing of the floe determines its final behavior when it meets a resistant ice cover.

BOOM TESTS

Allegheny River

Oil City, located in northwestern Pennsylvania, has been plagued by ice jam flooding since the mid-1800s. In February 1979, Oil Creek flooded the downtown business district, causing an estimated $800,000 in damages. As a result of this flood the U.S. Army Engineer District, Pittsburgh, asked CRREL to find a solution to the flooding on Oil Creek. Deck and Gooch (1981) concluded that controlling the production of frazil ice on the Allegheny River and Oil Creek would eliminate future flooding.

In the winter of 1982-83 an ice boom was installed on the Allegheny River upstream of the confluence with Oil Creek to alleviate ice jam flooding. The configuration, design load and general design criteria for the ICS were furnished by CRREL to the U.S. Army Engineer District, Pittsburgh. They developed the anchor and detailed structural design and awarded the contracts to fabricate and install the structure prior. The cost of these contracts was about $650,000 (Deck and Gooch 1984).

The Allegheny River ice boom has a multiple-sag design (Fig. 1b) and is located about 1600 ft (487 m) upstream of the mouth of Oil Creek at the downstream end of a pool in the river. The ice boom consists of 20 floating steel pontoons. Each pontoon is attached by chains to a 60-mm-diam. wire rope and is 613 cm long, 91 cm wide and 40 cm deep. Two 77-m spans of wire rope are used to cross the river. Alterations of the streambed could not be made to anchor the structure to the bed because of strict environmental regulations. Therefore, four shore anchors were used. One wire rope is attached to each anchor and joined at a junction plate at the approximate centerline of the river. Floats support the weight of this junction plate and the two wire ropes to which the pontoons are attached.

Oil Creek

Single-sag ice booms were tested at two sites on Oil Creek, for three successive winters (1981-1984). The intent of the ICS is to encourage a stable ice cover to form upstream of the ICS, both to capture transported surface ice and to suppress ice production upstream. Unfortunately a floating boom is effective in forming a stable ice cover only if the surface velocity at the boom is less than a critical velocity. This critical velocity is determined by the properties of the ice floes arriving at the boom: thickness, shape, overall density and strength. If the surface velocity at the boom is greater than this critical velocity, ice floes arriving at the boom will tend to underturn and pass under the boom (Gooch and Daly 1994). These conditions typically result in Froude numbers above 0.10.

During the first winter the river site was 58 m wide and 0.6 m deep, with an average velocity across the river of 0.4 m/s and a pool length of 98 m. Ice collection screens hanging below each boom unit (Fig. 5) captured frazil and resulted in a 0.3-m increase in water level and a 200-ft ice cover upstream (Fig. 3). The upstream open-water area resembled a funnel, forcing the majority of the floating frazil toward the center of the structure and allowing nearly all of it to pass. As the

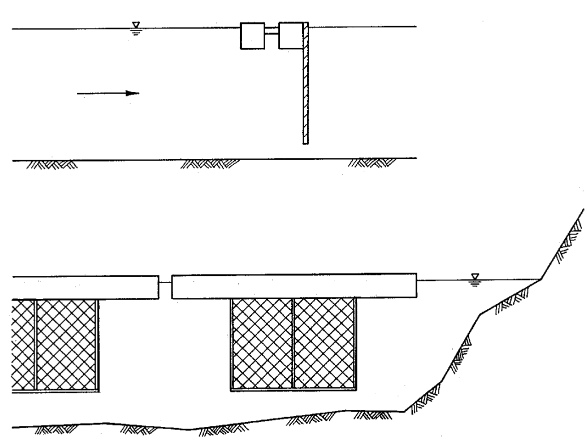


Figure 5. Oil Creek ice boom screens.

upstream ice approached the structure, the ice velocity increased because of the constriction caused by the ice blockage in the channel, reducing the structure's ability to create an arch as the floating ice made contact with the intact ice cover. The frazil flocs would shove against each other and compress, decreasing their diameter and allowing them to pass through the constriction. At this point the structure could no longer capture ice or influence the ice cover progression upstream. This could explain the poor performance of the first Oil Creek structure. Since frazil is difficult to capture if the river velocity is above 2.0 ft/s (0.6 m/s) and the water depth is less than 1.0 ft (0.3 m), the use of a boom alone to initiate the formation of an ice cover incorporating frazil ice may be ineffective without some source of hydraulic control to reduce the velocity (Deck 1984).

In December 1983, researchers selected a site with a water depth 0.8 ft (0.2 m) deeper than the previous location but with only a 76-m pool length. By increasing the depth the resulting velocity would be reduced, thereby improving the ice formation potential. A stable ice cover formed in four hours, with 70% of the cross-sectional flow area restricted. All additional incoming frazil ice was submerged, however, and transported downstream. The initial capture efficiency was excellent, but the length of the pool and the stage rise were inadequate to allow the ice cover to advance through the steeper upstream reach. As a result, the ice boom failed to effectively capture frazil ice and cause significant ice cover formation.

In 1984 a more conventional and costly $2.2-million, 306-ft (93-m) fixed-crest concrete weir with a 45-ft (13.7-m) bascule gate was designed by the Pittsburgh District. The Oil Creek ICS, which was completed in 1988, provided the hydraulic control needed to form an ice cover. The gate is raised by mid-December, creating a 5.0-ft- (1.5-m-) deep pool, lowering the Froude number from above 0.10 to 0.04 and increasing the length of pool upstream of the structure by a factor of 10 from previous test sites (Table 1). A timber single-sag boom deployed approximately 200 ft upstream of the structure captured ice to form a stable ice cover during high flows. The ice boom is no longer used because of continual cable failures. However, the weir by itself provides the hydraulic control needed to form an adequate ice cover each winter. There has been no ice jam flooding on Oil Creek since the installation of the Allegheny River ice boom in 1982-83.

The success of the double-sag Allegheny River ice boom and the failure of the single-sag Oil Creek boom initially spurred interest in capture efficiency as a function of boom geometry. The Allegheny River's 650-ft (198-m) channel width required a double-sag boom design to position the boom in the low-velocity reach of the river without using riverbed anchors. This design directs the very large flocs or floating frazil ice pans to the shore, where the pans accumulate and thicken due to the shoving action created by the increase in hydrostatic forces acting on the ice accumulation. The ice capture efficiency is increased, and the load on the structure is reduced as the ice comes in contact with the shore and riverbed. This concept combines the direction feature of the shear boom and the collection and thickening capability of the formation boom. As a result of this geometry, the ice thickening process increases the upstream water level, reduces the flow velocity upstream and narrows the open-water channel. This eventually allows ice to arch more easily, joining the right- and left-bank ice sheets into one solid ice cover (Deck and Gooch 1983).

Salmon River

Two single-sag ice booms were tested on the Salmon River in Salmon, Idaho. Ice jams on the Salmon River have caused millions of dollars in damages in recent years. The Salmon River is characterized by a series of rapids and pools. The bed slope is 0.003 in the study reach and therefore very steep. Research efforts for a structural solution to ice jam flooding in Salmon have been the major focus. Because of cost and environmental constraints, the most favorable ice capture and freeze-up structure design with the least impact on the hydraulic conditions in the river is an ice formation boom.

The site chosen for an ICS was located about nine miles upstream from the city of Salmon. At this point the river is about 85 m wide and 1 m deep, with a pool length of 450 m. Surface velocities are 2.0–3.0 ft/s (0.6–0.9 m/s) at the expected winter flows of 25.0–37.0 m^3/s (883–1300 cfs). This site has a Froude number of 0.20 and would be considered unsuitable by the current Froude criterion for ice cover formation (Fig. 6). A single-sag formation boom was tested at this site during the winter of 1989-90. Field measurements and observations at the site included river cross-section geometry, ice boom loading, orientation and river velocity distribution. The ice boom failed, allowing the incoming ice to pass under the structure and continue downstream. This indicated that

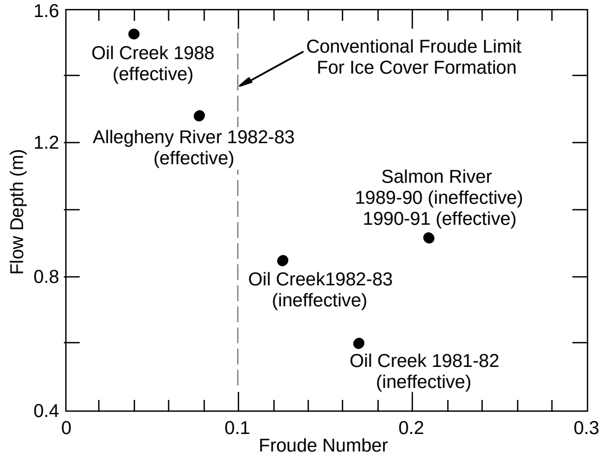


Figure 6. Froude number vs. flow depth for prototype booms.

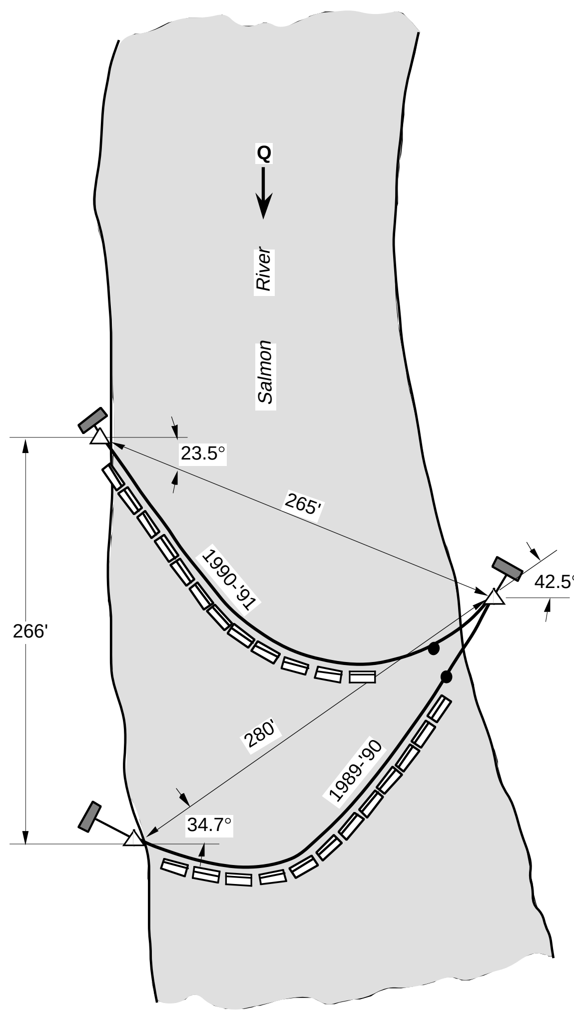
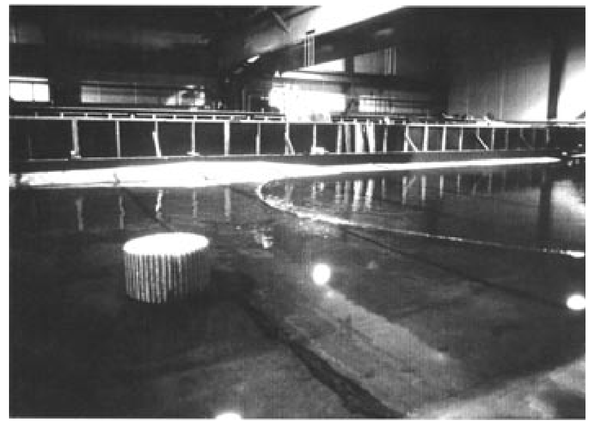


Figure 7. Salmon River ice boom geometry.



a. Sag boom.

b. Shear boom.

c. Sag and shear ice booms during testing.

Figure 8. Model booms.

the critical velocity had been exceeded at the boom and a reduction in surface velocity was needed. The current geometry of the boom carried incoming frazil ice pans to the outside of a riverbend, where the velocity was at a maximum. The anchor positions allowed the boom to sag in the direction of maximum velocity rather than taking advantage of the lower velocities and shallower depth on the left bank of the river (Fig. 7).

In May 1990, researchers at CRREL tested the shear boom concept in the laboratory in an effort to increase the frazil ice capture rate for the Salmon ice boom (Fig. 8). Model ice booms were built

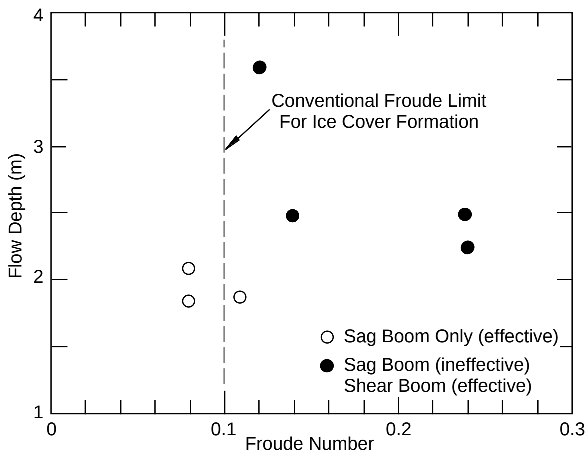


Figure 9. Froude number vs. flow depth for model booms.

at a 1:25 scale and tested in an existing hydraulic model and a 4-ft-wide rectangular flume. The performances of a shear boom and a single-sag boom were compared (Fig. 9). A 3-mm plastic bead material was used to simulate real ice. The plastic beads were introduced upstream of each boom. When the flow discharge was increased, the sag boom released the bead particles while the shear boom held them. By increasing the capture efficiency of the boom, the flow depth was increased and the velocity upstream of the boom was reduced.

During the tests a ripple line was observed on the water surface, created by the floating structures. The ripple lines followed the shape of the floating object and were distinctly different with changes in the boom geometry and discharge. The sag boom created a ripple line similar to the funnel shape observed on Oil Creek, indicating the water surface velocity distribution and the eventual freeze-up pattern (Fig. 10). The ripple lines created by the shear boom were parallel to the boom. The plastic particles decelerated once they passed through this line. This line appears to separate the water surface areas affected by the floating structure from those areas that are not.

The shear boom guided the incoming particles to the low-velocity collection zones along the shore. The distribution of the particles became more uniform as the accumulation of beads thickened, followed by a stage rise. The particles thicken due to shoving caused by the increase in a shear force acting on the underside of the cover. The bead cover progressed upstream at a rate dependent on the incoming concentration of particles and the amount of shoving and thickening. The capture efficiency improved as the ice boom geometry was changed (Table 2). A comparison between the model and the field data indicate a substantial improvement in the capture efficiency. If we compare Froude number (Fig. 6 and 9) prior to freeze-up at field sites and also prior to simulated ice conditions in laboratory simulations, we find similar results between the sag boom and shear boom designs. The shear boom can capture ice at higher flows and results in an immediate benefit by reducing the velocity further through the thickening of the ice accumulation. The fact that prototype and model measurements indicate a higher Froude number indicates how important the shape is in the ice collection ability of an ice boom and subsequent flow conditions upstream of the boom.

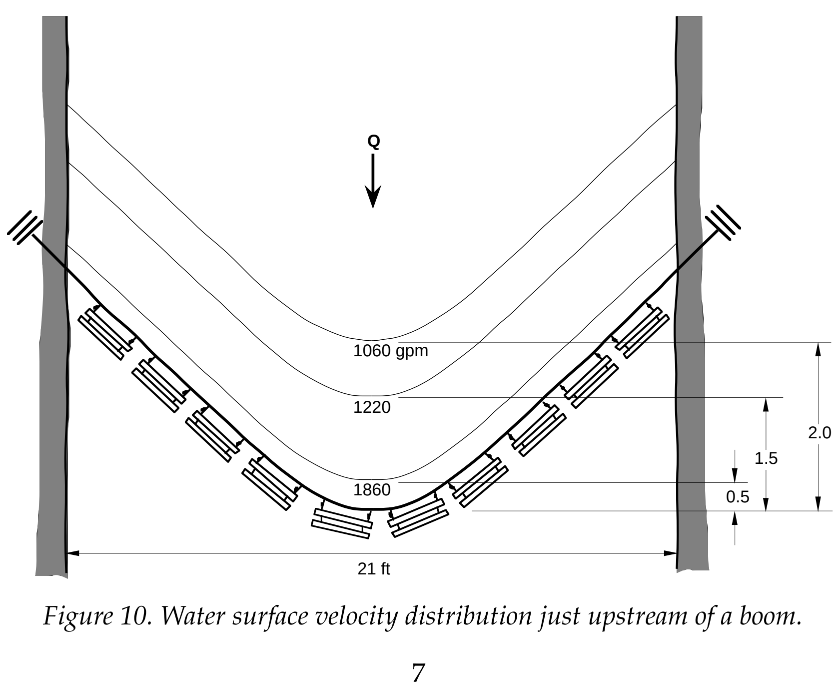


Figure 10. Water surface velocity distribution just upstream of a boom.

Table 2. Modeling results for Salmon River ice booms.

	Test 1			*Test 2*			
	Section 1	*Section 2*	*Section 3*	*Section 1*	*Section 2*	*Section 3*	*Test 3*
Average depth							
(ft)	6.1	6.9	6.2	8.2	8.2	7.4	11.9
(m)	1.9	2.1	1.9	2.5	2.5	2.3	3.6
Velocity							
(ft/s)	1.1	1.3	1.6	2.3	3.9	3.7	2.5
(m/s)	0.3	0.4	0.5	0.7	1.2	1.1	0.7
Froude number	0.08	0.08	0.11	0.14	0.24	0.24	0.12
Discharge							
(cfs)	2.3	2.3	2.3	4.1	4.1	4.1	1.0
(cms)	0.07	0.07	0.07	0.12	0.12	0.12	0.03
Capture efficiency							
Single-sag boom	high	high	high	negligible	negligible	negligible	negligible
Shear boom				high	high	high	high

A similar experiment on the arch shape design was conducted in a model study by Burgi (1971), with an ice boom named an "upstream V." Burgi noted that it provided a more stable ice cover than the sag boom configuration tested. The "upstream V" ice boom formed a 45° angle to the shoreline. Burgi concluded that the ice stability was a result of the wedging of the floating ice between the boom and the riverbanks.

Following the lab experiments the Salmon ice boom right-bank anchor was moved 266 ft upstream from its previous location (Fig. 7). This new geometry and orientation directed more ice to the lower-velocity zone on the left bank, increasing water levels and ice collection. The resulting ice cover progressed more than five miles upstream and reduced the total volume of ice available to cause a downstream ice jam. A detailed analysis of historical winter temperature records established a method to predict when an ice jam would reach the town of Salmon (Zufelt and Bilello 1992). They concluded that the reduction in ice volume could be attributed to the collection of frazil at the ice boom upstream of Salmon.

An evaluation of the performance of the Salmon River ice boom concluded that the change in the shape of the ice boom resulted in an ice cover formation upstream of the boom, preventing ice jam flooding at Salmon in the winter of 1990-91 (White and Zufelt 1993).

CONCLUSIONS

Full-scale tests in Salmon, Idaho, varied the ice boom geometry dramatically, improving the ice stability, capture efficiency and ice cover progression. Model and full-scale tests demonstrate the importance and sensitivity of the ice boom geometry. Use of this boom shape led to the success of the Salmon ice boom in a river where the Froude criterion was considered unacceptable. This suggests that the criterion has exceptions and warrants further study. The shear boom configuration should be considered for any future ICS installation.

Plastic beads are very sensitive to minor changes in water velocity and are difficult to capture, making them ideal for laboratory experiments studying model ice boom geometries. Laboratory experiments have shown conclusively that a change in orientation and shape of an ice boom can dramatically improve the plastic ice stability and capture efficiency.

The design of low-cost ice control structures is an ongoing research effort at CRREL. Total construction cost savings of $1 million or more may result when compared to the $2.2-million conventional Oil Creek structure completed in 1988.

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13. ABSTRACT (*Maximum 200 words*)

An ice boom's geometry is critical to the collection and retention of ice in small, fast-moving streams and rivers. Ice booms are designed to quickly form a solid ice cover much earlier than the ice cover would form naturally. Once formed, the ice cover insulates the river, eliminating the production of frazil ice locally. Frazil leads to thick ice deposits, which reduce the river's available flow area and contribute to midwinter and spring flooding. Model experiments, conducted at the Ice Engineering Facility at the Cold Regions Research and Engineering Laboratory, have varied the ice boom geometry to speed up the process of ice cover formation. Model simulations have used floating plastic beads to simulate real ice particles to determine what ice boom design works best. Under controlled laboratory conditions, boom geometry clearly affects the boom's ability to captured more beads. Comparison of field and laboratory tests indicates similar results.

14. SUBJECT TERMS
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