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Design of Ice Booms

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**US Army Corps
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Introduction

This technical digest provides basic engineering design guidance for floating ice retention structures or ice booms. Basic types of booms and their ice control objectives are described briefly. The basic theory and equations used in ice boom design are then presented and typical structural components described. The report addresses other design considerations, such as boom layout, geometry, and anchor systems, as well as the selection of wire rope and connection systems, and concludes with an example ice boom design at a specific site. This technical digest not only incorporates and builds on ice boom design information found in EM 1110-2-1612, *Ice Engineering* (U.S. Army Corps of Engineers 1982), but describes the actual design steps in greater detail, and elaborates on boom geometry and the forces acting on ice boom components.

Types of ice booms and their uses

Booms are flexible wire rope structures designed to control floating ice or debris. Ice booms are installed each winter by hydroelectric and navigation interests to promote rapid ice cover formation by retaining frazil and floating sheet ice. They are also used to prevent brash ice and floes from interfering with hydroelectric intakes and navigation channels. An ice boom typically consists of a series of floating structural members or boom units, attached to a main boom cable. Figure 1 shows a typical ice boom arrangement. An ice boom's ability to deform and submerge will, in most cases, prevent its failure under extreme loading. Ice retention by conventional ice booms is limited to hydraulic conditions

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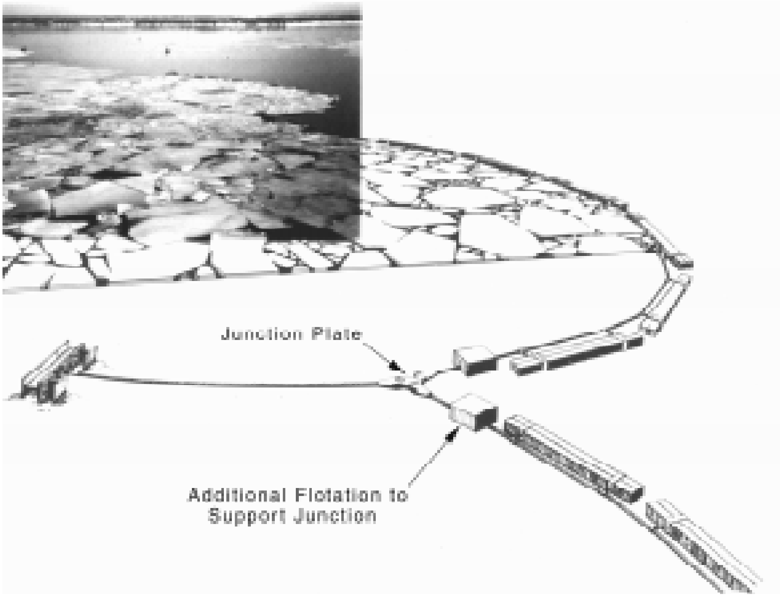
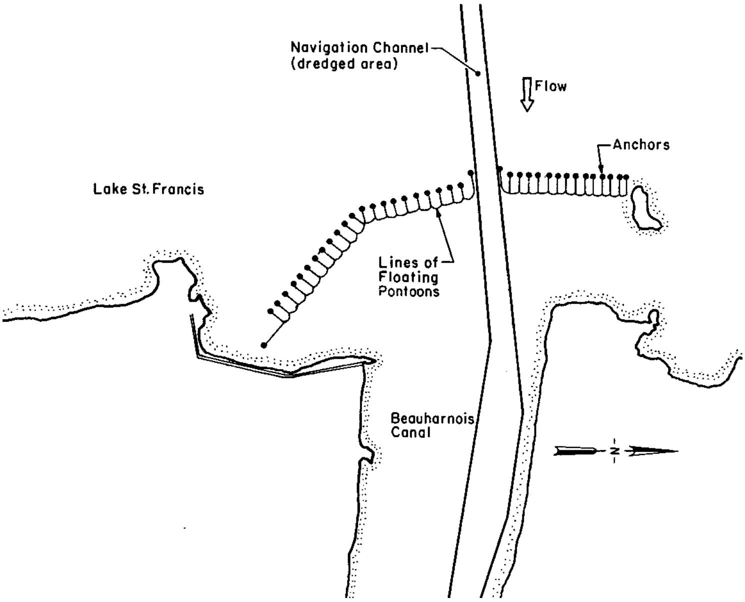


1. Typical ice boom arrangement. In this case, boom units are constructed of doubled 1- × 1- × 12-ft (0.3- 0.3- × 3.7-m) timbers, connected by chain to the boom cables. The boom cables connect to the anchor cable via a junction plate, supported by floats.

of mild slope and relatively low surface water velocity. Booms are typically not designed to retain breakup ice runs.

Ice booms having the main purpose of frazil ice retention, both to enhance winter hydropower production and to reduce the potential for ice jam flooding during freezeup, are sometimes termed “formation booms.” This type of boom is also used to form and stabilize shore ice adjacent to navigation channels and to alleviate frazil problems associated with winter navigation at the approaches to locks and dams. Other types of booms are designed to retain or divert brash or floes, and apply to ice problems associated with winter navigation, the operation of locks and dams, and winter hydropower production.

By retaining frazil ice, formation booms promote rapid ice cover growth during the early ice season. The ice cover that forms behind a boom insulates the water beneath, eliminating local frazil ice production. At the same time, the cover traps frazil arriving from upstream, preventing its transport to traditional ice problem sites downstream. Formation booms, often placed in series, have been used successfully for many decades to alleviate frazil ice problems associated with hydroelectric production. During the early ice season, these booms promote the rapid growth of a smooth sheet ice cover upstream of hydropower intakes, minimizing the head losses that commonly result from frazil accumulations and the formation of hanging dams. Where flow control is an option, discharge reductions during the critical ice formation period may accelerate the rate of ice cover growth and reduce



2. Ice boom with a navigation opening, designed to prevent wind-driven lake ice from entering a hydropower canal on the St. Lawrence Seaway.

force levels on the booms. Once a solid ice cover has formed, most of the downstream forces on the ice cover are transferred to the channel banks rather than to the boom, and the flow can be increased to pre-freezeup levels.

Formation booms are also used to reduce the threat of ice jam flooding on pool–riffle river reaches by capturing and retaining frazil at locations upstream of the problem area, thus preventing the formation of freezeup jams farther downstream. By decreasing the volume of frazil accumulations in problem reaches, the booms may also alleviate ice jam flooding by reducing the pre-breakup ice volume.

In addition to promoting ice formation, booms are used to control ice accumulations made up of floes or brash. Booms have been used successfully at channel constrictions, both to promote arching and to prevent brash ice from blocking the narrower downstream channels. Figure 2 is an example of a boom with a navigation opening, designed to prevent wind-driven lake ice from entering a hydropower canal. Booms may be designed to divert frazil or brash ice away from lock entrances or hydropower intakes. In some applications a boom may have the dual purpose of retaining frazil early in the ice season and controlling brash ice as the ice cover begins to deteriorate.

Additional information on successful ice boom designs may be found in EM 1110-2-1612 *Ice Engineering* (U.S. Army Corps of Engineers 1982) and CRREL Report 83-30, *Ice Sheet Retention Structures* (Perham 1983). CRREL Special Report 95-18, *Struc-*

tural Ice Control; Review of Existing Methods (Tuthill 1995) updates Perham (1983). CRREL Special Report 92-21, *Salmon River Experimental Ice Boom* (White 1992) provides background information on ice boom design, focusing on formation booms on pool-riffle rivers.

Advantages and limitations of ice booms

Ice booms have many advantages over fixed ice control structures such as weirs, piers, piles, and man-made islands. Booms are generally installed in the fall, just before the onset of the ice formation season, and removed in the spring, shortly after ice-out. They therefore do not interfere with open water uses of the river or lake, such as recreation and commercial navigation. Booms have a negligible effect on the natural hydraulic conditions of the river, causing only minor changes in water depth and current velocity. They typically do not cause scour or the deposition of sediment, nor do they present a barrier to migrating fish. In addition, floating structures avoid the foundation settlement problems typical of fixed structures in rivers and lakes with soft clayey bottom sediments. Ice booms are designed to submerge under extreme loading conditions, avoiding structural failure. This feature allows the structures to survive breakup and impacts from large floes. Ice booms may be assembled from a wide variety of commonly available materials and components, reducing costs and construction time, and booms are readily installed using standard maritime or land-based construction equipment.

One possible limitation of ice booms is that, although the initial cost of an ice boom is low relative to a fixed ice control structure, the ongoing costs of installation, removal, and maintenance may be substantial.

Hydraulic constraints

The main hydraulic constraint to floating ice retention structures is that they are effective only at sites with mild slope and associated low surface water velocity. Surface water velocity and depth are important, since they strongly affect the total ice force acting on the boom. Wind stress on the ice cover is also important. If the water drag and wind stress on the ice are too great, the ice pieces may underturn and pass under the boom, or the ice may ride up and submerge the boom unit to pass over the top. A great deal of research and practical experience gives a range of 0.08 to 0.12 for the maximum Froude number,* and 2–2.5 ft/s (0.6–1.4

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* Froude number: $F_R = V/\sqrt{gh}$, where V = average channel velocity upstream of the ice cover, h = average channel depth upstream of the ice cover, and g = acceleration of gravity.

m/s) for the maximum velocity. Ice retention at the upper end of these ranges can be achieved by modifying the boom configuration to avoid having the point of maximum boom sag coincide with the region of maximum flow velocity, and by designing the boom unit cross-sectional geometry to optimize ice capture efficiency. In deeper rivers, the velocity criterion is more important, since the greater depth would allow the Froude number criterion to be met at an unrealistically high velocity. Froude numbers and surface water velocities for a number of successful ice boom applications are provided in Table 1. Ice may override a boom where wind is the main driving force, even though the velocity and the Froude number are well within the acceptable ranges.

Under marginal conditions, ice cover formation behind a boom may require some form of hydraulic control, such as a downstream dam or weir, to raise the water level and reduce surface water velocity. As mentioned earlier, if flow control is available, favorable hydraulic conditions may be achieved through flow reduction during the critical ice formation period.

Design loads

The most important forces acting on an ice boom typically result from water shear on the underside of the ice cover and wind stress on the ice cover surface. Additional forces to consider include the downslope component of the gravity force on the ice accumulation, water drag on the upstream face of the ice cover or the boom unit itself, ice impact forces, and forces caused by vessel passage. The total force on an ice boom (f_b), per unit width of river, can be expressed as the sum of all forces:

$$f_b = f_w + f_a + f_g + f_d + f_i + f_v \tag{1}$$

where f_w = water shear on the underside of the ice accumulation

f_a = wind drag force on the ice cover

f_g = downslope component of the gravity force on the ice accumulation

f_d = water drag on boom unit or the upstream face of the ice cover

f_i = force resulting from ice impacting the boom

f_v = forces resulting from vessel passage.

One of the most difficult aspects in ice boom design is estimating the length or area of the ice cover that contributes to the ice load on the boom. In rivers, ice loads acting on a boom are often assumed to derive from an area that extends three to five river

Table 1. Information on successful ice boom designs.

Location	*Structure type*	*Function**	*Material*	*Geometry size ft (m)*
St. Lawrence River International Section	Single timber	icfs, p fr, br	Douglas fir	Rectangular 1.2 × 1.8 × 30 (0.4 × 0.5 × 9)
Lake Erie, Buffalo, New York	Single timber	icfs, p fr, br, fl	Douglas fir	Rectangular 1.2 × 1.8 × 30 (0.4 × 0.5 × 9)
Lake Erie, Buffalo, New York	Single pipe	icfs, p fr, br, fl	Steel	Circular 2.6 × 30 (0.76 × 9.1)
Lake St. Peter, St. Lawrence River	Single timber	icfs, p	Douglas fir	Rectangular 1.2 × 1.8 × 30 ft (0.4 × 0.5 × 9)
St. Marys River, Sault Ste. Marie, Michigan	Single timber	n brash	Douglas fir	Rectangular 1.0 × 2.0 × 20 (0.3 × 0.6 × 6)
Lake St. Peter, St. Lawrence River	Single pontoon	icfs, n	Steel pipe	Circular 2.0 diam. × 30 (0.6 diam. × 9)
Allegheny River, Oil City, Pennsylvania	Single pontoon	icfs, ijr	Steel, foam filled	Rectangular 1.3 × 2.7 × 20 (0.4 × 0.8 × 6)
Beauharnois Canal, St. Lawrence River	Double pontoon	icfs, n, p	Hollow steel	Parallel, 3 diam. × 20 6 on center (0.9 diam. × 6 1.8 on center)
Salmon River, Idaho	Triple timber	icfs	Douglas fir	1 × 1 × 20 (0.3 × 0.3 × 6)

*icfs = ice cover formation and stabilization
ijr = ice jam reduction
p = hydroelectric power
n = navigation

widths upstream from the structure (U.S. Army Corps of Engineers 1982). In other words, beyond three to five river widths upstream of the boom, forces on the ice cover are transferred laterally to the banks rather than to the boom. This assumption is greatly influenced by the ice cover type and the degree to which the ice is attached to the shore. A full explanation is beyond the scope of this report, but important factors are the ice piece size, ice cover thickness, and the river width, as well as the cohesion and the angle of internal friction of the ice accumulation. During the initial formation period, the greatest forces typically occur when the ice cover is the least consolidated. Peak force levels may also occur just before breakup, as the ice cover begins to fracture and detach from the shores. Once the ice pieces freeze to each other and to the banks, the force on the boom can fall off

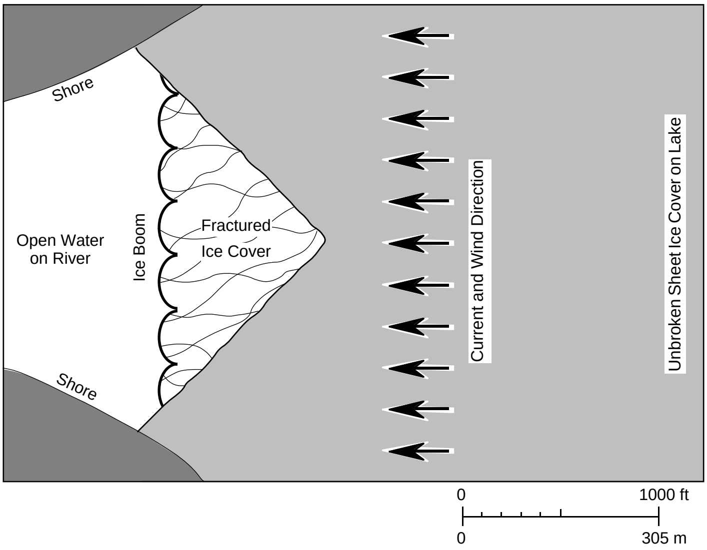
Span ft (m)	Force per unit width (kip/ft)† Designed	 (kN/m) Measured	Average depth ft (m)	Average water velocity ft/sec (m/s)	Froude number
400 (122)		0.58 (8.5)	17–29 (5–9)	0.95–2.75 (0.29–0.84)	0.02–0.12
400 (122)	1.38 (20.1)	0.37 (5.4)	18 (5.5)	1.5 (0.46)	0.06**
400 (122)	0.62 (9.1)	0.97 (14.1)	18 (5.5)	1.5 (0.46)	0.06**
400 (122)		0.64 (9.3)	100 (31)	1 (0.3)	0.06
205 (63) avg.		0.73 (10.7)	10–31 (3–9)	2.7 (0.82)	0.09–0.15
400 (122)		0.25†† (3.7)	10 (3)	1 (0.3)	0.06
250 (76)	1.12 (16.3)		5.4 (1.7)	1.15 (0.35)	0.09
118 (36)		3.2 (47)	34 (10)	2.4 (0.73)	0.07
260 (79)	0.66 (2.2)	0.42 (6.1)	5 (1.5)	2.5–3 (0.76–0.9)	0.16–0.012

†kips = kilopounds of force
**Wind driven lake ice can override boom
††Estimated force level at time of anchor cable failure

dramatically. For booms at lake-to-river confluences, where ice arch formation tends to occur naturally, the forces on the boom have been assumed to derive from a 45°–45°–90° triangular area of ice upstream of the boom, the long side of the triangle aligned with the length of the boom (Abdelnour et al. 1994). Figure 3 shows the fractured ice area that contributes to the ice loading for a wide boom on a lake. Note that the maximum load occurs at the central spans.

Water drag on ice cover

In rivers, the water shear on the underside of the ice cover is usually the primary force acting on a boom. If the drag force beyond five river widths upstream is not felt by the boom, the water shear force per unit river width for a wide rectangular channel can be determined by:



3. Schematic showing fractured ice area that contributes to the ice loading on a wide lake ice boom.

$$f_w = \gamma_{\text{water}}\, y_{\text{ice}} S_f\, 5B \tag{2}$$

where γ_{water} = the specific weight of water
y_{ice} = the average channel depth above the isoline of maximum velocity
S_f = the friction slope
B = the average width of the ice cover on the reach extending 3–5 boom widths upstream of the structure.

Expressions for y_{ice} and S_f are given in the following:

$$y_{\text{ice}} = \left(\frac{n_i^{3/2}}{n_b^{3/2} + n_i^{3/2}} \right) y_t = \left[\frac{1}{1 + \left(\frac{n_i}{n_b} \right)^{-3/2}} \right] y_t$$

where n_b = the Manning's roughness of the channel bed
n_i = the Manning's roughness of the ice cover
y_t = the average under-ice flow depth.

$$S_f = \frac{V^2\, n_c^2}{2.22\, R_{\text{ice}}^{4/3}} \qquad \text{(in English units)}$$

where V = average under-ice water velocity
n_c = the composite roughness for an ice-covered channel
R_{ice} = the hydraulic radius.

Table 2. Manning coefficients of roughness of the bottom surface of initial ice covers (after Nezhikovsky 1964).

Initial thickness (ft)	*Initial thickness* (m)	*Cover formed from loose slush*	*Cover formed from frozen slush*	*Brash ice cover*
0.3	0.1	—	—	0.015
1.0	0.3	0.01	0.013	0.04
1.6	0.5	0.01	0.02	0.05
2.3	0.7	0.02	0.03	0.06
3.3	1.0	0.03	0.04	0.07
4.9	1.5	0.04	0.06	0.08
6.6	2.0	0.04	0.07	0.09
10	3.0	0.05	0.08	0.10
16	5.0	0.06	0.09	—

Using SI units, the 2.22 constant disappears. The composite roughness n_c can be calculated from the Belokon-Sabaneev formula (U.S. Army Corps of Engineers 1982):

$$n_c = \left(\frac{n_i^{3/2} + n_b^{3/2}}{2} \right)^{2/3}$$

n_i can vary from 0.01 to 0.10, depending on many factors, including ice cover type, thickness, piece size, temperature and age. Table 2 gives ranges of values for different types of ice covers. Under conditions where an ice cover will form behind a boom, ice roughness will typically be in the 0.02–0.04 range.

The hydraulic radius R_{ice} of the ice-covered channel can be found from

$$R_{ice} = \frac{A}{P_{bed} + P_{ice}}$$

where A = the under-ice flow area
P_{ice} = the wetted perimeter of the underside of the ice cover
P_{bed} = the wetted perimeter of the channel bed.

For wide rectangular channels, the hydraulic radius can be approximated as one-half the under-ice depth.

If channel geometry data are available, standard step backwater models, such as HEC-2 with the ice cover option (U.S. Army Corps of Engineers 1990), are extremely useful in determining the hydraulic parameters used in the water shear calculation, since HEC-2 output variables include water/ice surface slope, water velocity, depth and channel top width.

Wind drag on ice cover

Wind shear is not the predominant force in most river situations, since outside forces are generally not felt by a boom beyond three to five river widths upstream of the structure. However, for ice control structures on large lakes, such as the Lake Erie ice boom, wind on the ice cover can be the most important driving force.

For rivers, the wind force per unit width of boom can be estimated by

$$f_a = C_d \rho_{air} U^2 5B \qquad (3)$$

where C_d = the drag coefficient of air flowing over an ice cover, in the range $1.7 - 2.2 \times 10^{-3}$
ρ_{air} = mass density of air (2.5×10^{-3} slugs/ft^3 at 32°F, 1.3 kg/m^3 at 0°C)
U = wind velocity 33-ft (10 m) above the ice surface.

To estimate the extent of the ice area contributing to the wind load on a wide lake ice boom, refer to Figure 3.

Gravity force

The downstream weight component of an ice cover results from water surface slope, S_f. Since slope is usually mild at sites where ice retention is possible (on the order of 0.001 to 0.0001), the gravity component is relatively small. This force can become significant if the ice cover is extremely thick, however. For rivers, the gravity force acting on a unit width of boom is given by:

$$f_g = (1-e)\gamma_{ice} t_i S_f 5B \qquad (4)$$

where e = the porosity of ice cover, which is on the order of 0.5 for conditions of maximum loading (newly formed freezeup jam, or accumulation of loose brash ice)
γ_{ice} = specific weight of ice (57.2 lb/ ft^3, 9000 N/m^3)
t_i = ice thickness
S_f = friction slope from Manning equation as defined above.

Drag on boom units

Because the boom units are relatively small, compared to the cross section of the river, and the size of the ice cover, the drag force on these units is generally negligible. In many ice boom applications, the bottom of the ice cover is roughly even with the bottom of the boom unit, rendering water drag on the boom unit insignificant. If needed, the water drag force on the boom unit, per unit river width, can be approximated from:

$$f_d = \frac{c_D h_s \rho_w V^2}{2} \tag{5}$$

where c_D = drag coefficient for the submerged portion of the boom unit (1.5–2.0 for rectangular shapes)
h_s = submerged depth of boom unit
ρ_w = density of water (1.93 slugs/ft^3, 1000 kg/m^3)
V = average water velocity.

Impact load from broken cover

In general, the impact loads on an ice boom from a broken cover are low. An exception occurs when an intact sheet upstream of the boom is released in the form of floes that can be as large as several acres. In most cases, large floes submerge the boom units and override the ice boom. Relatively large forces can act on the boom before it submerges, however. The impact of a large ice floe typically does not occur when any of the other loads are present, since large floes will be free to hit the boom only when the river is relatively free of other ice. Impact loads may be distributed along the length of the boom or analyzed as point loads. Distributed over the boom width, the impact force can be expressed as:

$$f_i = \frac{m_{ice} \Delta V}{L \Delta t} \tag{6a}$$

where L = length of the boom, perpendicular to the direction of flow.
m_{ice} = mass of the ice floe
ΔV = change in floe velocity, usually considered to end up at rest
Δt = estimated time for the ice floe to come to rest.

Estimating the time required for the floe to come to rest may be difficult. If the designer has an idea of the boom's compliance, an energy transfer approach can be used to estimate impact force per unit width of river:

$$E = f_i \Delta x = \frac{m_{ice} \Delta V^2}{2L}$$

where E is the energy transferred to the boom in the process of stopping the floe, and Δx is the distance required to stop the floe. If we rearrange the equation, the impact force can be expressed as:

$$f_i = \frac{m_{\text{ice}}\,\Delta V^2}{2\Delta x L} \tag{6b}$$

The designer must determine the length over which this force is to be distributed.

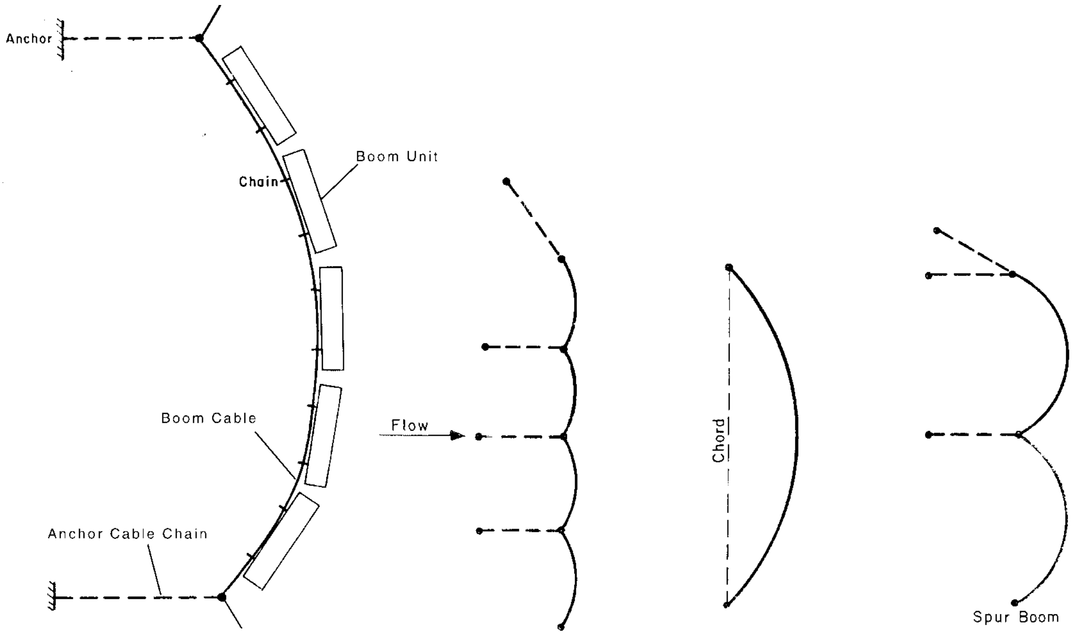
Forces from vessel passages

Large vessels navigating in winter can impose loads on an ice boom in a number of ways. First, a vessel may collide directly with the boom. Second, waves produced by a vessel passage can result in both vertical and lateral movement of an intact sheet ice cover, transmitting forces to the boom. The hydrodynamics of boom loading due to vessel-induced waves are quite complicated and beyond the scope of this technical digest. Third, waves or propeller wash from a vessel may push broken ice pieces or brash ice into a boom. The most common vessel effect takes place when ship traffic in the vicinity of the boom breaks shore ice free, allowing it to act on the boom. If the shore ice breaks into relatively small pieces, the increased ice load may be estimated by increasing the ice area subject to water, wind and gravity forces (eq 2, 3 and 4). If a large floe broken free by vessel passage moves against the boom, it may be treated as an impact force and estimated using eq 6a and 6b.

Typical ice boom configurations

Ice booms have been built in many configurations. Some booms cross the entire channel width, while others stabilize or retain ice only at the channel sides. The boom in Figure 2 has an opening for ship passage. Figure 4 illustrates a variety of boom configurations. The upstream vee design shown in Figure 4e effectively diverts arriving ice away from the highest velocity area at the channel center and avoids the use of a midchannel anchor by extending anchor cables to each shore. In more conventional configurations such as Figure 4b, the spacing between anchor lines is typically 100 to 400 ft (30–120 m), depending on the loading and the strength of the boom. Span lengths greater than 400 ft (Fig. 4c) are found in some debris boom applications, but are rare in booms designed to retain ice.

In some applications, it may be advantageous to orient the boom so that the region of maximum flow velocity does not coincide with the area of maximum boom sag (Fig. 4e). In the region of fastest current, the flow velocity component perpendicular to the boom will therefore be lower and the ice capture efficiency increased. This arrangement also tends to divert ice from the faster areas to slower parts of the channel, making it easier for the boom to retain ice. Often, the part of the river with

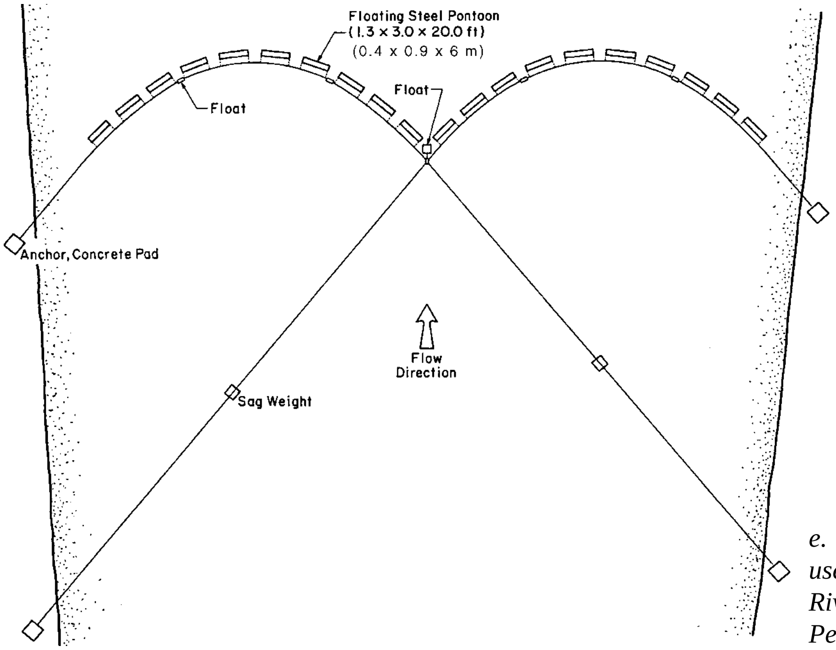


a. Conventional ice boom layout, showing components.

b. Multiple span boom. Individual spans are typically 100–400 ft (30–120 m) in width.

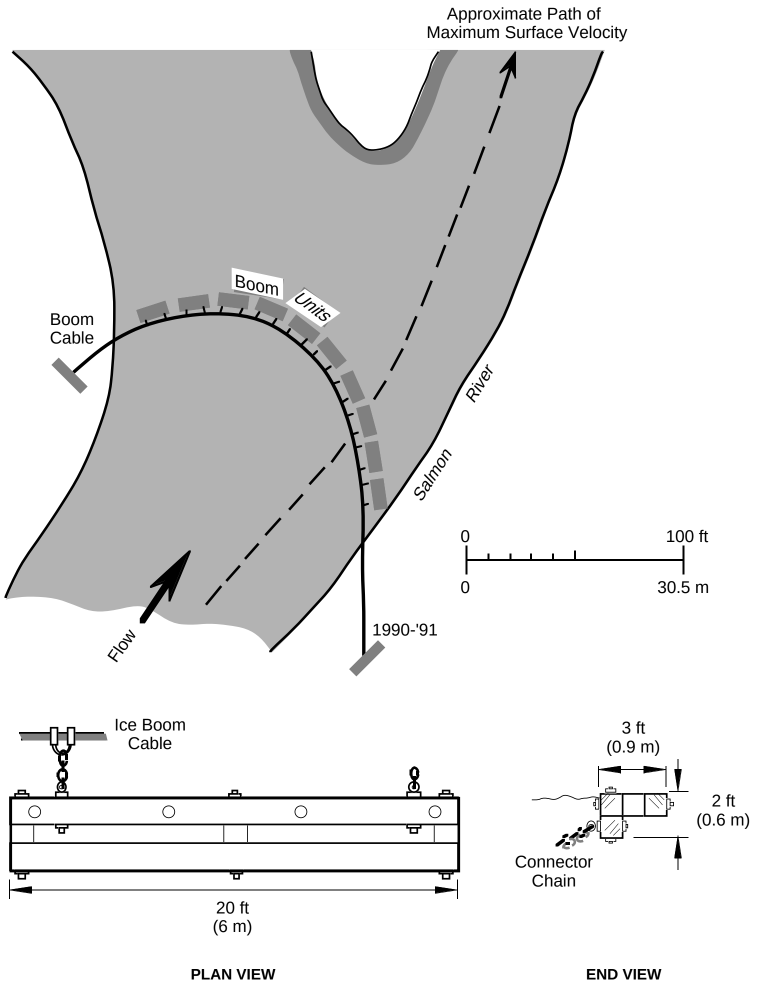
c. Single span boom.

d. Spur boom used to retain and stabilize an ice cover at the channel sides.



e. Upstream vee design used on the Allegheny River at Oil City in Pennsylvania.

4. Typical ice boom layouts.

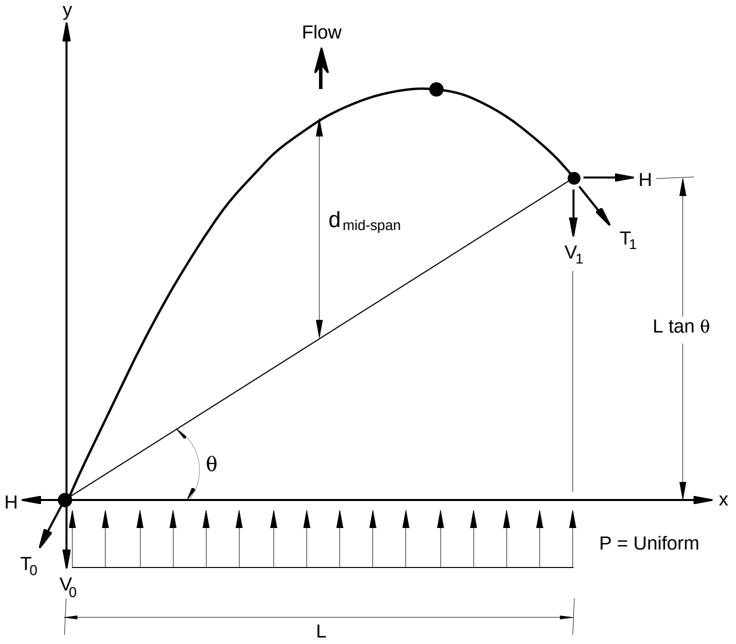


5. Salmon River boom. Note that the boom is aligned at an angle to the path of maximum surface water velocity.

the greatest depth and the highest current velocity is in the vicinity of the channel center. If the boom is oriented with the chord at an acute angle to cross-stream direction, the point where the boom is perpendicular to the flow is shifted away from the path of maximum surface velocity (Fig. 4e and 5).

Geometry of boom and wire rope tension

The following discussion is based on boom geometry as shown in Figure 6. Relationships exist between the location of the anchor points, the unstressed length of wire rope S_0, the sag ratio s, and the tension in the main support cable T. The sag ratio is defined as the ratio of the midspan deflection, d_{midspan}, to the perpendicular length L. Assuming a uniform loading across the river width results in a parabolic shape for the ice boom cable. For most applications, this shape is a reasonable approximation of the actual ice boom geometry.



6. Definition sketch for ice boom loading and geometry. A uniform loading is assumed across the channel width to produce a parabolic shape.

Calculation of main cable tension

Assuming a parabolic shape and an inextensible cable (Leonard 1988), the relationship among the unstressed length S_0, the sag ratio s, and the perpendicular chord length L may be approximated by:

$$S_0 = L\left(1+\frac{8}{3}s^2+\frac{1}{2}\tan^2\theta\right) \tag{7}$$

The x-component of the load H along the boom cable is constant and is given by:

$$H = \frac{pL}{8s} \tag{8a}$$

The y-component of the load V in the main cable at any horizontal distance x is given by:

$$V = H\tan\theta + \frac{pL}{2}\left(1-2\frac{x}{L}\right) \tag{8b}$$

Equations 8a and 8b can be combined to give a relationship that approximates the resultant tension, T, at any point x:

$$T = \frac{pL}{8s}\sqrt{1+\left[\tan\theta+4s\left(1-\frac{2x}{L}\right)\right]^2} \tag{9}$$

where p is the uniform load on the boom per unit width of river (= f_b as computed above in eq 1) and θ is the angle between the chord and the line perpendicular to the direction of force.

The complete geometry of the boom cable may be approximated by:

$$y = x\left[\tan\theta + 4s\left(1 - \frac{x}{L}\right)\right] \qquad (10)$$

Choice of wire rope

Several considerations affect the choice of a wire rope. First, and most important, published wire rope strengths are considered to be *breaking*, and not *working* strength, so a factor of safety is needed. Table 3 lists the load carrying capacity of common sizes and types of galvanized wire rope. Second, standard hoisting rope (6 × 19 construction)* is recommended for booms because of its high strength, good wearing characteristics, and availability. Third,

Table 3. Nominal strength of 6 × 19 galvanized improved plow steel wire rope.

Diameter (in.)	*Diameter (mm)*	*Nominal strength (tons)* of 2,000 pounds 6 × 19 galvanized improved plow steel*		*Approximate weight per foot (lb)***	
		Fiber core	*IWRC*†	*Fiber core*	*IWRC*
1/4	6.3	2.47	2.65	0.105	0.116
5/16	7.9	3.83	4.12	0.164	0.180
3/8	9.5	5.49	5.90	0.236	0.260
7/16	11.1	7.44	8.00	0.32	0.35
1/2	12.7	9.63	10.30	0.42	0.46
9/16	14.3	12.10	13.00	0.53	0.59
5/8	15.9	15.00	16.10	0.66	0.72
3/4	19.0	21.40	23.00	0.95	1.04
7/8	22.2	29.00	31.10	1.29	1.42
1	25.4	37.60	40.40	1.68	1.85
1-1/8	28.6	47.30	50.90	2.13	2.34
1-1/4	31.7	58.10	62.50	2.63	2.89
1-3/8	34.9	69.90	75.10	3.18	3.50
1-1/2	38.1	82.80	89.00	3.78	4.16
1-5/8	41.3	96.30	103.00	4.44	4.88
1-3/4	44.4	112.00	120.00	5.15	5.67
2	50.8	144.00	155.00	6.72	7.39

This type of information can be found in many engineering handbooks or suppliers catalogs. The above is taken from Washington Chain and Supply, Inc., 2901 Utah Ave. South, Seattle, Washington 98124.
* 1 ton of 2000 lb = 1.102 metric tonnes
** 1 lb$_{mass}$ = 0.4534 kg
† IWRC = independent wire rope core

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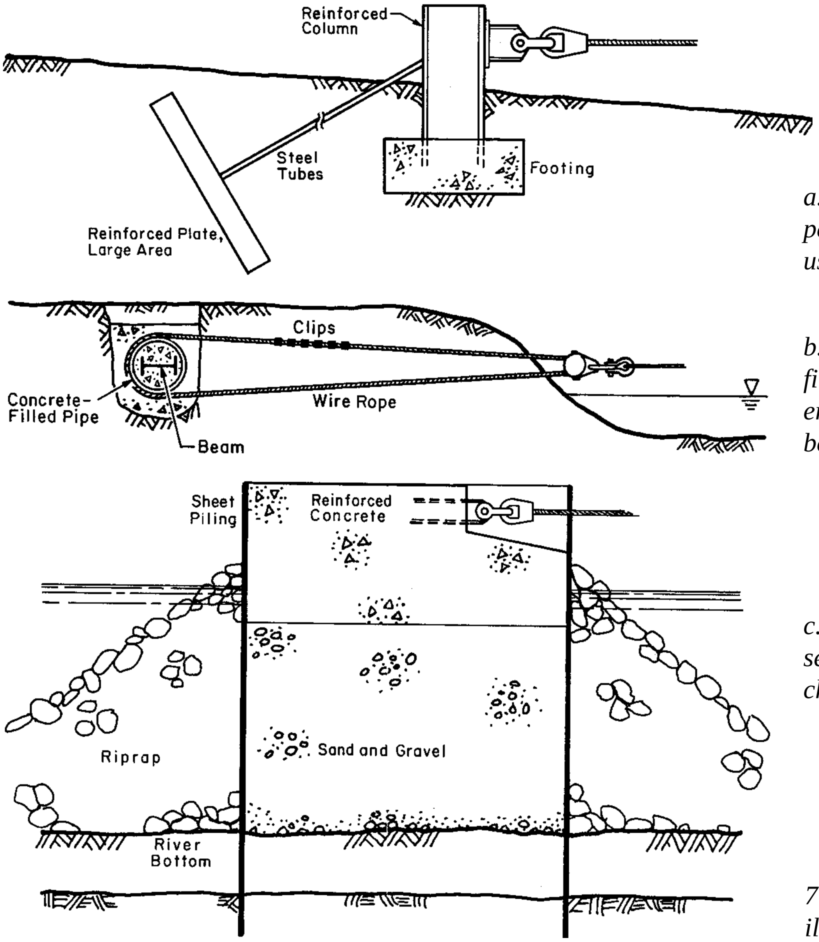
* 6 × 19 means that the rope is composed of six strands, and each strand is made up of 19 wires.

flexible fiber core wire rope should be used for members to be handled by heavy equipment. Fourth, because members are constantly wet, galvanized wire rope is used to minimize damage from corrosion. Fifth, because wire rope sizes over 2–3 in. (5–7.5 cm) in diameter are very difficult to handle, the structural load and therefore the wire rope size can be reduced by shortening the span length of the boom cable.

Anchoring systems

For midstream river-bottom anchors, the anchor cable should have a minimum "scope" of 7 (7 horizontal to 1 vertical). The Engineer Manual, *Ice Engineering* (U.S. Army Corps of Engineers 1982) recommends a scope of 12. This allows the structural system to absorb impact loads while maintaining a relatively horizontal load on the anchors. These midstream anchors can take many forms, such as ship anchors, driven piles, drilled and grouted piles, and buried steel plates. Examples of anchor types are shown in Figure 7. If the year-round river use conditions allow, perma-

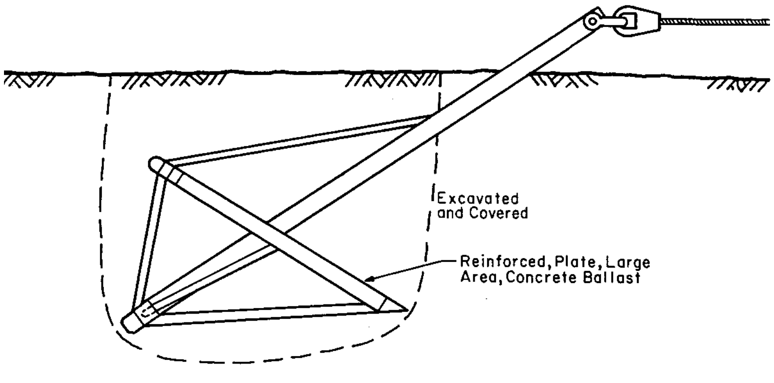


a. Deadman and pedestal type anchor used at the land end.

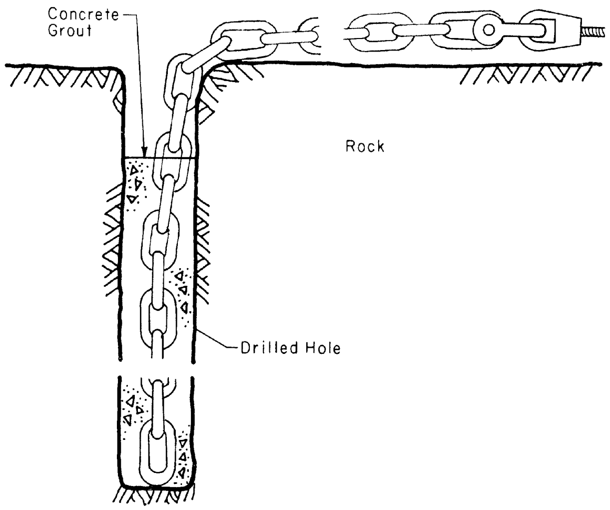
b. Buried concrete-filled pipe used as land end anchor. Note I-beam reinforcement.

c. Sheet-piling cell serving as a mid-channel anchor.

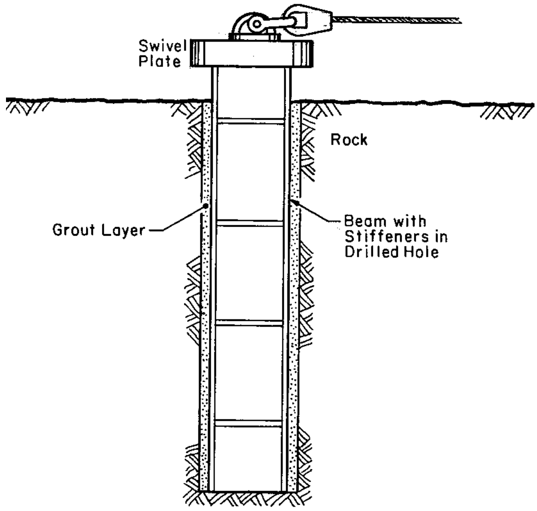
7. Anchor types illustrated.



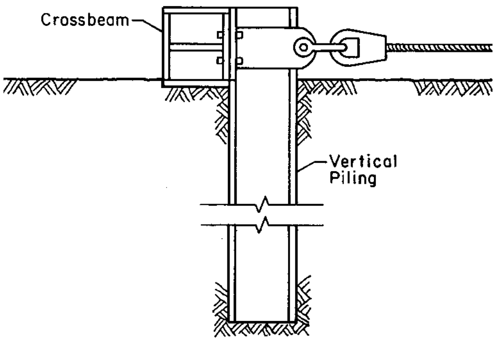
d. Ballasted steel mud anchor (midchannel).



e. Chain anchor grouted to drilled hole in bedrock (midchannel).



f. Anchor constructed of steel weldment grouted to drilled hole in bedrock (midchannel or land)



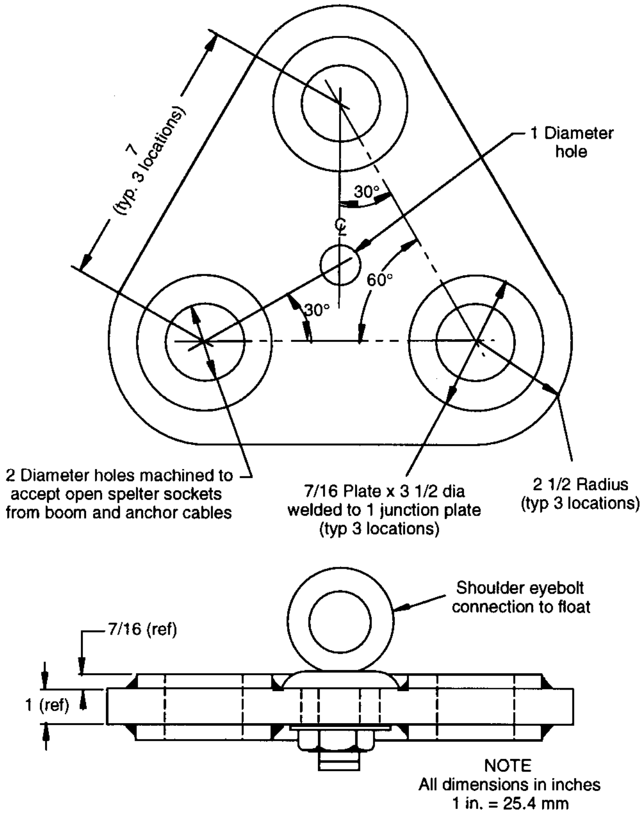
g. Anchor constructed of driven H-piles (midchannel or land)

7 (cont'd). Anchor types illustrated.

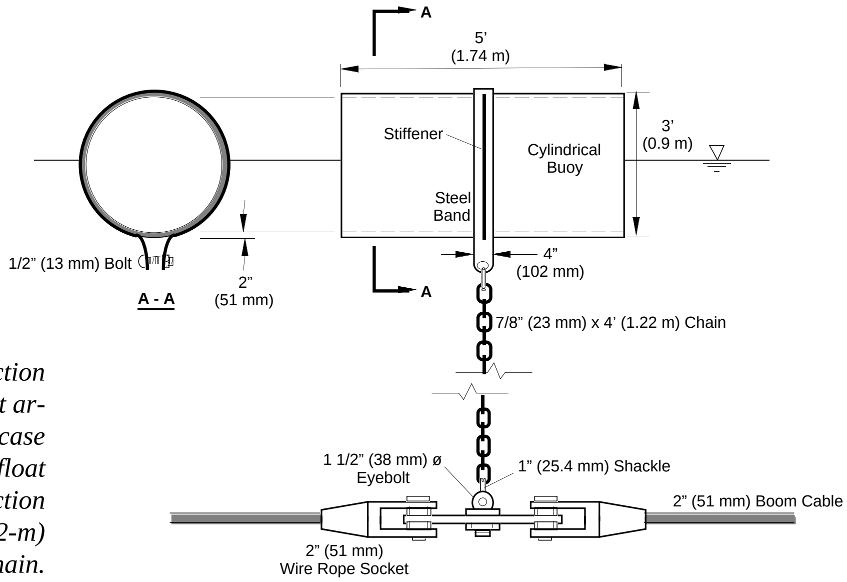
nent above-water anchors, such as rock islands, sheet-pile cells, and timber and rock cribs can be used. These above-water anchors provide the added benefit of increasing the overall stability of a sheet ice cover.

Anchor lines are generally made of wire rope. However, if the boom is being used in a large water body with commercial navigation, anchor lines of high strength anchor chain may be preferable, because a chain being more flexible will lie on the bottom without coiling. Furthermore, a chain is more resistant to abrasion if the bottom is rocky.

If the boom has midstream anchors, a junction plate must be used to connect the two boom cables to the single anchor cable. Because these junction plates must be designed for high loads, they usually require additional flotation to support their weight and prevent the boom from submerging near the anchor attachment points. This additional flotation is also needed to support parts of the submerged weight of the anchor cable and the adjacent boom cables. Figures 8 shows a typical junction plate design, and Figure 9 shows a typical junction plate and float arrangement.



8. Example of junction plate design. Note the reinforcing steel plates welded to each side of the three holes.



9. Example of junction plate and float arrangement. In this case a cylindrical float supports the junction plate with a 4-ft (1.2-m) length of chain.

Boom unit design

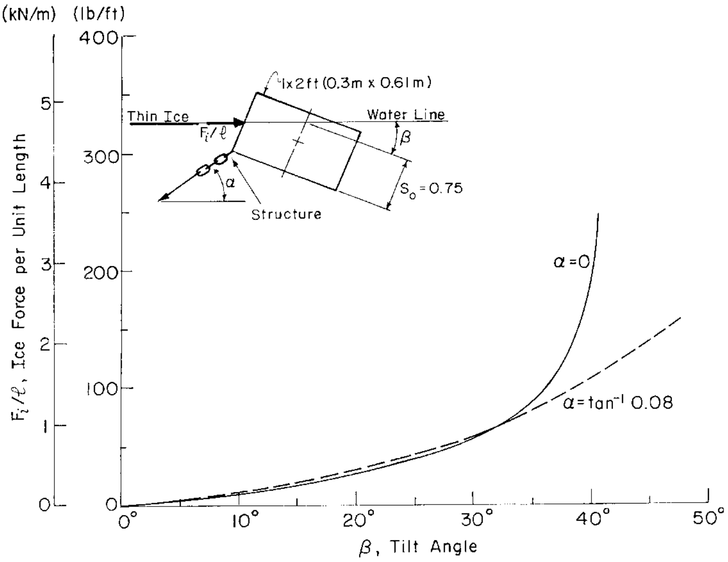
Important considerations in the design of the actual boom units are the type and thickness of the ice to be retained and the anticipated ice forces. The strength of the boom unit is also important, since a boom unit must resist bending failure under the design loads, particularly if large floes are expected to impact the structure. In addition, the boom unit must have sufficient frontal area to capture floating ice and debris. Size is also an issue, because a boom unit must be small enough to be easily handled by available equipment during its annual installation and removal.

Ice restraint capacity

The ice restraint capacity of a boom unit depends on the buoyancy, the righting moment, the location of the anchor connection, and the type of ice being retained. Figure 10, based on experimental data with thin ice covers, shows that a single 1 × 2 ft (0.3 × 0.6 m) timber boom, with a scope of 12.5 or more, has a maximum load capacity in the 80 lb/ft (1.2 kN/m) range, above which the tilt angle β reaches about 35°, resulting in the ice overriding the boom unit. With thicker, stronger ice covers, much higher loads are possible, however. Some double pontoon booms have load capacities as high as 500 lb/ft (7.3 kN/m). Measured force levels listed in Table 1 give an idea of the maximum ice restraint capacities of various other types of booms.

Successful ice boom designs

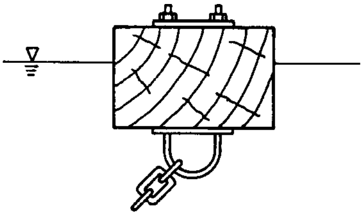
Table 1 and Figure 11 illustrate a variety of successful boom unit designs. Many others are possible. For years, single timber boom units (Fig. 11a) have been successfully used in both large



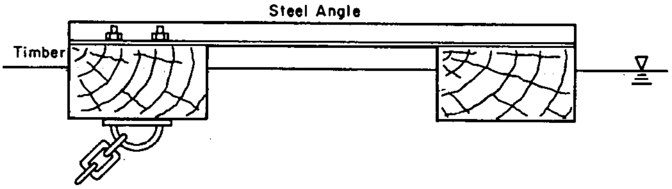
10. Ice restraint capacity of a rectangular timber boom. Note that $\tan^{-1}$ *(0.08) = 4.6° so the boom chain is nearly horizontal. For the thin ice case, the maximum ice restrain capacity of a rectangular timber boom is on the order of 50–80 lb/ft (0.73–1.2 kN/m).*

and small rivers. Douglas fir has been the timber of choice because of its strength and durability, particularly under conditions of constant wetting. Many of these booms were designed using 12- × 14-in. (30- × 36-cm) timbers, often in parallel, separated by timber blocks or steel struts, to increase the righting moment (Fig. 11b). In addition, some of these units have a second timber installed on the upstream face to increase the depth of the boom and the capture efficiency (Fig. 5). The lengths of these timber boom units are generally in the 20- to 30-ft (6- to 9-m) range, and the spacing between boom units is optimum at about three to six ice thicknesses. Timber booms have to be periodically removed from the water to allow for complete drying.

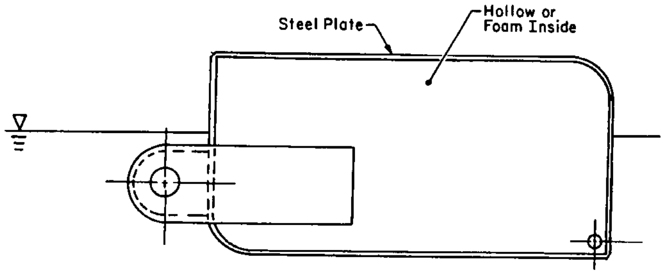
Douglas fir timbers are still being used on Lake Erie, the International Section of the St. Lawrence Seaway, and at Lake St. Peter on the lower St. Lawrence River. However, the Canadian Coast Guard and Hydro-Quebec are switching to steel pontoons due to their lower maintenance costs and the decreasing availability of large Douglas fir timbers. The steel boom units may be rectangular as shown in Figure 11c, or may use steel pipe as the flotation members as shown in Figure 11d and 11f. Some steel pontoon booms are filled with foam to maintain floatation in the event of damage and leaks. In this case, additional floatation is needed to compensate for the added weight of the foam. Often, a vertical face is installed on the upstream face of a pipe boom unit (Fig. 11f), particularly in the case of shear booms. Recently, the Canadian Coast Guard has had success with single-circular-



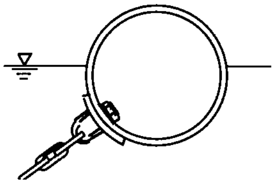
a. Single rectangular timber boom. Typical dimensions are 14 × 22 in. (36 × 56 cm).



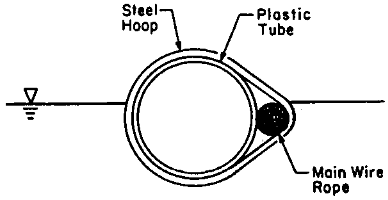
b. Boom constructed of double timbers connected with steel angles



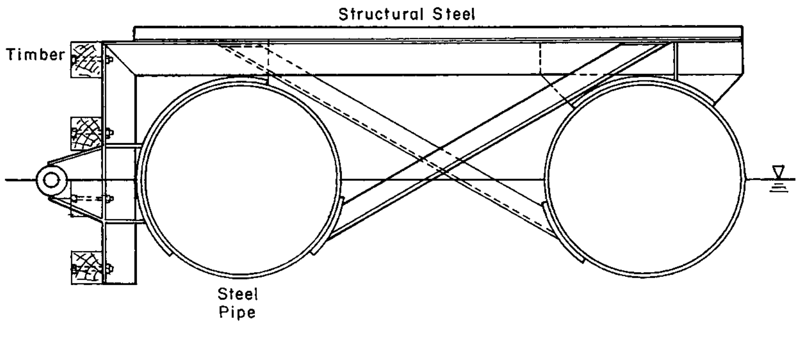
c. 2.5 × 5.5 ft (0.75 × 1.5 m) rectangular steel pontoon as used on the Allegheny River at Oil City, Pennsylvania.



d. Circular steel pontoon boom, 30-in.- diam. (76-cm), as used on Lake St. Peter on the lower St. Lawrence River.

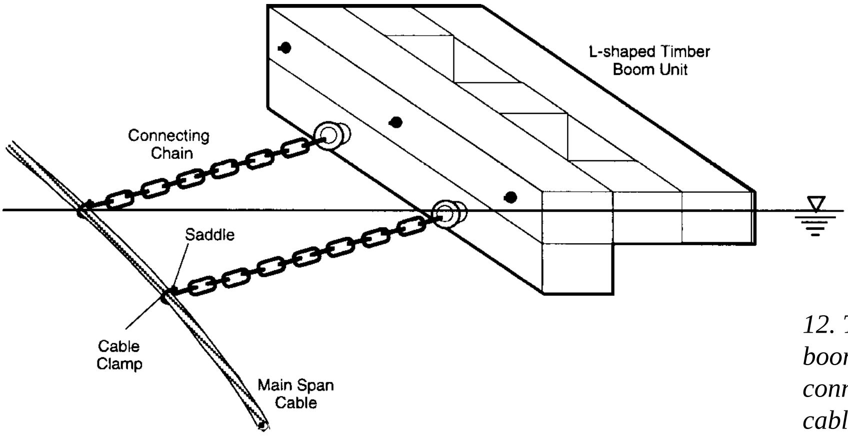


e. Boom unit constructed of plastic pipe, banded to the boom cable with wire hoops.

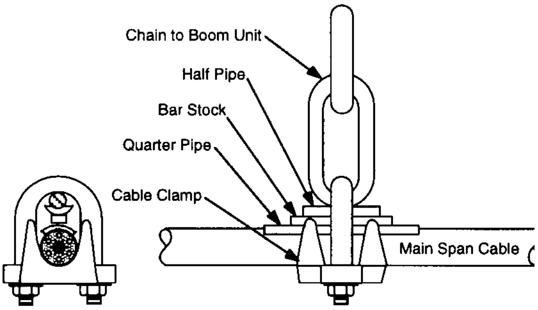


f. Double steel pipe pontoon booms used on the Beauharnois Canal. Pipe diameter in 3 ft (0.9 m). This boom withstood a maximum measured force of 3.2 kip/ft (47 kN/m).

11. Successful ice boom unit designs.



12. Triple timber ice boom unit, showing connections to main cable.



13. Fabricated steel saddles, designed to protect the main wire rope from pinching by the cable clamps.

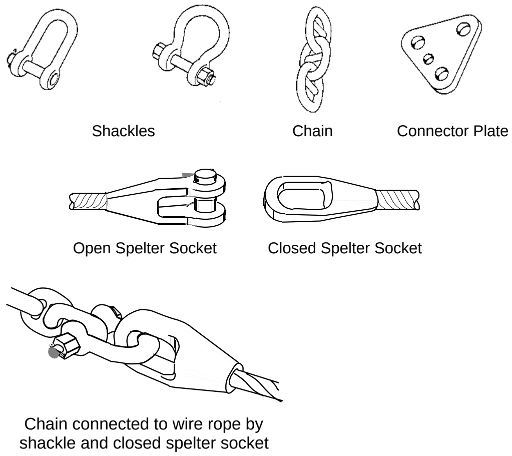
section steel pipe booms on the lower St. Lawrence River (Fig. 11d). Plastic tubing has also been used (Fig. 11e). For additional examples of possible boom cross-sectional geometries, refer to the *Ice Engineering* (U.S. Army Corps of Engineers 1982).

Boom unit connections

The boom unit is generally connected to the main load carrying cable by a 3- to 5-ft (0.9- to 1.5-m) length of chain or wire rope (Fig. 12). The location of the chain-to-boom-unit connection affects the righting moment, but structural considerations are equally important. The boom unit connector chains attach to cable clamps on the main span cable. Special steel saddles must be fabricated to protect the main wire rope from being pinched by the cable clamps (Fig.13). Figure 14 shows standard fittings useful in the design of ice boom connections. Included are open and closed spelter sockets used to link wire rope to various fittings such as shackles, chains, and connector plates.

Failure considerations

If one boom component fails, the load on adjacent components will increase substantially. A failure analysis should therefore be made on the multicomponent structure to examine the effect on adjacent members, should one member fail. Fuse-links, or spe-



Shackles

Chain

Connector Plate

Open Spelter Socket

Closed Spelter Socket

Chain connected to wire rope by shackle and closed spelter socket

14. Standard fittings useful in the design of ice boom connections.

cially designed weak points, may be incorporated in the design, permitting individual boom components to fail in a way that prevents failure of the entire structure. For example, a fuse link at one end of the boom cable would allow the span to open, reducing the force on the anchor cable. In contrast, if the anchor cable is allowed to fail first, the increased load on the adjacent anchor cables might cause their failure as well.

Design example

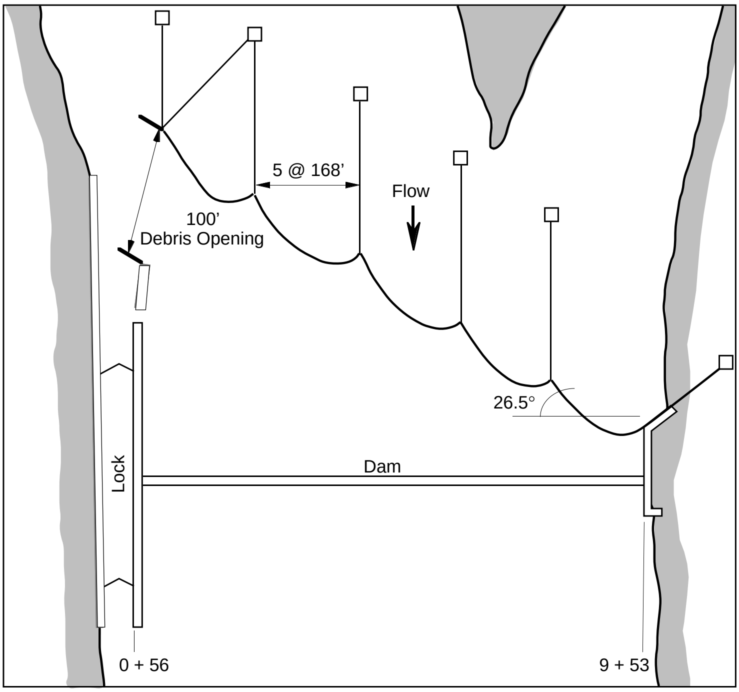
This example is based on an ice boom system designed for the Allegheny River Lock and Dam 8. Figure 15 shows a plan view of the river area upstream of the lock and dam. An elevation of the free overflow weir is shown in Figure 16. Average discharge values for the site are listed in Table 4.

The boom at this location is designed to be at an angle with the flow, providing for an ice and debris opening, which allows brash ice from the ship track to be flushed over the weir without clogging the lock entrance.

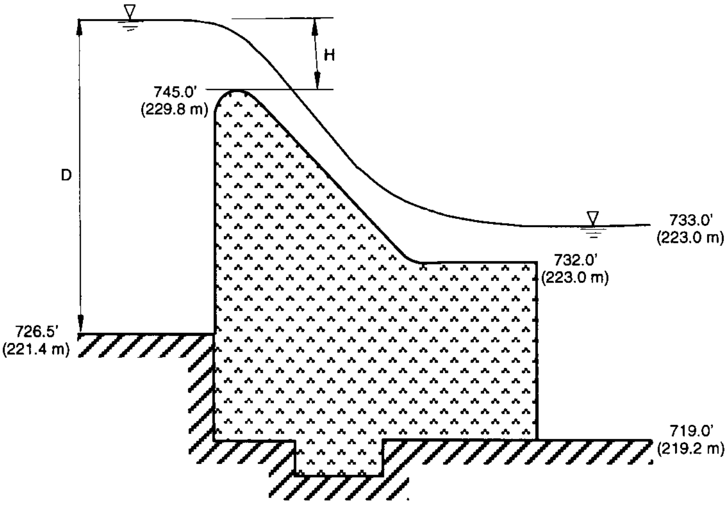
Since a boom is effective at Froude numbers less than 0.08, one approach is to determine the depth, discharge, and average velocity at this Froude number. This can be achieved by combining the weir and continuity equations with the definition of the Froude number. The calculated discharge is then checked against the observed average winter discharges listed in Table 4. Discharge over a weir can be estimated by:

$$Q = CL_{\mathrm{w}} H^{3/2}$$

where C = weir discharge coefficient, which varies between 2.5 and 3.5 depending upon the type of weir (3.3 will be used in this example)



15. Plan view of the river area upstream of the Lock and Dam 8 on the Allegheny River. The boom is made up of five, 168-ft (51-m) spans aligned at a 26.5° angle to the cross-channel direction.



16. Elevation view of a free overflow weir.

Table 4. Monthly average discharges for Allegheny River.

	December		*January*		*February*		*March*	
	(ft^3/s)	*(m^3/s)*	*(ft^3/s)*	*(m^3/s)*	*(ft^3/s)*	*(m^3/s)*	*(ft^3/s)*	*(m^3/s)*
MEAN	27,460	777	38,460	1090	17,550	497	54,950	1556
MAX	44,100	1250	88,500	2506	52,500	1486	99,200	2807
MIN	15,200	430	18,800	532	7,450	211	23,500	665

L_w = the length of the weir, which is 883 ft* for this example
H = the flow depth over the weir.

Assuming upstream channel width is roughly equivalent to the weir length L_w, average velocity upstream of the dam can be expressed as

$$V = \frac{Q}{A} = \frac{CL_w H^{3/2}}{L_w D}$$

where D is the flow depth of the river upstream of the dam. Using the elevations presented in Figure 16, the height of the weir = 745.0 – 726.5 = 18.5 ft. The upstream depth is then $D = 18.5 + H$. Combining these gives:

$$F_R = \frac{V}{\sqrt{gD}} = \frac{CL_w H^{3/2}}{L_w D\sqrt{gD}} \le 0.08$$

$$0.08 \ge \frac{CH^{3/2}}{(18.5+H)\sqrt{g(18.5+H)}}$$

$$= \frac{3.3H^{3/2}}{(18.5+H)\sqrt{g(18.5+H)}} = (0.5815)\left(\frac{H}{18.5+H}\right)^{3/2}$$

Solving for H by trial and error gives:

$H \le 6.7$ ft

The average depth (D) upstream of the weir, at a Froude number of 0.08 is then:

$D = 18.5 + 6.7 = 25.2$ ft

Discharge and average velocity at the boom location can then be calculated:

$Q = CLH^{3/2} = (3.3)\ (883)\ (6.7)^{3/2} = 50{,}500$ ft^3/s

Average velocity is then:

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*Only English units are used in *Design Example*.

$$V = \frac{Q}{A} = \frac{Q}{LD} = \frac{50,500}{(883)(25.2)} = 2.3\,\text{ft}^3/\text{s}$$

From Table 4, 50,500 ft^3/s is a reasonable winter discharge. Periods of higher discharge are possible, however. Under these conditions, Froude number and water velocity may be too high for successful ice retention by the boom. During the high discharge periods, measures such as raising the pool height or upstream flow control may be necessary.

An alternative method would be to select a maximum expected winter discharge, find the water depth using the weir equation, then check if the $F_R \leq 0.08$ and $V \leq 2.3$ ft/s criteria are satisfied. If channel cross-section geometry data are available, numerical models such as HEC-2 (U.S. Army Corps of Engineers 1990) are helpful in determining hydraulic conditions over a range of discharges at potential ice boom locations.

For this example, the following values of various parameters are assumed: channel bed roughness n_b = 0.02, ice roughness n_i = 0.03, brash ice cover thickness t_i = 0.75 ft and porosity e = 0.5. The average width of the upstream ice cover contributing to the load on the boom is assumed to be 900 ft.

Under-ice depth: $y_t = D - 0.92\,t_i = 25.2 - (0.92)(0.75) = 24.5$ ft

For wide rectangular channels, under-ice hydraulic radius (R_{ice}) can be approximated as half the under-ice depth:

$$R_{ice} = 0.5\,y_t = (0.5)(24.5) = 12.2\,\text{ft}$$

The composite roughness for the ice covered channel (n_c) can be calculated using the Belokon-Sabaneev formula:

$$n_c = \left(\frac{n_i^{3/2} + n_b^{3/2}}{2}\right)^{2/3} \left(\frac{(0.03)^{3/2} + \left(0.02^{3/2}\right)}{2}\right)^{2/3} = 0.025$$

Friction slope (S_f) may now be calculated:

$$S_f = \frac{V^2\,n_c^2}{2.22\,R_{ice}^{4/3}} = \frac{(2.3)^2\,(0.025)^2}{(2.22)(12.2)^{4/3}} = 0.000053$$

To find the shear stress on the underside of the ice cover, the average channel depth above the isoline of maximum velocity (y_{ice}) is needed:

$$y_{\text{ice}} = \left(\frac{n_i^{3/2}}{n_b^{3/2} + n_i^{3/2}} \right) y_{\text{t}} = \left(\frac{(0.03)^{3/2}}{(0.22)^{3/2} + (0.03)^{3/2}} \right) (24.5) = 1.59 \text{ ft}$$

The shear stress on the underside of the ice is computed using eq 2:

$$f_{\text{w}} = \gamma_{\text{water}}\, y_{\text{ice}} S_{\text{f}} 5B = (62.4)(15.9)(0.000053)(5)(900) = 237 \text{ lb/ft}$$

The wind drag forces are then determined from eq 3, assuming a critical wind of 25 mi/h (or 37 ft/s) in the direction of the river flow. Using a drag coefficient C_{d} of 2.2×10^{-3} and a mass density of air ρ_{air} of 2.5×10^{-3} slugs /ft^3:

$$f_{\text{a}} = C_{\text{d}} \rho_{\text{air}} U^2 5B = (2.2\times10^{-3})(2.5\times10^{-3})(37)^2(5)(900) = 34 \text{ lb/ft}$$

Equation 4 gives the gravity forces exerted by the ice cover on a unit width of boom:

$$f_{\text{g}} = y_{\text{ice}}(1\text{–}e)t_{\text{i}} S_{\text{f}} 5B = (57.4)(1\text{–}0.5)(0.75)(0.000053)(5)(900) = 5 \text{ lb/ft}$$

With a 0.75-ft-thick ice cover, the ice bottom will be roughly even with the bottom of a typical boom unit. Water drag on the boom unit is neglected in this design case.

For impact loading, it is assumed that the boom units displace an average distance of 10 ft while stopping a 2-acre × 1-ft-thick ice floe moving with an initial velocity equal to the average current velocity at 2.3 ft/s. The impact force f_{i} is considered separately, since a large floe would probably not impact the boom if an ice cover is already in place. From eq 6b:

$$f_{\text{i}} = \frac{m_{\text{ice}} \Delta V^2}{2d} = \frac{2(43,560)(1)(0.92)(1.93)(2.3)^2}{2(10)} = 40,900 \text{ lb}$$

If the floe is roughly square in shape, the length of one side would be approximately 300 ft. Distributing the impact load over this length gives:

$$\frac{40,900 \text{ lb}}{300 \text{ ft}} = 136 \text{ lb/ft} \text{ along the contact area}$$

Neglecting vessel-induced forces, water drag on the boom unit, and the ice impact forces, the total force acting on the boom f_{b} is the sum of these forces:

$$f_{\text{b}} = f_{\text{w}} + f_{\text{a}} + f_{\text{g}} = 237 + 34 + 5 = 276 \text{ lb/ft} \quad \text{(say 280 lb/ft)}$$

With the design loads determined, the cable tensions can be computed. It should be noted that a sag ratio s is usually in the range of 0.15–0.20. This range generally allows the midstream anchor cables to be the same size as the main boom cables. With lower sag ratios, the tension and, therefore the wire rope diameter, may become prohibitively large. With higher sag ratios, the tension decreases, but the length of the wire rope increases. The increased length may require additional boom units, which would result in higher costs.

Assuming that the downstream deflection of the boom is 32 ft, s would be:

$$s = \frac{d_{\text{midspan}}}{L} = \frac{32\,\text{ft}}{168\,\text{ft}} = 0.19$$

The wire rope tension is then computed for both ends of the cable using eq 9.

$$T = \frac{pL}{8s}\sqrt{1+\left[\tan\theta + 4s\left(1-\frac{2x}{L}\right)\right]^2}$$

$$T_0 = \frac{280(168)}{8(0.19)}\sqrt{1+\left[\tan 26.5 + 4(0.19)(1-0)\right]^2} = 49,750\,\text{lb}$$

$$T_1 = \frac{280(168)}{8(0.19)}\sqrt{1+\left[\tan 26.5 + 4(0.19)(1-2)\right]^2} = 32,000\,\text{lb}$$

Using the maximum tension of 50,000 lb and a factor of safety of 3.5 gives a boom cable tension of 175,000 lb or 88 tons.

From Table 3, a 1-1/2-in.wire rope of galvanized improved plow steel-fiber core (GIPS-FC) 6 × 19 construction with a breaking capacity of 82.80 tons would provide a factor of safety of 3.3. The next largest wire rope diameter (1-5/8 in.) with a breaking strength of 96.30 tons would increase the factor of safety to 3.9.

The length of the boom cable can be found from eq 7:

$$S_0 = L\left(1+\frac{8}{3}s^2+\frac{1}{2}\tan^2\theta\right)$$

$$= (168)\left(1+\frac{8}{3}(0.19)^2+\frac{1}{2}\tan^2(26.5)\right) = 205\,\text{ft}$$

The final “eye-to-eye” cable length has to be determined after the junction plates have been designed.

The horizontal load on the midstream anchors T_{anchor} will be the load acting on a tributary width of half of the wire rope span on either side of the anchor:

$$T_{\text{anchor}} = f_{\text{b}}(\text{tributary width}) = 280(168)(0.5 + 0.5) = 47{,}040 \text{ lb}$$

Use a 1-1/2-in. 6 × 19 GIPS-FC wire rope with a breaking capacity of 82.8 tons. With a depth of 25 ft and a scope of 7 horizontal to 1 vertical, the anchor cable length would be 175 ft.

Floats must be designed to support the half of the weight of the anchor cable and adjacent boom cables, as well as the weight of the junction plates and connections. Figures 1 and 9 show typical float arrangements. Table 2 gives a weight of 3.18 lb per lineal foot for 1-3/8 in. 9 × 16 GIPS-FC wire rope. The boom cable weight is then:

$$205 \text{ ft} \times 3.78 \text{ lb/ft} = 775 \text{ lb}$$

and the anchor cable weighs:

$$175 \text{ ft} \times 3.78 \text{ lb/ft} = 662 \text{ lb}$$

Assume the junction plate with wire rope connections weighs 100 lb and the float weighs 150 lb. The float at each junction must supply a buoyant force (F_{b}) adequate to support its own weight, the submerged weight of the junction plate and half the submerged weight of the anchor cable and adjacent boom cables:

$$f_{\text{b}} = 150 + \left(\frac{\gamma_{\text{steel}} - \gamma_{\text{water}}}{\gamma_{\text{steel}}} \right) \left[100 + \frac{1}{2}(662) + \frac{1}{2}(775) + \frac{1}{2}(775) \right] = 1200 \text{ lb}$$

where γ_{steel} = 490 lb/ft^3 and γ_{water} = 62.4 lb/ft^3.

The volume of water (V_{w}) displaced to provide this buoyant force is

$$V_{\text{w}} = \frac{W_{\text{w}}}{\gamma_{\text{w}}} = \frac{1200}{62.4} = 19.2 \text{ ft}^3$$

Assuming that 40% of the float's volume is submerged under static conditions, the total volume of the float must be 19.2 ft^3/40%, or 48 ft^3. A 3-ft-diam. × 6-ft-long cylindrical float, with a volume of 42.4 ft^3 would work in this case.

Conventional ice boom units are generally 20–30 ft long, with a spacing between units of 3–6 times the ice thickness. For each 205-ft-long main span cable, eight 20-ft-long boom units with 5.0- ft gaps between units would work well. A smaller gap width could be achieved by using nine 20-ft booms with 2.5-ft gaps.

At this point, the design of the main structural components of the boom is complete and anticipated force levels on anchor and connection systems are known. Typical types of connections are discussed earlier in the technical digest and contractor catalogs provide their working strength limits. Anchor system design alternatives are illustrated in Figure 7. Detailed anchor design depends on geotechnical conditions at the site, such as sediment type and depth to bedrock. These issues are beyond the scope of this report, however.

Sample ice boom designs may be obtained upon request by contacting the Ice Engineering Research Division at the U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, New Hampshire 03755, (603) 646-4378.

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Literature cited

Abdelnour, R. , R.D. Crissman, G. Comfort (1994) Assessment of ice boom technology for application to the Upper Niagara River. In *Proceedings or the IAHR Symposium on Ice, 23–26 August 1994, Trondheim, Norway*, vol 2. p. 734–743.

Leonard, J.W. (1988) *Tension Structures: Behavior and Analysis*. New York: McGraw-Hill.

Michel, B. (1978) *Ice Mechanics*. Quebec: Les Presses de l'Université Laval.

Nezhikhovsky, R.A. (1964) Coefficient of roughness of bottom surfaces of slush ice cover. *Soviet Hydrology: Selected Papers*, no. 2, p.127–150

Perham, R. (1983) Ice sheet retention structures. USA Cold Regions Research and Engineering Laboratory, CRREL Report 83-30.

Tuthill, A. (1995) Structural ice control: Review of existing methods. USA Cold Regions Research and Engineering Laboratory, Special Report 95-18.

U.S. Army Corps of Engineers (1982) Ice Engineering. USA Corps of Engineers, Office of the Chief of Engineers, EM1110-2-1612, 15 Oct. 1982.

U.S. Army Corps of Engineers (1990) HEC-2 water surface profiles. USA Corps of Engineers, Hydrologic Engineering Center, Davis, California.

White, K.D. (1992) Salmon River experimental ice boom 1989–90 and 1990–91 winter seasons. USA Cold Regions Research and Engineering Laboratory, Special Report 92-20.