Theoretical Development of Forces on Cylindrical Booms

By Brian Morse[1]

Abstract: This paper presents generic equations and analyses of a cylindrical pontoon boom's capacity to retain ice. The presentation arises out of actual booms deployed on the St. Lawrence River downstream of Montreal but are valid for any cylindrical ice boom deployment. The boom's retention capacity not only relates to the pontoon's dimensions but also directly relates to the ice sheet's characteristics including thickness and strength. The role of friction and the geometry of the ice at the interface of the pontoon also determine the behavior of the structure and the associated line loads that develop. The analyses of environmental load show that the traditional theory of ice, acting as an aggregate, cannot explain observed values. Instead, this paper suggests that the ice upstream of a boom is a relatively coherent sheet. The internal strength of the ice sheet is compared to the environmental forces and the boom's capacity. These analyses improve understanding of the observations of the St. Lawrence booms made over the last 30 years.

INTRODUCTION

Ice booms are wide flexible hydraulic structures built to provoke the formation of a stable ice cover or to store ice in a certain location. They are a relatively cheap and environmentally friendly way to manage river ice processes. The 1960s saw many booms deployed, particularly on the St. Lawrence River system:

- At the Beauharnois Canal for Hydro Quebec
- At the International Section near Ogdensburg, N.Y.
- At three locations downstream of Montreal (Lavaltrie, Lanoraie, and Lac St. Pierre)
- On Lake Erie for the New York Power Authority

Most traditional booms used simple 36 × 56 cm wooden pontoons. Those at Beauharnois used huge complex composite steel structures (Tuthill 1995).

Following a devastating ice jam in February 1993 on the St. Lawrence River, downstream of Montreal, the Canadian Coast Guard (CCG) hired the writer to find solutions to minimize ice jam risks. After a study of the events leading up to the jam, it was clear that, among other interventions, the river needed new ice booms. At the time, the wooden pontoons were inefficient and required substantial yearly maintenance. The Beauharnois pontoons were prohibitively expensive, whereas simple steel rectangular pontoons used in northern Quebec had failed due to faulty construction.

In conjunction with the staff at the CCG, Fleet Technology Ltd., Kanata, Canada, (Abdelnour et al. 1993), Carter (1994) and the Canadian Hydraulics Centre, Ottawa, (Timco and Cornett 1994), this study evaluated the use of cylindrical booms to replace the wooden pontoons. A prototype section was

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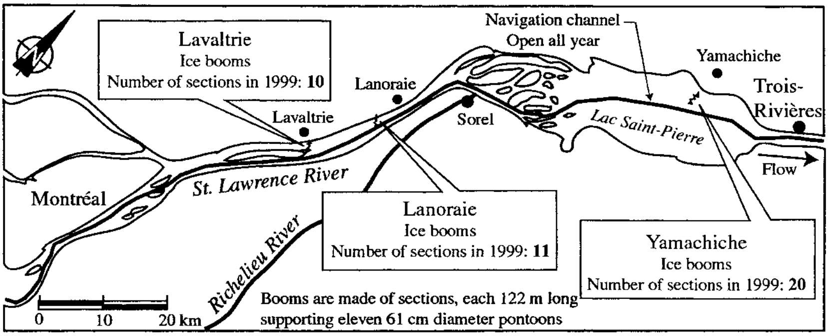

FIG. 1. Location Map of St. Lawrence River Ice Booms Downstream of Montreal

designed and deployed in 1993 and a 2.3-km boom was eventually constructed in 1994 on a wide portion of the St. Lawrence River some 100 km downstream of Montreal known as "Lac St. Pierre" (Fig. 1). The construction drawings were subsequently released and, since that time, Fleet Technology deployed many booms using cylindrical pontoons across Canada (Abdelnour et al. 1999). The wooden pontoons were also replaced with a new design at Lavaltrie and Lanoraie, and the New York Power Authority replaced those on Lake Erie.

The measured load on an ice boom depends on

- Environmental driving forces (including the push by the wind and water on the ice sheet behind the boom)
- Extent to which the cover can thicken by either an accumulation of layered pieces or through thermal thickening or both
- Ice sheet's capacity to internally sustain these forces without failing
- Amount of the load sustained by the boom as compared to that sustained by the river's banks
- Presence of special ice/boom boundary conditions (for example if the ice sheet freezes into the boom)
- Boom's capacity to retain the ice without submerging, thereby releasing hold of the ice

The following sections present a theoretical analysis of a cylindrical boom's capacity to retain ice. Capacity is compared to the ice's internal strength, but first, the environmental driving force required to push the ice over the boom is discussed.

ENVIRONMENTAL DRIVING FORCES

The important environmental forces are the shear stress applied to the ice cover by wind or water current or both. Other less important forces include the downstream weight component of the sheet, hydrodynamic push at the upstream end of the ice sheet, thermal ice expansion, and impact forces. To calculate the shear forces, one knows that they are proportional to a coefficient, the density of the fluid and the square of its velocity

$$F_a = \rho_a C_a U^2 A_e \tag{1}$$

$$F_w = \rho_w C_w V^2 A_e \tag{2}$$

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where F_a = driving force caused by the air on top of the ice sheet; F_w = shear force of water under the ice sheet; ρ_a and ρ_w = mass density of the air (1.3 kg/m^3) and water (1,000 kg/m^3), respectively; C_a = drag coefficient of air (normally between 0.001 and 0.004); C_w = water drag coefficient (normally between 0.003 and 0.03); U = sustained wind speed (m/s) measured at a given height; V = water velocity (m/s); and A_e = effective area (m^2) of ice behind the boom over which the environmental forces act.

Given the large range in the values of the drag coefficients, one should calibrate their selection based on field data. It is then necessary to estimate the effective area A_e of the ice sheet upstream of the boom. Based on experience, Foltyn and Tuthill (1996) suggested that the effective area is $A_e = 3W^2$ to $5W^2$, where W is the river width. Using Caquot's equation, Michel (1966) suggested that $A_e = 3.6W^2$ (this assumes that the ice acts as an aggregate and is contained between parallel banks). Abdelnour et al. (1993) suggested that the maximum load can occur during the consolidation period, at which time the banks do not yet contain the ice upstream of the boom. For this situation, the area behind the boom is $A_e = 0.25W_b^2/\tan(\alpha_i)$, where α_i is the local angle of internal friction, corresponding to half the apex angle at the head of the accumulation and W_b is the length of the boom, which is often only some 80% of W. Based on observed angles by Abdelnour et al. (1995) for the St. Lawrence River in the vicinity of the booms, they suggested a value of α_i = 30°. This corresponds to $A_e = 0.4W_b^2$, which can be translated to about $A_e = 0.3W^2$.

The effective area changes as the season progresses. During the no-confinement conditions, depending on the apex angle, it may start out as $A_e = 0.3W^2$. As the pieces arch across the gap between the boom and the bank, Caquot's theory may apply and the corresponding area may approach $A_e = 3.6W^2$. From there, as the pieces freeze together to form a sheet but have not yet fully frozen into the bank, the effective area may increase further to $A_e = 5W^2$. Over time, ice creep will see more and more of the stresses transferred to the bank so that the effective area may fall to zero ($A_e \approx 0W^2$). Later in the winter, if a melt causes a sudden rise in water levels, the sheet may become unstuck from the bank and the effective area on the boom may increase to $A_e = 10W^2$ or more.

OBSERVED LOADS

The observed loads on the boom are the least of (1) the ice's capacity to deliver the force; (2) boom's capacity to resist the force; and (3) environmental driving forces. As shown, the latter depends on the flow rate, drag coefficients, contributing area, and wind speed and direction. All of these parameters vary in time and space.

For the lower Saint Lawrence booms, based on observations, Carter (1995)

TABLE 1. Forces Contributing to Observed Loads

Location	River width W (m)	Water depth H (m)	Maximum water velocity (m/s)	Wind shear F_a/W (kN/m)	Water shear F_a/W (kN/m)	Total line load f_i (kN/m)
Lavaltrie	1,400	4.5	0.5	7	43	50
Lanoraie	1,400	4.5	0.5	7	43	50
Yamachiche	2,800	3	0.3	15	31	46

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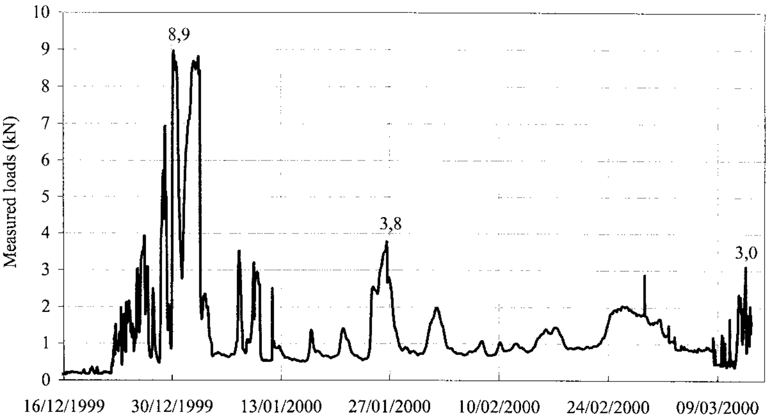

FIG. 2. Measured Loads on Midanchor Cable at Yamachiche

estimated C_a = 0.0034 for wind measured at 10 m and C_w = 0.041 for water measured at 1 m from the ice surface. Although A_e may vary by an order of magnitude, using a value of $3W^2$ allows one to estimate that the maximum environmental line load $f_i = (F_a + F_w)/W$ is about 50 kN/m at each of the three sites (Table 1).

Very localized line loads in excess of 40 kN/m have been inferred from the fact that chains connecting the pontoons to the section cables broke. Peak annual line loads measured on the anchor cables during six winters (1994–2000) at the three lower St. Lawrence boom locations fall between 3 and 14 kN/m (Cornett et al. 1998). Fig. 2 shows the time history of the line load measured on an anchor cable at midlength of the Yamachiche boom during 1999–2000.

The fact that the observed line loads are less than the theoretical maximum might suggest that the drag coefficients or the contributing area have been overestimated. On the other hand, the lower measured loads may be because the cover or the boom are unable to resist these peak environmental loads.

FORCES WITHIN UNCONSOLIDATED COVER

In this section a check is made to see if the ice is strong enough to transmit the total environmental loads to the ice boom structure. If the ice upstream of the boom behaves as an aggregate, Michel (1966) showed that it can transmit a line load f_i (kN/m) no greater than

$$f_i = 0.98H_i^2 \tag{3}$$

where H_i = ice thickness (m) upstream of the boom.

Furthermore, Michel (1966) reported that, when the environmental force comes from water shear under the ice accumulation, the ice can only thicken to a maximum of 40% of the local water depth H (m) behind the boom before becoming unstable. He developed his analysis for a typical ice accumulation when the water has nowhere to go but under the ice. (These conditions are little different from those on the St. Lawrence where the booms are placed across only part of the river.) For Michel's case

$$f_i = 0.16H^2 \tag{4}$$

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On the other hand, if the accumulation of ice is thickened by the wind, Michel (1966) assumed that it can reach the full depth of the river; therefore, substituting $H_i = H$, the maximum driving force is

$$f_i = 0.98H^2 \tag{5}$$

For the St. Lawrence booms at Lavaltrie and Lanoraie (H = 4.5 m), the calculated maximum line load [(4) and (5)] would be 3.2 and 20 kN/m, respectively. Based on 30 years of observation and 5 years of video surveillance of the booms, it is believed that, in the beginning stages of the ice cover's development, pieces of brash ice may stack up behind the boom. However, ice thicknesses of $0.4H$–$0.98H$ were never measured. In fact, the most seen in early winter is a thickness of about 50 cm. The corresponding line load according to (3) would only be 0.25 kN/m. Therefore, it is suggested that Caquot's theory does not describe the ice sheet's behavior behind the lower St. Lawrence boom because observations show that the actual line loads are at least an order of magnitude higher (3–15 kN/m).

Rather, it is thought that initially the ice passes over or through the pontoons or between the boom and the banks until such time that the triangular area behind the boom freezes into a cohesive sheet. Then, under contrary wind conditions, the sheet is arrested and brash ice floes arch the gap between boom and bank that eventually consolidates into shore ice. The sheet behind the boom then goes through a period of strengthening and thickening until such time as it can support the full environmental loads.

INTERNAL RESISTANCE TO FAILURE FROM FLEXURE

Because the aggregate theory doesn't seem to apply, this study examines a consolidated ice sheet's ability to pass on the environmental driving forces. When the ice sheet meets the boom, it is similar to an ice sheet overthrusting itself during the breakup of intact river-ice covers. For such conditions Demuth and Prowse (1990) provided the following equation to describe the vertical force P required to break an ice sheet in bending:

$$P = \left[\frac{\sigma_i e^{\pi/4}}{6\sin\left(\frac{\pi}{4}\right)}\right]\left[\frac{3KH_i^5}{E(1-\nu^2)^3}\right]^{1/4} W \tag{6}$$

where σ_i = flexural strength of the ice (typically 200–800 kPa); e = Neperion number 2.718; K = foundation stiffness of water ($K = g\rho$ = 10 kN/m^3); E = effective strain modulus (often taken as 3 GPa); and ν = Poisson's ratio (often

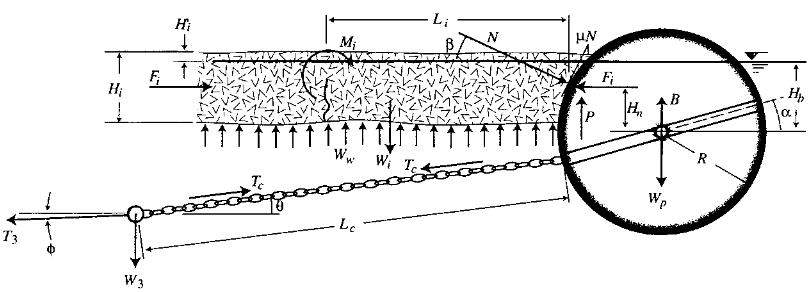

FIG. 3. Force Balance Free-Body Diagram for Pontoon-Cable System

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taken as 0.3). The equation is a valid simplification (within 3%) of a more general equation if the ratio of the axial force F_i to the vertical force $P < 20$, which is normally the case for $H_i < 50$ cm. Referring to Fig. 3, (18), and (19), a force balance at the ice/boom interface reveals that

$$F_i/P = \frac{[\cos\beta + \mu\sin\beta]}{[\sin\beta - \mu\cos\beta]} \tag{7}$$

where β = angle at which the ice contacts the boom's pontoons; and μ = coefficient of friction between the ice and the pontoons (typically 0.05–0.3).

Combining (6), (7), and $f_i = F_i/W$, one gets

$$f_i = \left[\frac{\sigma_i e^{\pi/4}}{6\sin\left(\frac{\pi}{4}\right)}\right]\left[\frac{3KH_i^5}{E(1-\nu^2)^3}\right]^{1/4}\frac{[\cos\beta + \mu\sin\beta]}{[\sin\beta - \mu\cos\beta]} \tag{8}$$

This equation describes a cohesive ice sheet's ultimate resistance to flexural failure near the boom interface.

INTERNAL RESISTANCE OF ICE AGAINST BUCKLING

Ice may also fail in buckling. Two equations could be used to estimate the sheet's ultimate resistance to failure by buckling. Sodhi and Adley (1984) gave the first:

$$f_i = CK\left(\frac{EH_i^3}{12K(1-\nu^2)}\right)^{0.5} \tag{9}$$

where C = dimensionless factor that depends on the structure's width and on the friction coefficient. For wide structures, C varies between 1 and 2, depending on the value of the friction coefficient μ. In this study, $C = 1$. Carter et al. (1998) developed the second buckling equation based on a theoretical development and many observations of ice forces generated on dams in wide reservoirs (f_i in kilo-Newtons per meter and H_i in meters)

$$f_i = 250H_i^{1.5} \tag{10}$$

BOOM'S CAPACITY TO RETAIN ICE

Now that an ice sheet's capacity to transfer environmental loads has been evaluated, whether the boom can hold the cover in place is investigated. In the following presentation, the dimensions, forces, and depths are based on typical values for booms on the lower St. Lawrence River.

In nature, an ice boom acts a a fully flexible 3D structure. The following describes the relationships between the boom's components, based on a 2D analysis. It also attempts to model some of a boom's flexibility and some of its 3D nature:

- Assume that ice pushes perpendicularly on the pontoons knowing full well that, because of the parabolic shape of the section cables, most pontoons are at an angle to the flow.
- Chains connecting the pontoons to the section cables have a very specific length (1.2 m). Chains play an essential role in absorbing point and dynamic loads (Timco and Cornett 1996). Note that, in special circum-

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stances, the chains may become embedded in the ice but this local effect is not taken into account.

- The boom includes numerous section cables that get displaced laterally under nonuniform loading conditions (Morse 2001). As a result, the sag-to-span ratios of the individual sections respond to conform to the loads with the least effort—this effect is not simulated.
- Junction plates, used to connect section and anchor cables, are held afloat by barrels (at a depth of about 1.5 m in the no-load condition). The barrels themselves may retain significant ice and thereby may help the section cable in pulling the junction plates up nearer the surface—this effect is not simulated.
- Anchor cables form catenaries that adjust their lengths and shapes to respond to the applied load—this effect is not accounted for in the analysis.
- Anchors hold the anchor cables at the riverbed—one assumes that they are stable.

To get a feel for the overall 3D nature of the boom, one notes that, typically, the anchor cable lengths are 10 times the local depth. Using an equation for a catenary, under significant loading conditions, the anchor cables pull at the junction plates at an angle of about 3° to the horizontal. Under uniform loading conditions, the section cables are 152 m long and have a span of 122 m and a sag of 41 m. Therefore, the section cables normally pull at the chains, at one end, at an angle of about $\phi = 0.3°$ to the horizontal. At the other end, the pontoon pulls the chain almost perfectly horizontal. In other words, under a no-load condition, the chain between pontoon and section cable hangs nearly vertically. Under significant loading conditions, the chain is nearly horizontal (typically $\theta = 2°$ to 4°). All of these parameters vary for different loading conditions and are determined precisely when the following equations are solved. One element that is not modeled is if the ice sheet itself pushes down on the chains, which would significantly modify the value of θ.

Subject to the above limitations and considering the central pontoon as representative of all the pontoons, the following are force equations of the system when an ice sheet pushes the boom. When solving the equations by trial and error (using a spreadsheet), one enters the typical lower St. Lawrence boom dimensions. One assumes an ice thickness and an ice-metal friction coefficient. One calculates the resulting equilibrium angles and forces (under the assumption that the ice sheet was strong enough to support the calculated loads). To calculate the ultimate bearing line load capacity of the boom, one assumes that the pontoons were fully submerged and that the ice still pushed against the pontoons' upstream face. (Of course, once the boom fails, the ice sheet pops up and begins to go over the boom. Then the boundary conditions change radically and the boom's line load capacity falls dramatically to the value $f_i = \mu 11B/122$ where $11B$ is the buoyancy force of the 11 pontoons and 122 m is the span width.)

For Pontoon Static Equilibrium (Fig. 3)

Moment:

$$(T_c \cos(\theta))(R \sin(\alpha)) - (T_c \sin(\theta))(R \cos(\alpha)) + \mu NR = 0 \tag{11}$$

Horizontal:

$$N \cos(\beta) - T_c \cos(\theta) + \mu N \sin(\beta) = 0 \tag{12}$$

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Vertical:

$$N \sin(\beta) + W_p - B + T_c \sin(\theta) - \mu N \cos(\beta) = 0 \tag{13}$$

For Section Cable Static Equilibrium
Horizontal:

$$T_3 \cos(\alpha_3) - T_c \cos(\theta) = 0 \tag{14}$$

Vertical:

$$T_3 \sin(\alpha_3) - T_c \sin(\theta) + W_3' = 0 \tag{15}$$

From Geometric Relationships
Buoyancy:

$$B = \gamma L_p (R^2(\cos(\delta)\sin(\delta) + \pi - \delta/\pi) \tag{16}$$

where $\delta = \arccos(H_b/R)$.

Load at:

$$\beta = \arcsin[(H_b - 0{,}5H_i - H_i')/R] \tag{17}$$

For Ice Sheet
Horizontal:

$$Fi = N \cos(\beta) + \mu N \sin(\beta) \tag{18}$$

Vertical:

$$P = N \sin(\beta) - \mu N \cos(\beta) \tag{19}$$

For Whole Structure
Horizontal:

$$T_3 \cos(\phi) - N \cos(\beta) + \mu N \sin(\beta) = 0 \tag{20}$$

where (Fig. 3) B = buoyancy of one pontoon, which depends on the degree of submergence H_b [when fully submerged ($H_b = R$), B = 26.2 kN for a 61-cm-diameter, 9.14-m-long pontoon]; F_i = horizontal thrust of the ice sheet (kN) that the central pontoon can support; H_b = submergence (m) of the pontoon (F_i is maximum when $H_b = R$); H_i = upstream ice sheet thickness (typically 0.1–0.6 m); L_p = length of the pontoon (typically 9.14 m); N = normal load applied by the ice sheet on one pontoon (kN); R = pontoon radius (typically 0.305 m); T_c = total tension shared by the two chains holding one pontoon (kN); W_p = weight of one pontoon (typically 12.3 kN for a 61 cm $\times$ 9.14 m pontoon); T_3 = tension created in the section cable to hold one pontoon (kN); W_3' = net weight of the cable and chains in water over the length of a pontoon (typically 1.1 kN/pontoon); γ = unit weight of water (9.8 kN/m^3); μ = coefficient of ice/steel friction (typically 0.05–0.3); α = angle of rotation of the pontoon (varies widely depending on f_i and μ); β = angle of contact between the ice sheet and the pontoon (given by the geometry of the ice/boom interface and the thickness of the ice sheet); δ = angle proportional to the degree of submergence (H_b/R) of the pontoon; ϕ = angle at which the section cable is being pulled with respect to the horizon (typically

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0.3° under full loading conditions); and θ = angle of the chain with respect to the horizon (varies widely depending on f_i).

Note that the analysis is for one pontoon. Therefore $11F_i$ is approximately the load in each anchor cable (kN) and $11F_i/122$ is the line load f_i (kN/m). The load in each chain is $0.5T_c$ (kN). These equations apply for any value of pontoon submergence for any ice cover thickness. However, when the ice cover is thicker than the boom, the angles of the thrust become so close to horizontal that the computed loads become very nonlinear. Under these conditions, the boom may be subject to very large loads but does not have the ability to support them for long (in this case, the effect of the ice sheet thickness on the chain angle may come into play).

RESULTS OF THEORETICAL ANALYSES

Figs. 4–7 present the solutions to the foregoing equations. For the analyses, one assumes that the edge of the ice sheet contacts the boom at half its thickness at an angle tangent to the boom's surface. Also, because in the literature the observed friction coefficient between ice and steel is variable, the solutions are presented for coefficients ranging from 0 to 0.3.

Fig. 4 shows that the friction μ between the ice and the pontoon has a significant effect on the angle θ of the chain when the applied loads are small (when the ice sheet is thin). However, as soon as the loads increase (corresponding to an ice sheet >20 cm), the angle of the chain becomes almost horizontal (<5°) regardless of the value of μ.

Fig. 5 shows the rotation α of the pontoon as a function of μ and H_i. There is a significant difference between no-load (thin ice) and load conditions. This finding supports the discussion about the ice sheet frozen into the boom. In their model studies, Timco and Cornett (1994) observed that the rotation of the pontoons between no-load and load conditions is an important phenomenon in freeing them when they get frozen into the sheet.

Fig. 6 shows the development of the maximum line load that the boom can support as a function of the ice sheet thickness for various values of μ.

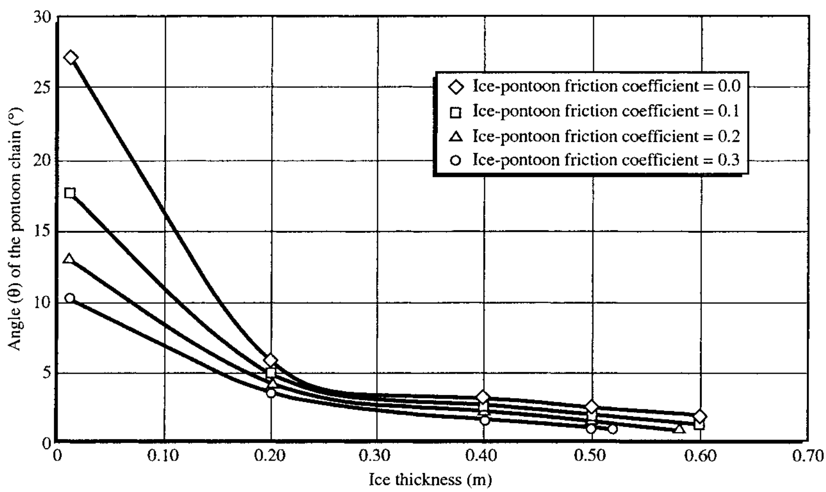

FIG. 4. Chain Angle θ as Function of Ice Thickness

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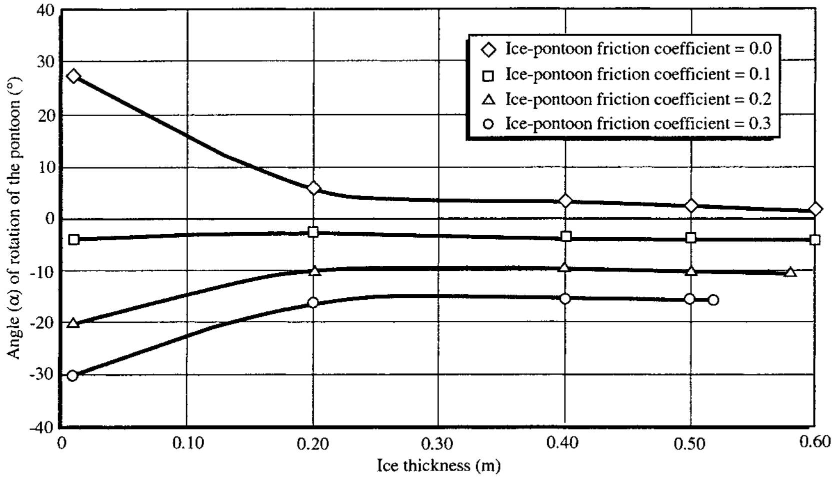

FIG. 5. Pontoon Rotation Angle α as Function of Ice Thickness

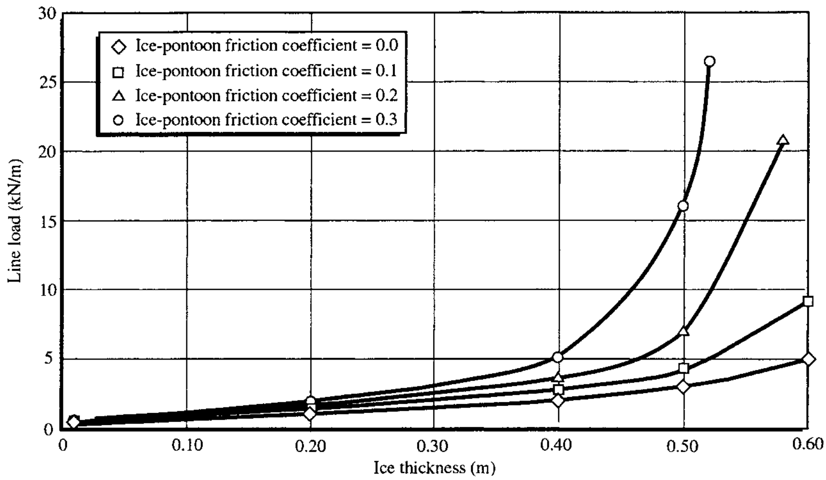

FIG. 6. 61-cm Pontoon Boom's Retention Capacity as Function of Ice Thickness

Any applied load greater than that indicated in the figure would cause the booms to submerge underneath the ice surface, resulting in an ice run:

- Assuming no friction between ice and pontoon, one can see that the line load gradually increases as a function of ice thickness to a maximum of 5 kN/m.
- For μ = 0.1, the 60-cm ice sheet would develop about double the line load of the no-friction case.
- For μ = 0.2, for ice sheets >45 cm, the calculated pontoon's resistance becomes very high (>20 kN/m) and very nonlinear.
- For μ = 0.3, the nonlinearity begins for ice >35 cm.

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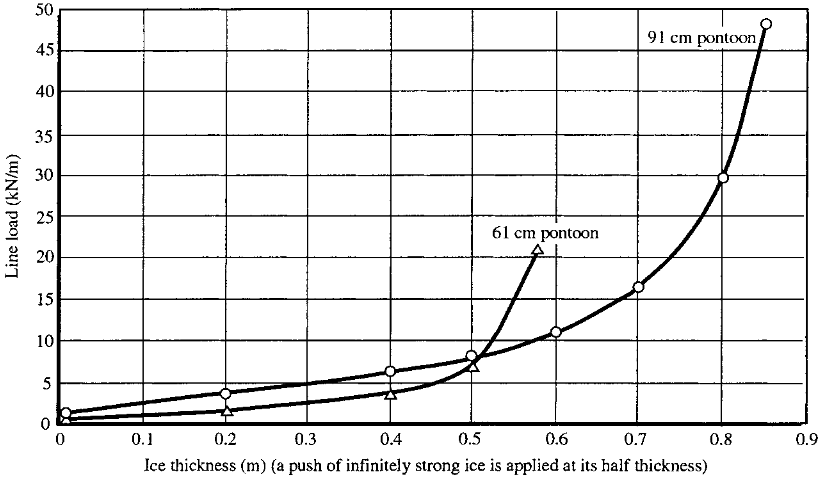

FIG. 7. Boom Retention Capacity for 61- and 91-cm Pontoons (for μ = 0.2)

Because the observed peak line loads on the St. Lawrence vary between 3 and 14 kN/m, the friction coefficient may be inferred to be around 0.1–0.2.

The results also demonstrate the extreme sensitivity of the boom's retention capacity to the geometry of the ice/pontoon interface. In this analysis, one assumes that the ice sheet contacts the pontoon at a precise point at half its thickness. If one assumes the ice sheet to have a vertical face, the theoretical contact would be at a lower point and the computed line load capacity for thin ice sheets would be greater. Also, in some special circumstances, the sheet edge may develop a circular face. In this case the calculated loads would be very high indeed. There is probably no single boundary condition that applies for all cases—the interface geometry probably changes in time and space. Therefore, the boom's retention capacity will also vary in time and space. This is borne out by the numerous load cell records (e.g., Fig. 2). One interesting phenomenon that is often observed is that, when a ship passes near the boom at high speed, its wake is enough to cause instability in boundary conditions and thereby to provoke an ice run.

One can also use (11)–(20) to examine the performance of different sizes of pontoons. Fig. 7 shows the retention capacity of two different sized booms for a friction coefficient of μ = 0.2. Whereas the 61-cm boom can easily retain a line load of 5–15 kN/m, a 91-cm-diameter pontoon can easily retain 3 times as much.

PUTTING IT ALL TOGETHER

The theoretical analyses of the boom's capacity assumed that the ice sheet was strong enough to transfer the environmental load. Fig. 8 demonstrates the link between the boom's capacity and the ice's internal capacity to transfer the load without failure by buckling [(9) or (10) or both], in flexure [(8)], or as deforming as an aggregate [(3)].

The first line of the graph [(10)] shows the applied maximum line loads to wide vertical solid dams based on the work of Carter et al. (1998). It is not surprising therefore that, for most common ice thicknesses, the computed

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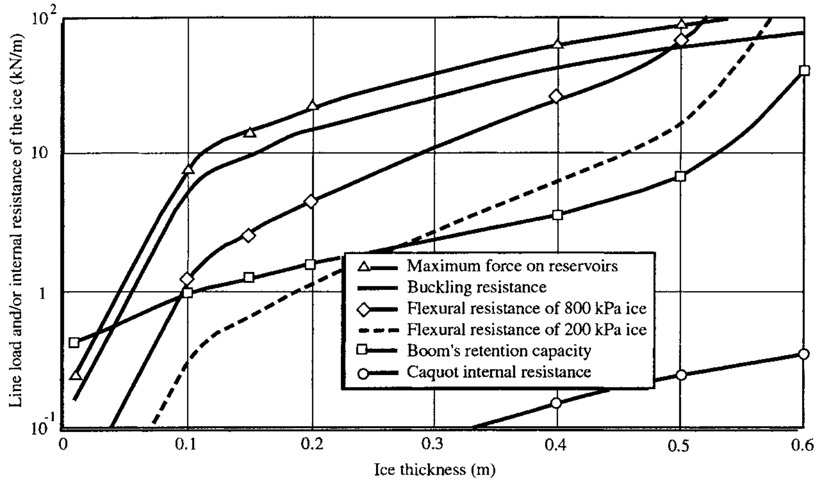

FIG. 8. Boom's Retention Capacity for μ = 0.2 Compared to Ice's Capacity to Push against Boom Subject to Buckling, Failure in Flexure, or Caquot's Aggregate Equation

values are about 15 times greater than the load retained by an ice boom. The next line shows the relationship [(9)] by Sodhi and Adley (1984) for estimating the resistance of a sheet to buckling. For most thicknesses, the resistance to buckling is about 12 times greater than the force on the boom.

For the flexural resistance analysis [(8)], one assumes a maximum flexural resistance of the ice of σ_i = 200 and 800 kPa. For 200-kPa ice, the ice sheet thickness must reach 27 cm before it is strong enough to submerge the boom. If thinner, it will break in flexure and push over the boom (or, in some special circumstances, accumulate upstream of the boom). The critical thickness for 800-kPa ice is only 9 cm. These findings imply that the boom breaks initial (thin) ice sheets until they eventually thicken through shoves and freezing or until there is a contrary wind that reduces the environmental forces to values that the ice sheet can withstand. Many years of observation on the lower St. Lawrence booms confirm this analysis: In some years, the cover has formed in a single night under very cold temperatures and contrary winds; in other years, it may take a few weeks before the cover finally stabilizes. Observations of the Lake Erie boom also confirm that sometimes thin ice (<20 cm) can override the boom while thicker ice will not.

Note that bigger booms induce less flexural breakage (the Lake Erie boom includes 76-cm-diameter pontoons), so not only can they ultimately retain more load, bigger booms help reduce the consolidation period. For example, on the lower St. Lawrence, the change from wooden timbers to steel pontoons has shortened the consolidation period by about 2 weeks.

Once the ice sheet is thick enough, maximum loads will depend exclusively on the environmental driving force and boom's capacity to retain the ice. For example, a 40-cm ice sheet, depending on its internal strength (200–800 kPa), has an internal resistance 2–7 times greater than the boom's power to retain it. So observed loads will depend exclusively on the amount of the water- and wind-induced shear stresses.

The last parameter plotted in Fig. 8 is the line load that an ice accumulation could develop upstream of the boom if that ice sheet behaves as an aggregate. Using Michel's presentation (1966) of Caquot's theory, the calculated line

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loads (0.4 kN/m) are almost 2 orders of magnitude less than observed and theoretically derived values.

FINDINGS

- An ice boom acts as a 3D structure where its shape funnels forces to the center pontoons. The relative geometry of all elements change as a function of the applied loads: pontoons submerge, chains pull section cables to the surface, and anchor cables lift off the ground and become taut. A boom's capacity to retain ice depends on the relative 3D geometry of all these elements.
- A boom's capacity to retain ice is highly dependent on ice thickness. In the early stages of ice growth, the boom's theoretical retention capacity increases quite linearly (especially when one assumes no friction between ice and boom) and is limited by the sheets' internal strength.
- When one assumes a moderate friction coefficient (typically 0.2), the boom's resistance can easily double.
- As the ice sheet thickens significantly and approaches the thickness of the pontoon's diameter, the pontoon's retention capacity increases dramatically. The retention capacity is about 4 times greater than that for thinner ice sheets. The boom may temporarily feel these large loads but, because they are so conditional on specific and unstable boundary conditions, one cannot count on their sustainability for any period of time. In fact, one often observes that either local pushes, ice melting under the sun, or the wake of a passing ship may provoke an ice run. This brings one to the conclusion that a conservative value must be used for design purposes (based on the linear portion of the f_i versus H_i curve) but that the cables must be built to withstand forces of about 4 times that amount.
- A spreadsheet has been developed that calculates the line load as a function of all these parameters as expressed in (11)–(20). For a friction coefficient of $\mu = 0.2$, one calculates the useable line load capacity of 5 and 15 kN/m for a 61- and 91-cm boom, respectively. This confirms the general rule of thumb stating that a boom's resistance is proportional to the net buoyancy of the pontoons. Special boundary conditions involving thick ice may subject the 61- and 91-cm booms, at times, to line loads of 20 and 45 kN/m, respectively. Eqs. (11)–(20) may be used to evaluate any other boom dimensions and other ice/boom interface hypotheses. The equations can also be used to calculate boom submergence as a function of the line load.
- One compares the boom's capacity to retain ice with the ice's internal resistance. Typically the ice's resistance to failure by buckling is 12 times greater than a 61-cm boom retention capacity. However, should the ice fail, the ice/boom boundary conditions force it to fail in flexure. In fact, depending on the ice's strength, a 10–30 cm ice thickness is required before the sheet is strong enough to submerge the 61-cm boom. For stronger and thicker ice (>40 cm), the ice's internal resistance to failure by flexure is about 2–7 times the boom's ability to hold it.
- An analysis of the ice sheet as an aggregate shows that, for measured thicknesses, the maximum line load would only be 0.4 kN/m. This is an order of magnitude less than recorded values of line loads. Obviously,

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one must reject the traditional assumption made in previous ice boom analyses. For the lower St. Lawrence booms, it acts as a cohesive sheet.

- Potential maximum environmental line loads for lower St. Lawrence booms are about 50 kN/m. These values are greater than the boom's capacity and the ice sheet's internal strength. Perhaps that is why the ice sheet only seems to stabilize and freeze into the banks when there is a wind contrary to the water current.

CONCLUSIONS

Cylindrical pontoon ice booms have dramatically outperformed smaller traditional rectangular wooden ones. Model tests show that the cylindrical shape helps break the ice sheet as it tries to go over the boom because of its increased sail height with respect to rectangular booms. However, the main advantage of cylindrical booms is that they have greatly superior buoyancy properties, are easy and cheap to build, and are fairly maintenance free. The last 7 years saw very successful deployment at a number of locations in the United States and Canada.

This paper demonstrates

- The need to use calibrated drag coefficients in calculating the principal environmental forces and to determine the extent of the contributing ice area providing the push behind the boom
- That the ice acts as a sheet, not as an aggregate, as suggested in traditional ice boom analyses
- That, for the ice cylindrical boom interface, the ice never breaks by buckling, only in flexure
- That weak (200-kPa) ice under strong environmental forcing requires a 27-cm ice sheet before it develops sufficient strength to fully mobilize the booms' capacity to retain it [stronger (800-kPa) ice needs a thickness of 9 cm]

Finally, this paper presents a set of equations that can be used to calculate any boom's capacity to retain ice as a function of

- Ice/boom interface shape
- Friction coefficient between the ice and the boom
- Ice sheet thickness
- Level of boom's submergence
- Size of the pontoons
- Overall layout of the boom cables

Typical design ice retention values for 61- and 91-cm-diameter pontoons are 5 and 15 kN/m, respectively. These analyses agree with typical maximum values of the three St. Lawrence 61-cm booms observed over a 7-year period (3–14 kN/m) and those observed for the Lake Erie boom during 1996–1997. The Lake Erie boom is a 76-cm pontoon structure. During the only year when loads were recorded, the range in peak loads for 13 events was 3–15 kN/m. One expects that, if more locations were monitored over more years, observed peak loads would be higher.

It also shows that loads can, for brief periods, reach about 4 times these values. This implies that the cable elements of the structure must withstand

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at least 4 times the desired ice retention capacity value. It is also true that, under very special boundary conditions (for example if the ice/boom interface is a perfect match), even higher line loads are possible. Because these situations cannot be avoided, the structure must be designed to fail in a controlled fashion. One must always avoid any domino effect such as that which occurred at the Lavaltrie boom in 1995. There, a fatigued section cable broke and, because the anchor cables were relatively underdimensioned with respect to the section cables, many boom sections failed one after the other.

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NOTATION

The following symbols are used in this paper:

A_e = effective area of ice behind boom over which environmental forces act;
B = buoyancy force of pontoon (typically 26.2 kN if fully submerged);
C = dimensionless factor relating ice buckling resistance to ice/structure boundary conditions (width and friction);
C_a = drag coefficient of air (normally between 0.001 and 0.004);
C_w = drag coefficient of water (normally between 0.004 and 0.03);
E = effective strain modulus (often taken as 3 GPa);
e = Neperion number 2.718;
F_a = driving force caused by air blowing over ice (kN);
F_i = horizontal thrust of ice sheet (kN) on one pontoon;
F_w = driving force caused by water shear against ice (kN);
f_i = horizontal force per unit width with which ice pushes on boom (kN/m);
H = local depth behind boom (m);
H_b = degree of submergence of pontoon [typically = R when fully submerged (m)];
H_i = ice thickness (typically 0.1–0.6 m);
K = foundation stiffness of water ($=g\rho_w$ = 10 kN/m^3);
L_p = length of pontoon (typically 9.14 m);
N = normal load applied by ice sheet on one pontoon (kN);
R = pontoon radius (typically 0.305 m for St. Lawrence booms);
T_c = total tension in two chains holding one pontoon (kN);
T_3 = tension created in section cable required to hold one pontoon (kN);
U = wind velocity over ice (m/s);
V = water velocities under ice (m/s);
W = river width (m);
W'_3 = net weight of cable and chains in water over length of pontoon (typically 1.1 kN);
W_b = length of river boom, which is often only some 80% of W;
W_p = weight of one pontoon (typically 12.3 kN);
α = angle of rotation of pontoon (depends on value of μ);
α_i = local angle of internal friction corresponding to one-half apex angle at head of ice accumulation;
β = angle at which ice contacts boom's pontoons (depends primarily on ice thickness relative to boom's diameter);
γ = density of water (9.8 kN/m^3);
δ = angle proportional to degree of submergence of pontoon;
θ = angle of chain with respect to horizon;
μ = coefficient of ice/steel friction (typically 0.1–0.3);
ν = Poisson's ratio (often taken as 0.3);
ρ_a = air (1.3 kg/m^3);
ρ_w = mass density of water (1,000 kg/m^3);
σ_i = flexural strength of ice (it can vary widely depending primarily on ice temperature—say, 400 kPa); and
ϕ = angle at which section cable is being pulled with respect to horizon (typically 0.3°).

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