Ice Booms in Rivers; Lessons Learned and the Development of Reliable Solutions

By

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Introduction

Since 1996, four ice booms have been designed and deployed to accelerate the formation of a stable ice cover in small rivers. The objectives were either to improve power production by reducing the ice blockages at the power plant water intake located downstream or to reduce the volume of ice generated through the river system, thus reducing the blockages of the river channel by the accumulation of frazil and slush. Both these events cause headlosses during the winter months, which leads to significant power generation losses. Most of these ice booms performed well and significantly benefited their owners. However, some of these ice booms have experienced problems where solutions had to be developed and implemented. However, in small rivers, and especially those with no control over the water discharge, a boom cannot be designed to control the ice and withstand the loads resulting from any probable environmental conditions. Therefore, problems are expected to develop during its service life and solutions have to be implemented on an ongoing basis.

This paper presents events that have occurred at a small river ice boom installed on the Gatineau River, upstream of the town of Wakefield, and where twice the resistance capacity of an anchor was exceeded.

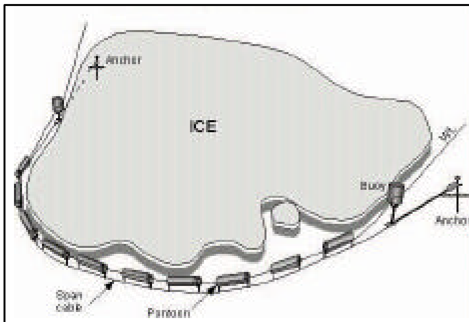

Figure 1: Pictorial view off an ice boom holding an ice cover

Ice Booms Main Characteristics

An ice boom consists of one span cable (as shown in Figure 1) or more span cables. The span cable is attached at each end to a buoy. The buoy is then attached to an anchor cable, which is in turn attached to an anchor in the riverbed.

The span can be in any size, however most booms in operation have between 50 and 300 m wide span. Depending on the span width, a number of pontoons are attached to the cable using chains, at the ends of each pontoon. These chains maintain the cable at a distance below the water surface to avoid interference with the ice. Buoys are used to facilitate the removal and the deployment of the boom.

The ice-retention capacity of the boom is directly related to its buoyancy. When the ice load exceeds the pontoon resistance capacity, it submerges and the ice drifts above the pontoon. This limits the load on the boom, and reduces the probability of ice damage. The pontoon's buoyancy varies with its size and should be selected based on the desired ice resistance capacity of the boom. For further information, reference is made to Abdelnour et al, 1999 and Foltyn et al, 1996.

The Wakefield Ice Boom

The Wakefield ice boom was installed on the Gatineau River by Hydro-Quebec in early 1990's and was re-designed then redeployed in its present form in November of 1999 (see Figure 2). The boom is located about 3 km upstream of Lake Wakefield, located about 50 km North of Hull, Quebec. The boom is between two hydroelectric dams, the Paugan Dam located about 35 km upstream, and the Chelsea Dam located about 20 km downstream. A description of this project is given in Abdelnour et al, 2000.

Figure 2: The accumulation of ice floes upstream of the ice boom 24 hours before the opening of the boom. This photo was taken on March 13, 2000.

The main purpose of the boom is to retain ice and form a stable cover and significantly reduce the amount of ice and slush that drifts downstream and is shoved under the ice cover blocking the water passage under the ice cover, particularly along the stretch downstream of Lake Wakefield. The blockage of the river channel resulted in an increased headloss at the Chelsea Dam from about 0.2 m for open water conditions up to 1.5 m when the ice boom failed in early winter. With the presence of the ice boom, the headloss was about 0.3 m.

Figure 3: Installation of «Stevin» Anchor.

The ice boom also has a second purpose. The boom was to retain the ice during the ice break-up to reduce the potential of ice jams downstream of the boom. A sudden break-up of the ice cover upstream of the Wakefield Lake can be a potential to form ice jams, which can result in a quick rise of the water level causing flooding in the town of Wakefield.

The mean water discharge of the Gatineau River is about 400 m^3/sec and varies approximately between 150 m^3/sec, and 700 m^3/sec. The short-term discharge is somewhat controlled by Hydro-Quebec at the Paugan hydroelectric Dam. During the freeze-up, the discharge is usually below 400 m^3/sec and after a solid ice cover forms, the discharge is raised significantly up to 700 m^3/sec.

The ice boom was designed to resist a maximum ice load of 100 tonnes. When this load is exceeded, the boom's East anchor, designed to resist up to 50 tonnes, breaks through the mud and drifts downstream with the ice. The anchor acts as a fuse to ensure no other components are damaged (see Figure 3).

Two events occurred during the past two years where the east anchor exceeded its retention capacity and resulted in the opening of the boom.

<u>Event March 14, 2000:</u>

During the winter of 1999/2000, the boom operated without exceeding anchor failure load. The ice started to form in late December and started to melt in early March 2000. Toward the end of the ice break-up, on March 14, 2000, the East anchor exceeded its retention capacity and allowed the boom to open, thus releasing the ice that had already accumulated in large quantities upstream of the boom.

The ice boom pontoons should have submerged under water to discharge the ice over the pontoons and relieve the load. The boom retention capacity is below 5 kN/m, which is equivalent to about 70 tonnes. Based on a discussion with a local resident the ice was not released, but accumulated upstream in large quantities.

Since there was no other information available, it was assumed that the ice did not clear the span cable, which resulted in retaining the ice despite the large ice forces on the boom. In fact, based on simple analysis of the ice/pontoon interaction shown in Figure 4, the ice boom can clear the ice up to 0.9 m in thickness (maximum thickness in the area). It was concluded that the problem was probably caused due to the thicker fast ice, which prevented the ice from clearing past the span cable and prevented the ice boom from releasing the ice.

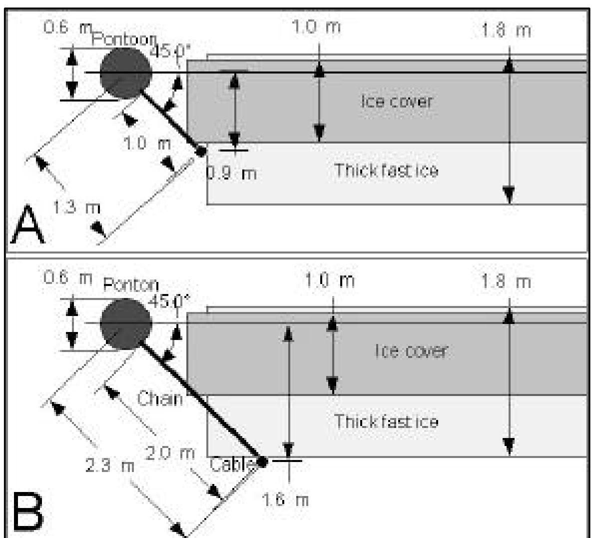

Figure 4: Extension of the chain from 1 to 2 m to prevent the impact of ice on the cable.

When the boom pontoon fails to submerge, the drifting ice from at least 35 km upstream starts to accumulate behind the boom. The combination of an increased discharge and increased ice accumulation area results in increased ice loads on the boom. The hydrostatic pressure applies a load on the boom that is equal to the water level difference between the upstream (a distance of few times the river width) and downstream side of the ice cover. The load was confirmed during tests carried out in the laboratory (Michel et al, 1976). For example, for a loss of 0.7 m, applies a load on the ice boom of about 35 tons (the necessary load to pull the anchor out of the bottom). The headloss was not measured during the event of March 14, 2000, so it is not possible to confirm that the hydrostatic pressure was the main reason for exceeding the resistance capacity of the east anchor.

Impact load of the ice on the boom is another possible reason for exceeding the resistance capacity of the east anchor. Assuming the ice does not clear the span cable, the ice impact force of a large ice floe on the boom can be very significant and depends on the impact scenario. The duration of the impact, the ice floe mass and its velocity are the main factors that can influence the loads. For example, an ice floe; 50 m long, 100 m large and 1.5 m thick ice and moving at a speed of 0.5 m/sec (during the vent the discharge was 330 m^3/sec and the corresponding current velocity was estimated to be 0.5 m/sec) can produce impact energy of:

$$E = \tfrac{1}{2}(mv^2) = 843{,}750 \text{ N-m.} \qquad [1]$$

If the considered impact duration is 2 seconds (1 m of penetration is considered reasonable), the load would be 843,750 N or a total load on the boom of 86 tonnes, 43 tonnes on each of the two anchors. This shows that for thicker ice and faster drifting velocity, the load can increase significantly and can surpass the retention capacity of the boom span cable (87 tonnes) and it is essential to provide a fuse in the system to prevent failure of the boom's main components.

Figure 5: Burying the East Anchor in 4 m depth.

During the summer of 2000, the boom was modified to allow thicker ice to clear the boom by extending the central chains from 1 m to 1.8 m to allow ice up to 1.4 m thick to clear the span cable (see Figure 4).

The anchor was also retrieved and re-buried in a 4 m crater and rocks were placed on top to add to its resistance capacity (Figure 5).

Event of December 12, 2000

During the ice formation period and 12 hours following the start of one of the heaviest snowstorms during the winter of 2000/01, a second event occurred at noon on December 12, 2000. The snowstorm followed a period of cold air temperature and was –12°C during the storm. Small thin ice flows started to form between the boom and 35 Km upstream, starting at the Paugan Dam. Two days earlier, the ice had already started to form behind the boom as shown in Figure 6.

Figure 6: The ice boom as seen from the East side on December 9, 2000.

The east anchor retention capacity was exceeded and the ice combined with wet snow that had accumulated in very large quantities behind the boom and drifted about 300 m downstream and formed a barrier preventing any ice from drifting further downstream (see Figure 7). On December 14, a solid ice cover continued its progress at least 10 km upstream.

Figure 7: The snow behind the boom drifted 300 m to form a barrier and blocked the ice drift. Photos on December 12 and 20, 2000.

The scenario that occurred during this event was not considered during the design. The loads calculated for this scenario (as described later) were about three fold the calculated loads considered for the design. Since the safety factor was less than two fold for the East anchor, the peak load was exceeded.

The event was caused by the ice blockage of the river cross section behind the boom. The ice floes drifting from the Paugan Dam, some 35 km upstream, were covered with a thick layer of snow. The bulk density of this form of ice cannot form a progressing ice cover upstream of the boom for the prevailing current speed and Froude number in the river.

The ice floes were covered with 10 to 20 cm of snow. The snow was probably wet and very heavy (density estimated at 0.97). Ice flows submerged when it reached the leading edge of the cover behind the boom. Some of these floes were retained under the ice behind the boom span cable (see Figure 8). Because the span cable was lowered from 1 m to 1.8 m below the water

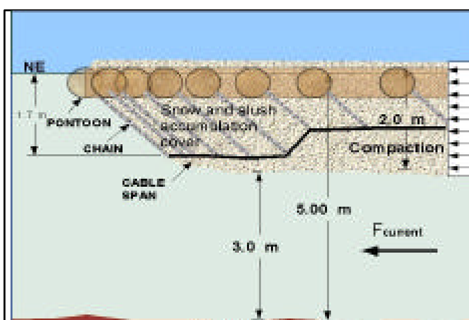

Figure 8: The wet snow retention by the boom.

surface (by extending the chains), it provided a larger space where the ice can be retained thus forming at least 2 m thick layer of wet snow cover behind the boom. The thickness of the accumulation may have exceeded half the total depth of the river depth of about 5 m at this site. In Figure 9, a visualisation of the wet snow movement downstream is presented.

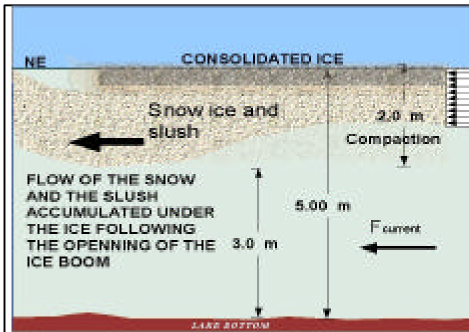

Figure 9: The wet snow flow downstream the boom after the anchor failure

A criterion using a semi empirical expression developed by Ashton, 1974 was used. The criterion provided the stability condition for an ice flow drifting toward a floating ice edge. The expression is given by:

$$V_{us} \; / \; \sqrt{(1-s_i)\ g\ t_i} \; = \; 2 \,/ \sqrt{5-3\left(1-\frac{t_i}{H}\right)^2} \qquad [2]$$

Although this formula neglects the effect of the ice piece size, it represents fairly the scenario at Wakefield ice boom site. The majority of the drifting pancake ice was relatively small. The formula provides for whether or not the ice will submerge or will stop behind the leading edge. The condition depends on whether the velocity upstream of the leading edge V is smaller than V_{us}, (as calculated by equation 2) the ice will progress upstream, and otherwise, it submerges under the ice and drift downstream.

Depth Upstream of Leading Edge	Velocity Upstream of Leading Edge	Density of Ice	Thickness of the Ice Block	Average Flow Velocity	Submersion or Upstream Progression
H	V	si	ti	Vus	
m	m / sec		m	m / sec	
FLOATING ICE					
5	0.6	0.9	1.00	1.129	Progression
5	0.6	0.9	0.80	1.043	Progression
5	0.6	0.9	0.60	0.938	Progression
5	0.6	0.9	0.50	0.874	Progression
5	0.6	0.9	0.25	0.654	Progression
5	0.6	0.9	0.20	0.593	submersion
5	0.6	0.9	0.10	0.430	submersion
WET SNOW					
5	0.6	0.97	1.00	0.618	Progression
5	0.6	0.97	0.80	0.572	submersion
5	0.6	0.97	0.60	0.514	submersion
5	0.6	0.97	0.25	0.358	submersion
5	0.5	0.97	0.25	0.358	submersion
5	0.4	0.97	0.25	0.358	submersion
5	0.3	0.97	0.25	0.358	Progression

Table 1: The stability of drifting floes at the leading edge of the an ice cover (Ashton, 1974)

Considering that the density of the wet snow is quite high and the ice flow thickness is relatively small, for 0.6 m/sec velocity, the floes loaded with wet snow are more likely to submerge under the ice cover than the floating ice (Table 1) even when these floes are 0.25 m thick. Progression of the ice will occur only when the current velocity is reduced to 0.3 m/sec.

This analysis is in agreement with the observations made after the event of the boom dislocation. The forces applied on the boom are presented in Table 2. The design load on the boom is about 20 tonnes, 10 tonnes on each anchor. The resistance load of the east anchor was about 25 tonnes, a safety factor of 2.5.

Input Data								
	Span Width	Apex Angle	Distance From Boom to Apex	Effective Area	Wind Speed	Average Current	Water Drag Force (2)	Wind Drag Force
	(m)	(Deg.)	(m)	(m2)	(km/hr)	(m/s)	(N/m2)	(N/m2)
Normal Ice conditions	140	30	261	18287	100	0.60	7.20	3.29
Low cover roughness	140	30	261	18287	0	1.00	20.00	0.00
High cover roughness	140	30	261	18287	0	1.00	50.00	0.00

Results of the calculations								
	Largeur	Force on the Boom	Line load on the Boom	Load on Boom	No of Anchors	Load on Anchor	Number of Pontoons	Ice Load on Each Pontoon
	(m)	(kN)	(kN/m)	(tonnes)		(tonnes)		(tonnes)
Normal Ice conditions	140	191.9	1.4	20	2	10	13	1.50
Low cover roughness	140	365.7	2.6	37	2	19	13	2.87
High cover roughness	140	914.4	6.5	93	2	47	13	7.17

Table 2: The calculated loads on the boom for a normal condition and for a thick ice accumulation under the ice cover.

The calculated load during the event, where the current velocity significantly increased due to the blockage of the river cross section and due to an increase of the ice roughness was calculated to be between 37 and 93 tonnes, depending on the water drag roughness coefficient used in the calculation (0.02 or 0.05). This is a significant increase where the anchor should fail to ensure no other components of the ice booms are affected.

Design modifications:

Because two events occurred during the past two-years in service, it was decided to increase the resistance of the ice boom east anchor to ensure the load that can be reached is closer to the span cable breaking resistance, which is rated at just over 90 tonnes.

Figure 10: The drilling rig on the shore ice.

Figure 11: Deployment of the chain inside the concrete filled 15 cm casing.

Since the present anchor was not capable to deliver this level of resistance no matter how deep it is deployed, it was decided to install the east anchor in rock. The only rock on the East side of the river was about 200 m downstream. However, since an approval was granted for the site where the east anchor was placed, it was decided to drill for rock at the same location where the east anchor was placed in the original set-up. To evaluate the approximate depth expected to reach the rock, Impulse Radar was used but was not capable of detecting any rock within a close distance.

Preparations were made for drilling a hole up to 15 metres. Because of the availability of a small window where an ice platform was available for drilling, it was decided to reach the rock regardless of the depth. The rock was found after drilling 40 m (see Figures 10 and 11). Two 15 cm diameter holes were drilled where a 7 m long anchor was placed. The anchor was welded to a 50 m long, 32 mm diameter chain all the way to the river bottom. The hole was grouted using cement. Each anchor resistance capacity is 136 tonnes and both anchors will provide a total resistance of 272 tonnes. A fuse was designed and installed at the east side of the boom, between the anchor cable and the span cable. The fuse is installed to ensure the boom would fail at this particular point rather than any other boom components particularly the span cable and the anchors. The fuse is designed to fail at about 80 tonnes load.

<u>Limitations of Ice Booms Deployed in Rivers</u>

The Wakefield ice boom allowed the operators of the hydroelectric power plants along the Gatineau River System and particularly the Chelsea plant to operate without significant loss of power due to ice. Despite the two incidents, the ice boom retained and formed a stable ice cover and prevented any slush or frazil from building up downstream and blocking part of the 16 km long channel between Wakefield and Chelsea Dam.

The headloss during winter 1999/2000, between Wakefield and Chelsea Dam, was less than 0.3 m. This loss in only 0.1 m larger than the headloss experienced for open water condition. The headloss without an ice boom can exceed 1.0 m, which would affect the electricity production of the Chelsea Generating Station. The Dam has a 30 m head and can produce up to 150 MW, for the entire winter period.

The discharge of the Gatineau River is highly affected by the discharge from the Paugan Dam which is located about 35 km upstream of the boom site. Hydro-Quebec operators normally reduce the production during the ice freeze-up (the discharge is usually below 400 m^3/sec) to provide the ice the necessary Froude Number and the current velocity that allows the ice to be retained by the boom and eventually to progress upstream.

Unfortunately it is not always possible to maintain a low water discharge during the ice freeze-up. A higher discharge not only increases the current velocity in the river, but it also decreases the travel time from the Paugan Dam to the boom site. Therefore, at the boom site the drifting ice is thinner and more difficult to retain. This will result in delaying the ice cover formation.

Conclusions

Ice booms, in relatively small rivers, and deployed to block the entire river width can be subjected to conditions not usually seen when deployed in lakes or in very wide rivers, with multiple sections. Several booms were installed and most appear to resist the loads. However, these booms were designed with large safety factors.

The Wakefield ice boom has seen two events in the past two years, where the ice loads are believed to have exceeded the east anchor design load. The anchor had a small safety factor since it was considered a fuse to prevent overloading the other boom components. Although no instrumentation was installed to monitor and record the loads, having a weak link provided information on the type of accumulations that can cause larger than expected loads. Usually, the design loads include large safety factors that overshadow any high loads that the boom may experience.

The first event occurred when thick ice did not clear the boom and allowed the ice to form a large accumulation upstream of the boom. This was believed to be a very highly probable event that may occur during future ice break-ups. The second event was less likely since it required three conditions to occur simultaneously during a short period of time; a snowstorm, air temperature below –10 ^{o}C and a relatively small ice cover upstream to the boom (50 to 100 m long). The probability of occurrence of these three events is believed to be relatively small.

The solution developed to reduce the risk of breaking the anchor during ice break-ups somewhat increased the probability of occurrence of the second event. The longer chains provided a larger space for storing a greater volume of ice.

It is believed that despite the longer chains, and the presence of a new fuse, with significantly higher resistance capacity, the risk of the boom opening during future winter seasons is quite low, but still possible to occur.

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