CGU HS Committee on River Ice Processes and the Environment
12th Workshop on the Hydraulics of Ice Covered Rivers
Edmonton, AB, June 19-20, 2003

Ice Control Structures using steel nets

Brian Morse[1], Jean Francoeur[1], Hugues Delcourt[1] and Michel Leclerc[2]
[1]Université Laval et [2]Institut national de recherche scientifique
Québec, Qc
Brian.Morse@gci.ulaval.ca, jean.francoeur@menv.gouv.qc.ca,
huguesdelcourt@ibelgique.com, michel_leclerc@inrs-eau.uquebec.ca

Ice control structures (ICS) come in many shapes and sizes. Their deployment over the last twenty years has almost always provided some degree of protection to local residents, although, in most of the seven cases we studied, their performance was less than optimal. Based at work done at the Cold Regions Research and Engineering Laboratory, Lever et al. (1997 & 1999) have explained their functionality and have optimized their design. The CRREL ICS consists primarily of a series of piers forming a comb-like structure that arrests ice jams. However, recent physical model studies at Laval University using polyethylene ice suggest that ICS's using either (1) widely-spaced piers supporting steel nets or (2) cylindrical steel ice booms supporting steel nets could represent more effective and economical structures for some applications. This paper presents these ICS-steel net structures, their performance under laboratory conditions and discusses potential implementation opportunities and problems.

1. Introduction

There are many types of structural interventions to control river ice: At one extreme, dams are built to reduce currents, form a stable ice cover and store ice during breakup (e.g. Sartigan dam on the Chaudière River near St. Georges, Qc.). Much lighter structures are ice booms consisting of cables and pontoons. They are designed to initiate the formation of an ice cover and to keep it stable during mid-winter thaws (eg. booms on the St. Lawrence River at Yamachiche, Qc. built to control ice jams in Lac St. Pierre).

Normally, however, the term 'ice control structure (ICS)' is reserved for a specific structural intervention that is not as flimsy as booms nor as massive as dams. Rather, it represents a comb-like structure (often built on top of a weir) that is designed to initiate the formation of an ice jam. These structures usually consist of reinforced concrete piers usually spaced a few meters apart that are designed to arrest large pieces of ice that are found at the frontal edge of a breakup event. A weir is normally included as a part of the structure to act as a foundation for the piers and, more importantly, to raise the water levels upstream in order to encourage the formation of a stable cover that can help arrest the breakup event. A Canadian example of a small ICS is the one built on the Duberger River in Québec (figure 1).

Figure 1. Duberger classical ICS

The role of an ICS is to provoke an ice jam at a selected location normally upstream of some community that is currently being flooded by ice jams. An ICS does not prevent a jam; rather, it forces the jam to occur in an upstream location where presumably, there will be little impact. ICSs have been around now for over 20 years. Over that time, we have increased our understanding of their design particularly through the work of Lever et al. (1997, 1999, and 2000) at the Cold Regions Research and Engineering Laboratory. They demonstrated that in addition to arresting ice, the structure should be built in a way to ensure that water can flow freely. In this way, the efficiency of the structure is maintained in controlling the rise of water levels upstream. Lever et al. provided some guidelines as to the geometry of the structure, the applied forces and the costs.

2. Case study

We wanted to apply this technology to a local river (the Montmorency that passes through 3 municipalities bordering Quebec City, QC) whose inhabitants are regularly and severely threatened by sudden and intense ice jams (Leclerc et al. 2001). However, before doing so, we wanted to ensure that the concept would work for this application because the slope on the Montmorency is fairly high (0.4 to 1% depending on the specific location). We therefore built a physical model representing channel reaches and flow rates typical of the Montmorency.

3. Laboratory setup

The physical model, about 9 m long, was built at an undistorted scale of 40:1 representing a river reach about 60 m wide (figure 2). For the first tests, the study reach was rectangular in section to which was incorporated a floodplain during some tests. The channel was then redesigned into a trapezoidal shape having side slopes of 1:1. We tested ICS's for slopes of 0.2, 0.7 and 1.2%. Breakup events were modeled using a fairly well graded mixture of polyethylene model 'ice'. Water levels were controlled downstream by a weir and the flow rate was measured at three locations: total incoming, that going past the structure and that going over the flood plain using triangular notched weirs.

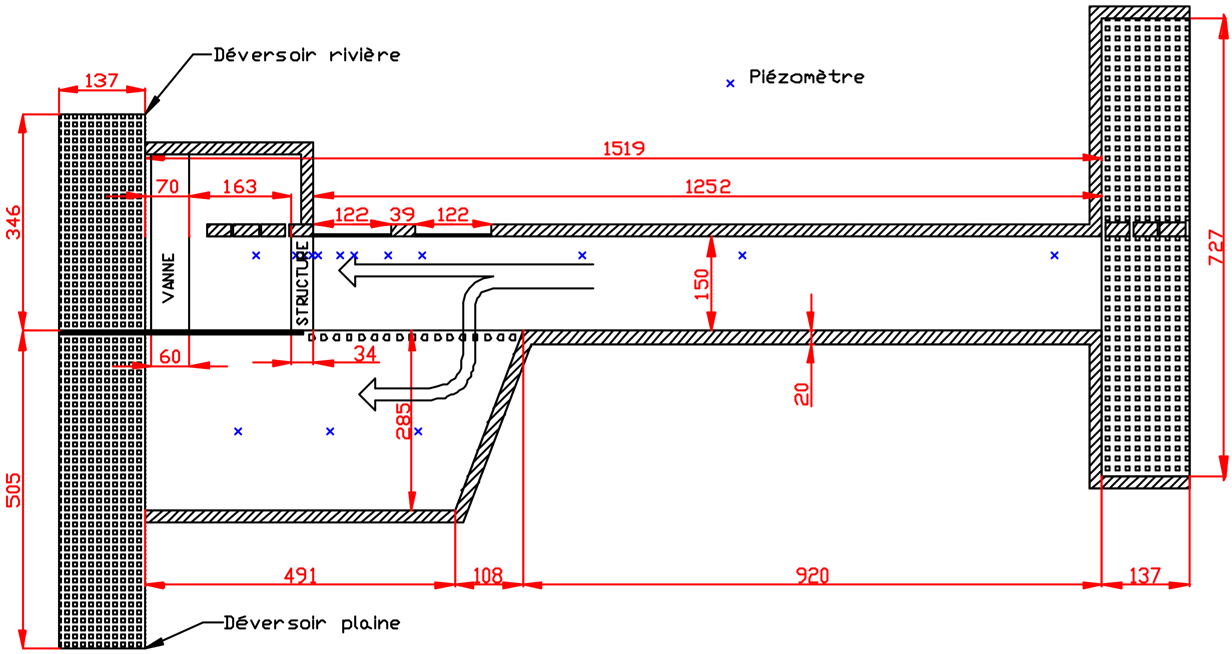

Figure 2. Laboratory flume layout for tests on ICSs

At first, we tested the traditional comb-like design of piers about 1.2 m in diameter spaced about 4 m apart. We had very little success in arresting the onslaught of ice. Floes simply went through in between the piers. To have any luck at all, we required an extremely small spacing of the piers. The structure ended up looking ridiculous. We are unsure as to why this ICS in our experiments performed so much more poorly than those tested with real model ice at CRREL and we did not have the time to address this point. However, one thing was clear: there was no way that we were going anywhere with the comb-like design. We therefore modified the structure.

We wanted a structure that was reliable: One that would always arrest the ice during breakup regardless of the ice properties and the flow rate. We did not want to install a structure upstream of a community only to give them a false sense of security and/or a sense of dread that the structure may (or may not) hold the ice for some time (but for how long was unsure). We therefore investigated the use of a suspended net to catch the ice floes and initiate a jam (Francoeur et al. 2001).

4. Boom-net ICS and Pier-net ICS

In fact we tested two variations one this theme: (1) the net was unrolled from one channel bank to the other and supported by pontoons – the idea being that the pontoons would keep the net afloat and that ice coming down river would wedge itself under the pontoons into the net forcing the toe of the jam to form there. We call this variant the ***boom-net ICS***. (2) In the second variant the ***pier-net ICS***, the net was directly suspended between piers spaced some 15 to 20 m apart. Under this second variation, pontoons are not required because the piers can be built high enough to hold the net up sufficiently off the bottom in order for the breakup ice to get wedged in during an event.

The advantage of the (1) boom-net ICS is that it completely spans the river without any in-stream intervention. It is therefore less intrusive than a traditional ICS and may offer some simplicity from a construction point of view. The boom-net ICS may be quite suitable for locations where the water depth is sufficient to float the pontoons at all times and specifically during low flow conditions. However, should local depths be too small, the pontoons and the net may get frozen into the river ice. In this case, they may never rise up with the swelling waters that come at breakup and therefore the structure would offer absolutely no protection. Of course, in the lab figure 3) we could not test this aspect because we did not have the ability to freeze the net in place. We do however caution against use of the boom-net ICS where water depth may be a problem.

Figure 3. Boom-net ÌCS

Secondly, the boom-net ICS can only be deployed on relatively narrow rivers because otherwise the forces in the anchors and cables become too great to make the structure worth while. However, with these limitations in mind, there may be some applications where the boom-net ICS would be ideal because during laboratory tests, it performed very well. Note that Tuthill (1995) discusses a frazil net structure for ice control. However, it was deployed in order to act as a self-made weir during winter time through clogging in order to raise water levels and therefore form an ice cover upstream. A boom-net like breakup structure was also once deployed on a tributary to the Chaudière River in the late 1960's for one season only (because it failed). Although accounts vary as to the cause of its failure, the design of the boom anchors and cables seemed to have been an important issue. The only other deployment of this type of structure known to the authors is a sinkable boom used in Japan to protect a harbor from frazil ice intrusion. Other than that, a modified version of the type of design presented here may soon be deployed on another small tributary of the Chaudière called “rivière Chassé” (about 15 to 20 m wide) after an ice jam severely flooded a local factory in circa 1999. Once this is constructed, we may have further information on the performance of these types of structures.

The advantage of the (2) pier-net ICS is that it can be used on rivers of any width using nets unencumbered by pontoons supported by a visually and environmentally very light structure (figures 4 & 5).

Figure 4. Pier-net ICS

Although at the application level, there may still be some performance issues related to the net partially freezing into the river's ice sheet under low flow conditions, we believe that these may be more manageable since the designer has the option of selecting a suitable span and length/span ratio to ensure that the net holds up. From laboratory tests, the structure seemed very robust and dependable under a wide variety of channel slopes, channel shapes and discharge conditions. In our view, the structure is very versatile and offers the designer a number of options. We have recommended its use to protect the Montmorency communities from flooding.

Figure 5. Pier-net ICS

The three municipalities have favorably accepted our report (Morse et al. 2002) and plans are underway to find the budget to proceed with the project. Until such time as there is a field trial, we can only report our laboratory observations and try to foresee problems (and solutions) that may occur during implementation.

5. Results of model studies

The following gives an overview of the laboratory experiments for both type of net ICSs tested. We performed model tests in a flume having a Manning value that varied from one test to the next depending on discharge and slope (Delcourt, 2002). Since the bottom was quite rough, its average value was about 0,025. For the rectangular channel, the sides were artificially roughened and for the trapezoidal channel, the sides were composed of the same rough (semi-exposed gravel) material used for the bed.

Depending on the test the number of piers that were used varied: Many were used to model a classical ICS; two piers were used to support the boom-net ICS and four were used to support the pier-net ICS. We had a maximum of three that were fully instrumented to calculate force and moments in both the longitudinal and lateral directions. We had redundancy in the amount of strain gauges used to ensure a better quality control.

Each test was carried using a methodology similar to that used at CRREL during their studies: At the beginning of the test, there was a low discharge and model ice was held back a couple of meters upstream of the ICS. The model ice was then released. It flow downstream until it reach the ICS and then gradually started to form a jam. Watching our water levels and forces on the piers, we waited until equilibrium conditions were more or less achieved. We then stepped up the flow rate to a new value and once again waited until equilibrium conditions prevailed. We continued this process until the structure ultimately failed.

In general, the ice would come into the structure and get wedged between the floor of the flume and the top of the net. Although initially, some pieces would go over or through the net, the jam formed almost immediately. As we increased the discharge, tension in the net increased as did the jam thickness upstream. At first, the jam would be anchored for about a meter upstream (40 m prototype) but as the flow rate increased, the jam floated more and more as water levels rose. At the same time water poured through the jam and the net.

5.1 Mesh size

When a large mesh was used (3.6 m high by 6.8 m long prototype), this porous flow could cause piping that would eventually led to failure. However, for most of the tests, the net mesh was sufficiently refined enough to prevent ice from escaping through the net. In fact one interesting result of the tests was that there seemed to be an optimal net mesh size: if the net size was too big, eventually ice would pop through leading to massive failure while if the net mesh was too small (1.8 x 1.7 m), the net was so efficient that no ice got through and therefore, the jam could not consolidate as well as it otherwise did when some minor amount of ice went through our standard mesh size (3.6 x 3.4 m) that never allowed massive failure due to piping.

5.2 Presence of a flood plain

For those tests performed in the presence of a flood plain, once the ice jam height exceeded bank-full depth (4 m prototype), more and more flow would leave the channel and escape over the flood plain. For our set-up, in general, equilibrium jam levels were 11% lower when there was a flood plain compared to simple channel results.

5.3 Mode of failure

Of course, ultimately the ICS would always fail. During the first phase of failure, more and more flow would overtop the net. Ice would build up against the net to levels well above its height. Eventually, the net would sink somewhat under the weight of the ice and water (figure 6). This effect was the greatest at the center of the spans to which point more and more flow would be funneled. The concentrated flow would then lead to a general failure and the whole jam would empty over the net at center span (figure 7).

Fig. 6. Pier-net ICS near failure

Figure 7. Boom-net ICS at failure (ice run over structure)

From a hydraulic performance point of view, the smaller the cable length to span ratio, the better the net's performance. To ensure that the net is sufficiently high, a shorter net would allow larger pier spacing (in the case of the pier-net ICS) or, for an equivalent spacing, a shorter net can withhold more important ice jams. Also, just downstream of the net, the use of smaller length to span ratios means that the porous water flow exits in a less severe longitudinal angle and therefore attacks the river banks that much less. However, as in the design of any cable, there is always a length to span ratio that is most economical since the shorter the cable, the greater the internal stresses in both the cables and lateral anchors.

5.4 Importance of span and length of net

For a given length to span ratio, by carefully choosing the height at which the net is attached to the piers, one can predict the flow rate at which the jam will overtop the structure. For example, according to our tests in the rectangular and trapezoidal channel without a floodplain, a net spanning 14.8 m between piers having a 3.6 x 3.4 m mesh held 2 m above the channel bottom will hold back 160 m^3/s (2.7 m^2/s) of water before being overtopped while a 8 m high net will hold back 360 m^3/s (6.0 m^2/s).

5.5 Determination of net height and design discharge

To know the correct design height, the design flow rate must be chosen with care on the basis of its probability, the level of protection required for to the community downstream and by evaluating the consequences of the structure's failure. In the case of the Montmorency River, Doyon (2001) examined historical known ice jams (about 23 over 57 years) and their locations. We noted that while the spring freshet could reach 300 to 600 m^3/s, no jam was ever reported for values greater than 200 m^3/s. We therefore made the hypothesis that should the flow exceed 200 m^3/s all the ice would be completely flushed through the system without forming a harmful ice jam to any community along the way. We believe that for flow rates greater than 200 m^3/s, there would be a sufficient driving force to carry the ice all the down to the end of the river where it does no harm. We therefore assumed that jams could only occur at $Q < 200$ m^3/s. We therefore recommended a design net height of 4 m for our application (figure 8).

Figure 8. Artist's view of possible ICS on the Montmorency River

One final note: Before making our recommendation, we considered what would happen if the structure did not perform as well as anticipated. After some discussions and reflection, we came to the conclusion that in no way would it make matters worse. First, in all our tests, the pier-net ICS performed in a predictable fashion. Second, even if it did not live up to the laboratory tests, it would certainly arrest the ice for some time before overtopping. This time would make all the difference in the world since it would provide time for the community to evacuate downstream. In 1995, elderly people were awoken at 4 a.m. with ice cold water flooding their bed. It was only because their cries were heard by their neighbours (standing on their roof) that they were able to be rescued. Therefore, time to intervene is one of the important benefits of an ICS even if it does not succeed in holding the ice back and thereby preventing a jam at a critical downstream location.

Conclusions

The use of boom-net or pier-net ICSs may present an interesting alternative to the classic comb-like ICS structure found in the literature. Although the use of a net may present some annual hassles during deployment and retrieval, there is the advantage that the net can be removed. This may be an important consideration during the summer months during the recreational seasons. For the net to work, it must not be frozen into the river bed. Otherwise drift ice during breakup will not properly get wedged into it. However, if this operational difficulty is overcome, the laboratory tests show that both structures are very efficient and can retain significant ice jams even in reaches having slopes in excess of 1%. We note that the construction of a weir is not normally required though, in some applications, it may be used to increase local depths and thereby prevent the net from freezing into the river bed. We also note that a flood plain is not required for the structure to work well because the net allows porous flow through it. However, the presence of a floodplain can greatly increase (in the lab tests – doubled) the structure's efficiency. We believe that the pier-net ICS may be more appropriate for rivers in excess of 25 m and that the boom-net ICS may be advantageous when there is sufficient local river depth to ensure that the pontoons do not freeze into the river bed. The capital cost of the pier-net ICS for a 60-m wide river to withhold ice jams up to flow rates of 200 m^3/s has been evaluated at about $1.2M by a local engineering firm and this includes a 20% contingency fee. The structure therefore offers an economical alternative to protect communities at risk.

References

Delcourt, H. 2001. *Infrastructures à filets pour le contrôle des embâcles. Application au cas de la rivière Montmorency.* Mémoire présenté à la Faculté des études supérieures de l'Université Laval pour l'obtention du grade de maître ès sciences (M.Sc.)

Doyon, B. 2001. *Débâcles et embâcles de la rivière Montmorency : examen rétrospectif.* Rapport interne présenté à Brian Morse, Université Laval.

Francoeur, J., Morse, B., Leclerc, M. (2001). *Trois solutions structurales novatrices pour le contrôle des embâcles.* Proceedings of the CSCE Annual Conference, Victoria. BC, May 31- June 2.

Francoeur, J. 2002. *Développement d'une estacade-filet pour la protection contre les embâcles – application à la rivière Montmorency*. Mémoire présenté à la Faculté des études supérieures de l'Université Laval pour l'obtention du grade de maître ès sciences (M.Sc.)

Leclerc, M., Morse, B., Francoeur, J., Heniche, M., Boudreau, P., Secretan, Y. 2001. *Analyse de risques d'inondations par embâcles de la rivière Montmorency et identification de solutions techniques innovatrices*. Rapport conjoint INRS-eau R577 et Université Laval – Département de Génie Civil.

Lever, J.H et Gooch, G.E. 1999. *Low-Cost Ice Control Structures for Small Rivers*. 10th International Conference on Cold Regions Engineering, Lincoln, NH, 631-640. Ed J. Zuefelt.

Lever, J.H et Gooch, G.E. 1999. *Model and field performance of a sloped block ice control structure*. Ice in Surface Waters, Shen (ed.) © 1999 Balkema, Rotterdam, 647-652.

Lever, J.H., Gooch, G. et Daly S. 2000. *Cazenovia Creek Ice-Control Structure*. ERDC/CRREL TR-00-14, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Lever, J.H., Gooch, G., Tuthill, A., Clarck, C. 1997. *Low-cost Ice-control Structure*. Journal of cold regions Engineering, 198-220.

Morse B., M. Leclerc, H. Delcourt, J. Francoeur, P. Boudreau (2002). *Développement de solutions techniques innovatrices pour le contrôle des embâcles de la rivière Montmorency – Rapport de la Phase II – Faisabilité. Rapport présenté au Comité de suivi*. Rapport conjoint enregistré à l'Université Laval - Département de Génie civil GCT-2002-03et à l'INRS-Eau-Terre-Environnement R577b. Janvier. 178 pages.

Tuthill, A.M. 1995. *Structural Ice Control. Review of existing methods.* CRREL, Special report 95-18. Cold Regions Research and Engineering Laboratory, Hanover, NH.