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Hydraulic Interaction Between Ice And Bridges

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The interaction between ice and bridges can result in damage to infrastructure, riparian property, and the environment. River ice runs and jams may damage or destroy bridges resulting in direct costs of bridge replacement or repair, and indirect socio-economic costs associated with a disruption of transportation. Bridge piers and abutments may obstruct ice passage thereby increasing the frequency and severity of local ice-jam occurrence to the detriment of local ecosystems, riparian property, and nearby communities. Insufficient design guidelines and anticipated changes in ice regimes due to climatic change were the motives for considering the interaction of ice and bridges and their effect on the environment, as presented herein. A methodology to assess quantitatively a bridge's capacity to cause ice jams is presented.

1.0 Introduction

The interaction of ice and bridges can result in damage or destruction of the bridge structure, and can alter ice movement such that ice impacts riparian property and the environment. Therefore, it is important to understand the factors governing the interaction between bridges and ice in order to appropriately design bridges on rivers with seasonal ice covers.

River ice can have many effects on bridge structures (RTAC, 1981). Horizontal and vertical ice forces can damage piers, while local scour can undermine a pier and cause it to fail. Broken ice accumulations striking the bridge superstructure (e.g. shown in Fig. 1) can vibrate slender structural elements, and buckle, lift and dislodge a bridge's superstructure. To avoid ice-related damage to a bridge, the height of the waterway opening required for ice passage and the effects of surges on stage and scour depths need to be considered during design.

In New Brunswick, it has been estimated that over 500 bridges have been damaged or destroyed by floods (Kindervater and Walker, 2000). Several ice-related flood events (e.g. March 20-April 5, 1846; March 17-23, 1902; March 16-25, 1909; and February 2-6, 1970) resulted in five or more bridges being damaged or destroyed. The February 2 to 6, 1970 flood was the most devastating with 32 major bridges destroyed by the mid-winter breakup and ice run and over 75 bridge structures damaged.

The obstruction to ice passage by piers and abutments may enhance the frequency and severity of local ice-jam occurrence, to the detriment of the local ecosystem or nearby communities. There is little guidance in the literature on how to account for ice-jam impacts in bridge design, beyond determining clearance requirements via empirical stage-frequency analyses in the rare instances where historical stage data are available.

Climatic considerations underscore the need for advancing beyond empiricism and developing rational design criteria. Anthropogenic climatic change may significantly alter river ice processes in the future. To anticipate the effects of climatic changes on bridge design, it is necessary to thoroughly understand factors that may affect the interaction between a bridge and ice over the design life of the bridge structure, normally 50 to 100 years. Therefore, it is important to take into account any climatic changes that may occur within this time frame.

The lack of information on the interaction of ice jams and bridges was the primary reason for initiating the present study, which is jointly carried out by the National Water Research Institute, the New Brunswick Department of Transportation, and the New Brunswick Department of the Environment and Local Government. It focuses on breakup ice jams and ice runs, which generally are associated with higher river flows, greater velocities, and thicker and stronger ice than occur during freeze-up.

The interaction between bridges and river ice, particularly at breakup, is examined herein. Following an introduction, a methodology to assess quantitatively a bridge structure's capacity to restrain ice movement and cause ice jams is briefly described. A criterion is developed for ice passage by relating the potential ice driving force to the sum of the maximum ice loads that can be applied on each pier. The proposed approach is illustrated for the site of the international bridge over the Saint John River between Clair, New Brunswick, and Fort Kent, Maine, and for the Upper Blackville bridge over the Southwest Miramichi River, New Brunswick. The application of existing theories and models to determine design stages and scour potential with respect to ice-related processes is then discussed followed by initial study findings and concluding remarks.

Fig. 1. Ice striking the bottom chords of the Quarryville Bridge on the Southwest Miramichi River, New Brunswick, April 15, 1994.

2.0 Theory and Methodology

2.1 Interaction of Ice and Bridges

Most of the work done so far on this topic pertains to loads that can be applied by the ice on the bridge piers, and the state of the art is sufficiently advanced to enable inclusion of specific design formulae in the Canadian bridge code (CSA, 1988). For instance, Montgomery et al. (1984) identified two categories of ice loading: static loads generated by the thermal expansion or contraction of an ice cover and the underlying water, and dynamic ice loads that develop when moving ice strikes a pier during ice breakup and movement. They stated that the geometry of the pier, the strength of the ice, and the size of the floe influence the dynamic forces created by ice striking a pier. Observed types of ice failure included crushing, whereby the ice fails by local crushing across the width of the pier before being cleared around the pier; bending, whereby the ice rides up an inclined pier and fails as flexural cracks form; splitting, whereby small ice floes split along stress cracks formed from the impact with the pier; impact failure, whereby small ice floes are halted against the pier before failing by bending, crushing or splitting; and buckling, whereby compressive forces cause large floes to fail by buckling in front of a wide pier. Both ice thickness and ice quality are important factors in calculating crushing strength.

Montgomery et al. (1984) also discussed forces caused by ice jams. A breakup ice jam is considered a cohesionless accumulation of ice blocks that transfer ice loads to a bridge pier as a granular mass lightly confined by buoyancy. For a wide pier relative to accumulation thickness, the pressure imposed on the pier could be determined by multiplying the confining normal stress by the passive pressure coefficient, which depends upon the internal friction angle of the ice accumulation.

Ice jams can also damage the bridge when the river stage is high enough to bring the ice rubble in contact with the superstructure. The latter is then broken, dislodged, and carried away by the ice and water. Notable examples of superstructure damage are the Honeymoon bridge over the Niagara River (1936) and the Perth-Andover bridge over the Saint John River (1987). An indirect effect of ice jamming is the scour around bridge piers that can result from high flow velocities generated by surges that accompany ice-jam releases. A number of bridges are known to have been damaged or destroyed as a result of ice-jam related scour.

A question that often arises in bridge design is whether a bridge can instigate ice jams by virtue of the obstruction created by piers and abutments. For instance, Kawai et al. (1997) stated that during breakup, the interaction between the bridge piers and the sheet ice cover might lead to ice jamming. This is an important element of the design because the creation of a new ice-jamming site will have repercussions to nearby communities and to local ecosystems. There is very limited, and largely anecdotal, information on this subject, which has thus been one of the focal points of the present study (see also next section).

Ice-related issues were an important consideration in the design of the Confederation Bridge, which crosses the Northumberland Strait linking the Provinces of New Brunswick and Prince Edward Island. As a part of the environmental studies, a comprehensive modelling program was undertaken to determine the impact of the bridge on the ice regime (Brown, 1997). This work focused on the potential for localized ice jamming against the bridge and potential for ice breakup in the Northumberland Strait to be delayed. Brown (1997) stated that an ice jam could develop from a single ice floe that lodges against adjacent piers or by an accumulation of floes that arch between adjacent piers. The likelihood of the first type of ice jam depends upon the size distribution of ice floes and the spacing between piers. The frequency of ice arching leading to ice jamming is more difficult to determine and depends in part upon the mean ice floe size and the ice concentration.

2.2 Potential of Bridge Piers to Initiate Ice Jams

The first step in assessing whether a bridge can cause ice jamming is to understand how breakup ice jams form under natural conditions. The relevant processes have been described by Beltaos (1997), as follows: rising flows and water levels due to snowmelt, rainfall, or water released from storage, augment the forces applied on the underside of the ice cover. At first, hinge cracks form along and near the riverbanks (excepting very small streams where there is a single, central crack), allowing the main portion of the ice cover to rise with the water level. The action of gravity and the under-ice flow subjects the ice cover to bending moments and flexure in the horizontal plane, which eventually leads to transverse cracking and formation of a series of separate ice sheets. The meandering planform of the river constrains the ice cover until the water surface width increases to a level that enables some ice sheets to move. The first sustained movement of the ice at any particular site is called the onset or initiation of breakup at that site. When ice sheets are set in motion, they impact other ice sheets and/or the channel boundaries and break down into small fragments that are transported downstream. If the broken-ice blocks encounter stationary sheet ice or a channel feature that impedes ice movement, then an ice jam is initiated.

A set of bridge piers placed across a river can locally retard the onset of breakup by retaining sheet-ice cover that would have otherwise been set in motion. The restrained ice cover can thus act as a jam instigator. This concept can be quantified by comparing ice-driving forces to bridge-generated resistance forces at the time when the river stage is equal to that which would have initiated breakup under natural conditions, i.e. in the absence of the bridge (see also later discussion). It can thus be stated that ice jamming would occur if the total ice-driving force, F_D, were less than the total force resisting ice movement, F_R:

$$F_D \le F_R \Rightarrow \text{ice jamming} \qquad [1]$$

In other words, the piers will hold back the upstream ice cover beyond the naturally occurring breakup-onset stage, until the driving forces increase to the point that F_D just exceeds F_R. If F_D is above F_R, it can be concluded that the piers will not retard the movement of the ice cover. The bridge will not cause ice jamming because the ice cover will be able to move once the naturally required stage is reached, even with the bridge in place.

The potential driving force, F_D, results from the combined action of the flow shear stress and the downslope component of the cover's own weight. It can be calculated by summing all contributions from upstream ice sheets, with appropriate allowances for changes in direction between them. For any individual ice sheet, the driving force, T, can be determined as:

$$T \equiv \tau \; L \; W \qquad [2]$$

where τ is the tractive stress, equal to the sum of the flow shear stress that is applied on the underside of the ice cover, and the downslope component of the cover's weight; L and W are the length and width of the floe respectively, as shown in Fig. 2.

The total streamwise force acting on the $(k+1)^{th}$ ice sheet is equal to the driving force acting on that individual sheet plus the appropriate component of the streamwise force acting on the upstream k^{th} ice sheet. With reference to the definitions given in Fig. 3, this can be stated as follows:

$$N_{k+1} = N_k \cos\theta + T_{k+1} \qquad [3]$$

where N_{k+1} and N_k are the streamwise forces acting on the $(k+1)^{th}$ ice sheet and upstream ice sheet respectively, θ is the angle between the downstream channel directions of the two ice sheets, and T_{k+1} is the streamwise combined forces of gravity and flow acting on the $(k+1)^{th}$ ice sheet.

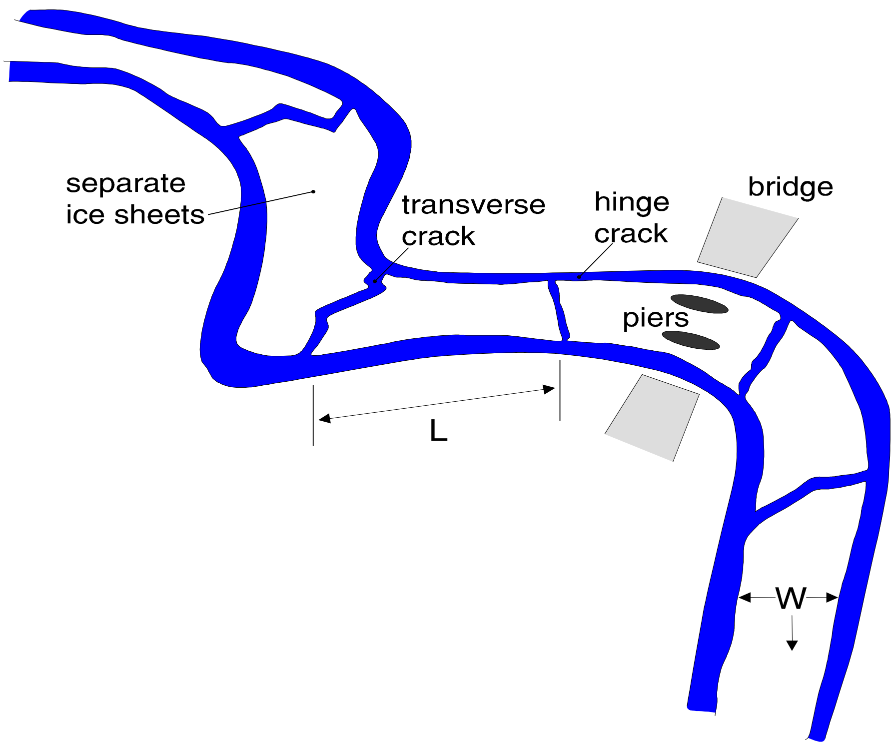

Fig. 2. Definition sketch of ice sheet width and length relative to hinge and transverse cracks.

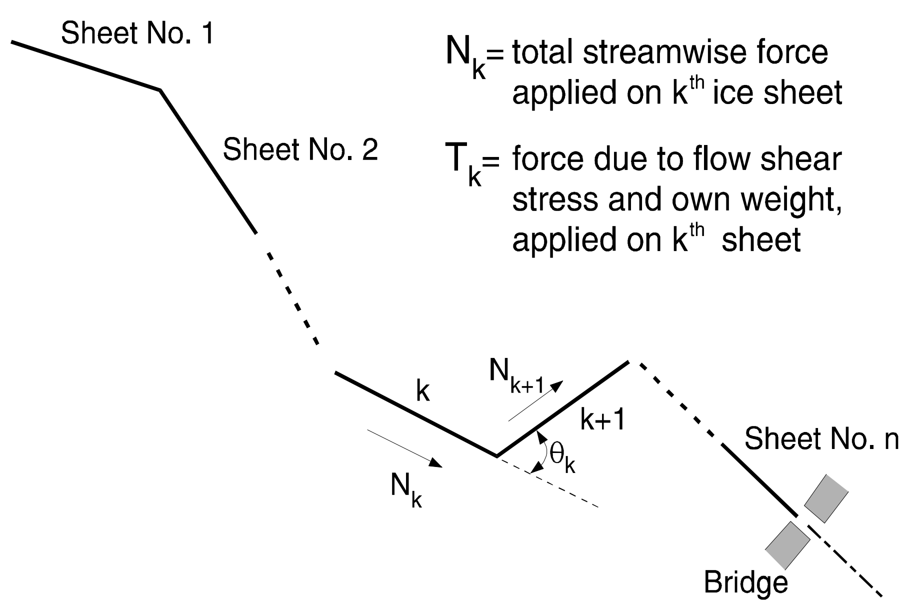

Fig. 3. Definition sketch for forces acting on ice sheets.

The designer, based on river plan and knowledge of past ice jamming events, must determine the location of the first upstream ice sheet that is contributing to the driving force at the bridge site. No streamwise force can be transmitted by an upstream ice sheet to a downstream ice sheet if $\theta \geq 90°$.

Replacing each sheet by a linear segment for simplicity, the following is obtained:

$$F_D = (\sum_{j=1}^{j=n-1} T_j \prod_{k=j}^{k=n-1} \cos\theta_k) + T_n \quad [4]$$

in which the n^{th} ice sheet is assumed to end at the piers (not generally true, but makes little difference in the total force). All angles, θ, are less than 90°. Even where θ is less than 90°, its cosine could be much less than one, hence a bend could greatly reduce the transmission of streamwise force from upstream reaches. If L, W, and τ do not vary appreciably, Eq. 2 can be simplified by factoring out T ($\approx T_j \approx T_n$), so that:

$$F_D \approx \tau W L_e \quad [5]$$

where L_e is the "effective" length of river contributing to load, and is defined as follows:

$$L_e \approx L\{(\sum_{j=1}^{j=n-1} \prod_{k=j}^{k=n-1} \cos\theta_k) + 1\} \quad [6]$$

The breakup initiation stage, H_B (see also Section 2.5), is used to calculate the potential ice driving force, F_D. This stage is defined as the water surface elevation at the time when the ice cover is set in sustained motion and depends on antecedent conditions as well as local river morphology (Beltaos, 1997).

The potential resisting force, F_R, may hold an ice cover in place which, in turn, may cause ice jamming by arresting any rubble that arrives from upstream. F_R is equal to the sum of the maximum ice loads that can be applied on each pier. For large ice sheets acting against a pier, the Canadian bridge code (CSA, 1988) gives:

$$F_R = \Sigma \min(C_a phb,\ C_n ph^2) \quad [7]$$

in which the two terms inside the brackets represent ice failure by crushing or by upward flexure respectively; p is the effective ice crushing strength; h is the ice thickness; b is the pier width at the level where the ice load is applied; and the coefficients C_a and C_n are given by:

$$C_a = \sqrt{(5h/b)+1}\text{; and} \quad [8]$$

$$C_n = 0.5 \tan(\alpha + 15°), \quad [9]$$

with α is the pier nose angle, measured from the downstream horizontal; the crushing strength always governs for $\alpha > 75°$. The summation sign in Eq. 7 simply indicates that all in-stream piers must be considered. Both crushing- and flexure- generated loads use the crushing strength of the ice. One must thus conclude that a constant ratio of flexural strength to crushing strength has been implicitly assumed in the code (see also the review paper by Neill (1983)).

To avoid the potential of bridges to instigate ice jams during breakup, the driving force should be increased relative to the resisting force. The above analysis implies several practical recommendations, such as:

a. to maximize the driving force:

  - Locate the bridge so as to maximize the length of the upstream reach that can contribute to the driving force. Avoid bends, especially sharp ones.
  - Avoid placement of piers within small streams where W and L_e may be too small to permit development of appreciable driving forces.
  - Avoid reaches of low gradient. Not only is the parameter τ likely to be small (thus reducing the driving force), but the ice just before breakup may be thicker as well (reduced heat transfer at the ice-water interface).

b. to decease the resisting force:

  - Keep the blockage by instream piers of the waterway opening under the bridge to a minimum. Slender piers are preferable if crushing is the mode of ice failure.
  - Use inclined pier noses that induce flexural failure of the ice and greatly reduce the maximum ice load (see Eq. 1). In this case, the ice load does not depend on pier width so that a thicker pier will not enhance the resisting force.

Interestingly, some of these suggestions can also be found in Shattuck (1988) who discussed empirically known criteria.

2.3 Potential of Ice to Damage Bridge Structures

Bridges can be damaged by the impact of ice on structural elements, by the dislodgement or displacement of the superstructure due to ice impact or the buildup of ice (resulting in the lifting of the superstructure off the piers), and by the undermining of the bridge substructure (piers and abutments) via general and local scour. River conditions that damage or destroy a bridge can result from ice jams upstream or downstream of the bridge site.

2.3.1. Maximum stages caused by ice jams

The superstructure of the bridge should have sufficient clearance to avoid being damaged or destroyed by moving or jammed ice. The maximum stage that occurs during open water conditions is often exceeded by the stage of water and ice resulting from ice jams, and therefore ice movement and jamming should be considered in the design of bridges on rivers subject to ice covers.

If ice jams are known to form downstream of the bridge, the local stage can be determined via the simple equilibrium-jam analysis (Beltaos, 1995) or by means of numerical models. Public-domain models include ICEJAM (Flato, 1988); RIVJAM (Beltaos, 1993, 1996); and the HEC-RAS River Analysis System, Version 2.2 (available on the Internet; developed by the Hydrologic Engineering Centre of the US Army Corps of Engineers). A crucial question here pertains to the flow that has to be used in the ice-jam computation. If sufficient historical data exist, the best approach would be to determine the flow that results in the 100-year stage that is caused by an ice jam. This flow is generally less than the 100-year peak breakup flow because the probability of ice-jam formation is usually less than one (Gerard, 1989) and may decrease with increasing flows (Grover et al., 1999). Where historical information on past events is lacking, it would be prudent to consider the maximum possible stage that can be caused by an ice jam. This stage may be limited by (a) floodplain inundation and spreading-out of ice and water; (b) availability of upstream ice; and (c) "ice clearing" flow (Beltaos, 1997).

If it is known that no major jams form downstream of the bridge, the jam-related high stage will likely be that of the surge created by the release of an upstream ice jam. Approximate surging water levels can be calculated via a simple analysis (Henderson and Gerard, 1981) or by numerical unsteady flow models (for example, Beltaos and Krishnappan, 1982; Hicks et al, 1997).

2.3.2. Scour potential of a surge

Even a relatively brief surge can result in large scour depths. Surging velocities can be much greater that those experienced during open-water floods, especially in wide and steep rivers at high flow (see Beltaos, 1995). The velocity influences the rate of scour (Hoffmans and Verheij, 1997) and the height of bedforms that develop during a surge. Surge analysis can furnish either (a) an approximate value of the maximum flow velocity in the case of the simple analytical method; or (b) a complete temporal variation of the velocity at the bridge site, as part of the numerical model output.

During a surge resulting from release of an upstream ice jam, the maximum live-bed scour depth should be considered approximately equal to the maximum (or equilibrium) depth plus one-half of the bedform height. Therefore, if the design includes local-scour protection, surge velocities must be taken into account in determining the size of riprap. Nevertheless, the maximum depth of scour during an open water event of longer duration may exceed the maximum depth of scour during an ice jam surge.

2.4 <u>Onset of Breakup</u>

As previously stated, the driving and resisting forces at a bridge are determined at the onset of ice breakup. Based on extensive field observations and data, Beltaos (1997) proposed the following equation to quantify the onset-of-breakup index, Φ_B:

$$\Phi_B \equiv \frac{8m^2\tau}{m-0.50}\frac{W_B-W_i}{h_o} = \beta\sigma_o\frac{\sigma h}{\sigma_o h_o} \quad \left(=\beta\sigma_o F(S_5)\right) \qquad [10]$$

in which W_B is the water surface width at the time breakup is initiated; W_i is ice cover width, usually equal to river width at the stage of the preceding freeze-up, minus shore strips formed by hinge cracks; h is ice cover thickness at the time of breakup; h_o is ice cover thickness before the start of thermal deterioration ($h_o \geq h$); m is local radius of curvature divided by the river width; τ is the tractive stress defined in Section 2.2 (immediately following Eq. 2); σ is flexural strength of the ice cover at the time of breakup; σ_o is undeteriorated ice strength; and β is a dimensionless coefficient in the range 0.3 to 1.5, with a likely value of 1.0. The fraction on the RHS of Eq. 10 reflects the relative loss of strength due to thermal deterioration of the ice cover. There is no reliable way to predict this fraction at present, owing to numerous uncertainties as to snowmelt, rate of ice ablation, and short wave radiation absorption by the ice cover (e.g. see Prowse et al., 1990). Consequently, an empirical index has been used as a first approximation. This is the quantity S_5 in Eq. 10, representing the accumulated degree-days of thaw relative to a base temperature of -5°C (Bilello, 1980).

2.5 Breakup Initiation Stage

To assess the effects of a bridge on ice jamming, it is necessary to know the breakup initiation stage, H_B, which can be deduced via the index function Φ_B (Eq. 10). Breakup initiation stages are best evaluated from field observations, coupled with local hydrometric surveys to enable application of an onset equation, such as Eq. 10. Ideally, such observations should be carried out *before* a proposed bridge is built, however, this is not always feasible. Where a bridge is *already* in place, the observed values of H_B may or may not represent naturally occurring ones, because of possible restraints introduced by the piers. In this case, ice movement past the bridge necessarily implies that $F_D > F_R$ and the above-formulated criterion (Section 2.2, Eq. 1) does not necessarily apply. If a bridge does restrain ice movement and augments the naturally occurring H_B value, F_D will be slightly greater than F_R upon dislodgment of the ice cover. The converse is not always true because it is conceivable that slight force excess may still be due to naturally occurring breakup. On the other hand, if F_D is well in excess of F_R, one could be certain that the piers do not retard the natural occurrence of breakup initiation; the ice would have already moved at slight force excess, but is held in place by the natural constraints imposed by the channel boundary configuration.

3.0 Example Applications

3.1 Saint John River at Clair, N.B

One of the selected sites for the study is the international bridge between Clair, in northeastern New Brunswick and Fort Kent, Maine, over the Saint John River (Fig. 4). Water levels and flow data were available from a hydrometric station located at Fort Kent (station number 01AD002; drainage area = 14 700 km^2). Generally, this stretch of the Saint John River is wide and shallow, with occasional islands. Fig. 5 depicts the channel cross-section just upstream of the bridge.

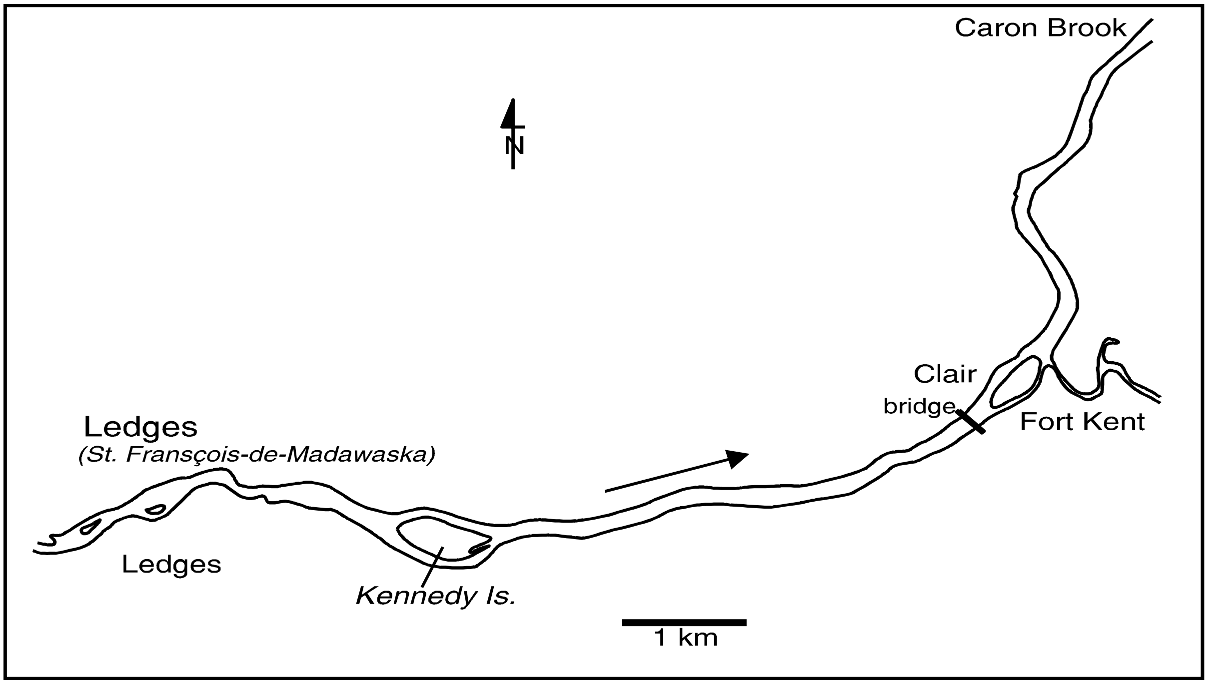

Fig. 4. Plan view of the Saint John River in the vicinity of the Clair-Fort Kent International Bridge.

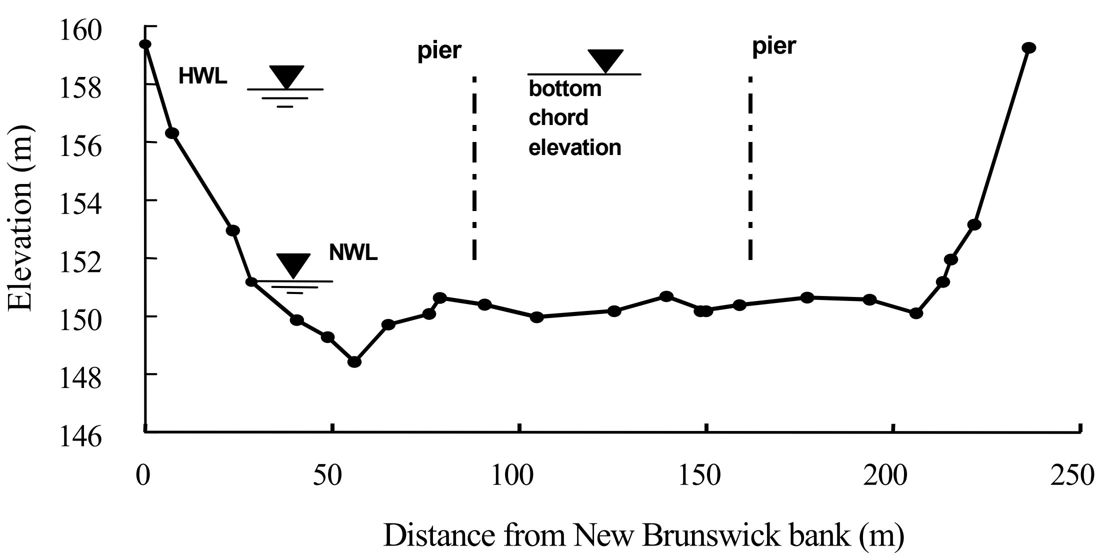

Fig. 5. River cross-section just upstream of the Clair-Fort Kent International Bridge. HWL = High water level; NWL = "normal" water level, prevailing on day of survey, August 27, 1993.

Detailed field observations that have been carried out as a part of the International Saint John River Ice and Sedimentation Study (1993-1997) indicate no ice jamming that can be attributed to the bridge has taken place during the study period. The same is true of the 1991 breakup, which generated the highest known water level at the bridge site (157.9 m). Observations during the 1991 event by two of the authors (Beltaos, Burrell) indicated that this stage occurred during an ice run that was caused by the release of an ice jam located far above the bridge. The closest known jamming sites to the bridge are: (a) Baker Brook, located 11 km downstream of the bridge, where short jams have been observed on occasion; and (b) Ledges, located about 7 km upstream of the bridge. Ledges jams are often major, that is, they extend for many km upstream. Release of a Ledges jam produces a surge that dislodges the ice cover and any ice jams downstream, usually for a distance of 30 km to 50 km.

From this description of ice processes, it follows that a Baker Brook jam can only comprise an ice volume of ~19000 m x 0.5 m x 190 m (distance to Ledges, times ice cover thickness, times ice cover width), or 1.8×10^6 m^3. With estimated jam thickness and porosity of 3 m and 0.4, respectively, the maximum jam length would be about 5 km, leaving 6 km of open-water between the jam and the bridge. This greatly moderates the effects of the jam on the water level at the bridge site and points to surges from upstream ice-jam releases, as the governing factor in the maximum ice-influenced stage. Local experience appears to support this conclusion: on a few occasions (1991, 1993, 1994), upstream ice runs have come close to the bottom of the bridge superstructure, which has a much higher elevation (158.29 m) than what can result from downstream jams (no more than 155.5 m). The latter figure is based on RIVJAM runs using flows in the known breakup range of 500 m^3/s to 1500 m^3/s, and applying the estimated limiting ice volume of 1.8×10^6 m^3. At the same time a calculation of equilibrium-jam water levels (e.g. see Beltaos, 1995) for the bridge reach indicates that high breakup flows (~1500 m^3/s) would produce much higher stages (~161 m) than the highest stage on record (157.9 m; 1991 breakup).

Having established the governing role of surges from upstream ice-jam releases, upper limits on stage and flow velocity at the bridge location can, in principle be calculated by means of a dynamic flow model. The initial water-surface profile, which is a necessary part of the model input, can be estimated by application of an ice-jam model to simulate a major jam whose toe is located at the known jamming site of Ledges. This approach requires detailed model calibration, which to date, has only been established for the RIVJAM model, using data obtained during the 1993 breakup. At present, therefore, only a first approximation for the surge velocity can be obtained, using the simple theoretical analysis of Henderson and Gerard (1981), in which bed-friction and slope effects are neglected. This method requires water depths upstream and downstream of the jam prior to release. These depths have been calculated using RIVJAM and assuming a flow of 1500 m^3/s, an upstream depth ~ 7.2 m, and a downstream depth ~ 4.0 m. With these values, the velocity works out to be 3.6 m/s, which is close to visual estimates (3-4 m/s) during the ice run of 1991. The Henderson and Gerard equations also furnish an estimate of the celerity of the surge, i.e. C ~ 9.5 m/s.

The potential of the bridge to instigate ice jams can be examined by means of the analysis presented in Section 2.2. Using local bathymetric data, the relevant reach-average hydraulic parameters at a typical onset-of-breakup stage are: water surface elevation = 153.2 m; W = 190 m; τ = 15 Pa; h = 0.5 m. There are two piers in the river, each having a width, b, of about 2.3 m at the breakup level; nose inclination angle is about 80°. From the Canadian bridge code (CSA, 1988) the value of p is estimated to be 1.1 MPa and thence Eq. 7 gives $F_R = 2C_a phb = 2 \times 1.45 \times 1.1 \times 10^6$ Pa x 0.5 m x 2.3 m = 3.7 MN for both piers. To have $F_D > F_R$, the "effective" length, L_e (Eq. 6), has to be at least 3.7×10^6 N / (190 m x 15 Pa) = 1.3 km. For the case under consideration, it is estimated that L ~ 500 m (Beltaos, 1990). The start of the contributing reach is selected at just below Kennedy Island, which is likely to absorb any ice forces from further upstream; small contributions by the ice cover on the sub-channels around the island are ignored. The first known ice-jam site upstream of the bridge is above the island. The angles between adjacent ice sheets are estimated graphically (10° to 20°) and the calculation results in $L_e \sim 3.2$ km, more than twice the length needed to equate F_D to F_R. This suggests that the Clair-Fort Kent bridge does not cause ice jams, a result that is in full agreement with the observational experience discussed earlier. It must be kept in mind, however, that the above analysis is not complete and only given here as an illustration. The variation of the quantities L, W, and τ (assumed constant for simplicity) can be assessed using a more elaborate approach that would take into account changes in river planform, cross-sectional geometry, and slope. Moreover, additional calculations should be performed for extreme values of ice thickness and freeze-up levels, to examine their effects on the ratio F_D/F_R.

Recently, the NB Dept. of Transportation applied this methodology to the Clair site, as part of the engineering design of a new bridge that will replace the aging structure that is presently in place. The proposed piers have vertical sides and a width of 2.40 m. It was found that four piers would generate a combined resistance in excess of the available driving force, while three piers would not. However, the three-pier resistance was not sufficiently less than the driving force to provide an adequate safety factor. It was thus decided to use two piers, a choice that results in a driving-to-resisting force ratio of 2.4 for a typical ice cover thickness of 0.5 m. The ratio decreases to 1.6 when a less likely, but not impossible, value of 0.7 m is used for the thickness of the ice cover.

3.2. Southwest Miramichi River at Upper Blackville

The Southwest Miramichi River originates in the highlands of west-central New Brunswick and flows in a generally easterly direction to the New Brunswick Lowlands where it joins with the Northwest Miramichi River to form the tidal Miramichi River that empties into Miramichi Bay. Approximately half of the flood events along the Southwest Miramichi River, New Brunswick are ice-related. Ice runs and ice jams have resulted in damage to, or destruction of, bridges along the Southwest Miramichi River and its tributaries (see Beltaos et al., 2001).

Two bridge sites were selected for investigation along the 80-km long study stretch of the Southwest Miramichi River: the Upper Blackville and the Quarryville bridges. The Upper Blackville bridge is on a relatively straight river reach (Fig. 6) with moderate slope and approximate width of 100 m.

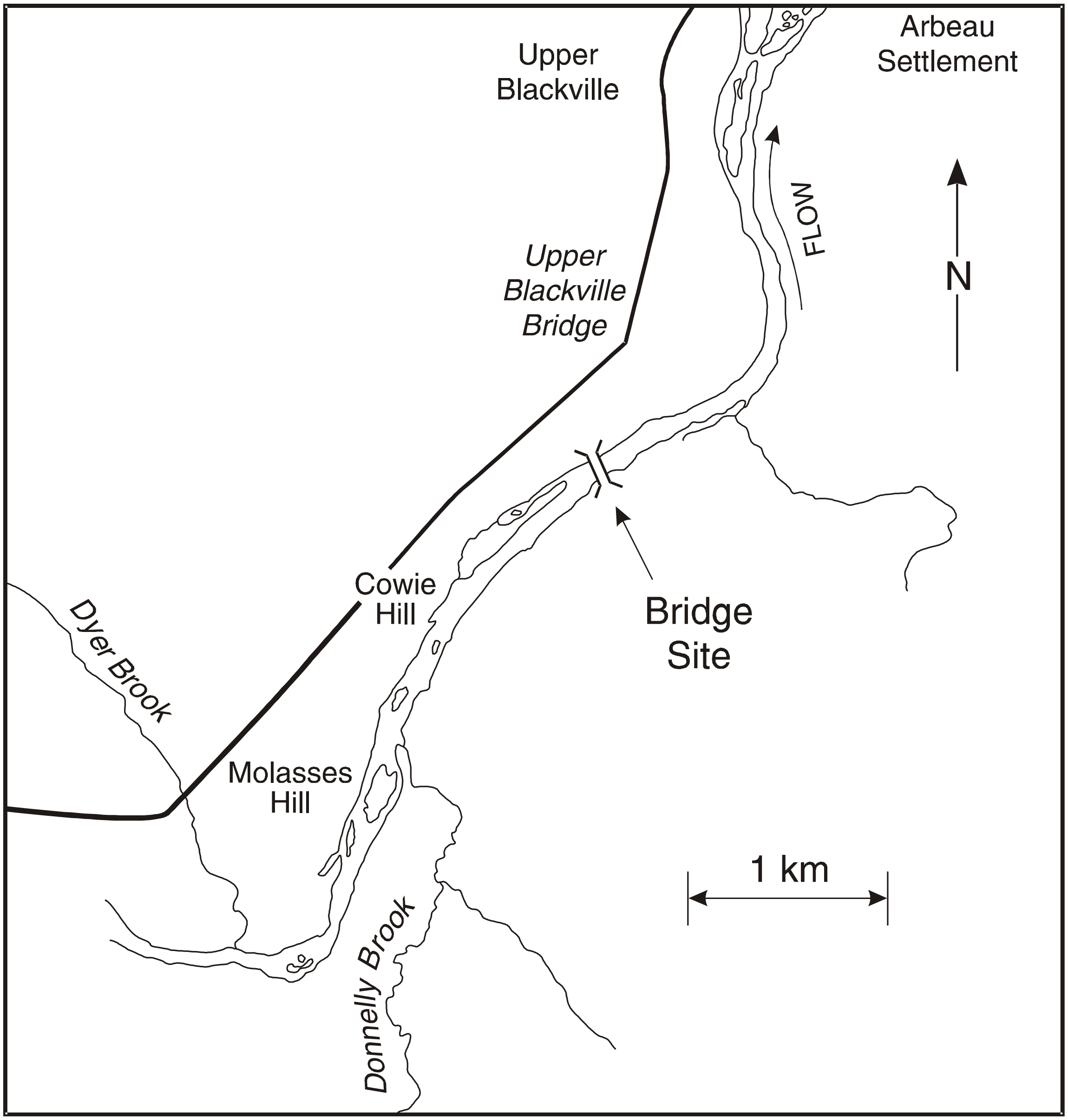

Fig. 6. Stretch of the Southwest Miramichi River near the Upper Blackville Bridge at Upper Blackville.

The bridge has two piers with an upstream nose inclination of 45^o. Observations have been made of river ice conditions during the 2000, 2001 and 2003 ice breakup period, which were similar in nature with relatively low mechanical competence left in the ice cover by the time the breakup was initiated. Herein the 2000 event is described, and extrapolated to "premature" breakup events that take place while the ice cover retains its full competence.

The development of the 2000 breakup event was influenced by a spell of mild weather and runoff in late February and early March. The river stage increased by 1 m, which was not sufficient to trigger a winter breakup, but did cause hinge cracking. The stage gradually decreased after peaking on March 3, but never returned to the pre-runoff winter low. The persistence of relatively high flow may have contributed to the decay of the ice cover, which by late March was highly deteriorated. The flow began to increase again on March 24, leading to breakup a few days later. Rainfall on March 28 and 29 accelerated the progress of the breakup. Continuous day-time and (when deemed necessary) night-time monitoring of ice conditions commenced on March 25 and was discontinued on the 30th, after most of the ice had moved out of the study reach.

During most of the time the ice cover was in motion at the bridge site, it was breaking up against the one bridge pier that was in its path. Due to the presence of an island near the left river bank, and the increasing river stage prior to breakup, a 2nd pier near the left bank was mostly outside the reach of the ice cover width. Typically, the ice approaching the pier failed in bending, as evinced by the radial-circumferential cracking pattern in Fig. 7, and as might have been expected from the 45° inclination of the pier nose.

Fig. 7. Ride-up of ice wedges formed by radial and circumferential cracks on a pier of the Upper Blackville bridge. Fracture pattern is typical of bending failure.

From the local river slope, cross-sectional geometry, and applicable stage at the time of ice movement, the tractive stress, τ, that appears in Eq. 5 (section 2.2) is estimated as 5.24 Pa. The corresponding width of the ice cover is 108 m, while the applicable river length is 0.9 km. This is less that the potential contributing length of ~2 km (reach between bridge to large island near

Molasses Hill in Fig. 6), because in situ observations indicated that there was open water above the slight bend located 0.9 km upstream of the bridge. Using the above data, the total driving force that would be applied on the cover just prior to release is calculated as 510 kN.

Equations 7 to 9 can be used to calculate the force resisting ice movement past the bridge. For Upper Blackville, $\alpha = 45°$, b = 2.45 m, and h is estimated as 0.20 m, based on measurements on ice blocks that were stranded on the river banks following ice movement. The strength of the ice cover is unknown, but estimated to have been considerably decayed as a result of the prolonged mild spell preceding the breakup. For such conditions, the Code suggests a p–value of about 400 kPa. Using this value, the two-pier force due to flexure would have been about 28 kN. This value is much less than the available driving force of 510 kN. It can thus be concluded that the piers did not influence the breakup process.

The probability of pier interference with breakup initiation and progress may be greater for strong and thick ice covers. For instance, if the ice cover had not been subjected to significant deterioration, its thickness and crushing strength would have been about 0.65 m (Beltaos et al, 2001) and 1100 kPa (from CSA, 1988). The two-pier resisting force is then calculated as 400 kN. The corresponding driving force would likely exceed the previously estimated value of 510 kN because: (a) it would take much higher stages and flows than those of the 2000 event to dislodge so competent an ice cover; and (b) it is highly unlikely that an open-water section can develop within the driving-force reach, as it did in 2000, when the ice cover retains its full strength and thickness upon dislodgment. This bridge is thus considered unlikely to aggravate ice-jam occurrence, due largely to the relatively long straight reach upstream, but more evidence is needed to confirm this expectation. To this end, it is necessary to either: (a) obtain additional breakup-onset data for a range of ice conditions and flows; or (b) synthesize such information, based on findings in other rivers. The former option is by far the preferred one, but it is only the latter option that can be explored at present, as discussed next.

The field observations for the years 2000 and 2001, combined with independently surveyed local hydraulics, and with weather records, can be used to determine respective values of Φ_B and S_5, the two main indices in Eq. 10 (section 2.4). The corresponding data points are plotted in Fig. 8, along with those obtained via a comprehensive analysis of the hydrometric records of a nearby gauge, located about 20 km downstream (Beltaos, 2002). Though not shown in Fig. 8, the data points for both sites are consistent with those of seven other Canadian rivers. The 2002 measurements have not yet been analyzed, but the respective data point should not be far from those of 2000 and 2001. All three years are on the high end of the S_5 scale, and approach the conditions characterizing thermal breakups (Beltaos, 2003). With a few more data points, particularly at low S_5, the entire function $F(S_5)$ could be defined and used to investigate the potential for the piers to cause ice jams under a variety of flows and ice conditions.

If, as a first approximation, it is assumed that $F(0) \sim 80$ kPa, the breakup-onset width and stage can be calculated as a function of the freeze-up stage, H_F. Using a value of 16 m for the latter (very close to 2000 and 2001 values), it is estimated that the breakup stage is ~ 19.0 m, which corresponds to a value of ~ 9 Pa for τ. With a corresponding width of ~ 142 m, the potential driving force is equal to 9 Pa x 142 m x 2000 m ~ 2600 kN, which is much greater than the previously estimated resisting force (400 kN) under conditions of a thick and strong ice cover.

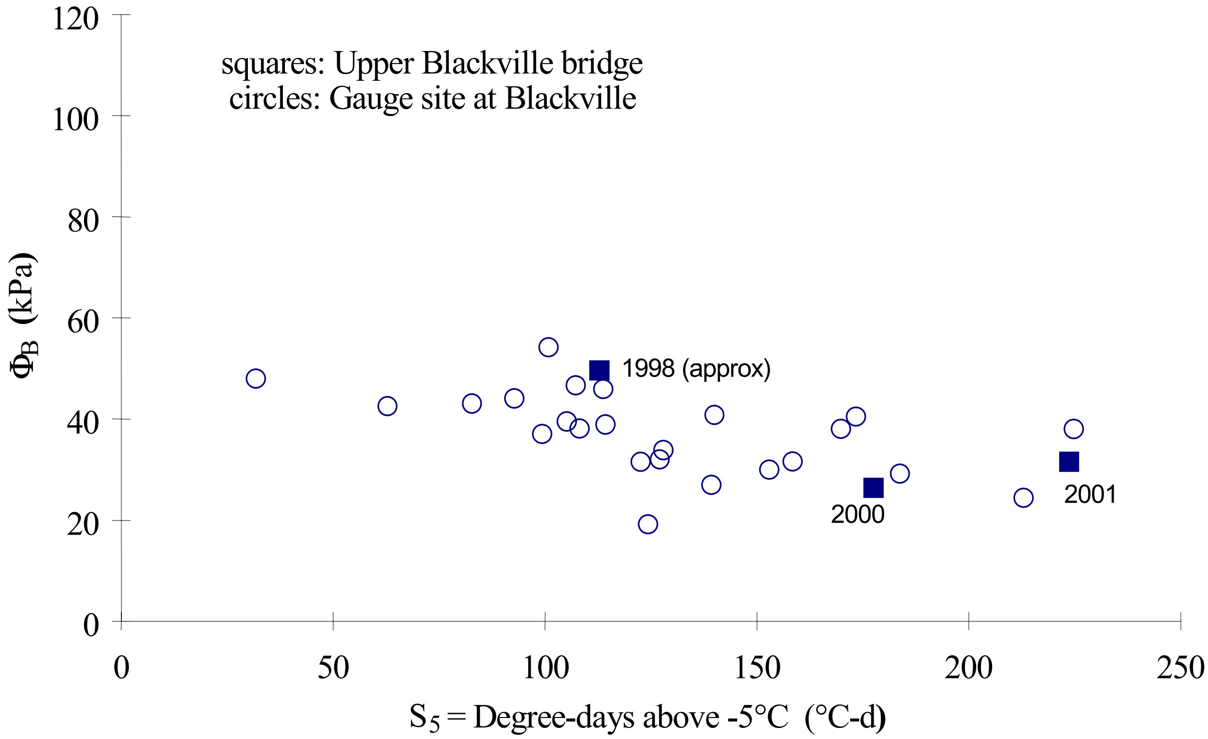

Fig. 8. Onset of breakup conditions at Upper Blackville and at the downstream gauge site.

This implies that even with a premature breakup of a fully-grown ice cover the bridge is very unlikely to cause ice jamming. Experience to date (1998-2002) corroborates this deduction: a jam only formed in the Upper Blackville reach during the 1998 ice breakup event and did cause significant flooding over the low, southern, floodplain. However, the toe of this jam was well downstream of the bridge, signifying that it was initiated by a natural geomorphic feature of the river, rather than by the bridge.

4.0 Summary and Conclusions

The interaction of ice and bridges can result in environmental and property damage, in addition to damage that can be experienced by the structure itself. However, very little is known about such interactions, and this hinders introduction of physically based methods in the engineering design of a bridge. To help fill such knowledge gaps, a joint study is being carried out by federal and provincial (NB) agencies that incorporates theoretical analysis, field observations, and numerical modelling. The effects of the ice on the structure can be quantified by examination of local river ice processes, and especially ice jamming. High water levels caused by ice jams are a threat to the superstructure of a bridge, while surges caused by ice-jam releases can undermine the piers via local and general bed scour. The potential of a bridge to cause ice jams is quantified using recent advances concerning the onset of breakup, and comparing concomitant driving and resisting forces that are respectively generated by hydrodynamic and structural processes. This analysis results in several qualitative guidelines for selecting bridge sites so at avoid ice-jam instigation, some of which are already known empirically. Long, relatively straight reaches upstream of the bridge site, devoid of major islands, and carrying fast or, at least not tranquil, flow, are all desirable features. A low number of bridge piers is also desirable because it reduces the resistance to sheet-ice passage.

The proposed methodology has been applied to two New Brunswick case studies: the international bridge on the Saint John River at Clair and the bridge on the Southwest Miramichi River at Upper Blackville. In the former case, ice-generated flood stages were shown to be caused not by downstream jams, but by surges resulting from releases of upstream jams. Very high surge velocities and celerities were calculated by an existing theoretical method, though it is recognized that the theory neglects certain important effects. Presumably, results that are more credible can be obtained by numerical modelling. It was further shown that the Clair international bridge is unlikely to cause ice jams, a conclusion that is in full accord with local experience. The same conclusion was reached for the Upper Blackville bridge, based on field observations (2000-2002) and extrapolation to, yet undocumented "premature" breakup events. In this case, too, the bridge does not seem likely to cause ice jams, in accord with the limited field evidence that is available. This conclusion is preliminary and subject to further confirmation by continued field observations. The success of the design is in both cases related to the low number of piers in the main flow and to relatively long, unobstructed stretches above each bridge.

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