# CRITICAL PHYSICAL PROCESSES IN THE NUMERICAL MODELLING OF RIVER ICE.

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## ABSTRACT

The litterature on numerical and physical modelling of river ice has often been based on processes occuring in the transport of sediments in rivers. There is, indeed, some similarities between river ice hydraulics and sediment transport. However, the differences are so important that adequate simulation cannot be made without a full understanding of the specificity of river ice processes.

The major areas of misunderstanding that will be discussed in this paper are the following:

-freeze-up processes are very different from break-up processes and should be treated differently

-ice floes at freeze-up are physicaly different and behave differently than simple parallepipedic blocks or solid granular material

-frazil slush and pans are not transported as sediments in suspension and neither do they deposit on a solid ice boundary as bed load transport on a river bed.

Fortunately, break-up jams that occur when the solid downstream cover is still strong, can be treated as accumulations of simple blocks that can be analyzed with theories of pure hydraulics and soil mechanics, and modelled as such.

## 1-INTRODUCTION

The basics laws of ice dynamics are required in order to model correctly, either numerically or physically, the ice processes in rivers. Some of these laws are poorly known and there has been a natural tendency to assume that the ice processes are very similar to those of sediment transport in rivers, and make the same hypothesis. This often leads to erroneous results that are very difficult to reject because the ice phenomena are so poorly documented in the field.

The major difference between these two phenomena is the action of freezing that not only makes ice floes geometry very different than that of sand or gravel, but also affects in a drastic way the behavior of the already formed ice cover.

## 2-FREEZE-UP AND BREAK-UP PROCESSES

Freeze-up processes may be defined as those occuring under continuous cold weather while break-up processes are those happening when the air temperature is above the freezing point.

In cold regions, like northern Quebec for example, only freeze-up processes are occuring at time of ice formation and during the winter months because of continuous cold weather. In much warmer climates, like northern U.S.A. for example, both freeze-up and break-up processes are occuring in sequences, many times during the winter, so the analysis of the ice phenomena is much more complicated.

In Figure 1 we see a chart of freeze-up processes.based initially on the type of ice feeding the ice cover. A clear distinction in made between fast consolidating ice covers and unconsolidated ice accumulations.

In Figure 2 is a chart of break-up processes. There are two major alternatives corresponding either to a mechanical break-up or the thermal break-up. In the latter case, the downstream ice cover is melted and destroyed by the hydraulic or wind forces..This last type of break-up is normally much less severe and of lesser practical importance than the mechanical break-up where the solid ice sheet is still very resistant when the upstream jam is shoving through it.

It can be seen that are major differences between the basic processes of freeze-up (without the unconsolidated ice jam) and break-up (without the destruction of the downstream ice cover by melting and weakening). These differences are:

-geometry of ice floes feeding the cover

-cohesion or strength of the ice cover

-transport and deposit of ice floes

An example of the importance of the weather on the occurrence of one process or the other is shown by comparing the characteristics of ice covers formed in a 42 km reach of the St-Lawrence River for two winters, for which all the hydraulic conditions were about the same. This is shown on Figure 3 (Michel,1984). During ice cover formation in 1947-48, the air temperature was continuously cold until january 4 and the ice cover progressed continously each day until it got to a high velocity reach where a jam was formed. On the contrary during the winter 1949-50, the air temperature oscillated continuously from freezing to melting during the formation of the ice cover and heavy shoves and packing (called short shoves in the figure) were observed until the cover reached the critical reach on January 20. Measurements showed that the ice cover was then thicker in this reach by about one meter, than in the previous year.

## 3-GEOMETRY OF ICE FLOES

During continuous freeze-up, the ice "floes" that are produced and feed the ice cover are either made of slush, slush balls or pans and large ice plates. Matousek (1984) has shown how much freezing is required to form either one or the other ice type. It is surprising to see that, under very cold weather, very large plates of ice are formed even at velocities as high as 0,8 m/s.

None of these types of ice corresponds to the parallepidedic or granular ice pieces that have been extensively studied in flumes of hydraulic laboratories. In fact large ice plates are very stable in front of a progressing ice cover and juxtapose easily. The velocity of equilibrium of a thin block in front of an ice cover is usually given by the formula of the type (Michel, 1957, Pariset and Hausser 1961):

$$V = K\sqrt{2\,g\left(\frac{\rho-\rho'}{\rho}\right)h}$$

where:

V-velocity in front of block
K-form coefficient without dimension
g- acceleration of gravity
h-thickness of block
$\rho$-specific mass of water
$\rho'$-specific mass of block

For short blocks the form coefficient K as been found to vary between 0,6 to 1,3. However, for very long and thin floes as occur in nature it is obvious that the drag force will act only on the edge and the resisting force to submersion will increase very much. Larsen(1975) has shown that the form coefficient increases very quickly for very small and decreasing aspect ratios (Figure 4). Drouin et al (1984) have found that this coefficient was at least equal to 2 for large ice plates 12,5 cm thick that were formed in the LaGrande River. This shows that ice cover can progress by juxtaposition of floes in a much easier way than usually predicted.

On the other hand, frazil slush and pans accumulate to form very unstable progressing ice covers and hanging dams, subjected to packing, with Froude numbers for frontal stability only of the order of 0,06 to 0,08 (Michel, 1984).

Finally, at break-up. the ice pieces that have travelled and have been rebroken, attain sensible size ratio of 3 to 6 times the ice thickness and can well be assimilated to simple laboratory blocks. It can then be expected that they will form a stable frontal edge of an ice jam with a Froude number of the order of 0,12 as found in laboratory tests ( Pariset and Hausser 1961, Mathieu 1966, Uzuner and Kennedy 1972, Ashton 1974, Larsen 1975, Tatinclaux 1977).

It thus appears that major efforts have been made to model break-up processes and very little has been done with the geometry of ice pieces occurring during freeze-up processes in nature.

## 4-COHESIVE FORCES IN THE SOLID ICE COVER

A most critical process in the modelling of river ice is the determination of the possibility of shoving in the cover itself. In freeze-up processes, the ice pieces forming the frontal edge freeze quickly together and there is little possibility of shoving.

Up to now freezing has been considered in jam studies by introducing a constant value of internal cohesion Ci, usually evaluated between 100 to 500 Pa (Ashton, 1986). No effort was made to relate this value to actual freezing and sintering phenomena in ice jams.

The growth of the solid ice between ice floes in an accumulation can be computed from the basic heat transfer equation:

$$h = \frac{k_i}{H_{ia}}\left[-1 + \sqrt{1 + \frac{2\,H_{ia}^2\,D}{k_i\,\rho_i\,L}}\right]$$

where:

$$D = \int_0^T |\theta_a|\,dt$$

in this equation:

$\theta_a$ = air temperature in $^oC$

$H_{ia}$ =heat transfer coefficient ( 22 W/m$^2$·°C for a rough surface)

$\rho_i$ = density of ice ( 910 kg/m$^3$)

$k_i$ = thermal conductivity of ice (2,24 W/m°·C )

L = latent heat of fusion of ice ( 3,34 x10$^5$ J/kg)

h = ice thickness (m)

t = time ( s)

With the preceeding values of the parameters and for small values of D, the equation reduces to:

$$h = 2{,}6 \times 10^{-4} D$$

where D is in degree-hours.

The resistance to shear of newly formed solid ice can be taken to be close to 0,5 Mpa. The resisting shear force Rs in N/m of the solid ice is then:

$$Rs = 130 D$$

When ice is forming, the air temperature is usually much below -10°C and the value of D is higher than 10 in one hour. The resistance to shear of the solid crust is then at least 1300 N/m in one hour and increases quickly. Furthermore the cold ice floes that plunge under the cover sinter easily because of their cold content. This adds to the cohesive effect.

The shear resistance Ra in N/m, at the side of an unconsolidated ice accumulation can be computed from formulas in Michel (1971):

$$R_a = \frac{g\,\rho(\rho - \rho')}{2\rho}(1 - e)\sin\varnothing\cos\varnothing\,H^2$$

where:

H = total ice thickness in m
∅ = angle of internal friction of ice
e = porosity of accumulation

For values of $\varnothing = 35^\circ$, $\rho' = 0{,}91$, and e=0,5, this leads to:

$$R_a = 114\,H^2$$

It is interesting to compare the values of Rs and Ra. One hour of freezing at -10°C gives about the same resistance to shear in a jam as the friction of a 3,4 m thick accumulation, without taking into account the added effect of sintering. For a more normal accumulation 1 to 2 m. in thickness, it takes only 5 to 20 minutes to form a solid bound as resistant to shear as the accumulation itself. Because it takes a length of acccumulation of 2 to 3 times the river width to mobilize the friction resistance, it is obvious that freezing adds considerably to the total resistance of an ice cover, so that shoving is practically excluded at freeze-up unless there is an extremely fast progression of the frontal edge.

## 6-TRANSPORT OF ICE

Ice transport is also a different phenomenum at freeze-up than at break-up. With well defined ice pieces at break-up, surface and under ice transport can be rather well studied and modelled. However, at freeze-up. the evolutive and shapeless forms of frazil render the phenomenum very difficult to analyze in details and, at this time, only rough first approximations can be used.

During frazil formation, the individual discoid crystals exist only for a very short period of time. For example measurements made in the more active zone of frazil formation in the Lachine Rapids of the St.Lawrence River (Michel et al, 1986), have shown that only 17% of the total ice content was suspended in water, in more or

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For all practical purposes, the frazil is transported in the form of slush and pans at the upper surface. This ice feeds the ice cover at freeze-up and makes it either progress or the slush layer plunge underneath the solid cover. The entrainment and transport under the existing cover of this deformable , formless and exceedingly porous layer cannot be compared to the phenomenum of saltation of individual well defined ice pieces of sand and gravel that is observed on river beds.

Furthermore, when the slush with pans has adhered to the bottom of the ice, it gets welded to it by sintering. The boundary between moving slush and solid boundary is smooothed out, as can be observed at the surface along border ice. So once an equilibrium has been reached in the deposit it becomes more difficult to deposit more slush, even at a lower velocities. On the other side, it is also difficult to erode the existing sintered deposit at higher velocities.

This is the reason why hanging dams are formed by deposit of frazil slush and pans in the dead waters at the end of an equilibrium channel. This is not done simply, in large rivers, as many channels are formed successively at different locations while the hanging dam is developped. As a first approximation, measurements of existing hanging dams (Michel and Drouin, 1981) have shown that the velocity of equilibrium of the deposit under hanging dams is of the order of 0,7 to 1 m/s. A value in the upper range can probably be used to make numerical computations on the formation of hanging dams. The same measurements and others also show that the slope of the water line in a hanging dam is surprisingly a constant at about 1/1000, showing indeed a constant cross section and flow velocity, whatever be the discharge, and simplifying considerably all preliminary computations.

## 7-CONCLUSION

In conclusion we would like to stress the fact that there is still a lot of difficulties in modelling correctly, as they happen in nature, freeze-up and break-up processes.

Freeze-up processes are very difficult to model physically because of the effects of freezing on the geometry , transport and accumulation of ice floes. Mathematical modelling has a better chance of success if the natural phenomenum are reproduced and interpreted correctly.

Because there is no freezing effect during break-up and the geometry of ice pieces is simple, physical modelling can be done with a lot of success, above all if the strength of the solid ice cover , behind a jam, is reproduced to scale. Mathematical modelling will then give only approximate results as there is yet no known method to quantify the stress distribution and failure in a three dimensionnal ice jam.

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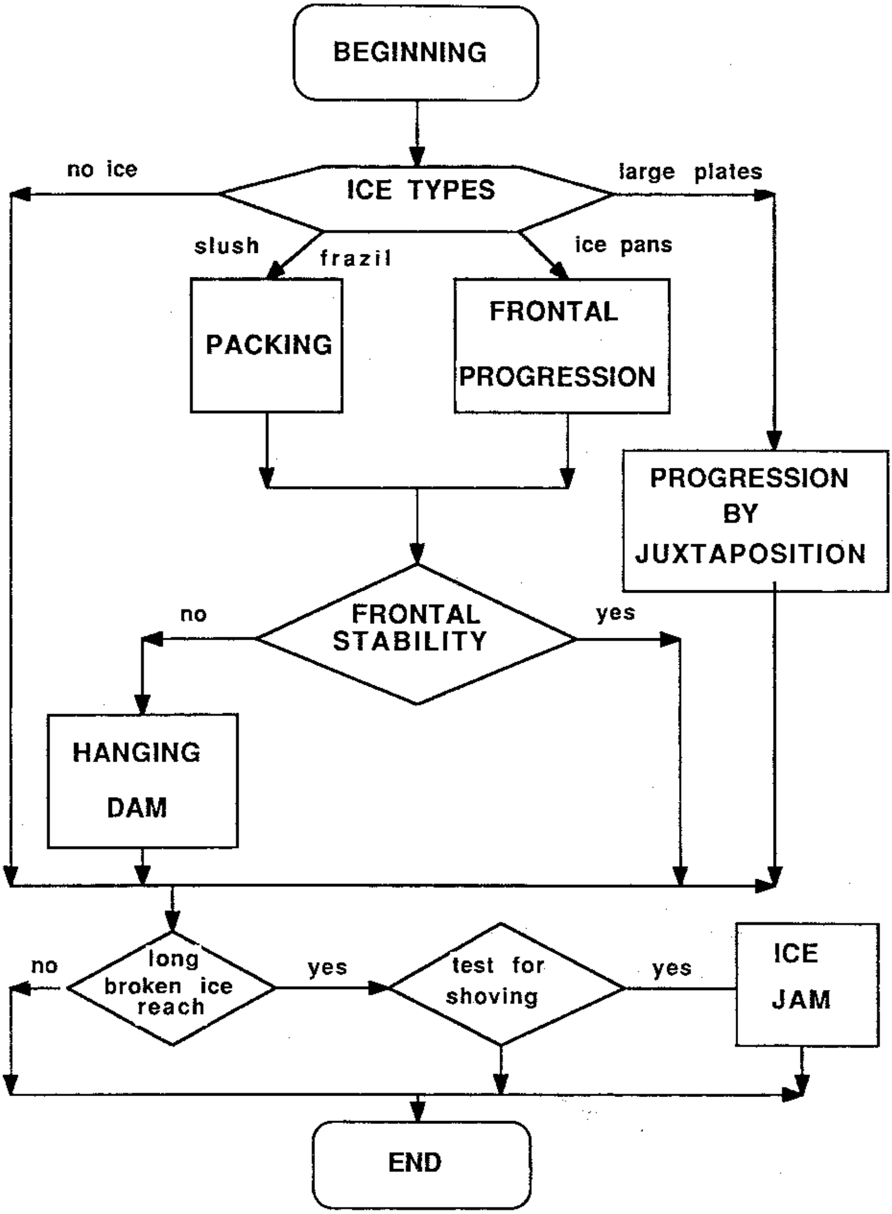

FIGURE 1. Flow chart showing the formation of an ice cover during a unit time period (Michel 1986).

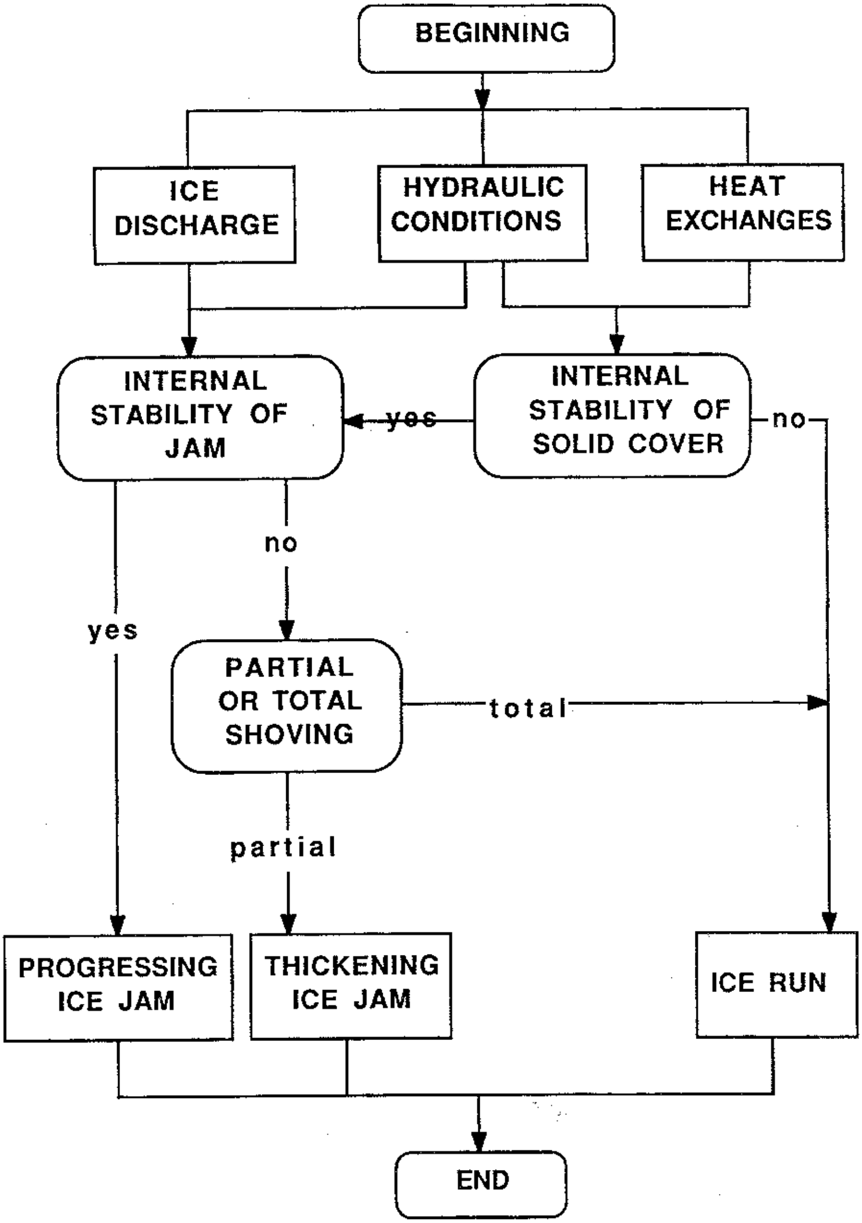

FIGURE 2. Flow chart of processes at the edge of the ice cover at breakup.

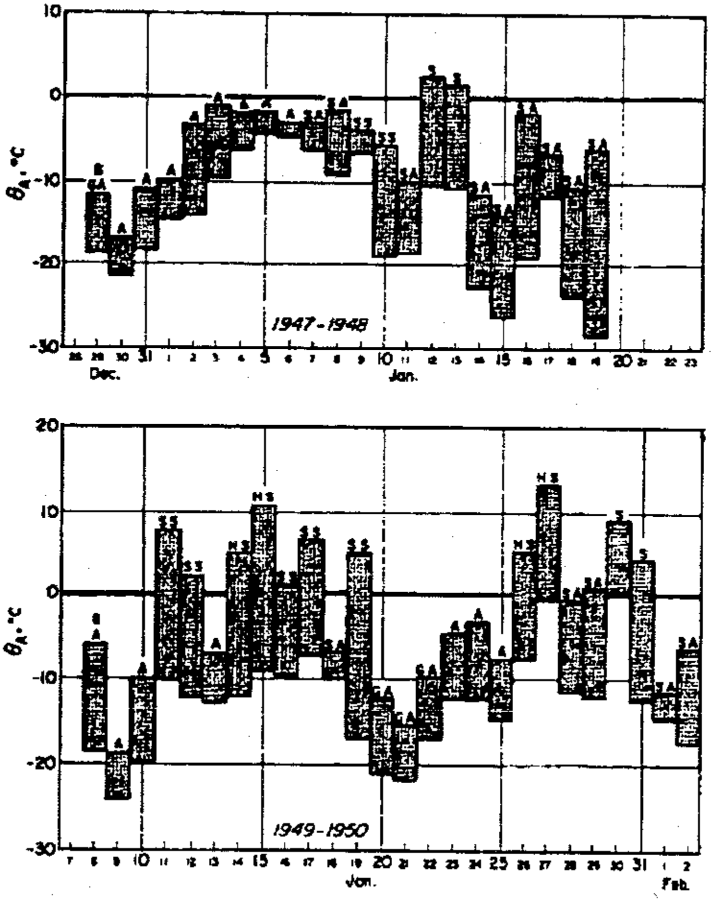

FIGURE 3. Variation of air temperature and shoving events in the St.Lawrence River 1947-48 and 1949-1950. Legend:B bridging, A advance, GA good advance, S shove, HS heavy shove, SS packing.

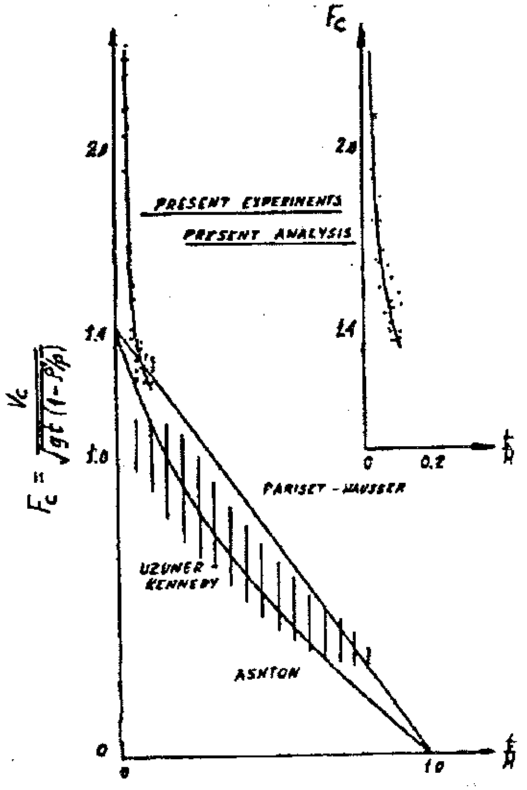

FIGURE 4. Froude number at instability as a function of block thickness over flow depth (Larsen 1975)