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Design of Ice Cover Evolution Modules for RIVICE

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Abstract

Ice cover evolution is simulated in five modules of RIVICE.

- Border ice - A range of options from full user-specified extent of border ice, to calculated border ice progression dependent on meteorological conditions and river flow velocity.
- Initiation - This module checks on the possibility of an ice bridge formation due to border ice coverage, and also allows a user imposed bridge at any location and at any time during the simulation period.
- Evolution - This module represents leading edge accumulation, ice cover thickness changes due to hydraulic forces, ice transport and deposition, and erosion of ice cover at high velocity zones.
- Breakup - This module allows for user defined breakup of the ice cover, as well as program initiated breakup based on shear stresses and/or excessive increases in water level.
- Breakup Jams - This is similar to the evolution module in that it represents the accumulation of an ice cover resulting from the supply of broken ice from upriver. Key parameters such as leading edge stability and cohesion can be specified as having different values from those used for formation.

The details of these modules are described in this paper.

Keywords
RIVICE, ice modules, border ice, leading edge, jamming, breakup

1 Introduction

At the time of writing this paper, the first version of RIVICE had not been completed. Tests on the various modules were underway. The descriptions of the modules of ice cover evolution which follow are therefore to some extent preliminary and subject to change as the program development continues. This paper should be read in conjunction with the other papers which describe the other modules and the global design of the program, so as to fully appreciate the RIVICE concept.

2 Module Descriptions

2.1 Border Ice

The state of the art in predicting the rate of growth of border ice is not well advanced. Therefore, several options are incorporated in RIVICE to offer the user flexibility. These options are, in increasing levels of complexity:

(1) A specification by the user of border ice width at each cross section at specific times during the winter simulation.

(2) A specification of a relationship between cumulative degree-days of freezing and total border ice width, entered for individual cross-sections, on the basis of known or observed conditions in the river under study, the user's judgement or the product of an externally devised methodology.

(3) Invoking of a computation of border ice growth based on meteorologic/hydraulic factors. Two alternative methodologies are incorporated for the user, as follows:

(i) A modified Newbury relationship (1968), which has been used with moderate success in Northern Manitoba:

$$W_b = mD_d \qquad \text{........ Equation 1}$$

$$m = \frac{a_1}{V^{b_1}} \qquad \text{........ Equation 2}$$

where:

W_b = total border ice width at a cross section (m)

m = coefficient to relate degree-days of freezing to border ice growth (m/°C-Day)

D_d = degree-days of freezing (°C-days)

a_1, b_1 = coefficients supplied by the user and based on observations of the river under study. Reasonably representative values for northern Manitoba conditions are a_1=0.054 and b_1=1.5

v = average velocity of flow at the cross section (m/s)

(ii) The method developed by Matousek (1984)

$$V_{sb} = \frac{\Phi_e}{1130(-1.1.-T_w)} - \frac{b_2 U_2}{1130} \qquad \text{... Equation 3}$$

where:

V_{sb} = maximum vertically averaged velocity of flow into which border ice advances laterally (m/s)

Φ_e = net heat flux per unit area due to heat exchange between water surface and the atmosphere (watts/m^2)

T_a = air temperature (°C)

If $0 > T_a > -12°C$

then

$$\Phi_e = -81+12T_a+3.2(0.8T_a-0.1)U_2+0.1(318+4.6T_a) \qquad \text{... Equation 4}$$

If $T_a < -12°C$

$$\Phi_e = -96+11T_a+3.2(0.7T_a-0.9)U_2+0.1(326+4.6T_a) \qquad \text{... Equation 5}$$

T_w = water temperature (°C)

b_2 = coefficient
= -0.9 + 5.8 log (open water width in metres)

U_2 = wind velocity at an elevation of 2 m above the water surface (m/s)

2.2 Ice Cover Initiation

The state-of-the-art in predicting bridging of moving ice in a channel is not considered sufficiently advanced to justify a detailed simulation of this process in RIVICE. This module has therefore been formulated as a user specification of ice cover initiation, in combination with a programmed check on border ice status and whether it closes the channel during each time step. The user is free to start an ice cover at any time(s) and at any location(s) during the simulation period.

2.3 Ice Cover Evolution

This module simulates the upstream advancement of an ice cover due to accumulation of incoming ice pans or floes, changes in thickness due to hydraulic forces and transport of ice under the cover, including effects of deposition and erosion.

(1) Leading Edge Progression

Accumulation of incoming ice at the leading edge(s) of the ice cover(s) can be represented in RIVICE by one of three optional methods:

(i) juxtaposition of the ice according to the following relationship (Pariset, 1966; Michel, 1971)

$$\frac{V}{\sqrt{gH}} = \sqrt{2\frac{(p-p_i)}{p}(1-e)\frac{t}{H}}\left(1-\frac{t}{H}\right) \qquad \text{........ Equation 6}$$

where:

V = mean velocity of flow in open water upstream of leading edge (m/s)

H = mean hydraulic depth in open water upstream of leading edge (m)

p = density of water (kg/m^3)

p_i = density of ice (kg/m^3)

e = porosity of ice pans/floes approaching leading edge (i.e. ratio of *volume of voids filled with water to the total volume of the ice pan* - user specified)

t = thickness of ice accumulation (m) which will form with the combination of V and H; this relationship only holds for **t/H** ratios less than ⅓, which is the limiting condition for juxtaposition.

(ii) An alternate relationship developed by Ashton (1971), which applies to individual ice blocks may be incorporated for optional use, usually in a spring breakup condition. This relationship is:

$$\frac{V}{\sqrt{gt\left(1-\frac{p_i}{p}\right)}}=\frac{2\left(1-\frac{t}{H}\right)}{\sqrt{5-3\left(1-\frac{t}{H}\right)^2}} \qquad \text{........ Equation 7}$$

where:

V = mean velocity (m/s)

g = acceleration of gravity (m/s$^{2)}$

t = ice floe thickness (m)

p_i = density of ice (kg/m^3)

p = density of water (kg/m^3)

H = mean hydraulic depth (m)

(iii) It has been observed that in conditions where ice approaches the leading edge in a steady stream of pans that the classic leading edge stability equations as defined by (i) and (ii) do not apply. In this case the ice cannot be drawn under but crushes against the leading edge. The user can represent this case, which results in a leading edge thickness of 0.15 m. Further thickening downstream of this edge would occur if shoving is shown to be necessary, as described in subsequent parts of this section.

(2) Thickening of Cover Due to Hydraulic Forces

An ice cover on flowing water is subjected to hydraulic forces which can cause deformation and thickening. The classic means of analyzing this has been with the "bell-curve" developed by Pariset, Hausser and Gagnon (1966). However, two disadvantages arise from direct use of the bell-curve:

- It can only represent the ice cover thickness and stability at a distance of several river widths from the leading edge.

- It represents the stability of a constant width channel, with constant velocity, etc., which rarely occurs.

A refinement to this concept which avoids the difficulties cited above has been used in RIVICE and is suited to computation by a computer program. It involves the incremental summation of computed forces on the ice cover in a step-mode beginning from the leading edge and advancing from cross-section to cross-section in the downstream direction. It computes:

(i) forces exerted by the flowing water on the ice cover:

- ○ hydrodynamic thrust on the leading edge (Michel, 1971)

$$F_t = \left(1 - \frac{d}{H}\right)^2 V_u^2 B H \frac{\gamma}{2g} \qquad \text{........ Equation 8}$$

where:

F_t = hydrodynamic thrust of the flow (N)

H = depth of water upstream of leading edge (m)

d = depth of flow under the leading edge (m)

V_u = velocity under the leading edge (this is a mean value across the width of the channel, in m/s)

B = width of ice cover (m)

γ = specific weight of water (9800 N/m^3)

g = acceleration due to gravity (m/s^2)

- hydraulic drag of the flow on the ice under-surface (Michel, 1971):

$$F_d = \left(\frac{\gamma d_t s n_i^{1.5}}{2 n_c^{1.5}} \right) A_{iw} \qquad \text{........ Equation 9}$$

where:

F_d = hydraulic frictional drag force (N)

γ = specific weight of water (9800 N/m^3)

S = slope of hydraulic grade line

n_i = Manning's roughness coefficient of the ice undersurface

n_c = Manning's roughness coefficient of the composite cross section

d_t = depth of flow under the ice cover (m)

A_{iw} = under-surface area of ice exposed to flow (m^2)

- the component of weight of the ice cover and the water contained in its voids, acting along the hydraulic gradient:

$$F_w = \gamma_i V_o S \qquad \text{........ Equation 10}$$

where:

F_w = gravitational force acting along the channel (N)

γ_i = specific weight of ice (9020 N/m^3)

V_o = volume of ice cover (including voids infilled with water) (m^3)

S = slope of hydraulic grade line

(ii) Force shed to the river banks includes cohesion of the ice cover to the banks and friction of the ice cover against the river banks.

The cohesion expression (Pariset, 1966) is given as

$$F_c = 2ctL \qquad \text{........ Equation 11}$$

where:

F_c = force of cohesion of ice to two river banks (N)

c = cohesion per unit area of ice/bank interface (Pa)

t = average thickness of ice cover between cross sections (m)

L = distance between cross sections (m)

The hydraulic forces exerted on the ice cover in the stream-wise direction create stresses in the ice which are spread laterally towards the riverbanks. The lateral stress results in a reaction of static friction at the bank, which acts as a stabilizing influence on the cover.

From Pariset (1966):

$$F_f = 2ftLK_1 \tan\phi \qquad \text{........ Equation 12}$$

where:

F_f = friction force on the ice along the river bank (N)

f = accumulative stress in the ice cover in the direction of flow (Pa)

K_1 = a coefficient equal to the ratio of lateral stress to longitudinal stress in the ice cover (a ratio less than or equal to 1.0)

$\tan\phi$ = tangent of angle of friction of ice/bank interface

L = distance between cross-sections (m)

t = average ice thickness between sections (m)

As the calculation proceeds downstream, the stress in the ice cover is determined from

$$S_i = \frac{(F_t+F_d+F_w-F_c-F_f)}{tW}$$ .... Equation 13

where:

S_i = stress in the ice cover (Pa)

F_t, etc = as defined above

t = ice thickness (m)

W = ice width (m)

If the stress exceeds the maximum resistance of the ice cover, shoving or telescoping of the ice must occur to attain the minimum required thickness. The resistance is determined from Pariset (1966):

$$F_{ir} = \gamma_i \left(1-\frac{\gamma_i}{\gamma}\right)\frac{t^2W}{2}K_2$$ .... Equation 14

where:

F_{ir} = internal resistance of ice cover (N)

K_2 = a coefficient greater than or equal to 1.0, a Rankine passive coefficient in solid mechanics

t = ice thickness (m)

W = ice width (m)

γ_i = specific weight of ice (9020 N/m^3)

γ = specific weight of water (9800 N/m^3)

The values of K, tan ϕ, and K_2 are key components of this procedure. The value of each is not known precisely, but it has been shown that the combination:

$$\mu = K_1 K_2 \tan \phi$$ .... Equation 15

is normally between 1.0 and 1.60 (Acres, 1986; Pariset, 1966; Beltaos, 1983; Beltaos, 1988). The value of the individual factors K_1, K_2, $\tan \phi$ is left to the discretion of the user, with default values of .18, 8.7 and .9, respectively.

The simulation of a shove is done by:

- thickening of the ice cover at an unstable location (i.e. stress in ice cover exceeds its interval resistance) to achieve a stable thickness; this may be restricted in any given time step by the maximum rate of movement of the ice as described below.

- reduction in ice volume at the leading edge to be equivalent to the volume required to thicken at the unstable location (a downstream "recession" of the leading edge results).

The volume of ice which is supplied to thicken the cover at an unstable location is limited by the maximum rate of movement of the ice cover, estimated to have a maximum speed equal to the average flow velocity:

$$V_M = V_s t_s W_s \Delta t$$ .... Equation 16

where:

V_M = maximum volume which can shove to an unstable location during a given time step, (m^3)

V_s = mean flow velocity at the unstable cross section (m/s)

t_s = ice thickness at unstable cross section before shoving occurs (m)

W_s = width of ice cover at unstable location (m)

Δt = time step (seconds)

(3) Cover Thickness Changes Due to Deposition/Erosion

If the user-selected algorithm for leading edge stability (see (1) above) indicates that ice will be drawn under with the flow, then ice transport under the cover is considered by the program. The ice-in-transport can deposit at locations where the velocities are low and cause a hanging dam. The characteristics of the deposition are not well defined, and three options are available to the user:

(i) A maximum velocity of deposition, whereby the incoming ice would deposit until the maximum velocity is exceeded, and then pass downstream to the next point of low velocity.

(ii) A treatment of the problem by a sediment transport approach, using the Meyer-Peter equation, which when adapted to the ice covered condition (Acres, 1980) is

$$3281\frac{V^2}{C^2} = 12.3d_i+0.84q_u^{\frac{2}{3}} \qquad \text{....... Equation 17}$$

where:

V = mean velocity under ice cover (m/s)

C = Chezy roughness coefficient for water passage ($m^{1/2}/s$)

d_i = characteristic dimension of ice fragments (m)

q_u = ice discharge per unit width under the cover weighed under water with apparent density 0.08

The main difficulty of this method is the determination of the appropriate dimension "d_i" for the problem being analyzed. The transport rate computed by the Meyer-Peter method will be no more accurate for ice transport than it is for sediment transport. However, it does acknowledge the concept that ice will have more tendency to deposit at higher velocities if the incoming ice volumes are high.

(iii) a densimetric Froude number (Tesaker, 1975)

$$F_r = \frac{V}{\sqrt{gH\frac{(p-p_i)}{p}}} \qquad \text{....... Equation 18}$$

where:

F_r = maximum Froude number at which deposition of ice will occur (user selected)

V = mean velocity of flow (m/s)

g = gravitational acceleration (m/s^2)

H = hydraulic mean depth below the ice under-surface (m)

p_i, p = density of ice and water respectively (kg/m^3)

d_i = dimension of ice particle (m)

Transport of ice under the ice cover is tracked by RIVICE from time period to time period. Movement is estimated to occur at the following velocity:

$$\mathbf{V_{ice} = V_{water} \times VFACTR} \qquad \text{........ Equation 19}$$

where:

V_{ice} = velocity of ice-in-transport at a specific location (m/s)

V_{water} = mean velocity of flow at that cross-section (m/s)

VFACTR = a user specified factor which gives the ratio of ice movement speed to the mean velocity of flow

Under some conditions such as increasing flows or large increases in ice thickness due to shoves, high velocities can occur under the ice cover. These high velocities would tend to erode the ice under-surface and pass the entrained ice downstream. Two means of representing this are included in the logic of RIVICE:

(i) A simple specification of the mean velocity above which erosion will occur.

(ii) Calculation of tractive force at the ice/water interface, using the formula

$$F_d = \gamma d_t S \qquad \text{........ Equation 20}$$

where:

F_d = tractive force (Pa)

γ = specific weight of water (N/m^3)

d_t = depth from water surface to ice under-surface (m)

S = friction slope

The user would specify the maximum allowable value, and erosion would be simulated by the model if it is exceeded at any cross section.

The erosion of the ice cover in both cases would be uniform over the bottom of the ice cover. This is a simplified representation of the real phenomenon whereby erosion occurs preferentially in parts of the cross section where the velocity is highest, and can result in grounding of ice in shallow areas.

Erosion is not allowed to completely eliminate the surface ice at any location during any time step. The ice cover thinning due to erosion is not allowed to cause thicknesses less than 0.15 m.

2.4 Ice Cover Breakup

Through this module the user is able either to specify the breakup of the ice cover in a selected reach, or to have the program identify breakup on the basis of shear stresses at the ice/bank interface (as determined by the Ice evolution Module) which may exceed a user specified limit, or on the basis of increases in water level above a user specified maximum. At present, this mode represents ice breakup as an instantaneous conversion of stationary ice into moving ice in transport on the surface of the river flow. Refinement of this may be required as testing of RIVICE proceeds.

2.5 Breakup Jams

This module is structured like The Ice Evolution Module (Section 2.3) in that it simulates accumulating ice at the leading edge of the unbroken cover, with thickening of the fragmented cover in response to the hydraulic forces which occur. Algorithms which are used to determine leading edge stability, ice cover stresses, etc., are as described for the Ice Evolution Module, and the program allows for different options and/or values of parameters in the breakup mode, as compared to the formation mode.

3 Conclusion

The RIVICE modules which control ice accumulation are presently in testing with the rest of the RIVICE program. While some refinements will be required, the methodology presented in this paper will form the basis for these modules. Future refinements will be possible as the knowledge of ice processes expands, and the program is applied by a variety of users.

References

Acres Consulting Services, Ltd., December 1980, "Behaviour of Ice Covers Subject to Large Daily Flow and Level Functions", for CEA.

Ashton, G., Editor, 1986, "River and Lake Ice Engineering", Water Resources Publications.

Beltaos, S., 1983, "River Ice Jams: Theory, Case Studies, and Applications", ASCE Journal of Hydraulic Engineering, Vol 109, No. 10.

Beltaos, S., August 1988, "Configuration and properties of a Breakup Jam", Canadian Journal of Civil Engineering, Vol. 15n, No. 4.

Matousek, V., 1984, "Regularity of the Freezing-up of the Water Surface", IAHR Ice Symposium Proceedings, Hamburg.

Michel, B., April 1971, "Winter Regime of Rivers and Lakes", U.S. Army Corps of Engineers Publication.

Newbury, R., 1986, "The Nelson River - A Study of Subarctic River Processes", Phd Thesis to Johns Hopkins University.

Pariset, Hausser and Gagnon, 1966, "Formation of Ice Covers on Rivers", ASCE Journal of Hydraulics Division, Vol. 92, No. HY6.

Tesaker, with note by Lavender, 1975, "Accumulation of Frazil Ice in an Intake Reservoir", Proceedings of IAHR Symposium on Ice Problems, Hanover.