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Accelerated ice growth in rivers

Darryl J. Calkins

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Solid ice growth rates due to the presence of frazil slush beneath the ice cover have been shown to be greater than the so-called static growth. The frazil slush reduces the effective heat of ice solidification and the frazil particles freeze into the interstitial water. Numerical schemes are presented which clearly show the effect of frazil ice porosity on ice cover growth rates and the numerical model using air temperature as the major input is compared with field data on ice thickness in a small river laden with frazil ice beneath its cover.		

ACCELERATED ICE GROWTH IN RIVERS

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INTRODUCTION

The growth of an ice cover, once it is formed, results from the continuing heat loss from the cover to the atmosphere. The thickening of the cover is often related to accumulated degree-days of freezing with an appropriate correction factor α for the geographic setting or heavy snow conditions. The prediction of the so-called static growth of the ice cover thickness can take the form $\eta_i = \alpha (\Delta T t)^{1/2}$ where η_i = ice thickness, $\alpha = 0.6$ to 0.9 , and $\Delta T t$ = the accumulated degree-days below freezing.

The effects of frazil ice deposits beneath an ice cover on the thickening of the solid ice cover have not been thoroughly analyzed. But Bengtsson (1978) reports ice thicknesses, due to frazil ice, up to 100% greater than those formed by normal static growth in a river in Sweden. This report considers the impact on the growth of the solid ice sheet due to frazil deposits beneath the solid ice cover. It compares the numerical scheme suggested in this study with field data collected on a river having approximately 1 m of frazil beneath a solid ice sheet.

ANALYSIS OF HEAT LOSS

Figure 1 gives a definition sketch of the problem. The heat flux from the moving water to the frazil ice deposition is given as

$$\phi_{wf} = h_{wf}(T_w - T_{wf}) \quad (1)$$

where h_{wf} is a heat transfer coefficient, T_w is the water temperature, and T_{wf} is the melting point of the ice water mixture, 0°C . Since the frazil ice deposition is maintained at 0°C , the temperature at the solid ice/frazil slush interface T_{fi} is also 0°C . Therefore, there is no heat transfer through the frazil slush to the solid ice; and until the frazil ice

is removed in some manner, there will be no heat transfer from the river water mass to the solid ice underside. Consequently, this convection heat term can be neglected in the analysis.

The thickening of the ice cover is then related to the amount of heat extracted by atmospheric sources. The heat flux ϕ_i and ϕ_s through ice and snow layers, assuming a linear temperature distribution through the respective thicknesses, can be represented, respectively, as

$$\phi_i = k_i \frac{T_{fi} - T_{is}}{\eta_i} \quad (2)$$

and

$$\phi_s = k_s \frac{T_{is} - T_{sa}}{\eta_s} \quad (3)$$

where k_i and k_s are the thermal conductivities of the ice and snow; η_i and η_s are the thicknesses of the ice and snow layers; T_{fi} is the frazil ice temperature; T_{is} is the ice/snow interface temperature; and T_{sa} is the snow surface temperature, which is $< 0^\circ\text{C}$.

The heat flux from the snow surface (neglecting evaporation or condensation) can be calculated in a similar manner to ϕ_{wf} through the use of a heat transfer coefficient h_{as} , such that

$$\phi_{sa} = h_{as}(T_{sa} - T_a) \quad (4)$$

where T_a is the air temperature. Since $\phi_i = \phi_s = \phi_{sa}$, the snow/ice and snow/air interface temperatures can be eliminated in eqs 2, 3, and 4, such that

$$\phi_i = \frac{T_{fi} - T_a}{(\eta_i/k_i) + (\eta_s/k_s) + (1/h_{as})} \quad (5)$$

PREFACE

This report was prepared by Darryl J. Calkins, Research Hydraulic Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

This study was funded under DA Program, *Ice Engineering*; Subprogram, *Ice Formation*; CWIS 31350, *Formational Processes of Frazil Ice*.

Dr. D. S. Sodhi and Dr. G. D. Ashton of CRREL reviewed the technical content of this report.

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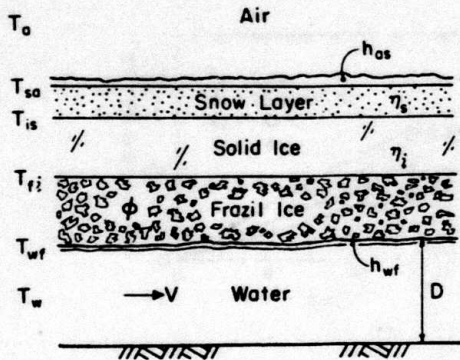


Figure 1. Definition sketch.

ICE COVER GROWTH

The thickening of the ice cover is governed by the energy balance at the solid ice/frazil slush interface. Since the heat flux to the solid ice from the river water is zero, the governing equation is

$$\phi_i = \rho_i \lambda \frac{d\eta_i}{dt} \quad (6)$$

where ρ_i is the ice density, λ is the latent heat of solidification, and $d\eta_i/dt$ is the rate of ice thickening. The heat of solidification is the energy required to change the phase of water from liquid to solid at 0°C .

Frazil ice slush comprises a mixture of individual ice crystals, mostly flocculated frazil discs, and water. The growth of solid ice in the presence of these frazil discs can increase substantially because the frazil ice crystals freeze into the interstitial water due to heat loss from the atmosphere. Since the frazil ice occupies a given percentage of a fixed volume, the amount of heat necessary to convert the ice-water mixture to ice is correspondingly reduced by the ratio of volume of water to the total volume of the mixture.

A correction for the latent heat of solidification for ice-water mixtures should be introduced. The correction is related to the porosity ϕ of the frazil ice suspended in the fluid, where the porosity is defined as the ratio of void volume (the water fraction) to the total volume. Consequently, eq 6 should be more appropriately written as

$$\phi_i = \rho_i \phi \lambda \frac{d\eta_i}{dt} \quad (7)$$

and combining it with eq 5 yields

$$\frac{T_{fi} - T_a}{(\eta_i/k_i) + (\eta_s/k_s) + (1/h_{as})} = \rho_i \phi \lambda \frac{d\eta_i}{dt} \quad (8)$$

which is very similar to the equations proposed by Assur and Weeks (1963) and Ashton (1978).

Because of the dependence of some parameters in the above equation on time (i.e., T_a , η_s and h_{as}), it is impractical to present the exact solution as one would be continually updating these parameters. An analytical integration is suggested such that

$$\Delta\eta_i = \frac{1}{\rho_i \phi \lambda} \frac{T_{fi} - T_a}{(\eta_i/k_i) + (\eta_s/k_s) + (1/h_{as})} \Delta t \quad (9)$$

NUMERICAL RESULTS

The prediction of ice thickness can be written as

$$\eta_i^{k+1} = \eta_i^k + \Delta\eta_i^k \quad (10)$$

where the superscript k is the increment of time. The values of various parameters have been assumed as follows: $\lambda = 3.34 \times 10^5$ J/kg, $\rho_i = 916$ kg/m³, $T_{sm} = 0^\circ\text{C}$, $k_i = 2.24$ W/m-deg and $\Delta t = 1$ day. Numerical schemes with idealized but realistic values for given meteorological conditions are given in Figures 2 and 3, and the effect of frazil ice slush on the ice covering thickening is quite apparent.

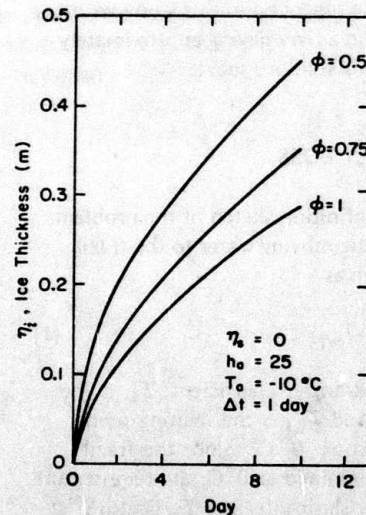


Figure 2. Ice growth for different frazil ice porosities.

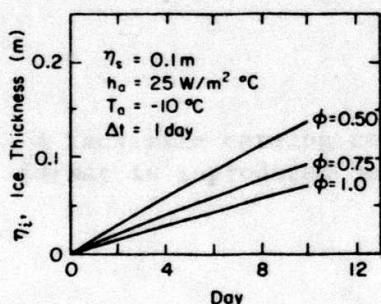


Figure 3. Ice thickness influenced by a combination of snow and frazil.

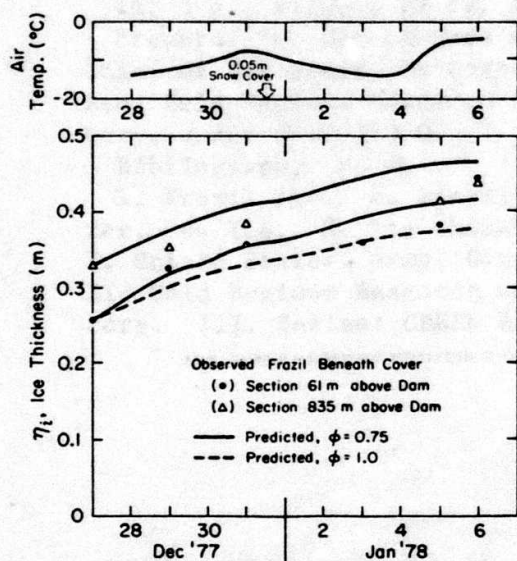


Figure 4. Ice thickness growth at Ottauquechee River, Quechee, Vermont.

Dean (1978) made field measurements on the porosity of frazil ice slush where the variations of frazil depth were from 2 to 12 m and the porosity values were 0.48 to 0.34, respectively. However, more information from the field is needed to confirm these values as well as observations of any changes that occur throughout the winter season.

FIELD VERIFICATION

To verify the above analysis, field data were chosen from a small river with frazil ice deposits

beneath the solid cover. Two sections were chosen that had detailed measurements over a 10-day period, with minimal snow cover. The average wind velocities over this 10-day period were less than 4 m/s. An average heat transfer coefficient ($25 \text{ W/m}^2 \cdot ^\circ\text{C}$) suggested by Ashton (1978) for open water conditions was used; and an average thermal conductivity of the snow was taken as 0.3 W/m-deg after Mellor (1976). The ice thickness measurements were resolved to 0.0032 m . The snow depth increment was taken as the measured value at a nearby snow course. The 10-day period began with no snow on the ice cover and with only one storm occurring on 31 December, with a snowfall accumulation of roughly 0.05 m .

The numerical scheme was run for two different sites on the Ottauquechee River, Quechee, Vermont. The first site was evaluated using $\phi = 1.0$ and $\phi = 0.75$; at the end of 10 days, the numerical scheme with $\phi = 0.75$ more nearly predicted the final growth, although the predicted value was low (Fig. 4). When the ice prediction scheme used $\phi = 1.0$, a significant underprediction of roughly 18% was noted. For the second site, using $\phi = 0.75$, the numerical method predicted a slightly greater ice thickness. The insulating effect on the snow cover is very evident in the field ice thickness data, but the numerical method does not reflect the significant decreased growth over this time period. Since neither the snow thickness nor its thermal conductivity was measured at the time on the river itself, there could be a substantial difference in values due to just snowdrifting.

The porosity of the frazil ice was not measured but, since the average frazil ice depth was less than 1 m, $\phi = 0.75$ appears a reasonable value at this time.

DISCUSSION

The prediction of ice thickness is paramount in trying to establish a safe ice sheet to support heavy loads. The growth of ice cover thickness is accelerated by frazil ice beneath the cover due to the reduction in the effective latent heat of solidification. The field data gathered by the author support this theory, as well as the data gathered by Bengtsson (1978) on two rivers in Sweden, where excesses of 0.12 m and 0.50 m were measured above the so-called *static growth* in rivers laden with frazil slush beneath the solid ice cover.

On the river where the excess ice growth exceeded 0.50 m, the so-called static ice growth was roughly 0.50 m. These two ice thickness measurements were roughly 40 m downstream of each other in a rather large pool. Just upstream of this pool was a long rapids section where the frazil ice was produced.

CONCLUSIONS

The effects of frazil ice deposits beneath a solid ice cover are very significant in increasing the solid ice thickness. The effective latent heat of ice solidification is reduced proportionally to the porosity of the slush ice beneath the cover. The increase in the amount of solid ice thickness, as shown in two very idealized examples in this study, can be roughly 50% to 90% depending on meteorological conditions. One set of field measurements from Sweden indicated a 100% increase in solid ice thickness caused by frazil ice slush.

Ice growth rates of the numerical model used and field data were compared; and the numerical model predicted the ice thickness after 10 days to within a reasonable accuracy, with less than 13% error for two sites studied. Although a more thorough field investigation is necessary to substantiate some of the physical constants of snow and ice, the results of this study clearly indicate the effect of frazil ice on solid ice growth rates.

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