CHAPTER 11

Modeling Ice-covered Rivers

HEC-RAS allows the user to model ice-covered channels at two levels. The first level is an ice cover with known geometry. In this case, the user specifies the ice cover thickness and roughness at each cross section. Different ice cover thicknesses and roughness can be specified for the main channel and for each overbank and both can vary along the channel. The second level is a wide-river ice jam. In this case, the ice jam thickness is determined at each section by balancing the forces on it. The ice jam can be confined to the main channel or can include both the main channel and the overbanks. The material properties of the wide-river jam can be selected by the user and can vary from cross section to cross section. The user can specify the hydraulic roughness of the ice jam or HEC-RAS will estimate the hydraulic roughness on the basis of empirical data.

This chapter describes the general guidelines for modeling ice-covered channels with HEC-RAS. It contains background material and the equations used. For information on how to enter ice cover data and to view results, see Chapter 6 and Chapter 8 of the HEC-RAS User's Manual.

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Modeling Ice Covers with Known Geometry

Ice covers are common on rivers during the cold winter months and they form in a variety of ways. The actual ways in which an ice cover forms depend on the channel flow conditions and the amount and type of ice generated. In most cases, river ice covers float in hydrostatic equilibrium because they react both elastically and plastically (the plastic response is termed creep) to changes in water level. The thickness and roughness of ice covers can vary significantly along the channel and even across the channel. A stationary, floating ice cover creates an additional fixed boundary with an associated hydraulic roughness. An ice cover also makes a portion of the channel cross sectional area unavailable for flow. The net result is generally to reduce the channel conveyance, largely by increasing the wetted perimeter and reducing the hydraulic radius of a channel, but also by modifying the effective channel roughness and reducing the channel flow area.

The conveyance of a channel or any subdivision of an ice-covered channel, K_i, can be estimated using Manning's equation:

$$K_i = \frac{1.486}{n_c} A_i\, R_i^{2/3} \tag{11-1}$$

Where: n_c = the composite roughness.
A_i = the flow area beneath the ice cover.
R_i = the hydraulic roughness modified to account for the presence of ice.

The composite roughness of an ice-covered river channel can be estimated using the Belokon-Sabaneev formula as:

$$n_c = \left(\frac{n_b^{3/2} + n_i^{3/2}}{2} \right)^{2/3} \tag{11-2}$$

Where: n_b = the bed Manning's roughness value.
n_i = the ice Manning's roughness value.

The hydraulic radius of an ice-covered channel is found as:

$$R_i = \frac{A_i}{P_b + B_i} \tag{11-3}$$

Where: P_b = the wetted perimeter associated with the channel bottom and side slopes

B_i = the width of the underside of the ice cover

It is interesting to estimate the influence that an ice cover can have on the channel conveyance. For example, if a channel is roughly rectangular in shape and much wider than it is deep, then its hydraulic radius will be cut approximately in half by the presence of an ice cover. Assuming the flow area remains constant, we see that the addition of an ice cover, whose roughness is equivalent to the beds, results in a reduction of conveyance of 37%.

Separate ice thickness and roughness can be entered for the main channel and each overbank, providing the user with the ability to have three separate ice thicknesses and ice roughness at each cross section. The ice thickness in the main channel and each overbank can also be set to zero. The ice cover geometry can change from section to section along the channel. The suggested range of Manning's n values for river ice covers is listed in Table 1.

The amount of a floating ice cover that is beneath the water surface is determined by the relative densities of ice and water. The ratio of the two densities is called the specific gravity of the ice. In general, the density of fresh water ice is about 1.78 slugs per cubic foot (the density of water is about 1.94 slugs per cubic foot), which corresponds to a specific gravity of 0.916. The actual density of a river ice cover will vary, depending on the amount of unfrozen water and the number and size of air bubbles incorporated into the ice. Accurate measurements of ice density are tedious, although possible. They generally tell us that the density of freshwater ice does not vary significantly from its nominal value of 0.916. In any case the user can specify a different density if necessary.

Table 11.1
Suggested Range of Manning's n Values for Ice Covered Rivers

The suggested range of Manning's n values for a single layer of ice

Type of Ice	Condition	Manning's n value
Sheet ice	Smooth	0.008 to 0.012
	Rippled ice	0.01 to 0.03
	Fragmented single layer	0.015 to 0.025
Frazil ice	New 1 to 3 ft thick	0.01 to 0.03
	3 to 5 ft thick	0.03 to 0.06
	Aged	0.01 to 0.02

The suggested range of Manning's n values for ice jams

Thickness ft	Manning's n values Loose frazil	Frozen frazil	Sheet ice
0.3	-	-	0.015
1.0	0.01	0.013	0.04
1.7	0.01	0.02	0.05
2.3	0.02	0.03	0.06
3.3	0.03	0.04	0.08
5.0	0.03	0.06	0.09
6.5	0.04	0.07	0.09
10.0	0.05	0.08	0.10
16.5	0.06	0.09	-

Modeling Wide-River Ice Jams

The wide river ice jam is probably the most common type of river ice jam. In this type, all stresses acting on the jam are ultimately transmitted to the channel banks. The stresses are estimated using the ice jam force balance equation:

$$\frac{d\left(\overline{\sigma}_x\, t\right)}{dx} + \frac{2\,\tau_b\, t}{B} = \rho' g\, S_w\, t + \tau_i \tag{11-4}$$

where: $\overline{\sigma_x}$ = the longitudinal stress (along stream direction)
t = the accumulation thickness
τ_b = the shear resistance of the banks
B = the accumulation width
ρ' = the ice density
g = the acceleration of gravity
S_w = the water surface slope
τ_i = the shear stress applied to the underside of the ice by the flowing water

This equation balances changes in the longitudinal stress in the ice cover and the stress acting on the banks with the two external forces acting on the jam: the gravitational force attributable to the slope of the water surface and the shear stress of the flowing water on the jam underside.

Two assumptions are implicit in this force balance equation: that $\overline{\sigma_x}$, t, and τ_i are constant across the width, and that none of the longitudinal stress is transferred to the channel banks through changes in stream width, or horizontal bends in the plan form of the river. In addition, the stresses acting on the jam can be related to the mean vertical stress using the passive pressure concept from soil mechanics, and the mean vertical stress results only from the hydrostatics forces acting in the vertical direction. In the present case, we also assume that there is no cohesion between individual pieces of ice (reasonable assumption for ice jams formed during river ice breakup). A complete discussion of the granular approximation can be found elsewhere (Beltaos 1996).

In this light, the vertical stress, $\overline{\sigma_z}$, is:

$$\overline{\sigma}_z = \gamma_e t \tag{11-5}$$

Where:

$$\gamma_e = 0.5\,\rho'\,g\left(1-s\right)\left(1-e\right) \tag{11-6}$$

Where: e = the ice jam porosity (assumed to be the same above and below the water surface)

s = the specific gravity of ice

The longitudinal stress is then:

$$\overline{\sigma}_x = k_x\,\overline{\sigma}_z \tag{11-7}$$

Where:

$$k_x = \tan^2\left(45 + \frac{\varphi}{2}\right) \tag{11-8}$$

φ = the angle of internal friction of the ice jam

The lateral stress perpendicular to the banks can also be related to the longitudinal stress as

$$\overline{\sigma}_y = k_1\,\overline{\sigma}_x \tag{11-9}$$

Where: k_1 = the coefficient of lateral thrust

Finally, the shear stress acting on the bank can be related to the lateral stress:

$$\tau_b = k_0 \overline{\sigma}_y \tag{11-10}$$

Where:

$$k_0 = \tan\varphi \tag{11-11}$$

Using the above expressions, we can restate the ice jam force balance as:

$$\frac{dt}{dx} = \frac{1}{2k_x \gamma_e}\left[\rho' g S_w + \frac{\tau_i}{t}\right] - \frac{k_0 k_1 t}{B} = F \tag{11-12}$$

where: F = a shorthand description of the force balance equation

To evaluate the force balance equation, the under-ice shear stress must be estimated. The under-ice shear stress is:

$$\tau_i = \rho g R_{ic} S_f \tag{11-13}$$

Where: R_{ic} = the hydraulic radius associated with the ice cover
S_f = the friction slope of the flow

R_{ic} can be estimated as:

$$R_{ic} = \left(\frac{n_i}{n_c}\right)^{1.5} R_i \tag{11-14}$$

The hydraulic roughness of an ice jam can be estimated using the empirical relationships derived from the data of Nezhikovsky (1964). For ice accumulations found in wide river ice jams that are greater than 1.5 ft thick, Manning's n value can be estimated as:

$$n_i = 0.069 H^{-0.23} t_i^{0.40} \tag{11-15}$$

and for accumulations less than 1.5 ft thick

$$n_i = 0.0593 H^{-0.23} t_i^{0.77} \tag{11-16}$$

where: H = the total water depth
t_i = the accumulation thickness

Solution Procedure

The ice jam force balance equation is solved using an approach analogous to the standard step method. In this, the ice thickness at each cross section is found, starting from a known ice thickness at the upstream end of the ice jam. The ice thickness at the next downstream section is assumed and the value of F found. The ice jam thickness at this downstream cross section, t_{ds}, is then computed as:

$$t_{ds} = t_{us} + \overline{F}\,L \qquad (11\text{-}17)$$

Where: t_{us} = the thickness at the upstream section
L = the distance between sections

and

$$\overline{F} = \frac{F_{us} + F_{ds}}{2} \qquad (11\text{-}18)$$

The assumed value and computed value of t_{ds} are then compared. The new assumed value of the downstream ice jam thickness set equal to the old assumed value plus 33% of the difference between the assumed and computed value. This "local relaxation" is necessary to ensure that the ice jam calculations converge smoothly to a fixed value at each cross section. A maximum of 25 iterations is allowed for convergence. The above steps are repeated until the values converge to within 0.1 ft (0.03 m) or to a user defined tolerance.

After the ice thickness is calculated at a section, the following tests are made:

1. The ice thickness cannot completely block the river cross section. At least 1.0 ft must remain between the bottom of the ice and the minimum elevation in the channel available for flow.

2. The water velocity beneath the ice cover must be less than 5 fps (1.5 m/s) or a user defined maximum velocity. If the flow velocity beneath the ice jam at a section is greater than this, the ice thickness is reduced to produce a flow velocity of approximately 5 fps or the user defined maximum water velocity.

3. The ice jam thickness cannot be less than the thickness supplied by the user. If the calculated ice thickness is less than this value, it is set equal to the user supplied thickness.

It is necessary to solve the force balance equation and the energy equation (eq. 2-1) simultaneously for the wide river ice jam. However, difficulties arise because the energy equation is solved using the standard step method, starting from the downstream end of the channel and proceeding upstream, while the force balance equation is solved starting from the upstream end and proceeding downstream. The energy equation can only be solved in the upstream direction because ice covers and wide river jams exist only under conditions of subcritical flow. To overcome this incompatibility and to solve both the energy and the ice jam force balance equations, the following solution scheme was adopted.

A first guess of the ice jam thickness is provided by the user to start this scheme. The energy equation is then solved using the standard step method starting at the downstream end. Next, the ice jam force balance equation is solved from the upstream to the downstream end of the channel. The energy equation and ice jam force balance equation are solved alternately until the ice jam thickness and water surface elevations converge to fixed values at each cross section. This is "global convergence."

Global convergence occurs when the water surface elevation at any cross section changes less than 0.06 ft, or a user supplied tolerance, and the ice jam thickness at any section changes less than 0.1 ft, or a user supplied tolerance, between successive solutions of the ice jam force balance equation. A total of 50 iterations (or a user defined maximum number) are allowed for convergence. Between iterations of the energy equation, the ice jam thickness at each section is allowed to vary by only 25% of the calculated change. This "global relaxation" is necessary to ensure that the entire water surface profile converges smoothly to a final profile.