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ICE JAMS IN A SMALL RIVER AND THE HEC-RAS MODELING*

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ABSTRACT: This paper describes a model of a 3.06km long river reach between two small reservoirs under both open flow and ice covering conditions for different operational settings of the stoplogs in the downstream reservoir. The HEC- RAS model developed by the Hydrological Engineering Center of US Army Corps of Engineers was used to compare different approaches in terms of flow velocity, water level and the Froude number. The impacts of heavily vegetated main channel and floodplain on ice accumulations were investigated. And it is shown that this vegetation plays a significant role in the formation of river ice jam during winter period and thus the vegetated channel has strong influence on ice flooding. In addition, the paper explores the impact both of the operation of the stoplogs during the winter period and the presence of the downstream dam on the accumulation of ice jam along this river reach.

KEYWORDS: heavily vegetated channel, HEC-RAS model, ice-covering condition, ice jams, water level

1. INTRODUCTION

An ice jam is an accumulation of fragmented ice or frazil that restricts flow. Ice jams pose problems across Canada and are often accompanied by dramatic increases in water level due to their blockage effects. Surface ice jams and frazil ice jams are two basic types of ice jams.

An ice jam reduces the flow conveyance of the channel through its blockage effect and the increase in flow resistance. The reduced conveyance causes an increase in water level, as shown in Fig. 1 (Sui, 2002a). Moreover, the backwater effect of an ice jam on water level increases with increasing jam thickness. The increase in jam thickness, in turn, increases the channel slope and flow velocity. In shallow sections, a grounded ice jam can be initiated by submergence and blockage caused by ice floes. The grounding is serious problem since it can lead to a larger and faster rise in the river level than a non-grounding jam. When the leading edge of an ice cover or jam progresses to the section with high flow velocity, incoming ice floes will submerge and become entrained on the underside of the cover.

In a river with rapids, open water often remains continually in these sections. These open water reaches can produce large quantities of frazil ice that is subsequently supplied to the underside of the ice cover downstream during the winter. In this way, the entrained ice will be transported and accumulate underneath the ice cover to form so-called frazil jams. The formation of a frazil jam will further block the flow and thus further increase the water level.

Overall, the distribution and thickness of the frazil jam are governed by both the ice supply and the ice transport capacity of the flow (Shen and Wang 1995; Shen et al. 2000; Sui et al. 2000; 2002b; Wang et al. 1995). The ice transport capacity decreases with a reduction of either flow velocity or channel slope. Whenever the ice supply exceeds the transport capacity of the flow, frazil accumulation will occur; and by contrast, whenever the ice supply is less than the transport capacity of the channel, the existing frazil jam will erode.

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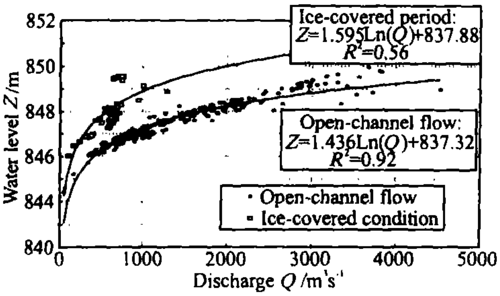

Fig. 1 Impact of ice on water level at the Hequ Gauging Station/ Yellow River

The most common locations for the formations of ice jam and hanging dam include places with reduced or non-uniform velocity. Obvious locations where this occurs include where the river enters a lake or reservoir, at river bends or when the flow encounters a deep pool. The formation of jams can be particularly dramatic when these features adjoin an upstream stretch of rapids where large quantities of frazil are produced.

Due to their essential nature, ice problems are invariably complicated. The following are just a sample of the factors which must be considered in the studies of river ice problems:

(1) River morphology, including channel slope, channel geometry, channel networks, shoals, riverbed roughness, vegetation in channel and floodplain, etc.

(2) Hydraulic conditions, including the flow velocities, water depth, water surface profile, influence of downstream.

(3) Meteorological factors including air temperature, water temperature, wind speed, snowfall, etc.

(4) Many other factors, including things like human interventions, ground heat input, etc.

From data on the St. Lawrence River in Canada/US, it was found that a consistent value of maximal Froude number, equal to 0.09, is of great importance. In particular, field observations and subsequent analyses at the Hequ Reach of the Yellow River in China showed that the frontal edge of ice jam can extend further upstream only if the Froude number *(Fr)* of flow at the upstream end of the jam is less than 0.09, and that the ice jam can not propagate upstream if $Fr > 0.09$ (Sui et al. 2002b).

Foltyn and Tuthill (1996) claimed that there was a critical hydraulic condition for retention of ice cover/ jam behind an ice boom (conceptually, ice retention behind the ice boom is a kind of blockage freezing-up process). Based on their extensive research and practical experience, they proposed maximum $Fr = 0.08–0.12$, maximum surface water velocity $v = 0.60–0.76$ m/s.

In fact, the ice jam formation with surface blockage process and congestion process depends also on the dimension of the floes in addition to the hydraulic factors such as the water surface flow velocity and *Fr* .

Flow under the ice cover/ ice jams is quite different from that under open flow conditions due to the nature of the shear stress caused by this additional solid surface and its wetted perimeter. The impacts of the ice cover/ jams should be considered in the course of the hydraulic simulation of the channel flow. The variation in water level and the discharge of a gradually varying flow in a river with ice cover/ jams can be described by the continuity equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{1}$$

and the momentum equation:

$$\rho\frac{\partial Q}{\partial t} + \rho\left[\frac{2Q}{A}\frac{\partial Q}{\partial x} - \frac{Q^2}{A^2}\frac{\partial A}{\partial x}\right] +$$

$$\rho g A\frac{\partial H_e}{\partial x} + \left[P_i\tau_i + P_b\tau_b\right] = 0 \tag{2}$$

where Q is the discharge, A the flow area, $H_e = Z_b + t_i + h$ the water level, Z_b the bed elevation, h the depth of flow, t_i the equivalent thickness of the ice cover/ ice jam, $\rho_i\theta/\rho$, P_b and P_i are wetted perimeter formed by the channel bed and the ice cover/ ice jam respectively, τ_b and τ_i are shear stress at the channel bed and the ice cover/ jam respectively, x, t are distance and time, respectively.

To solve these two equations for discharge and water level, it is necessary to know the equivalent ice jam thickness t_i and the resistance coefficient n_i of ice jam. In general, both the ice jam thickness t_i and the resistance coefficient n_i of ice jam are considered as the function of time and space. To solve these two equations, a finite-difference method, such as the four point implicit finite-difference scheme developed by Potok and Quinn, can be used.

The finite-difference form of the continuity equation for a riverreach could be written as

$$\frac{1}{\Delta x}[\varphi(Q_d^{n+1}-Q_u^{n+1})-(1-\varphi)(Q_d^n-Q_u^n)]+$$

$$\frac{1}{2\Delta t}[T_d(H_d^{n+1}-H_u^n)+T_u(H_d^{n+1}-H_u^n)]=0 \tag{3}$$

where the subscripts d and u represent downstream and upstream ends of the reach, respectively, the subscripts n and $n+1$ indicate the time levels at t and $t+\Delta t$, T the top width, φ temporal weighting factor.

Similarly, the finite-difference form of the momentum equation:

$$2\bar{Q}(\bar{A}\Delta x)[\varphi(Q_d^{n+1}-Q_u^{n+1})+(1-\varphi)\cdot$$

$$(Q_d^n-Q_u^n)]+g\bar{A}/\Delta x[\varphi(H_d^{n+1}-$$

$$H_u^{n+1})-(1-\varphi)(H_d^n-H_u^n)]-$$

$$\bar{Q}^2/(\bar{A}^2\Delta x)+\{\varphi[T_d\cdot(H_d^{n+1}-Z_d)-$$

$$T_u(H_u^{n+1}-Z_u)]+(1-\varphi)\cdot$$

$$[T_d(H_d^n-Z_d)-T_u(H_u^n-Z_u)]\}+$$

$$4.417n_e^2\bar{Q}|\bar{Q}|\bar{P}^{4/3}/\bar{A}^{7/3}+\frac{1}{2\Delta t}\cdot$$

$$[(Q_d^{n+1}-Q_d^n)+(Q_u^{n+1}-Q_u^n)]=0 \tag{4}$$

where

$$\bar{Q}=\frac{1}{2}[\varphi(Q_d^{n+1}+Q_u^{n+1})+(1-\varphi)(Q_d^n+Q_u^n)] \tag{5}$$

$$\bar{A}=\frac{1}{2}[\varphi(H_u^{n+1}T_u+H_d^{n+1}T_d)+(1-\varphi)\cdot$$

$$(H_u^nT_u+H_d^nT_d)-(Z_u+\frac{\rho_i}{\rho}t_i)T_u-$$

$$(Z_d+\frac{\rho_i}{\rho}t_i)T_d] \tag{6}$$

in which, Z_u and Z_d are the reference elevation of the upstream and downstream ends, respectively, ρ and ρ are mass density of water and ice respectively.

However, considering the complexities of a natural channel, many boundary conditions must be simplified in order to solve these equations. For this specific 3.06km long river reach with heavily vegetated channel/flood plain, the HEC-RAS model was used to simulate the flow and ice accumulation during the winter period.

2. GEOGRAPHICAL LOCATION AND ICE REGIMENS

The 3.06km long river reach (CD-TH Reach) considered in this study runs between two dams. The upstream section is at the Clendennan Dam (CD-Dam) and downstream section ends at the Thornbury Dam (TH-Dam). The Beaver River itself runs northeast, flowing through the village of Clarksburg before discharging into the Nottawasaga Bay downstream of TH Dam in the province of Ontario, Canada. Within this CD-TH Reach, this river is approximately 20m wide.

The upper part of this river reach is steep with limestone cliffs along both sides of the main channel. The lower section of the valley is mild and meanders through sand, silt and gravel deposit.

A site visit was conducted on Feb. 1, 2001. This inspection showed many features of significance to ice formation. For example, it was found that along the CD-TH Reach there are several pronounced bends, with one occurring within the backwater region of the TH dam and having a particularly sharp curve. As Fig. 2 indicates, the complex fluvial geomorphology is characterized by heavily vegetated channel/flood plains sections with some shoal reaches, resulting in a complicated set of flow conditions.

By late in Nov. or early in Dec. temperature will cause frazil ice to be produced in this river. The river typically breaks up by late March or early April.

Ice conditions along the CD-TH Reach were observed during site visit. Both reservoirs were ice-covered. The CD reservoir provides a depository for the frazil ice coming from the upper river reach. It helps to reduce the severity of ice jam formation in this river reach by reducing the ice supply to downstream. Velocity and ice thickness measurements were made in the vicinities of Sect. 757 (distance in meter from the downstream TH Dam) and the upper end of the TH reservoir

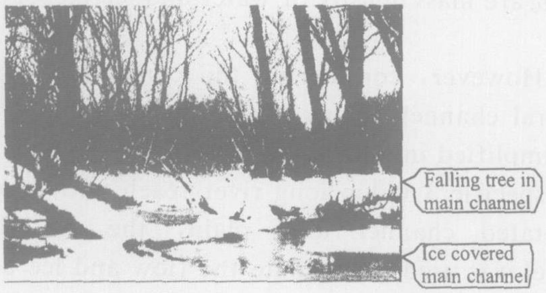

Fig. 2 Main channel/flood plain with tree/falling tree/bush (Beaver River, in Ontario, Canada)

(Sect. 857). No frazil accumulation was found under ice cover in the TH reservoir.

Using the survey of the channel profile, it is found that there is a very shallow section at Sect. 757 having pool sections both upstream and downstream of this section. The pool upstream of this section will help to initiate the surface jam formation. The pool downstream provides a section for ice accumulation. These conditions, together with the heavily woody condition at the site, indicate that an ice jam will often be initiated near Sect. 757. As a direct result, ice from upstream will be collected in this section and will not easily be transported downstream because of the low flow velocities and the influence of the trees/bushes.

The flow velocities in open area and under ice cover in the vicinity of Sect. 1400 were measured during site visit:

(1) Open water condition: the flow velocity of open water at the frontal edge of ice cover was 1.4m/s at the depth of 0.1m below the water surface, 0.95m/s at the depth of 0.2m, 0.66m/s at the depth of 1m and 0.51m/s at the depth of 2m (near the river bottom).

Ice covered condition: the flow velocity under ice cover (10m downstream from the frontal edge of ice cover) is 0.46m/s immediately under ice cover (the thickness of ice cover is about 0.3m), 1.22m/s at 0.5m from the bottom of ice cover and 0.8m/s at 1.5m from the bottom of ice cover (0.2m above river bottom).

In total, 7 holes were used to measure the flow velocities under ice cover in the TH reservoir region (at Sect. 549). The flow velocity under ice cover in the TH reservoir is less than 0.50m/s (main channel). In addition, no frazil ice was found under ice cover in the reservoir.

Hydraulically, at least, the trees in the channel/flood plain would promote the formation of an ice cover by reducing the flow velocity (see Fig. 2). Both the ice covers and the trees/bushes would collect the ice from the upstream. Thus, this area appears to be the most likely location of initiation and deposition of ice jam. Not surprisingly, then, ice formation and jamming frequently occur in this river reach and often lead to ice flooding, such as those occurred in Jan. 1996 and Jan. 1997. The winter of 1996 was one of the coldest in recent years and 1997 was a warmer winter with a severe cold spell late in the season. Both of these conditions were favourable for ice jam flooding. It is likely that during the winter of 1996, the ice cover persisted for longer, and the cause of the flooding was largely due to the contribution of a frazil jam. The 1997 jam was caused by the jam initiated in the vicinity of the wooded reach, and the water level was backed-up due to the heavy accumulation both here and upstream from this.

3. HEC-RAS MODELLING

Currently, it is impossible to precisely simulate a river system under ice-covered conditions due to the complexity of a natural river system and the associated meteorological conditions. However, approximations are possible and helpful, and this is the approach adopted here. In particular, the HEC-RAS software can be used not only to simulate the flow velocity and water level under open flow conditions, but also to determine the thickness of ice jam if an initial cover is given. The entered value of the initial ice thickness represents the minimum allowable thickness of ice cover. This thickness was selected on the basis of field observations, which showed that no cross section had a minimum thickness less than 0.1m here.

For this specific site, the ice jams could be caused by one or more of the following processes:

(1) Ice accumulation may occur in the backwater region of the TH reservoir. This could initiate the ice jam due to low flow velocity in the backwater region. If the velocity of incoming ice is less than the diving velocity of ice blocks, the ice cover (ice jam) will progress upstream with corresponding increases in water level.

(2) The meandering channel with shoals and heavily vegetated channel/floodplain along this river reach is likely the main reason for the formation of an ice jam. The ice jams generally initiate at the location where an ice bridge forms. This

specific river reach, having as it does trees and bushes in channel/ floodplain, creates favourable conditions for the formation of an ice bridge and thus of an ice jam that will then propagate upstream.

For this simulation, the Manning roughness coefficient (n) is one of the key input parameters. Considering the features of this river reach, the Manning roughness coefficient for main channel and flood plain was assumed to be 0.035 and 0.06, respectively.

The simulations were conducted for different discharges including $10m^3/s$, $20m^3/s$, $60m^3/s$ and $100m^3/s$. According to the field observation of the Canadian Weather Service, the maximum instantaneous discharge in this river reach (at Clarsburg gauging station) from 1957 to 1988 was $96.3m^3/s$ on 13 March 1977. This value is less than $97.8m^3/s$ (quantity le of the 100 year return period)

The following four different simulation alternatives have been chosen in order to cover all aspects considering ice condition and operations of stoplogs of the downstream TH dam (removal or in place) under ice-covering conditions:

Case 1: open flow condition (remove all stoplogs),

Case 2: open flow condition (all stoplogs in place),

Case 3: ice covering condition (remove of all stoplogs),

Case 4: ice covering condition (all stoplogs in place).

Figures 3, 4 and 5 summarized the results of HEC-RAS simulation with respect to the simulated water surface elevation, the flow velocity and Fr.

Case 2 (open channel conditions, all stoplogs in) is the most critical for flow under open channel conditions, similarly, Case 4 (ice-covering condition, all stoplogs in) is the critical condition for the flow under ice-covering conditions. However, Case 4 is not an allowable operation alternative with the TH Dam since all stoplogs must be removed out in winter.

The simulations show that the Fr of stream flows under open channel condition downstream from Sect. 857, namely the reservoir region, is generally less than 1.0, as shown in Fig. 5. This means that the open flow along this river reach is generally subcritical flow, since $Fr < 1.0$. However, hydraulic jump may be formed near Sect. 1000, since the simulated Fr is about 1.

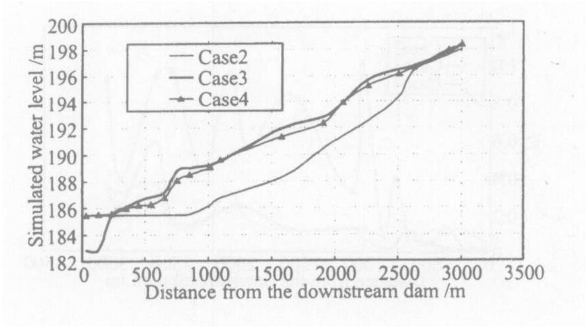

Fig. 3 Simulated water level along river reach ($Q = 20m^3/s$)

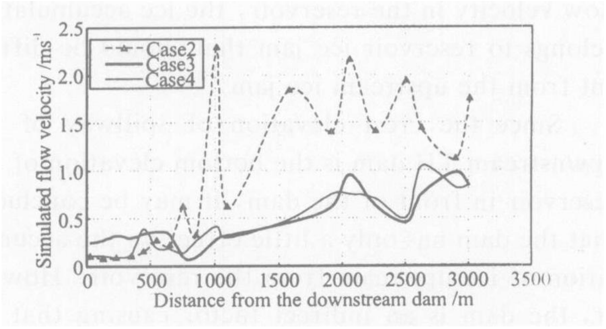

Fig. 4 Flow velocity along river reach ($Q = 20m^3/s$)

By comparing the simulation results between Case 3 and Case 4 (as shown in Figs. 3 and 4), it is found that the operations of stoplogs (moved out or in place) do not play a significant role on the accumulation of ice upstream of the TH reservoir, since the water level, flow velocity and the Fr under both conditions are approximately identical. Upstream from the Sect. 1097, the flow velocity and Fr increase significantly. As shown in Figs. 6(a) and 6(b), relatively more ice accumulates in the reservoir if all of stoplogs are removed out during winter period. Conceptually at least, this is reasonable, since the removal of the stoplogs increases the flow velocity and Fr in the reservoir due to the decrease in water depth.

As shown in Figs. 6(a) and 6(b), near Sect. 857 there is a deep pool that is one of the most possible sites for formation of ice jam. In addition, heavily vegetated shallow channel and floodplain between Sect. 549 and Sect. 857 should help to stabilize the formed ice jam upstream. This wide shallow section should be caused by the deposition of sediment in the backwater region of the reservoir. The impacts of existing trees and bushes in the channel and flood plain along this river reach on the accumulation of ice jam might be similar to the "steel in concrete".

Downstream of the Sect. 857, because of low flow velocity in the reservoir, the ice accumulation

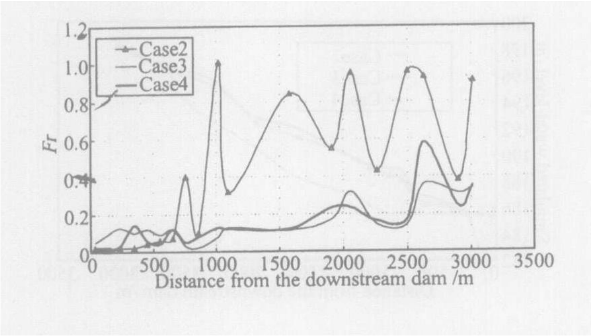

Fig. 5 Froude number along river reach ($Q = 20m^3/s$)

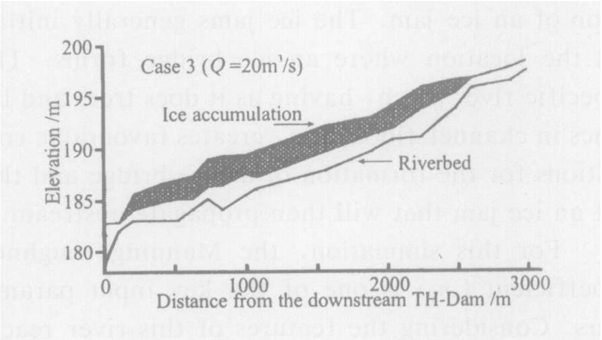

Fig. 6(a) Simulated accumulation of ice along the river reach (Case 3, $Q = 20m^3/s$)

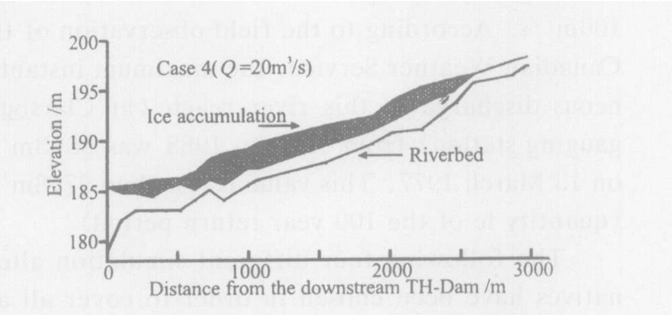

Fig. 6(b) Simulated accumulation of ice along the river reach (Case 4, $Q = 20m^3/s$)

belongs to reservoir ice jam that should be different from the upstream ice jam.

Since the crest elevation of spillway of the downstream TH dam is the bottom elevation of the reservoir in front of the dam, it may be concluded that the dam has only a little effect on the accumulation of ice upstream from the reservoir. However, the dam is an indirect factor causing that ice problem along this 3.06km long river reach, because the dam should be responsible for the deposition of sediment in the backwater region and thus the formation of the deep pool there.

Without decommissioning of the TH dam, the channel improvement may be the possible measure for reducing the flood potentials from ice jams along this river reach, such as removal of the trees and bushes in the main channel and flood plain. The clearing of the heavily vegetated section may enable the channel to transport the ice from upstream to the TH reservoir. Of course, this might have to be countered with other erosion control measures that the vegetation is currently performing.

4. CONCLUSIONS

Key features of channel/flood plain have been shown to play an important role on the formation and accumulation of ice cover/jam along a 3.06km long heavily vegetated river reach between 2 small reservoirs. Using the HEC-RAS model, the accumulation of ice jam and the associated hydraulic parameters, such as the water level, flow velocity and *Fr* , have been simulated and compared for different operational conditions and alternatives. The results show that this specific river reach is prone to the occurrence of ice jam problems because of its steep slope and irregular topography. The most important reason for the formation of ice jams in this river reach is the sections that are favourable to the initiation of ice jams, such as the wooded channel and flood plain as well as deep pool upstream of this section. The winter operation can be adjusted by adding or removing stoplogs at the TH dam has been shown not to affect the formation of ice jam in the CH-TH reach. The section in the vicinity of Sect. 757 is the location where an ice jam will form and collect most of the ice from upstream because of the heavily vegetated channel/floodplain and deep pool, and thus causes upstream water levels to rise. However, the dam is likely an indirect factor that causes that ice problem along this 3.06km long river reach, because the dam is likely responsible for the deposition of sediment in the backwater region and thus the formation of the deep pool in the backwater region of the TH reservoir.

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