SURGES RELEASED BY ICE JAMS

by

I. Joliffe and R. Gerard

Department of Civil Engineering
University of Alberta
Edmonton, Alberta

INTRODUCTION

Ice jams are important features of northern hydrology. Water levels caused by these events often far exceed the rarest open water floods. Ice jams can form and fail rapidly and in doing so, generate surges that travel downstream and upstream causing large and rapid increases in water level, as documented by Gerard (1975, 1979). Although there has been considerable study of the steady state features of an ice jam, this important unsteady behaviour had been largely neglected until recently. Henderson and Gerard (1981) presented analytical solutions describing events following sudden failure and reformation of relatively 'steep' jams on large rivers, and showed that the solutions provided a reasonable description of the surge released by failure of an ice jam documented by Doyle (1977) on the Athabasca River near Fort McMurray, Alberta. Beltaos and Krishnappan (1981) numerically simulated the failure of the same jam with good results. In particular they showed the influence of jam length and channel friction on the surge that would pass the town.

Despite the apparent success of the above analyses several questions remain. The first concern is whether the fragmented ice released by the jam influences the surge--in the above analyses it had been assumed it didn't. Other concerns are the influences of the jam and channel characteristics on the surge. The preliminary investigations described in this presentation, therefore, had two parts:

(i) a laboratory study to investigate whether the ice released with the surge modifies the surge characteristics, and

(ii) a numerical study to assess the possible influence of jam length and stream slope and resistance on the surge characteristics.

ICE-SURGE INTERACTION

A series of physical model tests was conducted to investigate the interaction of ice and surge released by an idealised ice jam failure. These tests were designed to answer two questions:

(i) Does the ice in the jam significantly alter flow conditions immediately after ice jam failure?

(ii) Does the ice modify the profile of the resulting surge as it moves downstream?

In this test series two parameters defining the ice jam geometry were varied: the ratios of ice cover thickness, t, to upstream depth (from zero to unity), and upstream to downstream flow depths. In all tests a constant volume of artificial ice was used. The ice cover length, therefore, varied inversely with cover thickness.

One test configuration is shown in Figure 1a. The ice jam was formed by placing a sluice gate in the flume and then placing artificial ice on the upstream side. The flume was 1.2m wide, with a length of 12m downstream of the sluice gate and 7m upstream. The artificial ice was polyethylene pellets. Ice jam failure was modelled by sudden removal of the sluice gate.

Figure 2 shows depth hydrographs recorded 150 mm upstream of the sluice gate. This test had an initial upstream depth of 300 mm, a downstream depth of 100 mm, and the ice thickness was varied from zero to 115 mm.

Results for no ice agreed well with predictions using classic dambreak theory, including the effect of the downstream flow depth. The predicted depth is indicated in Figure 2.

The 85 mm ice thickness test gave the lowest, and the 55 mm thickness the highest, flow depth after jam failure. The 115 mm thickness test gave a depth close to that for the 'no-ice' test. As there was no clear trend, it was concluded the ice presence in these tests did not significantly modify flow conditions immediately after ice jam failure.

Because the ice is transported at the average flow velocity, which is significantly slower than the surge celerity, it was felt the presence of ice in the flow should not influence surge propagation. This is confirmed by the typical profile shown in Figure 1b. Consequently, the usual unsteady flow equations can be used to predict surge propagation.

INFLUENCE OF JAM PROFILE, SLOPE AND FRICTION

The equations for unsteady gradually varied flow in a channel of arbitary shape and cross-section are:

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

and

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial Y}{\partial x} = gA(S_o - S_f) \tag{2}$$

where A = flow cross-sectional area, g = gravitational acceleration, Q = discharge, S_o = channel slope, S_f = frictional slope, t = time, x = distance and y = flow depth.

The first equation is the continuity equation derived by equating the net inflow rate into a channel element to the rate of change of storage within the element. The second equation, the momentum equation, is derived from a force balance analysis of the same channel element.

In the derivation of these equations it is assumed the water surface profile is gradually varying. Consequently, they should not be applied across a surge front like that shown in Figure 1b. However, real ice jam failures rarely, if ever, produce such step profiles and the gradually varied assumption is reasonable. For example, as mentioned above, Beltaos and Krishnappan (1982) found that a numerical model, using these equations, gave good prediction of events following an ice jam failure on the Athabasca River upstream at Fort McMurray, an event that was also well modelled by the simple dam break theory (Henderson and Gerard, 1981).

Although much more complex, using equations (1) and (2) to predict events following an ice jam failure has several advantages over the simple dam break theory:

(i) The important effects of channel slope and frictional resistance can be included in the analysis.

(ii) The effects of various jam profiles and lengths can be investigated.

In the simple analysis, it is assumed that the jam is infinitely long in a horizontal channel.

Several mathematical methods are available for solving the finite difference forms of the above equations. For reasons outlined in Joliffe (1982) the method selected used a Newton-Raphson iteration procedure.

This numerical algorithm was used to analyse events following the sudden release of the assumed "ice jam profile" shown in Figure 3. It simply follows the M2 profile caused by a step change in waterway roughness from 0.23 to 8 m in a prismatic rectangular channel of slope 0.001 with a flow of 326 m^3/s. The situation, therefore, had a significant channel slope, and frictional resistance, and represented a very "flat" ice jam, features that are in direct contrast to the assumptions involved in the simple dam break analysis.

In the analysis it was assumed open water existed downstream of the "jam" and that the jam failed instantaneously. Figure 4 presents calculated depth profiles at 4 and 6 hours after jam failure, while Figures 5 and 6 present dimensionless envelopes of the maximum predicted flow depths and velocities. The depth profiles show very little wave crest subsidence: after travelling 60km, the peak had subsided only 0.5m. The wave is, therefore, behaving much like a kinematic wave. This result is to be expected because the baseflow Froude number is 0.37, which is high for natural rivers. The depth predicted by simple dam break analysis is 3.16m, compared to 4.62m by the complete unsteady analysis.

Figure 7 presents depth-time histories at two locations along the channel, at the initial toe location and at a dimensionless distance of 1.9 downstream; x is the distance downstream of the toe of the jam and L is the length of the M2 profile. The downstream hydrograph should have a steeper rising limb, but steepening of the hydrograph has been masked, in the solution, by the effect of a large weighting coefficient used to ensure numerical stability of the solution procedure.

The results of these tests show that, for the configuration chosen, the parameters of slope, frictional resistance and jam profile have a significant effect on the resulting surge. In particular, and in contrast to the simple dam break analysis, the calculated wave was found to display little subsidence of the crest. It is apparent, therefore, that the simple analysis establishes a lower bound for flow depths and an upper bound for velocities. To assume no subsidence of the crest as the floodwave propagates downstream would give an upper bound on flow depths. Where the actual depths lie between these bounds depends upon the channel slope, roughness and jam profile.

CONCLUSION

This preliminary investigation has indicated that:

(i) In the absence of large friction at the banks, the ice in an ice jam has little influence on flow behaviour following sudden jam failure, and

(ii) The simple dam-break analysis should only be relied on when the jam conditions approximate the assumptions involved in the analysis i.e. small channel slope and frictional resistance, and a steep jam toe.

ACKNOWLEDGEMENT

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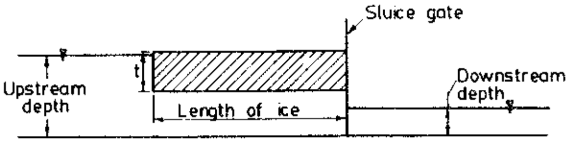


a) Initial profile

b) Resulting surge

Fig 1. Laboratory experiments

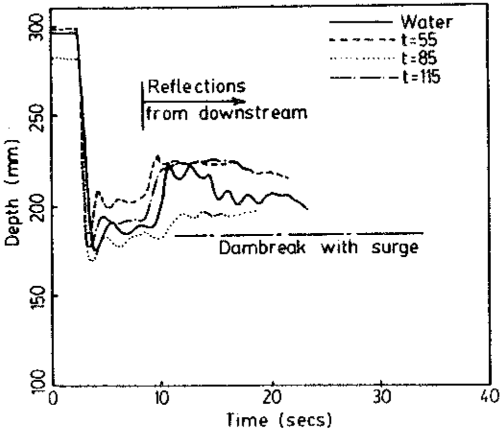


Fig 2. Observed and predicted surges

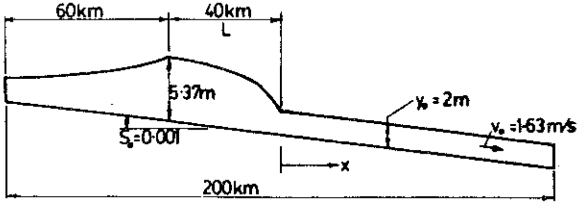


Fig 3. Jam profile used in numerical experiment

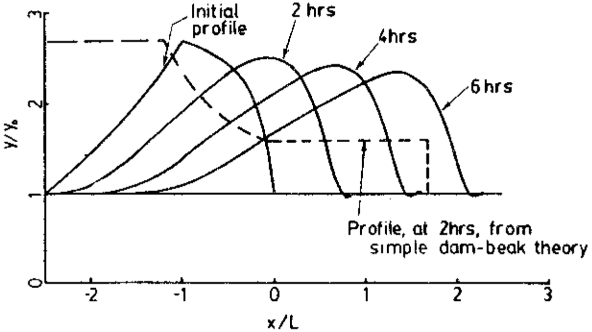
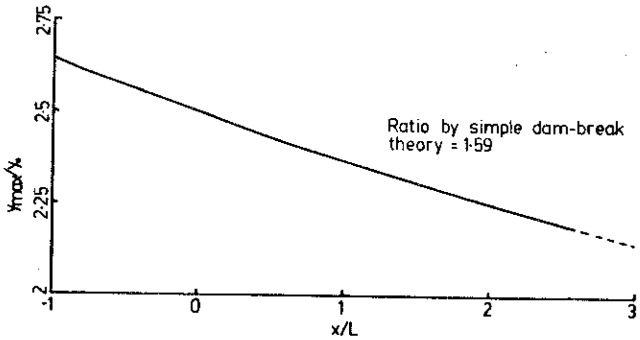
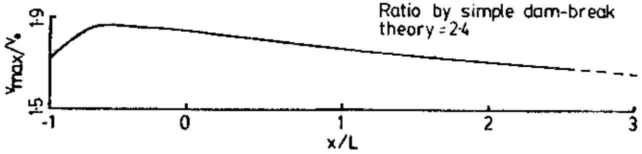


Fig 4. Variation of profile with time and distance



Ratio by simple dam-break theory = 1·59

Fig 5. Envelope of maximum flow depth



Ratio by simple dam-break theory = 2·4

Fig 6. Envelope of maximum flow velocity

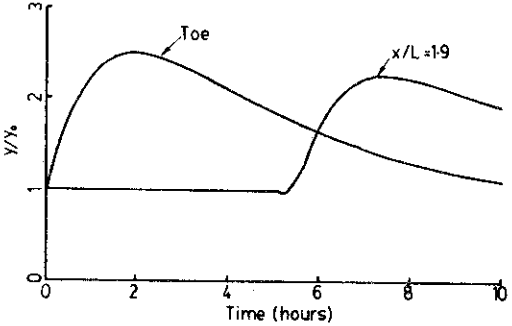


Fig 7. Depth hydrographs downstream of jam