145-2102-09

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Proceedings of the 5th Workshop on Hydraulics of River Ice/Ice Jams

92064

June 1988
Winnipeg, Manitoba

ISN NO. 0-921020-99-6

A PRELIMINARY STUDY OF SCOUR UNDER AN ICE JAM

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ABSTRACT

While the potential for scouring of a river bed during an ice jam event has often been cited as a cause for concern in association with pipeline crossings, bridge piers and other hydraulic structures, almost nothing is known about the subject. Significant changes in the river bed might also influence the formation of the jam itself and the water levels that result. This paper describes preliminary flume experiments to examine the effects of a floating accumulation of ice on a movable bed channel. The experiments consisted of establishing a uniform free-surface open channel flow just below the threshold of bed motion, and then installing artificial ice jams of assumed geometries and monitoring the resulting scour patterns.

INTRODUCTION

The influence of an ice cover on an alluvial system involves a complex interaction between the ice cover, fluid flow, sediment, and bed geometry. The presence of an ice cover roughly doubles the wetted perimeter of a wide channel, which in turn affects the magnitude and distribution of velocities and the boundary and internal shear stresses. In the case of rigid bed channels, variations in channel geometry exert a strong influence on the formation of an ice cover or ice jam. For a movable bed channel, however, the formation of an ice cover may also modify the channel geometry. Significant changes in channel geometry could, in turn, influence the formation of the jam itself and the water levels that result.

While the potential for scouring of a river bed during an ice jam event has often been cited as a cause for concern in association with pipeline crossings, bridge piers, and other hydraulic structures (for example Mercer and Cooper, 1977; Gerard, 1984; IAHR, 1986), almost nothing is known about the subject. This may be due in no small part to the difficulty of documenting such an occurrence. For open water events the maximum scour typically develops on the rising limb of a flood hydrograph and the eroded area may be refilled on the falling stage. While ice-related scour should also follow this general trend, it is likely to be further influenced by the period of maximum ice thickness. Thus, measurements of bed geometry after ice-out may not reflect the true magnitude of scour.

Lacking effective remote-sensing techniques, documentation of ice jam thickness and river bed geometry requires personnel access on the jam. Due to safety considerations this is often not possible, particularly for break-up events. In addition, effective documentation of bed scour requires measurements of the river geometry prior to the event. Given the complexities of ice jam formation and our limited capabilities for predicting the occurrence and severity of ice jams, field documentation of scour due to ice jams has not been attempted in the past. Further, the relatively infrequent opportunity to document jams at a particular site (usually not more than once a year to once in several decades) dictates that, while field data are invaluable, scour investigations may be limited to analytical and laboratory studies for at least the near future.

This paper describes some preliminary experiments in a laboratory hydraulic flume of scour under assumed local ice accumulation geometries. Due to a lack of field data, many assumptions had to be made as to the character of such a situation. The primary objective was to gain an understanding of some of the processes at work as a guide to planning future work.

BACKGROUND

Although ice-jam induced scour is frequently cited as a potentially significant problem, only one report could be found that dealt with it in any detail. That study, by Mercer and Cooper (1977), examined the potential for ice-induced scour in connection with several gas pipeline crossings proposed for the Mackenzie, Liard, and Peel rivers. Mercer and Cooper developed two numerical models to estimate scour: one for the period of break-up jam formation and another for jam release.

For the case of jam formation, Mercer and Cooper (1977) considered the hydraulic conditions that result in a jam propagating upstream or thickening in place. They suggest that lengthening jams do not present an erosional problem, and that it is only for the relatively limited conditions where thickening occurs that jams have the potential to cause severe scouring of the bed. These limits corresponded to the Pariset et al. (1966) criteria for jam stability and a Froude number greater than 0.08 so that incoming ice floes will contribute to thickening of the jam.

The initial pattern of scour under an ice jam proposed by Mercer and Cooper is shown in Figure 1. They suggested that while general scour would occur under the entire length of the jam, the most severe scour would occur at the upstream end of the jam where flow velocities are increased due to the constriction of flow by the suddenly decreased flow depth. Further, they assumed that the maximum scour depth that could occur was equal to the submerged ice thickness, since at that point the under-ice depth and velocities would match upstream values. Beyond the toe of the jam, reduced flow velocities would result in deposition of sediment eroded under the jam.

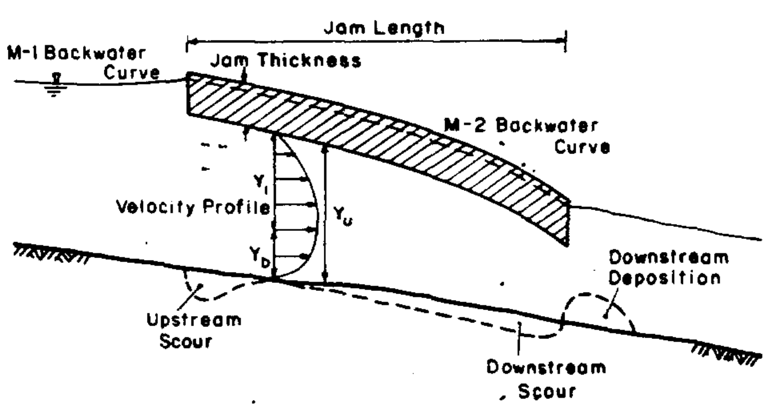

Figure 1. Proposed pattern of scour under ice jam (from Mercer and Cooper, 1977).

Following the release of a jam on the Mackenzie River, Mercer and Cooper (1977) observed that the flow slowly accelerated, reaching an estimated peak velocity in excess of 7.5 m/s after 30 minutes. While noting the significant potential for sediment transport during such an event, Mercer and Cooper nonetheless concluded that the potential for scour was much greater during the growth of an ice jam and put most of their effort into that phase. The results of their unsteady flow model showed that, following release, the location of maximum flow velocities propagated rapidly upstream from the jam location. Since this would indicate higher sediment transport rates upstream of the jam location, they concluded that rather than further deepening any scour holes that developed while the jam was in place, the surge would tend to fill them in. Even though a jam can be the generating agent for a potentially damaging flood wave, we will not consider it further here since it would appear that the ice itself has little influence on flow behavior following the sudden release of a jam (Joliffe and Gerard, 1982).

In a somewhat related study of scour due to large organic debris, Beschta (1983) conducted a flume study in which tree trunks were simulated by a variety of cylinders placed normal to the flow at several relative depths across the full width of flow. The objective of the study was to examine the influence of fallen trees on the development of scour holes to enhance fish habitat. The model cylinders were suspended at depths ranging from having their bottoms in contact with the gravel bed to only partial submergence in the water. Due to their cylindrical shape and large relative dimension (diameter/depth up to 0.45) the resulting scour was due in large part to a deflection of the flow against the bed, especially for tests with fully submerged cylinders.

Beschta found that the maximum scour depth for a given cylinder submergence increased nonlinearly with water discharge. Scour depths initially increased quickly with water discharge and then asymptotically approached a maximum, but the scour hole length continued to increase within the range of discharges tested. As scour continued during an individual test or the distance between the cylinder and bed was increased between tests, the longitudinal distance to the point of maximum scour depth increased (as might be anticipated from an analysis of flow conditions as a simple jet deflection).

Beschta also found that the deflection of a submerged jet against the bed was able to cause severe scour even when the mean values of the near-bed velocity components would indicate little or no transport. He attributed this apparent increase in transport capacity to locally enhanced levels of fluid turbulence, as indicated by gravel particles being lifted vertically from the bed and then subsequently saltating or rolling along the bed. This could be significant to ice processes in shallow streams or where a locally thickened ice cover comes near to the bed.

The maximum recorded scour depths for conditions where the water level was approximately level with the top surface of the cylinders was as much as 1.5 times the cylinder diameter. Beschta noted, however, that field data showed scour depths several times greater than the tree diameters. He attributed the difference to the smooth, perfectly cylindrical models in contrast to non-cylindrical trees with rough bark and protruding limbs. The same might be said for ice jams whose roughness can vary with block size and that exhibit significant local thickness variations.

EXPERIMENTAL APPROACH

An initial problem in designing a physical process model of ice-induced scour was how to represent the jam itself. Although ice jams can be classified according to several important characteristics, perhaps the most telling distinction is between freeze-up and break-up events. During freeze-up, water discharge tends to be relatively constant, and jam formation typically occurs through the gradual accumulation of incoming frazil ice. In contrast, break-up jams are normally highly unsteady events. When an ice cover breaks up, generally in response to a rising hydrograph, the release of storage sends a surge of water and ice downstream until it encounters a thicker, stronger section of ice cover or reaches a slower-moving river reach. Beyond these traits, freeze-up jams are typically dominated by the transport characteristics of the water flow (although internal collapse can occur), while for break-up events shoving and internal collapse of the ice jam structure are common, and hydraulic transport of discrete ice pieces is of less importance.

In either case, the jam thickness varies both along the length of the jam and within an individual cross section. The geometry of an ice jam, however, tends to be highly site-specific and variable from year to year. In the case of a break-up jam, thickness variations within a cross section tend to be random and unpredictable (Beltaos and Moody, 1986) and, with the possible exception of replicating a specific, documented event, there appears to be little basis for modeling anything other than a mean ice thickness. In the case of hanging dam formation during freeze-up, the deposition of incoming ice is significantly affected by the hydraulic transport characteristics of the flow, with maximum ice accumulation thicknesses occurring within the main thread of the water flow (Shen and Van de Valk, 1984). On rivers with sufficient frazil production, such deposits can extend to the bed, leaving only a fraction of the river cross section open to pass the flow. Since these variations are highly site-specific, however, they could only be employed in a scaled physical model of a specific site.

Along the length of a jam, relatively large variations in accumulation thickness are possible. When viewed on customary profile drawings with the elevation scale magnified greatly relative to horizontal distance, it is easy to envision a deflected jet condition similar to the previously discussed tests by Beschta (1983). However, a review of measured profiles for either freeze-up or break-up conditions shows the variation of ice thickness with distance to be very slight. Figure 2 from Beltaos and Dean (1981) shows a large hanging dam formation on the Smoky River in Alberta. Three years of data at that site indicated bottom slopes of the ice cover on the order of 0.1 m/m or less. Similarly, the data of Shen and Van de Valk (1984) for the St. Lawrence River showed slopes of 0.03 m/m or less, and the data of Deck (1984) for the Allegheny River in Pennsylvania showed a leading edge accumulation slope of about 0.005 m/m.

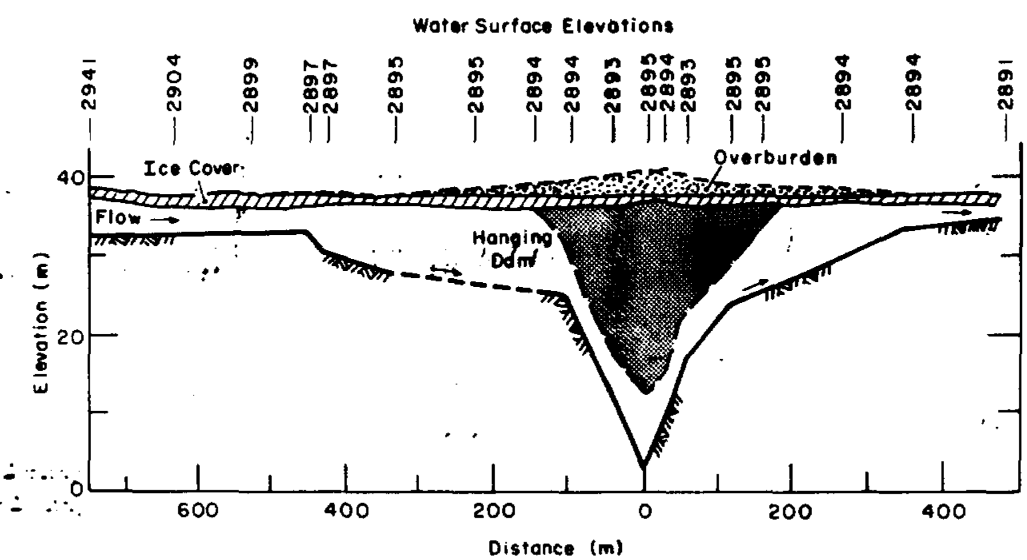

Figure 2. Longitudinal profile of hanging dam on Smoky River (from Beltaos and Dean, 1981).

Break-up jams show even milder longitudinal variations in thickness. Figure 3 from Beltaos and Moody (1986) for the Thames River in Ontario shows a variation in thickness on the order of 0.0002 m/m excluding the toe region. Data by Calkins (1978) and Wuebben and Stewart (1978) for two small rivers in Vermont show longitudinal thickness variations of 0.0003 to 0.0009 m/m. Thus, it would appear that

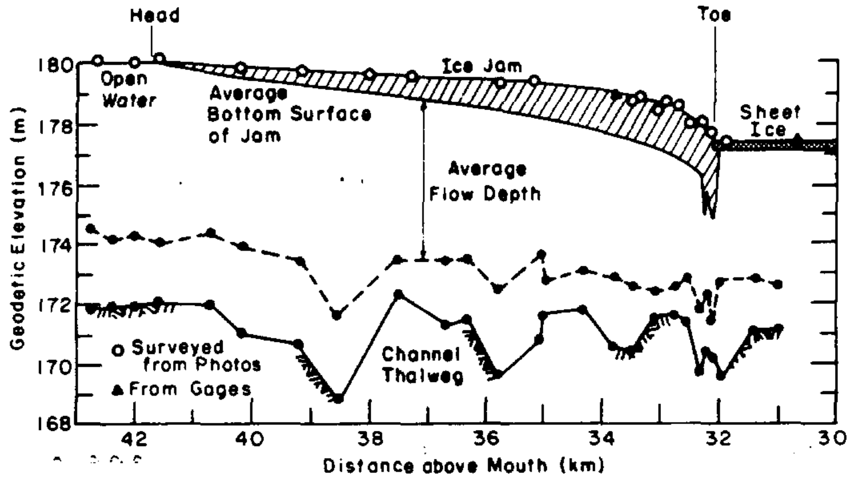

Figure 3. Longitudinal profile of breakup jam (from Beltaos and Moody, 1986).

for most jams the thickness varies relatively slowly over significant river lengths. While this variation can be significant for hydraulic and sediment transport processes, it would appear to be less than that required to deflect flow against the bed as a scouring jet as in the case of the experiments by Beschta (1983). Exceptions might include the toe region of a jam, partially grounded jams, or some very thick hanging dam formations.

While it might be possible to represent some of the variations in ice accumulation thickness in a scaled physical model of a specific ice jam site, there appeared to be little justification for selecting a particular trend of variation for a generic, physical process model. In view of the relatively mild variations in ice thickness discussed above, it was decided to run a series of tests with a model jam of uniform thickness. The bulk of the jam was represented by a floating plywood box that could be incrementally weighted to achieve submergence depths from approximately 5 to 20 cm. Along the centerline of the box, holes were drilled at 15-cm intervals and fitted with removable plugs to allow velocity and depth measurements.

To avoid the severe flow disturbance caused by a vertical jam face, a wedge was added to the leading edge that sloped at approximately 30 degrees to the water line. The model jam was freely floating and rested against a downstream ice cover made of 5-cm-thick Styrofoam. Depending on the submergence of the plywood box, this left a vertical step from the bottom of the box to the bottom of the Styrofoam that resulted in a separation zone with reverse flows.

Experiments were conducted in a 36-m-long recirculating flume that is 1.2 m wide and 0.6 m deep. The sediment bed was composed of a uniform 0.45 mm quartz sand that was smoothed and leveled parallel to the metal bed of the flume. In the initial series of tests, uniform flow was then established for free-surface conditions at or below the threshold of motion. This condition constitutes clear water scour, normally the most severe case. A qualitative run was also made at a flow rate generating general sediment transport in the flume to examine the difference in scour patterns relative to the clear water case.

The ice cover and jam (at minimum submergence) were then placed on the surface, and water velocity and the elevation of the water surface and bed were documented. The ice jam was then incrementally submerged and scour allowed to develop until steady state was reached. Velocities and elevations were documented and the ice jam submerged further until either the sand scoured to the metal bed of the flume or the dam could not be further submerged. Thus, for a constant water discharge and depth, the ice jam was incrementally thickened and the variation in scour documented.

To examine the potential for scour beneath a localized ice feature (such as a blunt leading edge, the toe of a jam, or a large tipped ice flow), a second series of tests was conducted using simple geometric shapes attached to the underside of a freely floating ice cover made of 5-cm-thick Styrofoam. The shapes included square, triangular, and semicircular elements with submerged depths of 7.6 and 15 cm that extended across the full width of the flume. The tests were conducted in a flume 90 cm wide and 7.3 m long with flow depths ranging from 20 to 60 cm. The bed of the flume was covered with a horizontal bed of the same sand described above. The development of scour was documented by profiling the same bed at several intermediate time steps and, after scour had reached equilibrium, velocity profiles were collected at several locations along the centerline of the flume.

RESULTS

Figure 4 shows the longitudinal pattern of bed geometry and velocity profiles that occurred for a run conducted with a water discharge of 0.076 cm/s, an initial open water depth of 30 cm, and a jam submergence of 13 cm. Flow conditions upstream of the jam were below the threshold of motion so that the bed remained undisturbed to some point under the wedge portion of the jam where the velocity was sufficiently increased and transport began. From that point the bed elevation dropped rapidly, at roughly the angle of repose until a depth was reached that provided flow velocities near the threshold of motion. Beyond the end of the jam, the reduced thickness of the Styrofoam ice relative to the jam section provided a deep flow section that could not sustain transport. Sediment eroded from beneath the jam quickly deposited out in a single massive pile as shown in Figure 4. Further downstream, the bed elevation and form remained unchanged from its open water condition.

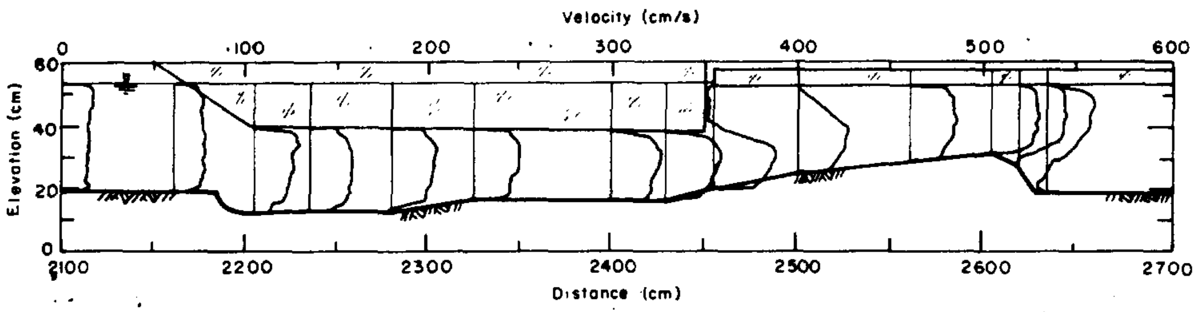

Figure 4. Scour patterns and velocity under a uniform depth model ice jam.

The results indicate that the maximum scour depth occurs near the leading edge of the jam where increased transport capacity first develops. At any point downstream of this initial scour hole the rate of erosion is reduced due to the increased rate of sediment influx from upstream. Given sufficient time, scour will progress downstream until a relatively uniform, but lowered, bed develops until the toe of the jam is approached. Apparently in response to the large sand deposit downstream, the transport rate just upstream of the toe of the jam was reduced by the local bed slope change leading up to that downstream deposit. In the case of a thickened jam toe, this may be counteracted by a local increase in transport capacity so that this transition occurs slightly farther downstream. For tests at higher flow rates in which there was sediment transport upstream of the jam, the general pattern of erosion and deposition was similar except that the transition from the upstream sand bed to the bottom of the scour hole was more gradual and the sand deposit downstream of the jam was shallower and longer.

The results of the tests for scour at very local ice features are summarized in Figure 5. The abscissa reflects the Froude number of the flow depth, which ranged from 0.15 to 0.4. As might be expected, the relatively streamlined semicircular elements resulted in the smallest scour depths while the vertical-faced, square elements caused the greatest relative scour. It is interesting to note that the scour depths can exceed the depth of the obstruction for Froude numbers greater than about 0.1.

In the previous sections we have discussed the effects of a thickened ice cover or a localized ice feature on bed scour. However, what are the effects of an ice jam on sediment transport in general? In an earlier section it was pointed out that based on published measurements of ice jam thickness, the rate of thickness

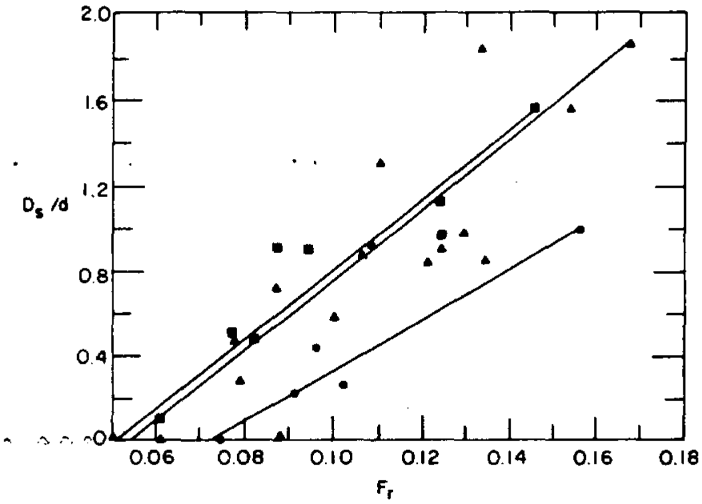

Figure 5. Variation in maximum scour depths under submerged, local model ice features.

along the length of a jam is relatively slight. Disregarding highly local features or very shallow streams, the prospect of deflecting the flow against the bed appears remote. The prospect of scour might then be addressed in terms of the effect of an added surface boundary on flow depths and velocities.

For jams containing an equilibrium reach, it is reasonable to examine the effect on sediment transport by examining a uniform flow relation such as the Manning's equation. Assuming a wide rectangular channel, the normal flow depth can be found as:

$$Y_o = [\,(Qn)/(BS^{0.5})\,]^{0.6} \tag{1}$$

where Q is the water discharge, n is Manning's roughness coefficient, B is the channel width, and S is the channel slope.

A similar expression can be written for the ice-covered case, but the hydraulic radius becomes $Y/2$ under an ice cover due to a doubling of the wetted perimeter. This results in the under-ice flow depth, Y_i:

$$Y_i = 1.32\,[\,(Qn_c)/(BS^{0.5})\,]^{0.6} \tag{2}$$

where n_c is the composite roughness of the ice-covered channel. Assuming that discharge and channel width are unchanged, we can see that the ratio of under-ice depth to free surface depth is:

$$Y_i / Y_o = 1.32 \, [\, n_r / S_r^{0.5} \,]^{0.6} \tag{3}$$

where n_r is the ratio of ice-covered composite roughness to free surface roughness, and S_r is the ratio of ice-covered to free surface slope. While Manning's equation is intended for uniform flow conditions and the slope of the system should not be allowed to change in equation 3, it may be used to examine trends in system behavior.

Equation 3 shows that, for an ice-cover roughness equal to the bed roughness, and unchanging slope, the addition of an ice cover results in a depth increase of 32 percent. A similar analysis shows that the mean under-ice velocity is reduced to 76 percent of the equivalent open-water value and average boundary shear to 66 percent of that for a free surface. Since the transport of sediment at the bed is highly sensitive to the applied shear stress, the above analysis would indicate a reduction in sediment transport under an ice cover. This conclusion is supported by the laboratory data for uniform flows under ice covers of Sayre and Song (1979), Lau and Krishnappan (1985), and Wuebben (1986).

Assuming that the supply of sediment from upstream of the ice cover is unchanged, this reduction in transport under the ice would indicate that sediment deposition should occur. In fact, in tests by Wuebben (1986) where the upstream sediment discharge remained constant between free surface and ice covered conditions, deposition did occur at the upstream end, resulting in a steepening of the bed slope. This change in bed slope, along with changes in bed form geometry and resistance to flow, resulted in relatively smaller increases in flow depth due to the addition of the ice cover than would be expected for conditions of constant slope.

It would appear that for jams containing an equilibrium reach, it is conceivable to induce deposition rather than erosion when there is an incoming sediment load to develop uniform flow; however, the increase in depth will be less than indicated by equation 3. For a very short ice cover or localized thickness variation, the change in water depth could be slight and a thick ice accumulation could lead to scour. The data in Figure 5 reflect a very local change in ice thickness that acts as a flow constriction or even a flow deflector for high Froude numbers. As a result, scour hole dimensions could easily exceed the size of the obstruction causing the scour. Even the results using the uniform depth artificial jam, such as those in Figure 4, reflect the case of a short, thick jam with minimal increases in water depth. As a result, that artificial jam acted largely as a flow constriction and resulted in bed scour until velocities under the jam decreased to the threshold of motion.

With increasing jam length upstream of the toe, the additional resistance to flow would cause depth to increase while water velocity and transport capacity would decrease. Since the distance required to achieve uniform flow is short for very steep rivers and goes to infinity as the slope approaches zero, this would imply that a mildly sloped river could be susceptible to bed erosion over relatively longer distances than a steep river.

SUMMARY

The potential for scour under an ice jam was reviewed based on a preliminary set of laboratory data. It appears that scour potential may vary significantly depending on the rate at which ice thickness changes with distance along the jam and the overall length of the jam. For an abrupt thickening, such as the toe of a jam or a large tilted ice floe, significant scour may occur due to a deflection of flow against the bed. For the bulk of a river ice jam, however, thickness variations are relatively slight. A thick, short jam can act as a flow constriction and result in scour until the channel is sufficiently enlarged by the erosion to reduce flow velocities and sediment removal. As a jam grows in length, the attendant resistance to flow can cause sufficient increases in water depth and decreases in water velocity and sediment transport capacity to prevent scour or even allow deposition.

REFERENCES

Beltaos, S. and A.M. Dean, Jr. (1981) Field investigations of a hinging ice dam. In Proceedings of the IAHR Symposium, Quebec, vol. 2, pp. 475–488.

Beltaos, S. and W.J. Moody (1986) Measurements of the configuration of a breakup jam. National Water Research Institute Contribution 86–123, Burlington, Ontario, Canada.

Beschta, R.L. (1983) The effects of large organic debris upon channel morphology: a flume study. In Proceedings of the Simons Symposium, Fort Collins, Colorado, pp. 8.63–8.79.

Calkins, D.J. (1978) Physical measurements of river ice jams. Water Resources Research, 14(4):693–695.

Deck, D.S. (1984) Controlling river ice to alleviate ice jam flooding. In Proceedings, IAHR Symposium on Ice, Hamburg, vol. 3, pp. 69–76.

Gerard, R. (1984) Ice jam research needs. In Proceedings, Workshop on the Hydraulics of River Ice, Fredericton, N.B., pp. 181–191.

IAHR Working Group on River Ice Hydraulics (1986) River ice jams: a state-of-the-art report. In Proceedings, IAHR Symposium on Ice, Iowa City, vol. 3, pp.

Joliffe, I. and R. Gerard (1982) Surges released by ice. In Proceedings of the Workshop on Hydraulics of Ice Covered Rivers, Edmonton, Alta., pp. 253–259.

Lau, Y.L. and B.G. Krishnappan (1985) Sediment transport under ice cover. ASCE Journal of Hydraulic Engineering, 111(6):934–950.

Mercer, A.G. and R.H. Cooper (1977) River bed scour related to the growth of a major ice jam. In Proceedings, Third Canadian Hydrotechnical Conference, CSCE, Quebec City, pp. 291–308.

Sayre, W.G. and G.B. Song (1979) Effects of ice covers on alluvial channel flow and sediment transport processes. Iowa Institute of Hydraulic Research Report No. 218, University of Iowa, Iowa City.

Shen, H.T. and W.A. Van de Valk (1984) Field investigation of St. Lawrence River hanging ice dams. In Proceedings, IAHR Symposium on Ice, Hamburg, pp. 241–249.

Pariset, E., R. Hausser and A. Gagnon (1966) Formation of ice covers and ice jams in rivers. ASCE Journal of the Hydraulics Division, 92(6):1–24.

Wuebben, J.L. (1986) A laboratory study of flow in an ice-covered sand bed channel. In proceedings, IAHR Ice Symposium, Iowa City, Iowa, vol. 1, pp. 3–14.

Wuebben, J.L. and D.M. Stewart (1978) Physical measurements of ice jams: 1976–77 field season. USACRREL Special Report 78-3, Hanover, NH.

LIST OF SYMBOLS

V = channel width (m)

D_s = depth of scour (m)

d = submerged depth of local ice feature (m)

g = acceleration due to gravity (m/s)

n = Manning's resistance coefficient, free surface flow ($m^{1/6}$)

n_c = composite Manning's n, ice-covered channel ($m^{1/6}$)

Q = water discharge (cms)

S = slope

t = ice thickness (m)

t_s = submerged ice thickness (m)

U = velocity (m/s)

Y = flow depth (m)

Y_o = free surface flow depth (m)

Y_i = under ice flow depth (m)

DISCUSSION

PAPER: A Preliminary Study of Scour Under an Ice Jam

AUTHOR: James L. Wuebben

DISCUSSION BY: Gordon D. Fonstad, Alberta Environment

QUESTION/COMMENT:

Having been part of the mathematical modelling team which led to the publication of Mercer and Cooper (1977) it was interesting to see that, with some minor variations, the flume study conducted at CRREL verified the purely theoretical model which we used.

The discussion of the filling in of the scour hole upon the release of the jam which followed the presentation was also interesting. It should be noted that the findings of Mercer and Cooper with respect to the upstream migration of the point of maximum velocity following release was a mathematical verification of field observations made by J.B. Nuttall, circa 1974, on the Mackenzie River.

It would be interesting to see if the maximum scour in the flume remains just downstream of the head of the ice cover if there is a sediment load in the approach reach, as there was in our mathematical model and as there would be in a natural watercourse.