NWRI CONTRIBUTION 86-108

Beltaos (34)

Wong (08)

This paper has been published in the Proceedings of the
IAHR Symposium on Ice 1986, Iowa City, Iowa, August 1986
and the contents are subject to change

PRELIMINARY STUDIES OF GROUNDED ICE JAMS

by

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August 1986

MANAGEMENT PERSPECTIVE

Flood levels in rivers are difficult to predict accurately from flow data. When floods are accompanied by ice jams, the predicted flood level becomes even more difficult, if not impossible, to deduce. This paper moves significantly towards providing a way to handle ice jams and grounded ice jam problems. Analysis is confirmed by experiment and the expressions contained in the paper are therefore probably reliable and useable by experienced persons for real situations.

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PERSPECTIVE DE GESTION

Le niveau des crues dans les cours d'eau est difficile à prédire de façon exacte à partir des données sur le débit. Lorsque les crues s'accompagnent d'embâcles, le niveau de crue devient encore plus difficile à prédire, sinon impossible. Le présent article vise à présenter une façon de traiter les problèmes liés aux embâcles, échoués ou non. Cette analyse a été confirmée par des expériences et les expressions contenues dans le présent article peuvent probablement être utilisées en situation réelle par des personnes expérimentées.

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RÉSUMÉ

L'expérience laisse supposer que les embâcles sont souvent échoués, habituellement près de leur extrémité aval. Déterminer si une embâcle est échouée et dans quelle mesure elle l'est constitue un facteur important de l'évaluation des possibilités, de la stabilité et du déclenchement des crues. On dispose toutefois de peu de données sur l'échouage des embâcles.

Il ressort des études faites en laboratoire que l'infiltration due à l'accumulation de blocs de glace varie proportionnellement à la racine carrée de la pente de la ligne d'eau. Le coefficient impliqué dans cette relation dépend des caractéristiques et de l'orientation du floe.

Des essais réalisés avec des blocs en plastique ont permis de constater deux mécanismes d'échouage. Le premier résulte de l'immersion et de l'empilement sous l'eau de blocs trop gros pour franchir un obstacle. Il y a échouage tant que le niveau d'eau en amont n'a pas atteint celui du début de l'immersion. L'atteinte de ce niveau peut provoquer des crues dans les cours d'eau étroits et peu profonds. Le deuxième mécanisme d'échouage se produit lorsqu'une accumulation de glace épaisse en mouvement se superpose à une couche et à des coins de glace compétente. Dans les essais en question, ces accumulations ont été produites par l'effondrement et l'accumulation d'embâcles de surface. Un troisième mécanisme d'échouage a été relevé par suite d'une analyse théorique fondée sur le concept d'effondrement interne et appliquée à la transition aval de l'embâcle. Dans les trois cas, la longueur de surface d'échouage était courte, correspondant à la largeur de quelques blocs ou à la profondeur de l'écoulement.

IAHR Ice Symposium 1986
Iowa City, Iowa

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ABSTRACT

Experience suggests that ice jams are often grounded, usually near their downstream end or "toe". Whether and to what extent a jam grounds are important questions in assessing flooding potential, stability and release but little is known about grounded jams.

Seepage through accumulations of ice blocks was studied in the laboratory and found to vary in proportion to the square root of the water surface slope. The coefficient implied in this relationship depends on ice floe characteristics and orientation.

Tests with plastic blocks revealed two grounding mechanisms. The first consists of submergence and piling up of blocks that are too large to advance past an obstacle. Grounding persists until the upstream water level rises to that of incipient submergence. This level may govern flooding potential in relatively flat and narrow streams. The second mechanism of grounding occurs when a moving, thick, ice accumulation encounters competent ice cover and wedges between it and the channel bed. In the present tests, such accumulations were produced by the collapse and "snowballing" of surface jams. A third grounding mechanism was identified by theoretical analysis based on the internal collapse concept and applied to the downstream transition of the jam. In all three cases, the length of grounding was short, amounting to a few block widths or flow depths.

INTRODUCTION

Observations of breakup jams suggest that grounding at their downstream end (or "toe") is a frequent occurrence (e.g., Andres and Doyle 1984). Though toe conditions are an important factor in ice jam analysis and mitigation, very little is known about grounded jams.

Laboratory tests by Mathieu and Michel (1967) revealed that grounded jams were initiated when the size of blocks, submerging on arrival at the edge of a floating cover, exceeded the available flow depth. More recently, Michel and Abdelnour (1976) reported formation of grounded jams upstream of a retaining grill during tests with a wax cover, intended to simulate the breakup of natural ice sheets.

To obtain preliminary but quantitative understanding of grounding processes and effects, laboratory and theoretical studies were initiated in 1982 and the main findings to date are reported herein.

SEEPAGE FLOW THROUGH ICE ACCUMULATIONS

In ice jam literature, seepage through the voids of a jam is customarily neglected. However, where a jam is very thick or grounded, seepage is the predominant flow component. Considering a porous medium, the law of seepage may be stated as (Bear, 1972)

$$S = au + bu^2 \qquad (1)$$

in which S = slope of water surface; u = apparent seepage velocity = discharge divided by wetted area; and a,b = dimensional coefficients that depend on fluid and porous medium properties as well as gravity. From existing data on a and b, it was deduced that the first term on the RHS of Eq. 1 (laminar seepage) should be negligible for the block sizes used in the tests as well as for those encountered in natural breakup jams. With this assumption, integration of Eq. 1 over the length, L_g, of a grounded accumulation of blocks, results in (Wong et al, 1983)

$$q = \lambda\sqrt{(H_u^3 - H_d^3)/3L_g} \qquad (2)$$

in which q = discharge per unit width; H_u, H_d = water depths just upstream and downstream of the accumulation, respectively; and $\lambda = 1/\sqrt{b}$ = coefficient having dimensions of velocity. The derivation of Eq. 2 utilizes a Dupuit-type approximation and should be realistic if $(H_u - H_d)/L_g$ is not excessive (see also Wong and Beltaos, 1985). Eq. 2 was confirmed by numerous tests using accumulations of both rocks and square plastic blocks (5.08 x 5.08 x 0.64 cm and 10.16 x 10.16 x 1.27 cm). Test details are contained in Wong et al (1983) and Wong and Beltaos (1985) while an example is shown in Fig. 1.

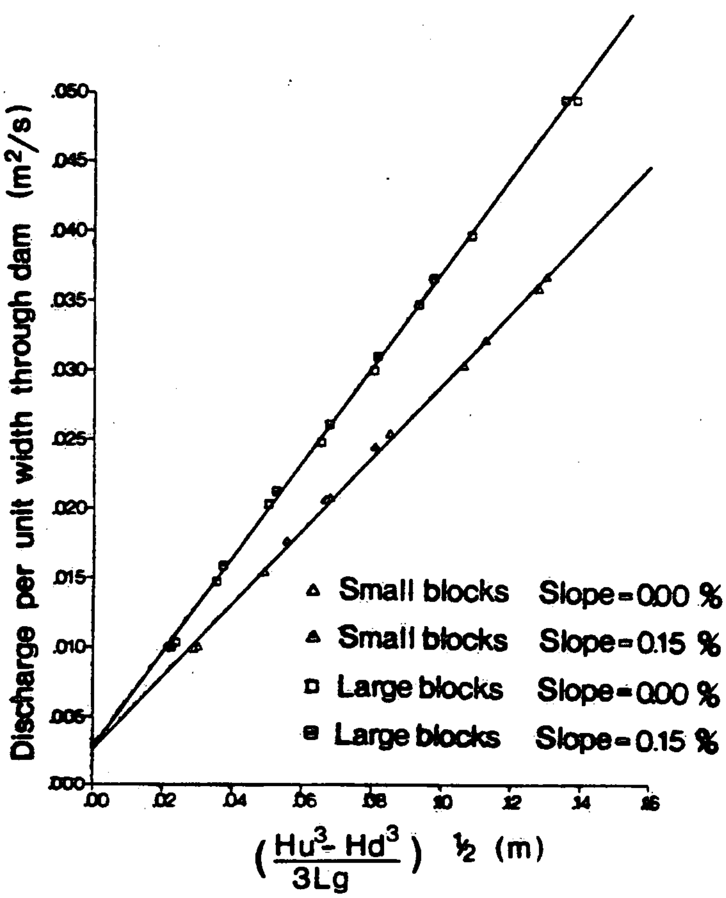


Fig. 1. Seepage relationships for blocks placed randomly in wire mesh cage.

Best prediction of the coefficient λ was obtained from Ergun's formula, as quoted by Bear (1972)

$$\lambda = \sqrt{\frac{\kappa p^3}{1 - p} g d_s} \qquad (3)$$

in which g = acceleration due to gravity; p = porosity of accumulation; $d_s = 6/M_s$, with M_s = specific surface area = surface area/unit volume of blocks; and κ = dimensionless coefficient that depends on the shape and orientation of blocks. For square blocks of uniform size, the experimental value of κ was 0.72 for randomly oriented blocks but dropped to 0.29 when the blocks were oriented perpendicular to the flow direction. For tests with small rocks ($d_s \approx 5$ cm), the value of κ was measured at 0.48 while that recommended by Ergun for soil-like materials is 0.57.

While it is not known whether the above values accurately describe natural jams, owing to possible shape and gradation effects, ballpark estimates can be made using the present results and "average" ice block geometry. Such estimates indicate that seepage through ordinary floating jams should be less than ten percent of the total discharge. However, when the jam thickness is several times the flow depth, seepage becomes a significant fraction of the flow.

MECHANISMS OF GROUNDING

Three grounding mechanisms have been documented and are described in this section, i.e., submergence of blocks arriving at an obstacle and blockage of the waterway; wedging of moving, thickened, accumulations of blocks between the channel bed and the ice cover; and progressive thickening by shoves and grounding at the toe.

Submergence and Blockage

From what had been available in the literature, it was deduced that a high degree of idealization should be adopted initially, in order to achieve repeatable tests and measurable parameters. Thus, the first test series consisted of introducing polyethylene blocks in a 1 m wide flume and allowing them to be transported by the flow to a "pier-gate", an obstacle comprising closely spaced vertical rods (Fig. 2). This type of obstacle is artificial but the attendant jamming mechanism can occur naturally, as was found in the next test series. Moreover, obstacles similar to the pier-gate could be used for ice control.

Details of the pier-gate tests are given in Wong and Beltaos (1985) and main results are reported herein. Typically, blocks underturned upon arrival at the gate and, after submerging, were pinned to the piers by the

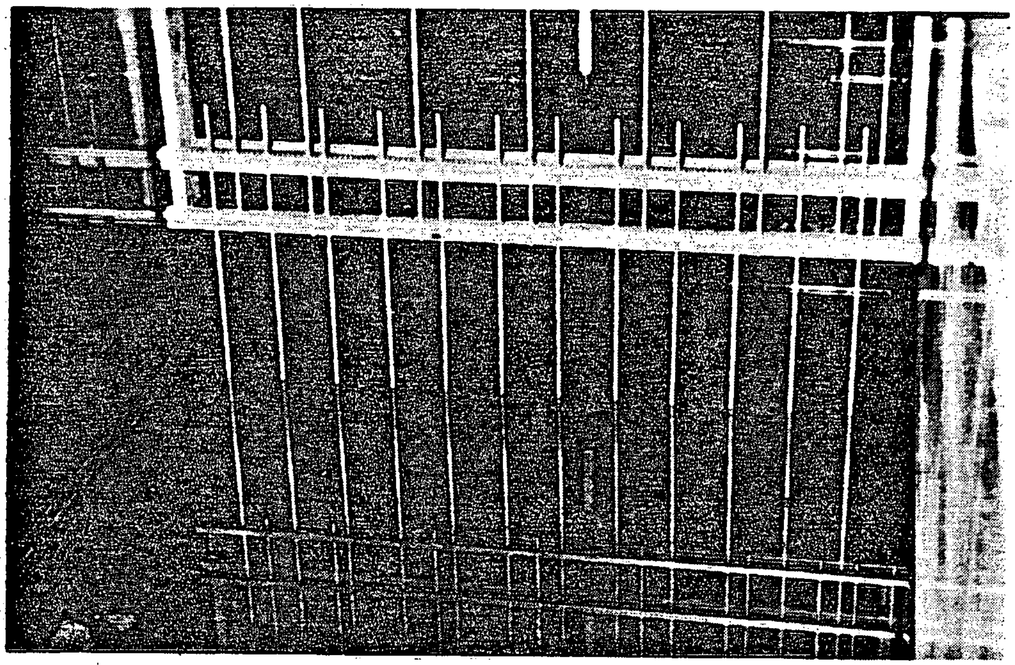


Fig. 2. Pier gate used to form grounded jam.

force of the current. As more blocks continued to arrive, they either underturned and packed behind those already submerged, or stayed on the surface, thus forcing downwards the blocks underneath. In this manner, a grounded accumulation formed upstream of the gate and grew in length. The water level upstream kept rising, owing to reduced conveyance. Eventually, incoming blocks no longer joined the grounded accumulation but floated in a single or double layer which marked the onset of steady-state conditions near the gate (Fig. 3). The blocks in the grounded portion of

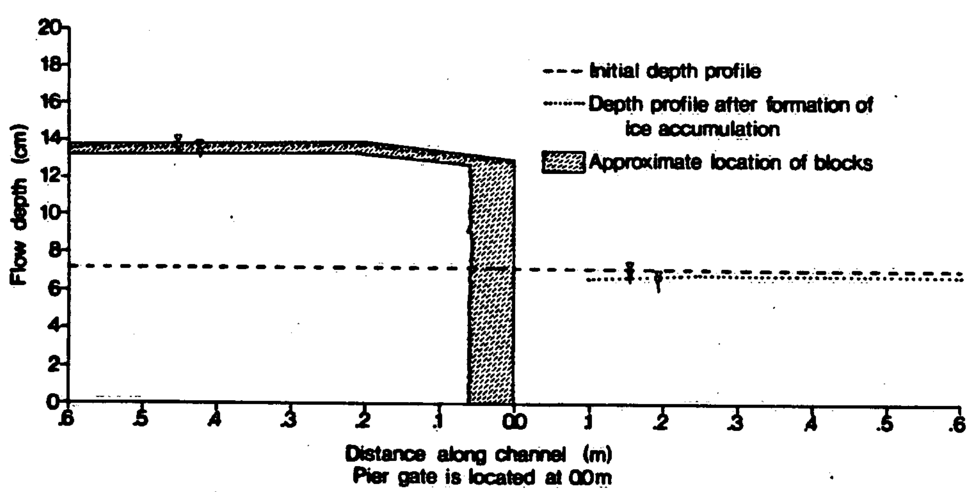


Fig. 3. Typical profile of jam formed at pier gate, after establishment of steady state.

the accumulation had a strong bias in orientation, i.e., they were mostly oriented perpendicular to the flow. It is for this type of accumulation that the value $\kappa = 0.29$ was obtained (see Eq. 3). The length of grounding was short, usually amounting to one or two block widths.

From the observed grounding process, it seems logical that steady state and maximum depth occur when the incoming blocks are in a state of incipient submergence. Using Ashton's submergence criterion (1974), along with Tatinclaux et al's modification for surface tension (1977), it is possible to show that

$$\bar{q} = q/t_i\sqrt{gt_i(1 - s_i + \frac{\delta}{t_i})} = \frac{2(\frac{1}{\bar{t}_i} - 1)}{\sqrt{5 - 3(1 - \bar{t}_i)^2}} \quad (4)$$

in which t_i = block thickness; s_i = specific gravity of block material = 0.92; δ = water surface displacement due to surface tension = 0.6 cm (Tatinclaux et al 1977); and $\bar{t}_i = t_i/H_u$, with H_u = final water depth upstream of the grounded accumulation. Note that Eq. 4 is equivalent to Ashton's criterion (1974) and was chosen because it allows straightforward determination of H_u when q and t_i are given. The postulated process is confirmed in Fig. 4 where the data points are seen to plot close to the theoretical line. Test No. 2 involved a very high initial Froude number (2.3), resulting in a jam whose floating portion was several layers thick and thus does not comply with Eq. 4.

The second series of tests utilized a 2 m long wood-and-polysterene board, intended to simulate a floating ice sheet. In these tests, the mechanism reported by Mathieu and Michel (1967) was confirmed, i.e., grounded jams were initiated when the block size exceeded the flow depth. Incoming blocks underturned at the edge of the cover and stopped, being supported by the cover and the flume bed. Subsequent development of the jam was similar to that observed in the pier-gate tests. The length of grounding was again short, about one or two block widths and blocks were mostly oriented perpendicular to the flow. There was a sharp rise in the water level through the grounded part of the jam, followed by a surface accumulation of blocks. In some of the tests, water and blocks spilled over the

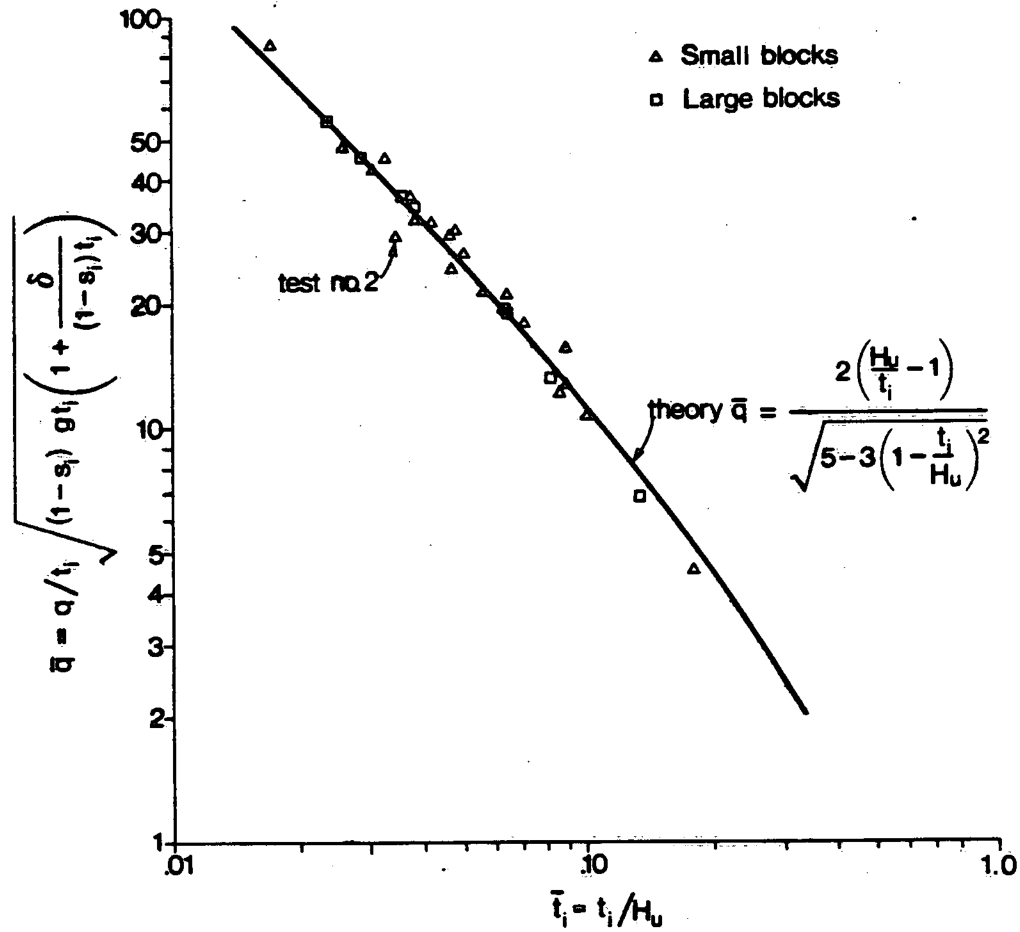


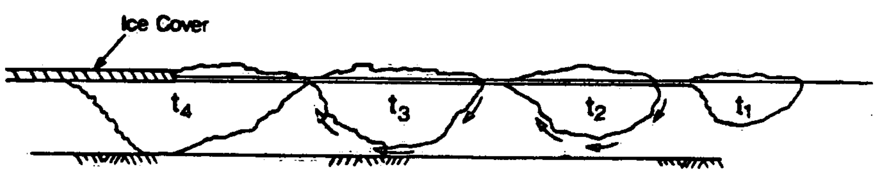
Fig. 4. Test of block submergence criterion (Eq. 4).

cover to the extent that the cover had to be manually raised or suspended from the flume rails in order to prevent the jam from moving out over the cover. It is suspected that, in nature, such spillage would cause local fracture of the ice sheet and incorporation of the fragments in the jam. Tests with "breakable" covers are needed to study such phenomena.

An immediate practical consequence of the present findings pertains to the maximum ice-influenced water levels. Using Eq. 4, it can be shown that flooding potential may, on occasion, be governed by the grounded jam rather than the conventional floating jam, expecially in relatively narrow and flat streams.

Wedging

To examine whether grounding can occur when the initial depth under the floating cover exceeds the block size, a few exploratory tests were performed. Here, the initial depth was large (up to 25 cm) and the approach velocity small, so that incoming blocks accumulated in a surface jam whose head advanced upstream until the block supply was discontinued. By gradually increasing the flow discharge, the blocks at the head of the jam began to underturn and form a "cluster", as shown in Fig. 5. This formation amplified the forces applied on the surface accumulation downstream. Eventually, a collapse occurred, possibly caused by a kind of instability described by Billfalk and Sodhi (1982). Subsequently, the cluster rolled downstream, thickening in "snowball" fashion, until it reached the flume bed. On arrival at the floating cover, a grounded jam was initiated (Fig. 6) by wedging of the cluster between the cover and the bed. The length of grounding was again short, amounting to a few block widths.



$t_4 > t_3 > t_2 > t_1$

At time t_1 –single layer with small cluster at u/s end

t_2, t_3 –cluster unstable –moving d/s while growing in size and collecting blocks in single layer

t_4 –cluster stopped by ice cover –stable grounded jam formed

Fig. 5. Sketch of "cluster

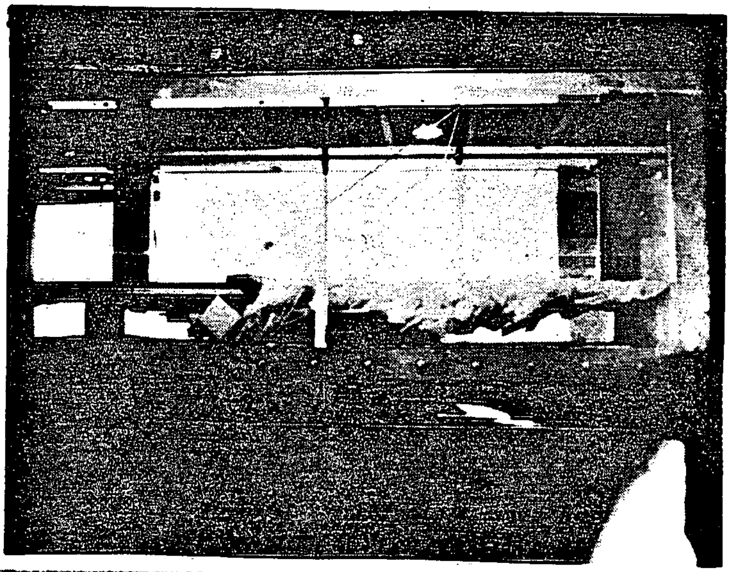


Fig. 6. Grounded jam formed by collapse of surface layer and cluster wedging

During these tests, it was evident that large uplift forces developed by the wedging process because the upstream end of the cover was raised significantly and, on occasion, completely emerged above the water surface. Again, it is suspected that this effect might cause fracture of the ice sheet in nature, whereby the final configuration of the jam would be influenced by structural factors.

Thickening by Shoves

A fully developed, "wide channel" jam (Pariset et al, 1966) forms by shoves, or internal collapse, until its thickness is large enough to effect a balance between the internal stresses and the strength of the accumulation, commonly assumed to behave as a granular material. The thickness of a cohesionless jam is then described by (Uzuner and Kennedy, 1976; Beltaos and Wong, 1986)

$$\frac{dt_s}{dx} = \alpha\left[\frac{\tau_i}{\rho g t_s} + S \right] - \beta \frac{t_s}{W} \qquad (5)$$

in which t_s = submerged thickness of the jam; x = downstream distance; ρ = density of water; τ_i = flow shear stress on the underside of the jam; S = water surface slope; W = channel width; and α, β are coefficients depending on s_i, p and internal friction of the jam. If the jam is sufficiently long, it contains an equilibrium reach where $dt_s/dx = 0$, whereby Eq. 5 provides a simple means to calculate the equilibrium thickness of the jam and, thence, the water depth, H_e.

Downstream of the equilibrium reach, the water depth decreases to that prevailing at the toe, H_t. Using Eq. 5, along with momentum, continuity, and seepage relationships, Beltaos and Wong (1986) obtained a numerical solution for t_s and h (= depth of flow under the jam). The solution proceeds downstream, starting with equilibrium values and indicates that t_s increases and h decreases with increasing x. Whether a jam will ground at the toe depends on how H_t compares to H_g (= water depth when h becomes zero), as illustrated in Fig. 7.

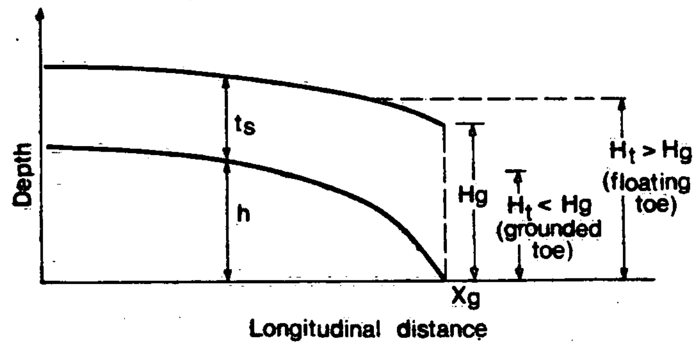


Fig. 7. Schematic illustration of toe conditions.

Using plausible ranges of the various coefficients involved in this analysis, it is estimated that H_g should be at least 0.7 H_e. On the other hand, if H_t is not influenced by downstream jams or controls, it can be estimated simply via a composite resistance formula for flow with sheet ice cover. Under this condition, it can then be shown that grounded toes should form frequently. Floating toes are more likely to be encountered in relatively narrow and flat streams. The length of grounding can be estimated from Eqs. 2 and 3 and depends on several parameters, i.e., q, λ, H_t and H_g. With "typical" values, L_g can again be shown to be short, amounting to no more than 10 H_t. Grounding in this case has no effect on the maximum water depth which can be calculated from the conventional ice jam theory.

SUMMARY AND CONCLUSIONS

Preliminary findings from a study of grounded ice jams, indicate that grounding may occur near the toe and is of limited length. Three mechanisms of grounded jam formation have been identified, i.e., submergence of blocks arriving at an obstacle and blockage of the waterway; wedging of thick moving accumulations; and thickening by internal collapse. The flooding potential of jams formed by these processes is usually governed by the depth of the conventional floating jam, with the exception of jams formed by submergence and blockage. Here, the grounded jam raises the water level until incoming blocks can no longer submerge. This depth can be calculated from Ashton's formula and, in relatively flat and narrow streams, may exceed that of the conventional floating jam.

Seepage through grounded jams has been investigated in the laboratory. It was found that the apparent seepage velocity is proportional to the square-root of the water surface slope while the coefficient of proportionality depends on block shape and dimensions, porosity of the jam, gravity, and block orientation relative to the flow direction.

A limitation of the present tests was the use of a rigid cover to simulate natural ice sheets. Observations made during the tests indicated that the interaction between the jam and the ice cover is likely to result in fracture of the latter. Subsequent development of the jam would then be influenced by structural factors, hence further tests with "breakable" covers are needed.

ACKNOWLEDGEMENTS

The tests described herein were performed with the assistance of Mr. W.J. Moody. Review comments by Dr. T.M. Dick, Chief of Hydraulics Division and by Dr. Y.L. Lau, Head of Environmental Hydraulics Section, are appreciated.

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