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Phreatic Water Surface Profiles along Ice Jams – An Experimental Study

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In Northern Regions, the formation of ice jams along many rivers is a common phenomena. These ice jams may occur during the freeze-up and more importantly during the spring break-up period. Ice jams in general have considerable effects on the water levels because they alter the water surface profile for stretches of tens of kilometers along the rivers. As a consequence, water levels increase significantly upstream of the ice jam and result in the flooding of towns situated along the river banks. Knowledge of the water levels within an ice jam can be used to estimate many parameters that are difficult to measure and observe. Examples of such parameters are the local and global ice jam resistance to the flow, and forces acting within an ice jam.

While ice jams are notorious causes of serious problems in hydraulic engineering, very little engineering methodology exists to deal with such problems. In this paper, the results of a laboratory study aimed at investigating the development of the water surface profile along an ice jam that is lodged in place, are analyzed and presented. A rectangular flume with a horizontal bed was used for the experiments. Twelve experiments carried out under different geometrical, hydrodynamic and ice conditions, were analysed. A simulated floating ice cover was used to arrest the downstream transport of the ice floes, forming the ice jams.

The experiments indicate two types of ice jams, those that are floating and others that are lodged at one or more locations along their length. The phreatic water level along a floating ice jam is up to 0.92 the ice jam thickness. This is not true when an ice jam is lodged in place. Different experiments have shown that the water surface profile along a lodged ice jam follows similar tendencies regardless of the geometry, ice floe size distribution and hydrodynamic conditions. It was found that the phreatic water level varies linearly from the trailing edge of the ice jam up to approximately 90% of its length downstream. Towards the remaining part of the jam's length the water level follows a cubic polynomial line.

Introduction

In cold regions, rivers are covered for most of the winter season. In late winter and early spring the increase in air and water temperatures result in the weakening of the ice covers. Subsequently, the ice covers begin to breakup and the resulting ice floes move downstream. At certain locations along the river reaches the downstream transport of the ice floes may be stopped and ice jams may form. Continuous feeding of ice floes increases the blockage of the river and results in an increase of the resistance to the flow. Higher water levels upstream of the jam are produced, thereby causing flooding of the river banks. Every year, ice jam induced floods cause substantial damage to properties, bridges and hydraulic structures across Canada. The prevailing hydrodynamic and ice conditions along the length of ice jams are still largely unknown, which results in a serious handicap for engineers planning hydropower dams, and bridges on rivers where severe jams are known to occur.

Ice jam measurements are difficult to obtain and involve an element of hazard. Researchers have mainly resorted to the measurement of water surface levels along ice jams. The water surface level data have been used mainly for the calibration of computer programs such as HEC2 and other numerical models. The use of these field data is limited due to the lack of other measurements such as the local ice jam thicknesses and bathymetric information. An experimental study was designed and executed in an attempt to measure and analyse the variation of the phreatic water surface profile along different ice jams. The objectives of the study were: 1) to better understand the development of the water surface profile along an ice jam in relation to its thickness profile; and 2) to evaluate the resistance of the ice jam to the main river flow.

Research work related to ice jams involve mainly the studies of stability of static ice jams. Joliffe and Gerard (1982) reported the results of laboratory and numerical studies performed to investigate whether the presence of ice modified surge characteristics and to assess the effects of jam configuration, stream slope and resistance. Wong, Beltaos and Krishnappan (1985) conducted laboratory tests to investigate the unsteady-flow condition after the release of an ice jam. The propagation of the surges resulting from the release of ice jams was studied in a rectangular flume by using polyethylene blocks. The experiments were used to test the model of Beltaos and Krishnappan (1982).

Rivard *et al.* (1984) presented an analysis of the water level profile through a long ice jam on a reach of the Mackenzie river. The water surface profile was computed using HEC2 in order to estimate ice cover thicknesses. Gogus and Tatincleaux (1981) studied the effect of a floating ice cover on the mean flow velocity distribution. Ferrick *et al.* (1992) studied the interaction between a surge and the intact ice cover based on field observations performed during controlled flow releases from river dams.

Though the work outlined above addressed several aspects of ice jam related problems, the variation of the phreatic water levels along ice jams length in relation to ice jam characteristics has not been tackled. It is also evident from the foregoing that field and laboratory studies on ice jams involve limited measurements and are missing important data such as actual phreatic water levels corresponding to measured ice jam thicknesses.

In this paper, twelve experiments on ice jams carried out in a rectangular horizontal flume are described, measurements are reported, and the analyses performed on the data are presented. Phreatic water surface levels and ice jam thickness profiles were measured directly from the flume walls. These measurements have been used to: 1) evaluate the effects of the ice jam thickness on local water levels; 2) assess the average water surface slope as a function of the ice jam thickness; and 3) determine the global resistance of an ice jam to the main channel flow.

Problem Description and Theoretical Background

A typical ice jam formed in a rectangular flume is shown in Fig. 1. The ice jam stretches from its trailing edge (head) located upstream, to its leading edge (toe) located downstream, and is characterized by its length *Lj*, and its thickness profile. The ice jam resistance to the flow produces a drop in the water level across its leading and trailing edges such that the water level rises upstream and drops downstream to attain levels Z_{us} and Z_{ds} respectively. Two distinct regions along the ice jam can be identified according to the slope of the water surface profile (WSP): the "gradually varying WSP" region, extending from the trailing edge to approximately 90% of its length; and the "rapidly varying WSP" region encompassing the remaining part of the ice jam up to the leading edge.

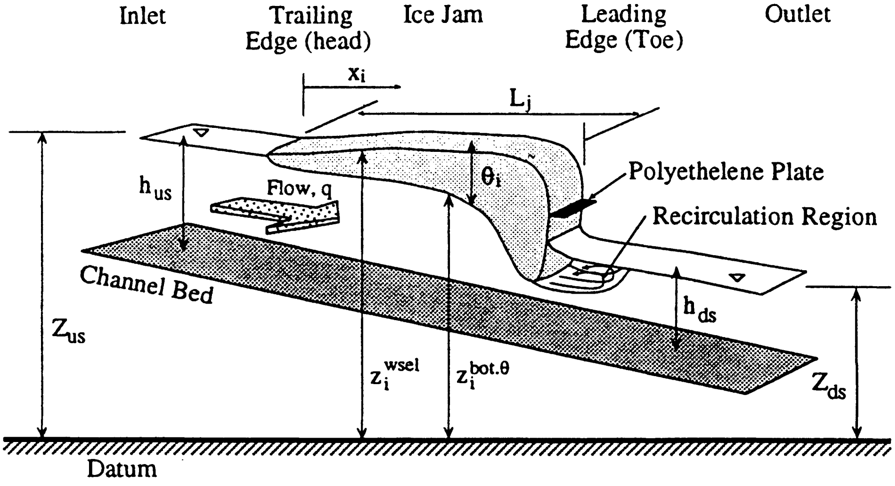


Fig. 1. Schematic of Typical Ice Jam

In this study dimensional analysis is used as a guide for the selection of flow variables. The determination of the dominant parameters and the relation between them is required. In order to obtain the dimensionless variables, the following five steps were taken: 1) Determination of the significant physical quantities for the problem; 2) Choice of an appropriate set of basic dimensions; 3) Writing of the dimensional matrix and evaluation of the rank of the matrix; 4) Determination of the non-dimensional π-terms and; 5) The development of functional relationships between the π-terms.

The parameters that we will use to describe the flow and ice conditions (shown in Fig. 1) are: the main channel water discharge per unit width q; the water surface elevations upstream and downstream of the ice jam Z_{us} and Z_{ds}, respectively; the total length of the ice jam L_j; the elevations of the phreatic water levels, z_i^{wsel}, and the ice jam underside $z_i^{\text{bot.}\,\theta}$, and the local ice jam thickness θ_i, all at a distance x_i from the trailing edge, where i is a spatial index along the length of the ice jam. Any other parameter describing the hydrodynamic conditions such as the velocity, and Froude number, should depend only on these variables.

Considering the mass M, length L, and time T as the basic dimensions for the analysis of the variables and after the construction of the dimensional matrix and the grouping of related variables, five primary π-terms are identified for the investigation of the phreatic water levels along ice jams. The π-term given by Eq. (1) represents the penetration at point i of the phreatic water level into the ice jam from its underside

$$\pi_{1i} = \frac{Z_i^{\text{wsel}} - Z_i^{\text{bot.}\theta}}{\theta_i} \tag{1}$$

The position along the ice jam normalized by its total length x_i/L_j is given by Eq. (2)

$$\pi_{2i} = \frac{x_i}{L_j} \tag{2}$$

Any additional inflow of ice floes from upstream may result in a change of the ice jam thickness profile but not in the total average ice jam thickness. The dimensionless jam length to thickness ratio giving an indication of the jam resistance to the flow is expressed as

$$\pi_3 \equiv \frac{L_j}{\theta_{\text{ave.}}} \tag{3}$$

where $\theta_{\text{ave.}} \equiv$ average ice jam thickness estimated using the measured ice jam thickness profile.

The total resistance of the ice jam to the main channel flow can be estimated by considering the spatial variation of the water level as well as that of velocity. The total resistance of the ice jam on the main channel flow can be expressed using

$$\pi_4 \equiv \frac{Z_{us} - Z_{ds}}{L_j} \tag{4}$$

$$\pi_5 \equiv \frac{F_{le} - F_{te}}{F_{te}} \quad \text{where} \quad F_k = \frac{u_{ave.}}{\sqrt{g(Z_k^{wsel} - Z_i^{bot.\theta})}} \quad \text{and} \quad u_{ave.} = \frac{q}{Z_k^{wsel} - Z_i^{bot.\theta}} \tag{5}$$

where

F_{le} and F_{te} – Froude number at the leading and trailing edges of the ice jam respectively;
$u_{ave.}$ – average velocity of the flow;
k – index indicating the location being either at the leading (le) or trailing edge (te).

Experimental Program

Experimental Setup and Measurements

The experiments were carried out in a rectangular flume 30 cm in width and 750 cm in length with a horizontal bottom, as shown in Fig. 2. This figure illustrates the plan and longitudinal cross sections of the flume. In order to form an ice jam in the flume, a polyethylene plate was installed a certain distance downstream of the inlet. This plate is restrained from moving along the horizontal plane and is allowed to displace in the vertical direction along guides and with the variation in the water surface.

An ice feeder specifically designed to feed the polyethylene ice pieces from the upstream end of the flume consists of a container trapezoidal in cross section and rectangular in plan as shown in Fig. 3. The length of the container is 90 cm with a top width of 25 cm and bottom width of 8.5 cm. A shaft is placed at the bottom along the length of the container such that when turned counter clockwise, the ice pieces are pushed by the shaft blades towards the end of the container where the container outlet is located. Having an internal diameter of approximately 2.7 cm and an external diameter of approximately 8.5 cm, a complete shaft revolution discharges approximately 500 cm^3. Ice pieces are loaded manually into the container and when discharged fall onto an inclined wooden plate which is installed to avoid splashing and significant disturbance to the flow when free-falling pieces hit the water surface.

Typical measurements taken during the experimental test runs consisted of: 1) discharge measurements from a 30° V-Notch weir; 2) direct readings of water surface levels and ice jam profiles which were possible since the channel walls are made of glass and; 3) a complete set of observations using a video camera. Velocity measurements were made with a velocity meter (Streamflo Velocity Meter, SVM). The SVM was used to measure low velocity flow. The SVM instrument has a mini-

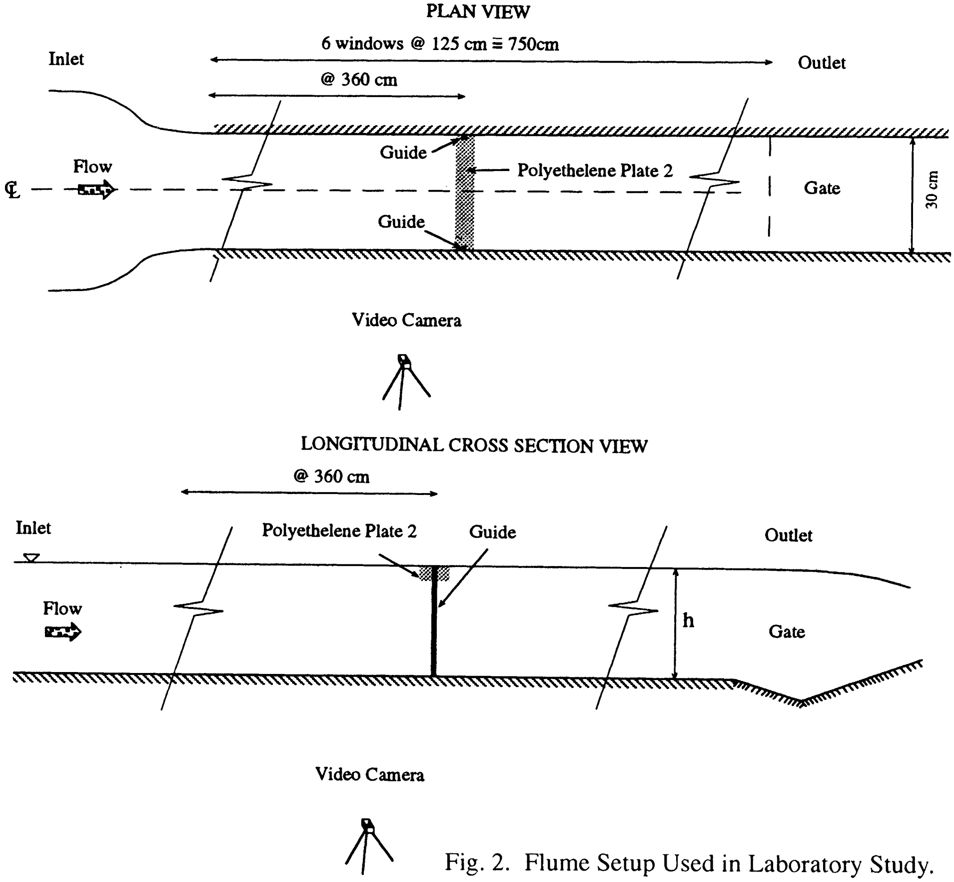


Fig. 2. Flume Setup Used in Laboratory Study.

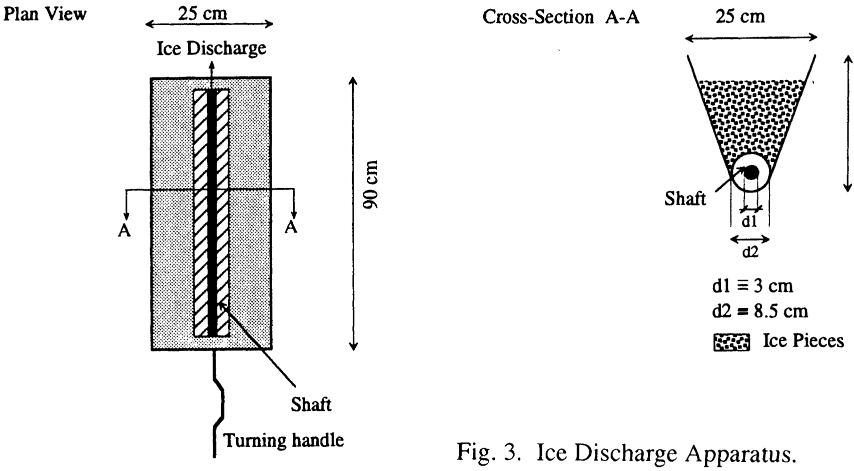


Fig. 3. Ice Discharge Apparatus.

ature head which can be inserted across the ice jam without interrupting the ice jam thickness profile, and can measure velocities as low as 2.5 cm/s. The miniature measuring head has a five bladed PVC rotor mounted on a hard stainless steel spindle. An insulated gold wire contained within the tube terminates 0.1mm from the rotor blade tips. When the rotor is revolved by the movement of water, the passage of the rotor blades past the gold wire tip slightly varies the measureable impedance between the tip and the tube. This variation is used to modulate a 15 KHz carrier signal, generated within the indicating instrument which in turn is applied to the electronic detector circuit.

Preliminary Experimentation and Developed Experimental Procedure

Early experimentation in the laboratory was aimed at exploring the possibility of forming an ice jam giving a significant drop in the water level across its leading and trailing edges. The objective of these experiments was to determine the best conditions under which the required drop in the water level across the leading and trailing edges of an ice jam would be obtained.

Various experiments were carried out with different channel configurations using either polyethylene or wood pieces. Table 1 identifies the three different sizes of polyethylene pieces and the four different sizes of wood pieces that were used to simulate ice blocks for the experiments. The polyethylene pieces have a specific gravity of approximately 0.92 while the specific gravity of the wood pieces were measured to vary in time as follows: Painted Pine 0.4-0.60; Pine (not painted) 0.41-0.72; Plywood 0.51-0.75; and Hardwood 0.64-0.86. From the four different types of woods, the density of hardwood at the saturation level was measured to be the closest to that of ice with a specific gravity of 0.89. Four different parameters, namely the type of ice floes (polyethylene or wood), channel bed condition (horizontal or sloped), distribution of ice pieces, and roughness of the flume, were varied in order to obtain larger ice jams and consequently greater drop in the water surface levels. Ice jams occurred at higher flow rates using wood as compared to those using poly-

Table 1 – Characteristics of Different Materials to Simulate Ice Floes

Type	Length (cm)	Width (cm)	Thickness (cm)	S.G.
Polyethyle Pellets (Cylindrical in Shape)	0.45 (Diameter)		0.35	0.918
Polyethylene	1.6	1.6	0.2	0.918
Polyethylene	2.0	2.0	0.6	0.918
Triangular Wood (small)	2.0-3.5	2.0-3.5	1.5-2.0	0.60-0.86
Triangular Wood (medium)	4.5-6.0	4.0-6.0	1.5-2.3	0.60-0.86
Triangular Wood (large)	3.5-5.5	2.5-5.0	2.5-4.0	0.60-0.86
Quadrilateral Wood	2.8-5.0	2.2-3.8	0.6-2.5	0.60-0.86

ethylene pieces. Experimentation showed that the required ice jams are formed using a mix of all sizes and shapes rather than one size and shape alone. Also, having a channel with a steep bed followed by a horizontal one improves the possibility of formation of the ice jam some distance after the steep bed. From the inlet of the flume up to approximately 300 cm downstream, polyethylene pelets of the same size as those used in the experiments (see Table 1) were glued on the flume walls and bed. Again, ice jams giving even more drop in the water level across its leading and trailing edges were possible.

The desire for the ice jams in this study to be formed under natural conditions made the experimental process difficult because one experiment requires nearly one day to complete and other conditions such as vibrations from the pump, transients in the main channel flow, and small perturbations resulting from the movement of individual ice floes, all contributed to the instability of the ice jam and its premature dislodgment during the period where measurements are being taken. These conditions may not even allow the required water surface profile to be attained. Many experiments were rejected because of their premature sudden failure before the completion of the measurements or due to the difficulty in obtaining the required water surface profile.

The early experimentation revealed that ice jams initiated by a floating downstream ice cover and giving a significant drop in the water level were possible. In order to ensure such ice jams, the following procedure was developed: 1) Impose a certain water discharge in the flume, 2) Adjust the downstream gate to obtain the required initial water depth and velocity at the location where the polyethylene plate is to be placed, 3) Allow for steady state conditions to be attained, 4) Place a polyethylene plate in its guides which represents a stationary ice cover, and let local conditions stabilize, 5) Feed polyethylene or wooden blocks of various dimensions and polyethylene beads at the upstream region (inlet) of the flume. At this point, the passage of the polyethylene blocks and beads or wooden pieces are arrested by the polyethylene plate. Keeping a relatively constant rate of ice inflow, the ice cover is then allowed to progress upstream through the process of juxtaposition, 6) If the leading edge of the ice cover stops progressing then stability conditions in that region would have been attained and any incoming ice floes will be submerged and deposited downstream underneath the ice jam. However, if the ice cover progresses upstream until the inlet, then stop feeding of the ice floes, 7) After steady conditions have been attained, the downstream gate which is located at the flume outlet is lowered in small increments such that conditions are allowed to reach steady state between each increment. By lowering the downstream gate, local velocities are increased and downstream depths are dropped, thereby allowing the ice jam to form through the processes of erosion, shoving and telescoping. The polyethylene or wood pieces are recovered in a wire basket and recirculated to the upstream end of the flume whenever necessary. Once the required ice jam profile is obtained, measurements of water surface and ice jam profiles and velocities are taken.

Presentation and Analysis of Results

A total of twelve experiments were retained for analysis. All the measurements for the twelve experimental test cases giving the ice jam thickness and phreatic water surface profiles are presented in Fig. 4. Tables 2 and 3 provide the flow conditions and channel characteristics respectively, of the experimental test cases. These test cases were subdivided into three groups identified by the channel configuration. The use of three different channel setups was performed in order to generalize the results of the phreatic water surface levels. The first group consisted of experiments 1, 2

Table 2 – Flow Conditions of Experimental Test Cases

Test Case	Q (m^3/s)	Z_{us} (m)	Z_{ds} (m)	Z_{us}-Z_{ds} (m)	Material
1	0.0028	0.074	0.056	0.018	Polyethylene piece mix
2	0.0054	0.101	0.050	0.051	Rectangualr wood mix
3	0.0046	0.071	0.049	0.022	Triangular wood mix
4	0.0031	0.099	0.033	0.066	Triangular wood mix
5	0.0039	0.104	0.037	0.067	Wood mix
6	0.0067	0.160	0.041	0.119	Wood Mix
7	0.0020	0.1089	0.031	0.0778	Polyethylene piece mix
8	0.0024	0.109	0.031	0.078	Polyethylene piece mix
9	0.0084	0.170	0.061	0.109	Wood mix
10	0.0094	0.180	0.070	0.110	Wood mix
11	0.0021	0.128	0.0425	0.0855	Polyethylene piece mix
12	0.0035	0.118	0.050	0.068	Polyethylene piece mix

Table 3 – Channel Characteristics of Experimental Test Cases

Test Case	Slope at Inlet Region (degrees)	Channel Rougness at Inlet Region	Length of Jam (cm)	Average Thickness (cm)
1	0	Low	150	2.1
2	0	Low	240	2.3
3	0	Low	185	3.1
4	1.5	High	260	3.5
5	1.5	High	270	4.5
6	2.6	High	260	5.8
7	2.6	High	220	4.6
8	2.6	High	225	4.5
9	2.6	High	260	4.5
10	2.6	High	250	4.7
11	2.6	High	220	5.5
12	2.6	High	170	5.3

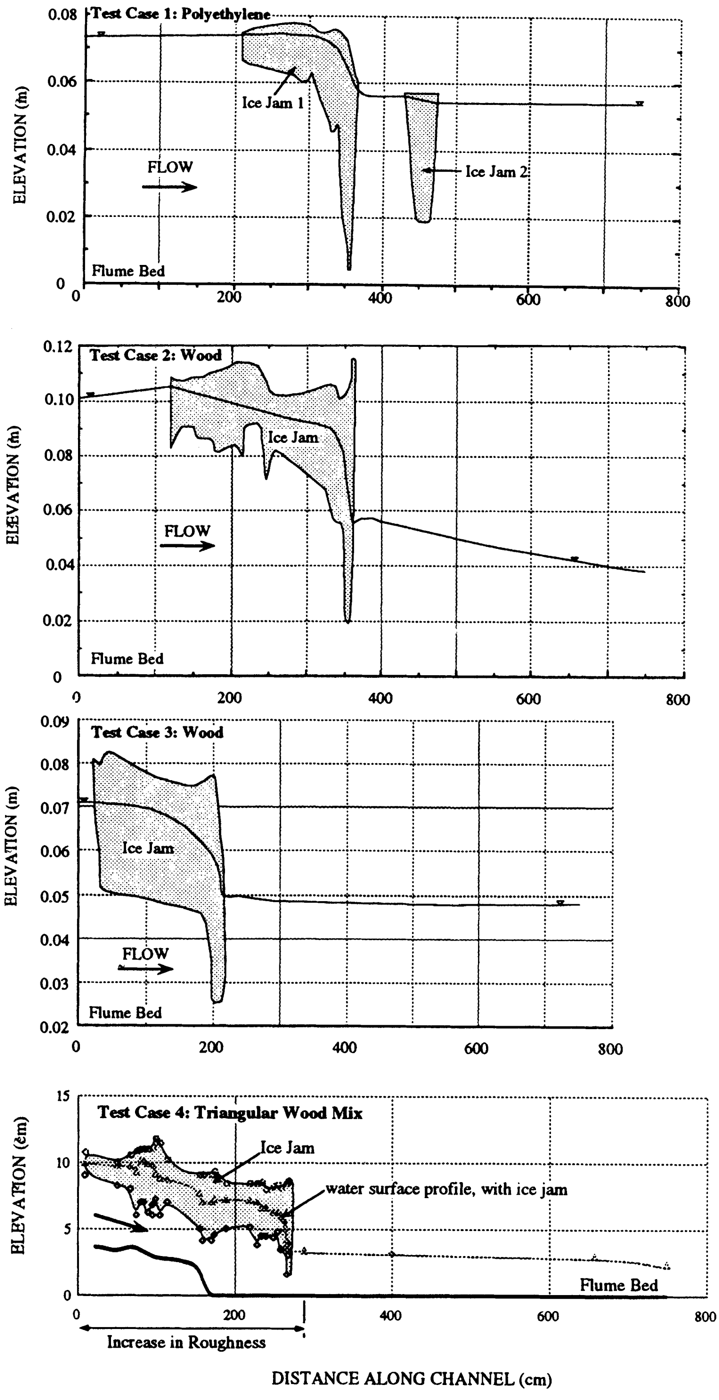


Fig. 4. Schematic of Ice Jams Obtained in Laboratory.

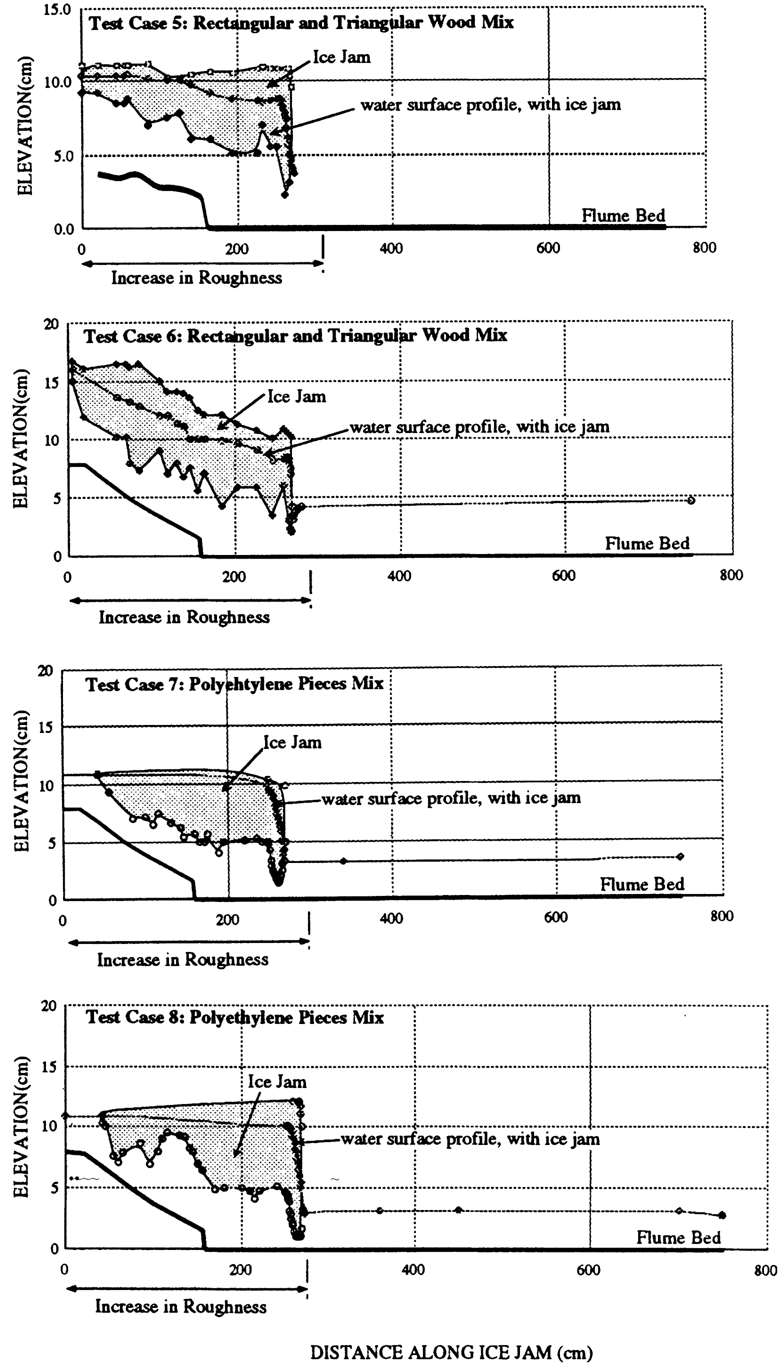
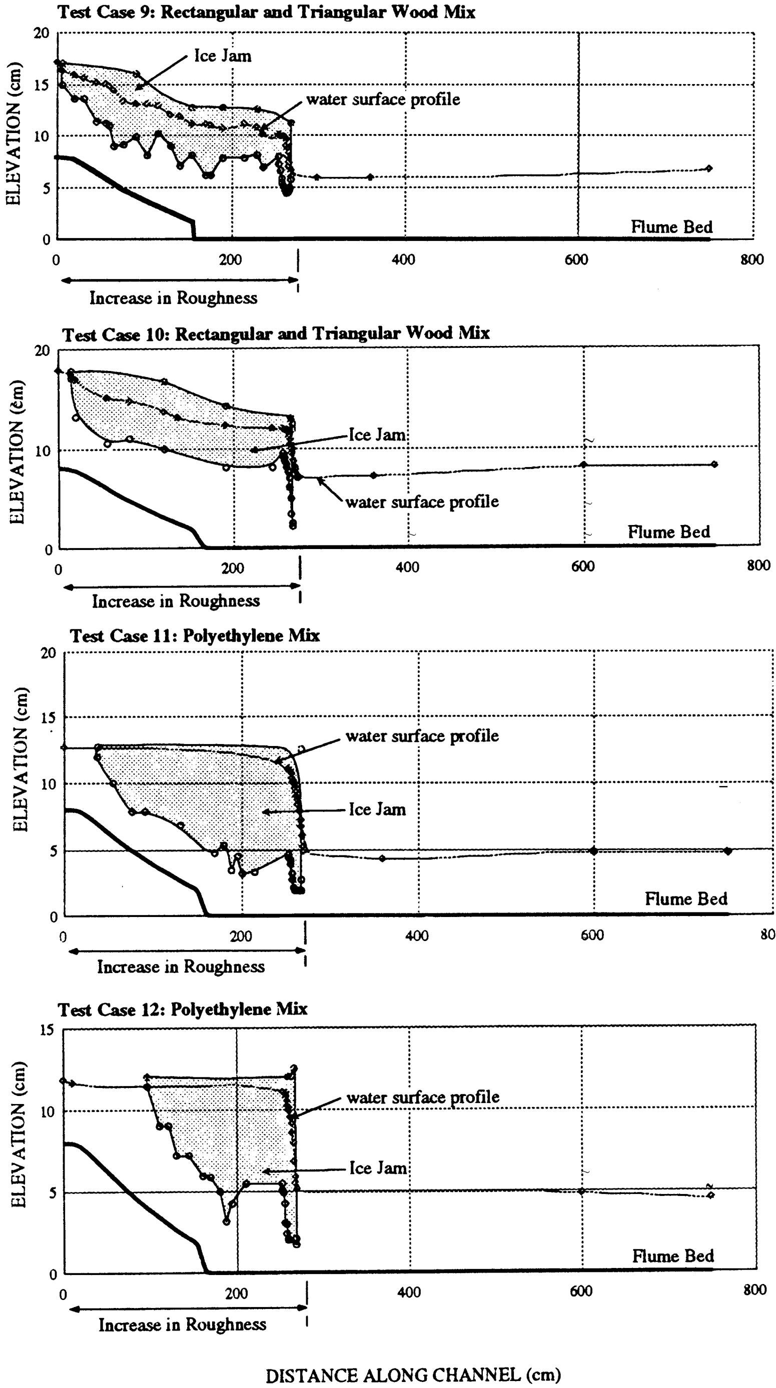


Fig. 4. continued



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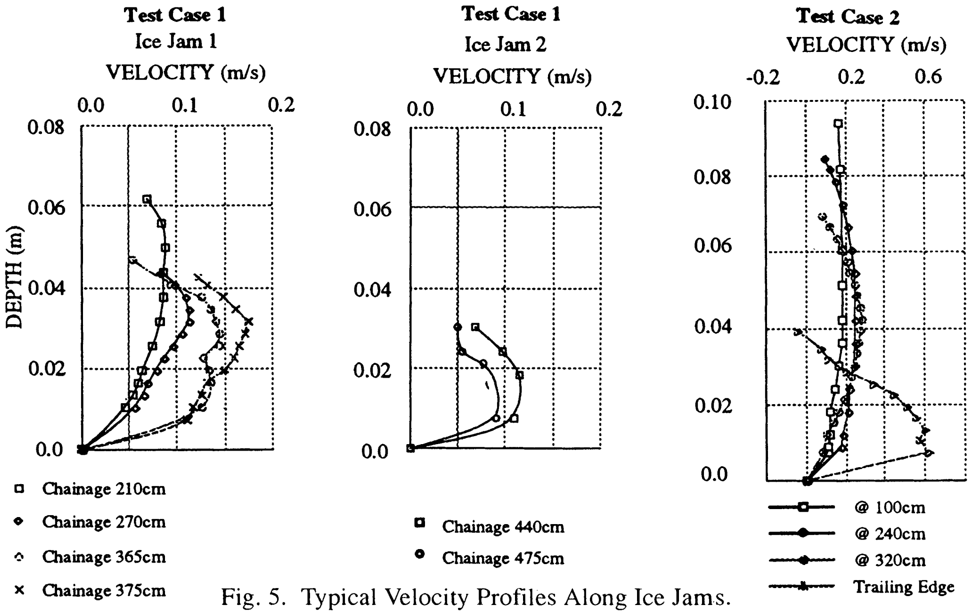

Fig. 5. Typical Velocity Profiles Along Ice Jams.

and 3 such that polyethylene pieces were used in the first experiment and wood pieces for the second and third. Moreover, a horizontal channel with constant roughness throughout its length was used. As shown in Fig. 4, two ice jams were formed in experiment 1. The first ice jam is lodged in place while the second is floating.

For test cases 4 to 12, the flow resistance was increased by randomly sticking polyethylene beads at the channel bottom and walls for a distance of 270 cm from the inlet. Also, for a distance of 175 cm from the inlet, a steep slope was imposed. Ice jams that resulted in approximately 75% drop in water depth were obtained regardless of the type of ice floes used (wood or polyethylene), size of ice floes, and channel discharge (0.0067 m^3/s in one case and 0.0024 m^3/s in another).

Common to all experiments, the leading edge of the ice jams extended approximately to the bottom of the flume. Also the water level immediately downstream of the jam is higher than the elevation of the ice jam underside at the leading edge. It should be noted that the measurements of water levels and top and bottom ice jam elevations are averaged across the width of the flume, since it was observed that the ice jam thickness and water level varied little in that direction.

Typical vertical velocity profiles measured at various locations in the flume and along the ice jams are presented in Fig. 5. The velocity profiles were measured immediately upstream of the trailing edge, at 60 cm downstream of the trailing edge, immediately downstream of the leading edge, and approximately 15 cm downstream of the leading edge for the first polyethylene ice jam. For the second jam in test case 1, velocity profiles were taken immediately upstream and downstream of the trailing and leading edges respectively. Similar profiles have been measured in the second experiment for the wooden ice jam. As is expected, the development of the vertical velocity profiles shows that both the average and maximum velocities increase in the downstream direction along a jam. Immediately downstream of the leading edge of the jams, the velocity profile extends well above their bottom elevation. Observations indicate that the ice jam thickness in the leading edge region can extend to the bottom of the channel at the sides leaving a region in the middle ice free or with large cavities. It should be pointed out here that the velocity profile immediately downstream of the leading edge of the wooden ice jam shows a negative value for the velocity close to the surface. A recirculation region in the vertical direction immediately downstream of the leading edges of the jams was confirmed by measurements.

Observations and measurements obtained from the ice jam experiments are analyzed from a global and a local point of view. Global measurements included water levels upstream and downstream of the ice jams, average ice jam thicknesses, and length of ice jams. Measurements for the evaluation of local conditions consist of phreatic water surface profiles, and ice jam bottom and top surface profiles.

The five dimensionless terms given by Eqs. (1) to (5) are used to analyze the influence of the ice jam on the water levels throughout the channel including the areas before, along and after the ice jams. The analysis of the results was carried out in two parts: the first part considered the variation of the local phreatic water levels along the ice jams in the downstream direction; while the second part related the influence of the ice jam as a whole on the main channel water levels. The first part of the analysis is limited to the ice jam region bounded by its leading and trailing edges, while the second part involved the variation in the water levels across the ice jam.

Fig. 6 presents the longitudinal variation of π, representing the phreatic water levels along the length of the polyethylene ice jams (five experiments). In this figure the local penetration of the phreatic water level into the ice jam thickness is shown as a function of π_2, the distance x_i along the ice jams measured from the trailing edge and normalized with the total ice jam length. The values of π_1 shown in Fig. 6 include those measured from the trailing edge to 0.91 L_j. Fig. 6 shows that the phreatic water level drops linearly from the leading edge to approximately 0.91 L_j. The slope of this line is estimated at -1/9.8 and the relationship between π_1 and π_2 is given by

$$\pi_1 = f(\pi_2) = -\frac{1}{9.8}\pi_2 + 0.92 \qquad (6)$$

This characteristic of the phreatic water surface did not depend on the channel bed and friction characteristics nor was it influenced by the main channel hydrodynamic conditions such as the flow discharge or velocity. Fig. 6 shows that at $\pi_2 = 0.91$, the value of π_1 has dropped nearly 8.4% from that which would have been obtained in the case of a floating ice jam in isostatic equilibrium. Since the hydraulic grade line is constant, the variation of the specific energy could then be considered linear if changes in the velocity head are assumed minor.

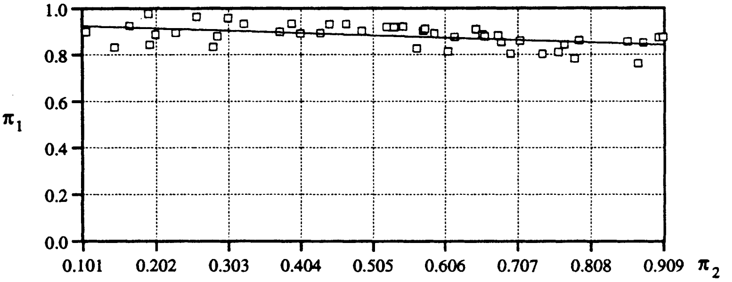

Fig. 6. Longitudinal Variation in Phreatic Water Level (0.0 L_j to 0.9 L_j; Polyethylene).

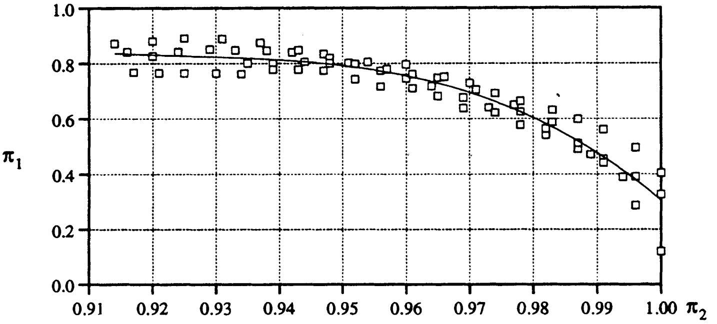

Fig. 7. Longitudinal Variation in Phreatic Water Level (0.0 L_j to 1.0 L_j; Polyethylene).

The variation in the phreatic water surface levels for the polyethylence ice jams between 0.91 L_j and 1.0 L_j is illustrated in Fig. 7. Downstream of 0.9 L_j, the water level drops sharply along a profile represented by a third-order polynomial. The variation of the water surface profile is given by

$$\pi_1 = f(\pi_2) = a\pi_2^3 + b\pi_2^2 + c\pi_2 + d \tag{7}$$

where $a \equiv -1128.9$; $b \equiv 3134.2$; $c \equiv -2901.2$; and $d \equiv 896.2$. A correlation coefficient of $r^2 \equiv 0.912$ was obtained for Eq. (7).

Fig. 8 presents the variation in the measured dimensionless phreatic water levels along the ice jam length for those ice jams obtained using wooden pieces. It is evi-

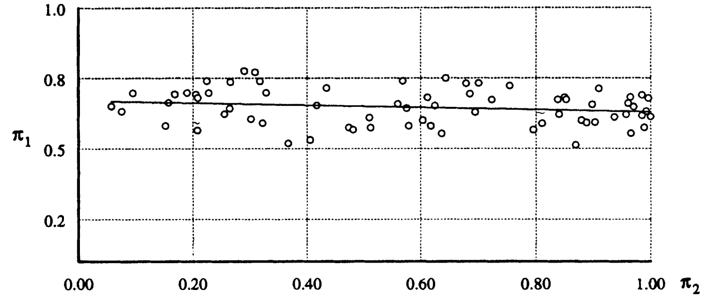

Fig. 8. Longitudinal Variation in Phreatic Water Level (0.0 L_j to 1.0 L_j; Wood).

dent from the figure that the measured water levels are highly non-uniform and the tendency in the downstream direction is nearly horizontal. This scatter in the local water levels is due to the fact that the wooden ice pieces are much larger than the polyethylene ones and that the wood has higher friction than polythylene. In this case local rise in the water levels was observed. The effects of the local increase in the water levels accumulate in the upstream direction thereby increasing the water levels upstream of the ice jam and decreasing the slope of the phreatic water surface as it drops in the downstream direction and along the ice jam length. The slope of the phreatic water surface profile along the ice jam is approximately -0.04 and the straight line which represents that profile is

$$\pi_1 = f(\pi_2) = -\frac{1}{25}\pi_2 + 0.67 \tag{8}$$

The profile shown in Fig. 8 indicates the penetration of the phreatic water surface level from the ice cover underside and since the slope is nearly horizontal, this penetration is uniform along the entire ice jam's length. In the downstream transition region, the phreatic water surface drops suddenly in a stepwise fashion contrary to what has been observed in ice jams using polyethylene pieces.

Fig. 9 depicts the increase in the Founde number π_5 across the ice jam's leading and trailing edges as a function of the jam length to thickness ratio for both wood and polyethylene jams. This difference in the Froude number taken across the leading and trailing edges of the ice jam gives an indication of the total force exerted by the jam on the channel flow. Fig. 9 shows that as the length of an ice jam increases with respect to its average thickness, the change of the Froude number across it increases as well, thereby implying greater force against the flow. The nondimensional term π_3 can be considered an indicator representing the extent of obstruction that the ice jam imposes on the flow. With that regard, Fig. 9 reveals that for an obstruction value of 60, a change in the Froude number across a wood jam is approximately 100%, meaning that the Froude number across the jam has doubled. It was observed that polyethylene jams results in greater increase in Froude number across its edges for lower obstruction index as compared to wood jams. This could be attributed to what was observed in the experiments: polyethylene jams were greater in thickness and less in length that wood jams, thereby reducing the obstruction index; and wood jams were formed at greater depths that polyethylene jams thereby reducing the increase in Froude number across their edges. Although the resistance to flow of wood jams is smaller than polyethylene jam, the wood jams result in greater drop in the water level across their leading and trailing edges as shown in the next figure.

The mean water surface gradient π_4 across the ice jam's leading and trailing edges as a function of the average stable jam thickness π_3 is presented Fig. 10. This figure includes the results of both wood and polyethylence ice jams. The mean water surface gradient across the jam increases non-linearly with increasing average jam thickness. Fig. 10 shows that wooden ice jams result in approximately 43% more

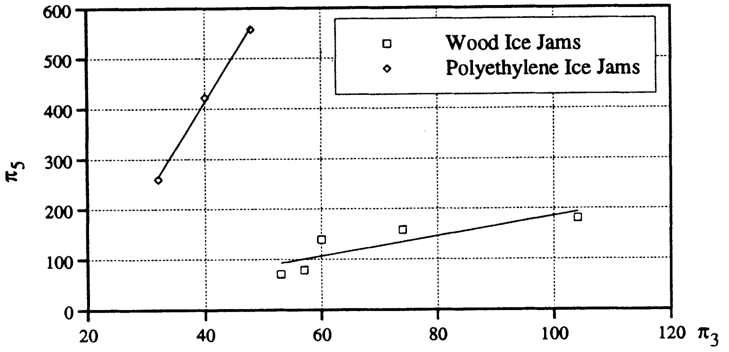

Fig. 9. Variation of Froude Number as a Function of Jam Length to Thickness Ratio.

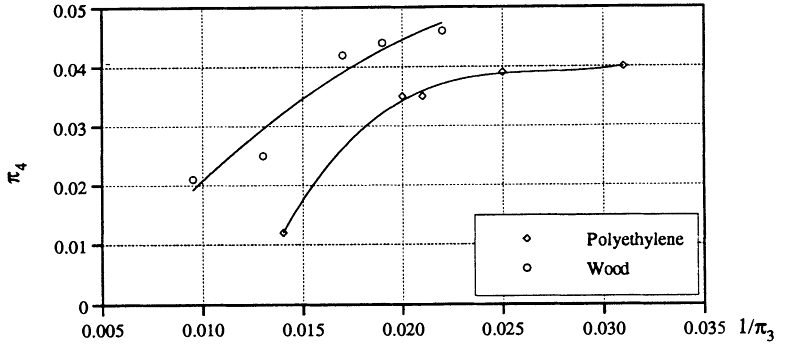

Fig. 10. Mean Hydraulic Gradient as a Function of Ice Jam Thickness.

steep average water surface gradients than polyethylene jams for all values of π_3. This is true since the variations between π_3 and π_4 follow the same pattern and are shifted by approximately 43%. Although the patterns of both curves shown in figure 10 are similar, this would not necessarily be true after a value of π_3 greater than 0.022.

Conclusions

In Northern Regions ice jams may occur during the freeze-up and spring break-up periods. The increase in the ice jam size may result in the major blockage of the river flow such that the water level rises upstream and drops downstream of the jam's trailing and leading edges respectively. The unavailability of field and laboratory data concerning ice jams make it a dificult process to understand. An improved understanding of the water levels along stationary ice jams is an important step towards providing a basis for extracting further information on the prevailing hydrodynamic and ice conditions.

In this paper, the results of an experimental program carried out to investigate the water levels along stationary ice jams that are lodged in place are presented. The ex-