ICE JAM PROCESSES IN A CURVED CHANNEL

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ABSTRACT

Ice jams formed in rivers are very complicated physical phenomenon. To uncover the formation and development mechanism of ice jams, multi-disciplinary knowledge involving thermodynamics, solid mechanics, hydrology, hydraulics and river dynamics is needed. Due to their inherent complexity, properties of ice jams still need to be further explored. Natural rivers meander on their way. Usually the formation of ice cover and ice jams starts from the locations where flow changes its direction, i.e., the curved sections of a river. Hence, to investigate the formation and development of ice jams at curved river sections is very important. Through the comparison of experimental data with forensic ice-jam study, the authors proposed a new Critical Froude Number (CFN) for determining the sequence of development of ice jam after the formation of ice-cover, i.e., whether the ice jam will start accumulating from upstream or downstream of a river. The results in this paper are valuable for both numerical study and engineering practice.

KEY WORDS: Thickness of ice jam; Curved channels; Velocity of flow; Critical froude number

1. INTRODUCTION

Many countries face the problems caused by river ice jams, such as China and Japan in Asia, 82% of North America, major part of the former Soviet Union, and Norway, Sweden and Finland in North Europe. Due to the presence of ice jams, the effective discharge area of a river decreases. This will cause the increase of upstream water level and may also result in flood and ice damage to land, structures, river transportation and other properties. Meanwhile, ice jams can also cause the interruption of water supply by blocking the intake pipes. Ice jams also scour the bank and bed of a river, which causes the disclosure of buried facilities and damage to ecological environment (Spyros Beltaos 2000). For the above reasons, it is very necessary and meaningful to investigate the property of ice jams. To precisely measure the complete data required for the study of ice jams on broad rivers, such...
as the thickness of ice and the accumulation of ice jams, is difficult; especially during the beginning and ending phases of freezing. Fortunately, experimental study provides an effective method for the investigation of the mechanism of ice jams in formation and evolvement. Regardless of the significant progress that has been made in studying the property of ice jams formed in straight channels, the properties of ice jams formed in curved channels, are still not clear due to the influence of the meander of natural rivers, the variation of the thickness of ice jams, the 3-D characteristic of flow, etc. Although research on ice jams formed in curved channels could be dated back to 1980’s, Gilberto E. Urroz (1988) was the first researcher to focus his research on this issue. He systematically investigated the influence of initial conditions and channel roughness on the formation of ice jams, the distribution of downstream discharge velocity and the thickness of ice jams (Gilberto E. Urroz 1992, 1994). In his pioneering research, Gilberto E. Urroz concluded that the Critical Froude Number for thickened jam is approximately 0.08. Froude number shows ratio between the average kinetic energy and the average potential energy of the unit weight of flow. Many researchers use it to decide if ice jams form or some other criteria, for example, Spyros Belotaos (1995) used Froude number to judge ice jam’s thickness. In this paper Froude number will be applied to evaluate the sequence of ice jam developing.

2. EXPERIMENTAL ANALYSIS

Flume test was carried out at the River Ice Laboratory, Hefei University of Technology.

![Figure 1: Experimental flume and the distribution of measure points at semi-circular portion](image)

The flume is a 180° self-supply water-circulation system with 36m in length, 0.5m in width and 0.6m in depth. It consists of two straight parts and a semi-circular observation section with radius of curvature equals to 1.5m. Details of the flume system are shown in Figure 1. In the research, we focus study on hydraulic conditions and don’t consider thermal factors.

The artificial ice particles used in this investigation have a cubic dimension of 0.5cm×0.5 cm×0.5cm, and average density of 0.903×10^3 kg/m^3, which is close to the density of real ice (0.917×10^3 kg/m^3).

2.1 Longitudinal velocity distribution in curved portion
The type of flow used for the experimental test belongs to subcritical flow \((Fr<1)\). Longitudinal velocity of flow at the straight portion of the channel can be regarded as evenly distributed with maximum velocity occurred at the center of cross-section if without any disturbance. For open channels, at the upper-part of the semi-circular portion, the maximum longitudinal velocity at a cross-section gradually moves to the outer perimeter of the channel as water flows across the 0° section to the 90° section; and the velocity distribution at a cross-section decreases from the outer perimeter toward the inner perimeter. However, after water passes the 90° section, the maximum longitudinal velocity of flow at a cross-section gradually moves to the inner perimeter of the channel; and the closer the distance to the 180° section, the larger the velocity near the inner perimeter.

This is due to the distinct distribution of water surface within the semi-circular portion: the surface is convex in shape near the inner perimeter and is concave near the outer perimeter of the semi-circular portion; the longitudinal slope of water surface near the outer perimeter is larger between the 0° and 90° section and that of the inner perimeter is larger between the 90° and 180° section of the semi-circular portion. Hence, the maximum longitudinal velocity at a cross-section happens near the outer perimeter of the semi-circular portion before the 90° section and gradually shifts to the inner perimeter after that. As a result, since the flow near the inner perimeter has larger velocity, higher water level, larger momentum and inertia force, the maximum longitudinal velocity at a cross-section still tends to approach the inner perimeter within certain distance after the water enters into the straight portion of the channel.

For open channel, velocity contour is non-closed before the 90° section and the maximum-velocity zone is close to water surface; after the 90° section, the maximum-velocity zone moves deeper and also gradually shifts toward the inner perimeter of the semi-circular portion and the contour of maximum velocity closes.

When only artificial ice cover are added into the flume, closed undercurrent is formed if other conditions are kept the same as before. Experimental results show that longitudinal velocity distribution at cross-sections is almost the same as that of without the influence of artificial ice. Due to the presence of ice cover, the wetted perimeter and the resistance are increased, the velocity of flow directly under the bottom surface of ice cover is then close to zero. Consequently, the maximum velocity at each cross-section moves deeper and also shifts toward the inner perimeter in the semi-circular portion and the velocity contour closes. Detailed information can be observed from Figure 2 and 3. The experiment and Sun(1992), Gilberto(1992) found the same phenomenon as mentioned above.

In a word, the curved (semi-circular) portion of the channel only has insignificant influence on the longitudinal velocity of upstream flows compared to its downstream counterparts. For same ice-cover condition and water depth, the larger the velocity, the longer the downstream flow that is affected. Similarly, the deeper the water the longer the downstream flow that is affected; provided the ice-cover condition and the velocity are the same. This happens because the intense of transverse circumfluence increases as the increase of velocity and the depth of water, which will cause the velocity distribute unevenly; in addition, momentum and inertia force per unit water also increase as the increase of velocity and the depth of water, which will influence the downstream flow in a longer range.
2.2 Transverse velocity distribution at the semi-circular channel with ice-cover

As flow passes the semi-circular channel portion, transverse velocity circumfluence is formed. If the water is not covered with ice, the surface water will flow toward the inner perimeter of the curved portion; however, when the water is covered with the artificial ice, the water directly under the ice-cover and directly above the bottom of the channel flows toward the outer perimeter; the water in the middle flows toward the inner perimeter of the curved channel. Hence, there are two sets of velocity circumfluence with reverse directions at the transverse section of the curved channel. Sun(1992) and Gilberto(1992) have found the same phenomenon in his research.

![Figure 2 Velocity distribution at the semi-circular channel portion without ice-cover](image1)

![Figure 3 Velocity distributions at the semi-circular portion with ice-cover](image2)

The characteristics of the movement of artificial ice were also studied. If without artificial ice-cover, the artificial ice particles float toward the inner perimeter of the curved channel following the surface water when they pass by the semi-circular portion; if covered with artificial ice-cover, the artificial ice particles directly under the ice-cover float toward the out perimeter after they enter the semi-circular channel portion since the water directly under the ice-cover has a velocity component toward the outer perimeter at this part. The above results again demonstrate that there are two sets of transverse circumfluence existed under the ice-cover.

2.3 Critical Froude Number (CFN) for ice jams forming sequence

The following experiment was performed to investigate the development sequential of ice jams. The ice discharge, $Q_i$, is 0.104~0.149L/s. An artificial ice-cover is added at the $180^\circ$ section of
the semi-circular portion for the purpose of providing an ice bump. For a lower water-flow with 
\(Fr=0.06~0.1\), the floated ice particles accumulate when they reach the ice-cover. The 
accumulation of ice increases toward the 0° section from the 180° section as the ice continues 
pouring in. Then after ice covering water surface, ice begins to submerge and accumulate under 
the ice-cover toward downstream until an initial jam is formed. The jam then expands toward 
the downstream of the 180° section. As the further accumulation of ice, the thickness of the jam 
reaches its threshold, i.e., balance thickness. After this, the incoming ice will be transported 
away under the jam by water and the thickness of ice jam stop increasing.

Experimental result shows that \(Fr=0.14\) is a critical value that determines the development 
sequence of ice jams: when \(Fr<0.14\), ice jams initiate at the 0° section of the semi-circular 
channel and develop toward downstream; when \(Fr>0.14\), ice jams initiate at the 180° section 
and develops toward upstream.

Similarly, the development of ice jams in natural rivers should also have two different 
sequences depends on the Froude number, i.e., 1) ice-cover with single or multi-layer 
thickness(or ice shoving) grows toward upstream after the formation of initial ice-cover; at 
certain locations, the ice-cover stop growing and ice jams start to accumulate after the formation 
of ice-cover; 2) the ice-cover and ice jam does not grow toward upstream immediately after 
the formation of initial ice-cover; on the contrary, the ice from upstream accumulates under the 
ice-cover, blocks the flow of water and causes the increase of upstream water-level and decrease 
of velocity in the beginning; then the ice jam starts growing toward upstream.

Hence, the Critical Froude Number (CFN) for ice jams is different from the submergence 
critical Froude number and the stability condition of ice under ice cover. The CFN determines 
whether an ice jam develops from upstream to downstream or reversely, from downstream to 
upstream in a channel. Although the exact CFN for natural rivers still needs to be investigated, 
the above experiment is very helpful in explaining why the “head” (i.e., thickest part) of an 
ice jam may occur at both the front and rear part (i.e., toe) of an ice jam in natural rivers.

The formation of an ice jam is a function of river boundary condition, ice discharge and the 
property of flow, etc. Moreover, the property of flow should also be characterized by using the 
CFN since it determines the sequence of the development of ice jams. This is not only helpful 
in qualitatively determining the flow property for numerical simulation, but also meaningful 
for engineering practice, especially for ice-jam prevention in rivers and reservoirs.

2.4 Influence of ice discharge on the thickness of ice jams

Figure 4 shows the ice jam distribution for \(Fr=0.17\). It can be seen that the thickness at outer 
perimeter is smaller than that of inner perimeter; which is consistent with the result of 

It is also found that for a given \(Fr\), the time for an ice jam to reach its equilibrium thickness is 
shorter for larger ice discharge than that for smaller. Figure 5 shows the thickness versus time 
plots as a function of ice discharge for ice jams with \(Fr=0.118\). Figure 6 shows the 
distribution of ice-jam thickness for two different ice discharge. The thickness distribution is 
uneven with larger ice discharge than that of smaller.
2.5 Influence of water depth

Figure 7 shows the influence of water depth on ice jam. The velocity of flow $V=15.00\text{cm/s}$, ice discharge $Q=0.098-0.122\text{L/s}$ and the depth of water varies from 8.6cm to 19.60cm in the experiment. In the curved portion of the channel, the shallower the water, the smaller the ice-jam thickness; which is similar as the straight portion (Wang, 1999). Moreover, the longitudinal distribution of equilibrium thickness for the case of shallower water is more uniform than that for deeper water. More details can be found at Figure 7.

3. COMPARISON WITH NATURAL RIVER RESULTS

A forensic study on the ice-jam situation at the meander section of the Yellow River was carried out by River Ice Laboratory, HFUT and Department of Water Resources of Shanxi Province during 1982–1990. 25 observation stations were set up along a river portion of 77 km; the average distance was 3.21 km. By 1991, more than 600,000 data were obtained about hydrographs, ice conditions, weather and riverway characteristics, etc.

3.1 Flow velocity

Without ice, minimum velocity happens close to the bottom of river due to the influence of bed roughness; the velocity increases toward the surface of water since the decreasing influence of bed roughness. However, due to the influence of air, the maximum velocity occurs around $0.2H$ from surface, $H$ being the depth of river, instead of the surface of water itself. In straight river sections, maximum velocity occurs at the middle of a cross-section and minimum velocity occurs near the bank. In meander river section, maximum velocity occurs
in the middle of the main flow close to the inner side of an river elbow. The velocity contour consists of non-closed curves intersecting with water surface.

After the river is covered with ice, flow velocity directly under the ice cover decreases obviously due to the impediment of ice particles under the ice cover; the maximum velocity shifts deeper and the rougher the bottom surface of the ice cover, the deeper the maximum velocity shifts. The maximum-velocity zone is then close to the middle-depth of the water and the velocity contour consists of closed curves (SUI et al 1994, WU 1993) under this circumstance.

The velocity distribution obtained from the forensic study is very similar to the experiment results, as shown in Figure 8. It is observed from Figure 8 that region of maximum velocity shifts to the middle of ice cover and riverbed.

![Figure 8(a) Velocity distribution at No.2 section in the reach of shiyaobu, Hequ county](image1)

![Figure 8(b) Velocity distribution at No.6 section in the reach of shiyaobu, Hequ county](image2)

### 3.2 Ice jams in the river

In the beginning, the ice cover starts from downstream toward upstream when the velocity of flow is lower than the critical submerging-velocity of incoming ice. As a result, the incoming ice submerges and accumulates under the ice cover, and gradually moves toward downstream. During this process, a large-scale initial ice jam is formed at this location.

After the formation of ice cover, the effective discharge area decreases and the discharge velocity increases due to the accumulation of more and more incoming ice under the cover. The additional incoming ice will be carried downstream and the volume of ice jam increases gradually.

In the river, it seems that the thickness along the concave bank is larger than that of the convex side in a curved river portion, which looks contrary to the experimental result. However, this is not the fact. Due to the irregularity of the cross-section of the river, the depth of water differs a lot in the same cross-section. Hence, the thickness of an ice jam also varies in transverse direction in addition to longitudinal direction. In the beginning stage, ice mostly accumulates at concave side of the river because the water here is not deep and the velocity is not large; as the ice jam becomes thicker, the velocity at the concave bank increases due to the decrease of cross-sectional area, the ice is then pushed toward the middle channel of river and starts accumulating at both sides of the middle thread. As the ice moves toward large-velocity zone, the distribution of the water depth and the flow velocity become uniform at transverse direction. In addition, the concentration of ice is enough larger than that of near the bank.

### 4. SUMMARY
At semi-circular portion of the experimental flume, due to the influence of artificial ice cover, the maximum velocity zone shifts down from the cover. Starting from the 90° section of the semi-circular portion, the maximum-velocity zone tends to approach the inner perimeter of the channel. For low water-depth and small ice-thickness, the jam distribution in the curved portion is similar to that in straight channel. As the increase of water depth, the distribution of the jam thickness in the flow direction becomes irregular.

Due to the existence of a couple of transverse velocity circumfluence under the artificial ice cover, one can observe the artificial ice particles moving from the inner perimeter toward the outer perimeter under the cover.

Experimental results indicate that a Critical Froude Number (CFN) can be used to determine the sequence of development of ice jams: a number that is larger than this value represents a different sequence as that of a smaller one. However, further investigation is required for obtaining the CFN for natural rivers.

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