Field Investigation of Frazil Jam Evolution: A Case Study

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Abstract: Using field measurements of frazil jams from 1982 to 1989 in the Hequ Reach of the Yellow River, this paper discusses both the mechanism of evolution of a frazil jam, and the associated variation in water level. The variation in water level depends not only on the thickness of the frazil jam but also on the ice discharge. An empirical power-law relationship between the dimensionless ice thickness and Froude number is established. It has been found that the critical Froude number (under an ice cover condition) describing the transition from an ice jam to a hanging dam (overloaded ice jam) is about 0.075, with a dimensionless ice thickness of about 0.4. Interestingly, the results from the St. Lawrence River show a similar tendency with similar limits.

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Introduction

A major consequence of ice cover formation on northern rivers is the jamming that occurs during spring breakup of the cover and, to a lesser degree, during the freeze-up period. Due to their large aggregate thickness and high hydraulic resistance relative to those of sheet ice, jams cause unusually high water stages. These effects have repercussions in many operational and design problems such as the overturning moment on river structures due to moving ice, forces on ice booms, flooding, and associated stage-frequency relationships during freeze up and, in spring, river bed scour due to surges from released jams, to mention only a few (Beltaos 1983). The evolution of a frazil jam and the related variation in water levels during the ice period (freeze up, breakup, and stable jamming period) is of profound significance. Based on field measurements of frazil jams from 1982 to 1989 in Hequ Reach of the Yellow River, the mechanisms of variation of water levels and evolution of frazil jams are studied in this paper.

Field Investigations

The Hequ Reach is a windy stretch of water situated within the middle reaches of the Yellow River. In fact, the Chinese name Hequ is derived from ‘‘he’’ (river) and ‘‘qu’’ (bend). As shown in Fig. 1, this stretch is found between 39° and 40 °N and 110° and 112 °E, and extends from Longkou Gorge (near section 1) to Tianqiao Power Dam (section 22) over a length of 70 km. After passing Longkou Gorge, the river broadens and meanders; the river width between sections 2 and 8 in the upper Hequ Reach is usually more than 500 m, but it exceeds 600 m at sections 5–7. Between sections 4 and 6, it attains a 1500 m width, with numerous shoals. The river width of lower Hequ Reach between sections 11 and 17 is usually less than 350 m. The slope of the riverbed is more than 0.15% between sections 1 and 2, more than 0.06% between sections 2 and 7, and less than 0.06% between sections 7 and 17. Upstream from Longkou Gorge, there exists a 100–200 km open water reach with numerous rapids due to high velocities in this reach. Due to cold air temperatures in the winter, an enormous amount of frazil ice is generated in this open water stretch, which contributes to the formation and accumulation of large frazil jams in the Hequ Reach.

River bends play an important role during the formation of jams. Urroz and Ettema (1992, 1994) described the mechanism of ice jam initiation as well as the characteristic features of ice jams in a curved channel. The Hequ Reach lives up to its name, having five major bends. One, the river bend at Shiyaobu (near section 10), has a radius of curvature of only 0.7 km. On the concave bank there is a rock projecting into the water, which leads to ice bridging. Before the operation of Tianqiao Power Dam, an ice jam was initiated only at Shiyaobu each winter and progressed to the vicinity of Longkou. After the operation of the Tianqiao Power Dam, an ice jam initiates at the Power Dam and progresses upstream, with a maximum jam length of about 70 km each winter.

The Hequ Reach experienced over 100 days of jamming each year between 1982 and 1989. Frazil ice jams of tremendous size have often formed upstream of Shiyaobu (near section 10), leading to high water levels and causing a serious ice flood disaster in 1982 (Sun et al. 1986). Since then, measurements of the ice jam profile along this reach have been made each winter. By the winter of 1986, 21 new measurement stations had been added to the one at the Hequ gauge station (section 9); the goal was to make detailed observations of water level, frazil jam thickness, current velocities under the ice, sediment concentrations during the jamming period, water and air temperatures, and a variety of other factors.

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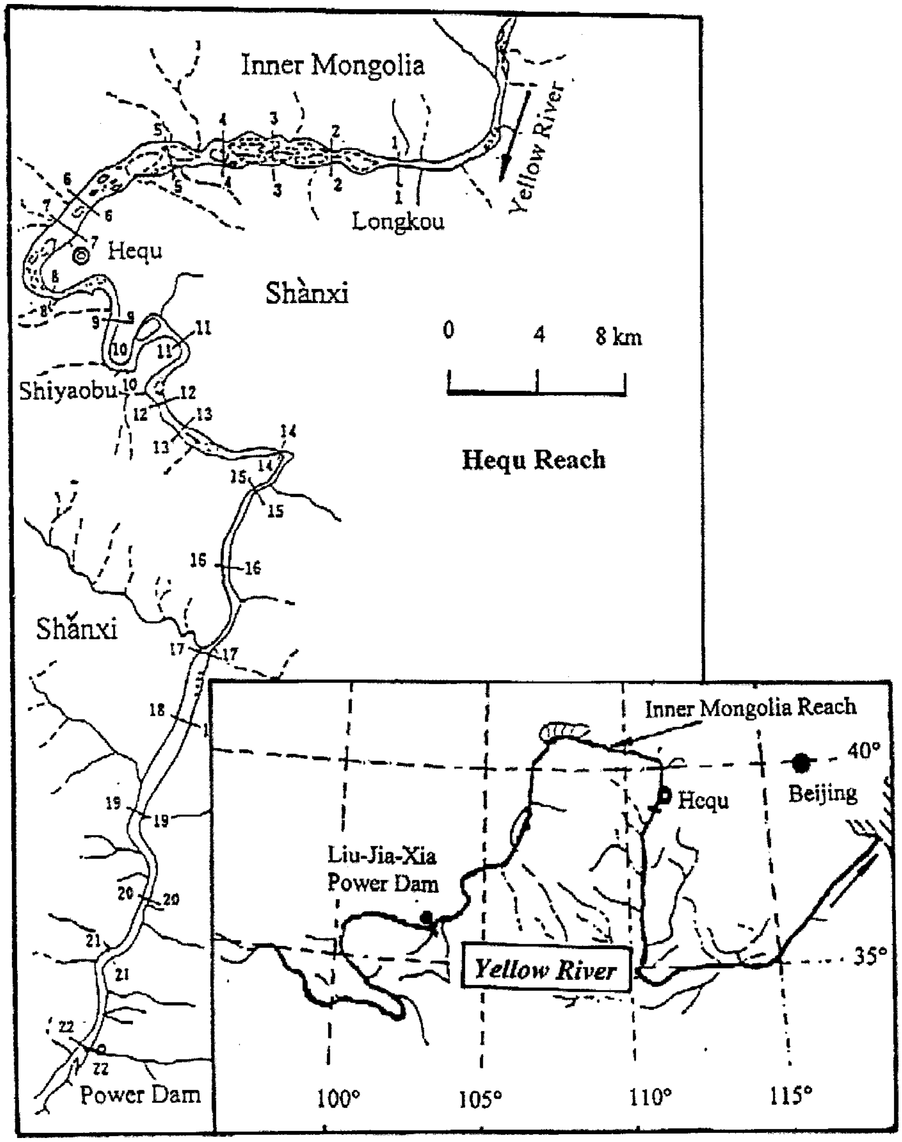

Fig. 1. Hequ Reach of the Yellow River

The long-term daily mean air temperature at the Hequ meteorological station (1955–1986) turns to subzero Celsius on November 16, about the same date as the average frazil ice running-date (November 20). On average, air temperature rises above zero on March 7. Therefore, there are on the average 108 days with subzero temperatures, and the long-term mean-air temperature during this period is $-7\,°\mathrm{C}$.

Because of the influence of ice jamming in the upper Inner Mongolia Reach (upstream from the open water reach), discharges at the beginning of freeze up and during breakup periods at Hequ Reach are often much larger than those during the stable jamming period. Observations from 1970 to 1987 at the Hequ gauging station (since the operation of the Liu-Jia-Xia Power Dam in the Upper Reach in 1969) of the mean monthly discharge, frazil ice running date, duration of ice running, date of freeze up and breakup, and duration of average jamming period are summarized in Table 1.

Field investigations have shown that after the formation of the initial frazil jams along the 70 km Hequ Reach, most of frazil ice generated in the open water reach upstream from Longkou is

Table 1. Average Parameters Related to Freeze Up and Breakup at the Hequ Gauge Station (1970–1987)

	November	December	January	February	March
Mean discharge (m^3/s)	637	409	481	745	740
Average frazil ice running data					November 20
Average duration of ice running period					14 days
Average data of freeze up					December 4
Average date of breakup					March 23
Average duration of average jamming period					109 days

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stored in the upper reach jams between sections 1 and 10, with only a small proportion transported downstream. As a result, the formation of the initial jam causes the upper reach jams to grow rapidly while the lower reach jams evolve more slowly due to the reduced rate of frazil ice supply and discharge.

The frazil jams between sections 1 and 10 (the upper reach jams) are different from those in the backwater area between sections 10 and 17 (the lower reach jams). Frazil jams between sections 17 and 22 form in the reservoir and are termed reservoir jams. This paper primarily considers the upper reach and lower reach jams.

Mechanism of Ice Jam Evolution

Field observations in the Hequ Reach and subsequent analyses have shown there is an interdependence between the evolution of frazil jams and the associated variation in water levels during the ice jamming period. More specifically, the variation in water levels and evolution of frazil jams depend not only on flow discharge, but also on frazil ice discharge, the configuration of channel section, and climatic factors. As the observed data in the Hequ Reach indicate, and as summarized in Figs. 2 and 3, the following regularities prevail with respect to variation in water levels and frazil movement (Sun et al. 1986; Sui 1988; Sun and Sui 1990; Shen and Wang 1995):

1. The trash boom at Tianqiao Power plant (section 22), a run-of-river plant on the Yellow River, initiates an ice jam at the Tianqiao Power Dam. The ice cover in the reservoir is formed by juxtaposition of frazil pans. Interestingly, the initial ice cover can be destroyed by the fluctuation of water level arising from the hydropower generation, and can lead to the accumulation of frazil ice (usually frazil granules) and thickening of ice jam. Thus, during freeze up, the ice jam propagates from the lower reach to the upper reach.
2. When frazil ice enters the ice covered section at the frontal edge, two things can happen. If the flow velocity at the frontal edge is larger than the critical velocity for frazil ice diving, the frazil ice accumulates under the ice cover at the frontal edge. Otherwise, the frazil jam propagates upstream with the progression of the frontal edge. Before the arrival of the frontal edge of the reservoir jam (ice jam between sections 17 and 22) and the lower reach jam (ice jam between sections 10 and 17), another ice jam (upper reach jam) can initiate due to ice bridging at Shiyaobu (section 10). Downstream from Shiyaobu, a short open reach is usually maintained by the large local flow velocities. During the initial jam formation, especially along the upper reach jam, a kind of ''shoving'' process can occur that can significantly influence the ice jam thickness. The thickness of the initial jam was much less than those observed under stable jamming condition, as shown in Figs. 2 and 3.
3. After the formation of the initial frazil jam along the river reach from sections 1 to 22, and due to the large velocity and large hydraulic slope upstream from Longkou Gorge, the frontal ice edge is unable to propagate upstream, and frazil ice plunges under the frontal edge of the jam and accumulates there. Because of the diving of the oncoming ice, the head region of the ice jam (Beltaos 1983) becomes thicker, causing a further rise in water level. By contrast, erosion of the frazil jam at the toe region (Beltaos 1983) causes the associated water level in this portion of the reach to decrease.
4. During the midwinter, with the unceasing supplying of frazil from the upstream, the accumulation under the head region (around section 1) increases. The increased accumulation reduces the cross section available for the flow, and causes a consequent rise in upstream water levels. With the increase in local flow velocity caused by the reduction in flow cross section, frazil ice from the jam head portion is more efficiently transported toward the toe region (from sections 9 to 10 for the upper reach jam, and from sections 16 to 17 for the lower reach jam) and water levels at the jam toe increase as well. This sequence is repeated throughout the ice period, so that the frazil jam gradually becomes thicker.

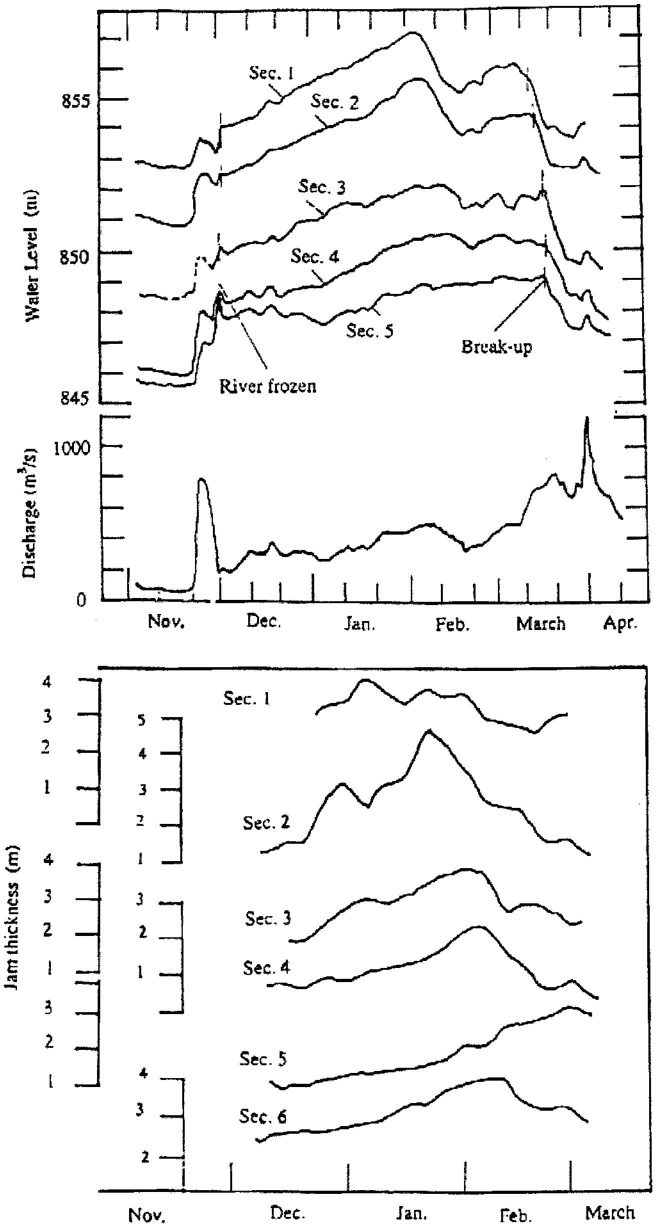

Fig. 2. Hydrograph of water level and discharge as well as jam thickness of upper reach jam at Hequ Reach of the Yellow River in winter 1986–1987

5. In mid-January, the air temperature drops to its lowest value and ice discharge reaches its peak value. Thus, the jam thickness near the jam head, the water level, as well as the ice transport capacity, reach their maximum values. After this time, air temperatures begin to rise, leading to a decrease in the frazil production in the upstream open water reach decreases. Both the frazil ice supply and the frazil ice accumu-

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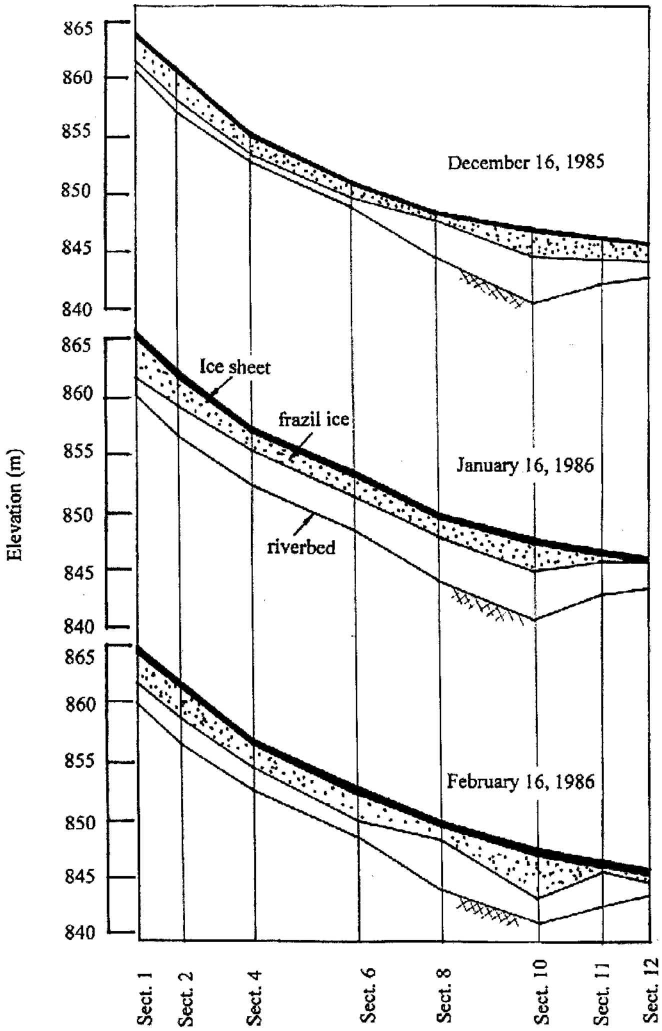

Fig. 3. Longitudinal evolution of ice jams at Hequ Reach of the Yellow River in winter 1985–1986

lation under the jam head region decrease. The existing frazil accumulation continues its migration to the jam toe. The water levels tend to decrease in the head portion and increase in the toe portion of the study reach.

6. During breakup, the frazil jam begins to dissipate, causing the water levels and thickness of the frazil jam along the 70 km river reach to decrease dramatically.

Analyses of Field Data

In view of the serious ice flooding that occurred in the Hequ Reach in 1982, the goal here is to study the key mechanisms for the evolution of ice jams and the associated variation in water level in this river reach. The current section briefly explores two empirical relationships that can be extracted from the data collected on the Hequ Reach.

In winter, after the formation of a river ice jam, the hydraulic and boundary conditions of the river are different from those of conventional open-channel flows. Factors affecting both the evolution of a frazil jam and the variation in water levels include the oncoming stream flow and its variations, the hydraulic slopes in each river reach, the geology and morphology of the river reach, oncoming ice discharge, the composition of frazil and drift ice, and many others. Oncoming ice discharge and composition of frazil and drift ice directly affect the size and shape of the ice jam. For example, for a given water discharge, larger ice concentration can lead to serious accumulation of ice at the jam, dramatic increases in water level, increased flow velocity, and intensified sediment erosion of the riverbed. By contrast, in the case of a surface ice jam, an increased ice discharge results in only greater jam length with no obvious effect on the water levels or other variables for a given water discharge. Clearly, it is of great value to be able to distinguish these two cases.

Unfortunately, due to the complexity of the physical processes, and the difficulty, expense, and danger associated with collecting field data, it was not possible to consider all of the related factors affecting the accumulation of frazil ice jam and the related variation in water level. Thus, focusing or concentrating on key variables only, the variation in water level during the ice period may be reduced to the following essential variables:

$$H = f_1(v,h,t) \tag{1}$$

in which H = mean overall depth (m); v = mean velocity of flow under ice jam (m/s); h = mean effective depth of water under jam (m); and t = mean thickness of jam (m). And, thus, field observations, following an empirical relationship between the dimensionless ice jam thickness (t/H) and the Froude number was established:

$$\frac{t}{H} = f_2\left(\frac{v}{\sqrt{gh}}\right) \tag{2}$$

The $v/(gh)^{0.5}$ parameter describes the hydraulic condition under the ice-jam condition. As reviewed in Michel (1984), the past five decades have seen many researchers use the so-called ice Froude number $[v/(gt)^{0.5}]$ to explore studies on river ice hydraulics. However, this parameter is not straightforward here, since its use would result in an awkward transcendental form, with jam thickness as an independent parameter and a dependent one, making its use conceptually difficult. For this reason, the water depth under ice jam *h*, and not the ice thickness *t*, was used here to conduct the analyses.

In fact, frazil ice concentration is another important parameter for river ice jamming and jam formation (Ashton 1986; Urroz and Ettema 1994). As mentioned above, the frazil ice generated in the open water reach upstream from Longkou is stored in the upper jam reach, and only a small amount is transported to the lower jam reach. Thus, there is an unceasingly replenishment of frazil to the upper reach jam during the ice period. By contrast, the quantity of frazil ice in the lower reach jam is limited by the supply. Unfortunately, for both technological and economical reasons, it was virtually impossible to measure ice discharge during the ice period, so this important variable could not be directly included. Nevertheless, to distinguish the different ice input conditions, and thus the distinct features of the upper and lower reach jams, the ice thickness measurements were analyzed separately.

The river morphology should also be considered. As discussed by Beltaos (1995), the thickness of the ice jam at the head region is different from that at the toe region, and varies along the jam. The location of the frontal edge at Longkou gorge is not stable, and sometimes propagates more than 10 km upstream from section 1, and at other times moves downstream of this section. However, this unsteady behavior is not considered here, nor is the influence of the dimensionless length of the ice jam.

In view of these factors, only the relation between t/H and $v/(gh)^{0.5}$ is investigated to describe the dependence of the dimen-

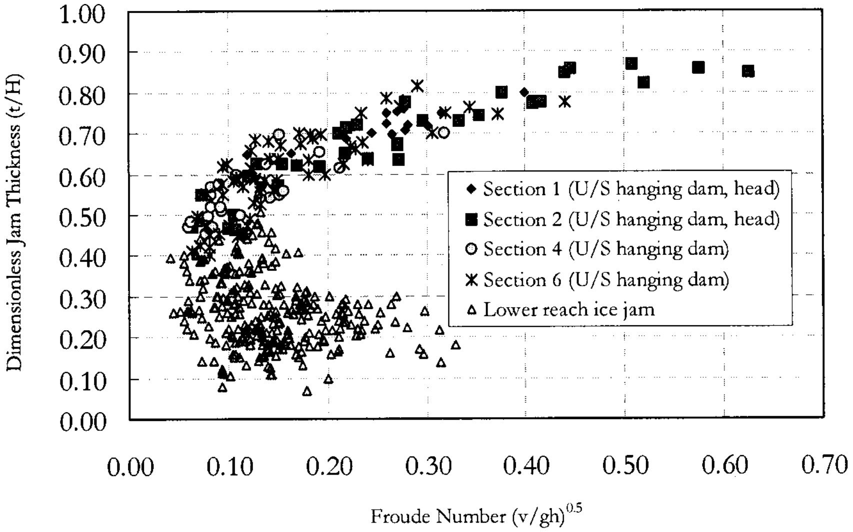

Fig. 4. Relationship between dimensionless ice thickness and hydraulic parameter under freezing condition

sionless thickness of the ice jam on the Froude number under jamming conditions for both the upper reach and lower reach jams.

Analyses are carried out on 139 groups of data observed at upper reach jams and 271 groups of data at lower reach jams. The relationships between t/H and $v/(gh)^{0.5}$ are shown in Fig. 4. Because of different rates of frazil replenishment, the results between t/H and $v/(gh)^{0.5}$ differ between the upper and lower reach jams. For the upper reach jams, the relationship can be approximated by a power-law relationship such as

$$\frac{t}{H}=1.047\left(\frac{v}{\sqrt{gh}}\right)^{0.285} \tag{3}$$

This is an empirical relationship between the dimensionless jam thickness (t/H) and the Froude number under ice covered condition $[v/(gh)^{0.5}]$. Given the complexity of the ice transport process, it is not surprising that the observed correlation is far from perfect. Moreover, there is also uncertainty in the channel and ice properties, such as particle size. The tendency of the curves reflects the dependence of the dimensionless ice thickness of the cross section on $v/(gh)^{0.5}$ as well as frazil ice replenishment.

In fact, the form of the data suggests another possible relationship. As the frazil ice accumulates, it effectively uses up or ‘‘clogs’’ the available hydraulic capacity in the remainder of the flow section, likely increasing the efficiency of the transport process in the portion that remains. This reasoning suggests an exponentially diminishing relationship of the form

$$\frac{t}{H}=1-b\exp\left(-c\frac{v}{\sqrt{gh}}\right) \tag{4}$$

where b and c = empirical constants. For the Hequ reach data, b is near 0.6 and c is approximately 3.6.

For the upper reach jam, the larger $v/(gh)^{0.5}$, the larger t/H. Conversely, for the lower reach jams, as $v/(gh)^{0.5}$ increases, t/H decreases. Eq. (3) or (4) provides an approximate empirical description of frazil jam evolution at the Hequ upper reach of the Yellow River, relating the dimensionless ice thickness to both the frazil jam parameter $v/(gh)^{0.5}$ as well as frazil ice replenishment. For the lower reach jams, t/H is usually less than 0.4. However, t/H is usually more than 0.4, and it can exceed 0.9, for the upper reach jams. Note that the turning point of t/H is about 0.4, with the critical Froude number from the ice jam to the hanging dam at the Hequ Reach being about 0.10.

Additionally, both Fig. 4 and common sense indicate that the maximum dimensionless jam thickness (t/H) approaches an upper limit of 1.0 no matter how large $v/(gh)^{0.5}$ grows. This means that Eq. (3) cannot accurately describe the upper reach jam if $v/(gh)^{0.5}$ is larger than about 0.40; by contrast, Eq. (4) does not require this limitation, and is superior for this reason.

Further Discussion and Comparison with Other Data

This section discusses a number of additional topics related to frazil ice transport and jam formation. In particular, a ‘‘hanging dam’’ (Michel 1984) forms as a result of a special ice transport phenomenon. A hanging dam occurs when the ice cover reaches a section of a river, such as the foot of the rapids, where the velocity is such that the cover cannot propagate upstream. In this situation, slush and ice pans are forced to pass underneath the cover and are carried downstream until the velocity of the flow becomes low enough for these to deposit on the underside of the cover. The ice accumulates and forms a hanging dam, reducing the downstream flow section until the velocity becomes high enough to carry the ice further downstream.

In the Hequ reach, owing to the locally high velocity, a stretch of over 100 km of open water remains throughout the winter upstream from Longkou Gorge (around section 1). Downstream from this section, the channel broadens dramatically, reaching a width between sections 2 and 8 of 500 m or more, and is even greater in the midsections. This naturally leads to a decrease in flow velocity. Thus, almost all of the frazil ice generated in the open water reach upstream from Longkou Gorge will initially be intercepted in the upper reach jam. Only a fraction of frazil ice is transported to the lower reach jam, and discharged to the reservoir jam. That means the upper reach jam is dominated by saturated ice transport, and the lower reach jam generally acts as an equilibrium ice transport that can be classified as an equilibrium ice jam.

The islands in sections 2, 4 (Niang-Niang-Tan village), and between sections 5 and 6, as well as the river bends between

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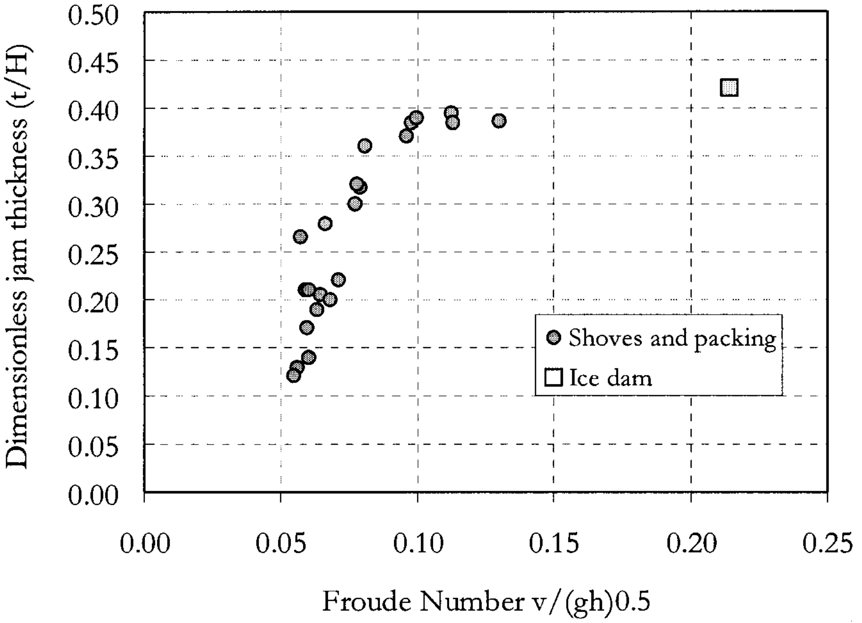

Fig. 5. Relationship between (t/H) and $[v/(gh)^{0.5}]$ under jamming condition, St. Lawrence River (1947–1950), data from Michel (1984)

sections 7 and 10, play a key role in stabilizing the upper reach jam, although the unstable frontal edge of the upper reach jam at Longkou Gorge causes it to move up and down the channel throughout the winter period. This leads to tremendous accumulation in the upper reach jam, with t/H sometimes exceeding 0.9. Thus, the upper ice jam can be characterized as a stable "hanging dam." For such a stable hanging dam, the Froude number appears to increase with the blockage of the cross section, since the effective depth under the hanging dam decreases and thus leads to an increase in the flow velocity. Conceptually, frazil ice under the hanging dam should be transported downstream when the flow velocity increases. However, in view of the large size of the stable upper reach jam (26.66 km from section 1 to 10), this self-regulation process in the stable hanging dam is not easily observed. Certainly, the water under the ice jam may not be easily conducted in a short run, which may influence the overall evolution of this jam.

According to the field investigation, the incoming ice discharge to the lower reach jam might be considered to be equal to the ice output from the lower reach jam, although it is much less than the supply of frazil ice to the upper reach jams. This is the main reason for the less dramatic development associated with the lower reach jam. In addition, the smaller riverbed slope of the lower reach is also an important influence on the evolution of frazil jam.

Using Michel's 22 groups of data of the St. Lawrence River from 1947 to 1950 (Michel 1984, Tables 1 and 2), Fig. 5 shows the overall relationship between t/H and $v/(gh)^{0.5}$. Interestingly, the results of the St. Lawrence River have a similar tendency to those at the Hequ reach, even though the field measurements in the case of the St. Lawrence River are less intensive. The data of the ice dam lie on the upper limb of Fig. 5, as it did for the Hequ reach. The data of the ice-jamming process (shoves and packing) lie on the lower limb of Fig. 5. The turning point of t/H is about 0.3, with the Froude number under ice condition about 0.10. The difference between these two results might derive from different kinds of incoming ice and river morphology.

Conclusions

On the basis of field investigations from 1982 to 1989 at the Hequ reach of the Yellow River, this paper considers the characteristic features of the evolution of frazil jams and the variation in water level during ice-jam periods. The water level depends not only on the thickness of the frazil jams but also on the ice discharge. The dimensionless thickness of the ice jam (t/H) depends mainly on the Froude number under the ice condition $[v/(gh)^{0.5}]$ and ice concentration in water. The results of the Hequ reach show the Froude number at the turning point from the equilibrium ice jam to the hanging dam is about 0.10, with the dimensionless jam thickness (t/H) about 0.40. Interestingly, the results of the St. Lawrence River have a similar tendency to those at the Hequ reach of the Yellow River.

Acknowledgments

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Notation

The following symbols are used in this paper:

$\mathbf{g}$ = acceleration due to gravity (m/s^2);
H = mean total or overall water depth during ice covered condition (m);
h = mean effective water depth beneath ice cover or jam (m);
t = mean ice cover thickness (m); and
v = mean velocity of flow under ice jam (m/s).

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