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Ice Jams at Highways and Bridges—Causes and Remedial Measures

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ABSTRACT

Ice jams cause substantial damage to highways and bridges yearly; however, the highway engineer often is not familiar with what causes them, how to remove or prevent them, or how to lessen their damage-causing potential. Presented in this paper are the basic types of ice and how to recognize them; how they might cause ice jams to form, where they might occur, how to remove them, how to prevent them, and how to compute the height they might reach. With this information the engineer should be aided in his design or reconstruction of highway facilities so that they will not be affected by, or cause, ice jams.

Property owners as well as the general public want a logical answer as well as action toward the elimination of, or at least the reduction of damage from, ice jams.

Highway facilities are usually the most immediate visible means of causing ice jams and often take the brunt of the damage; therefore, the highway agency must be as well prepared as any other federal or state agency to understand ice jams and must be able to take action to combat or prevent them from occurring. The purpose of this paper is to review the three aspects of ice and ice jams highway engineers must understand before they can adequately and successfully deal with ice jam problems. First, the different types of ice must be defined and understood. Different kinds and different forms of ice can create different kinds of problems. Second, the most likely places for ice to jam must be closely identified. Third, several methods of ice jam removal must be considered--some are more effective than others but these are also more expensive. In addition, two theoretical methods for predicting ice jam levels will be presented.

TYPES OF ICE

The U.S. Army Corps of Engineers' Engineering Circular "Ice Engineering" (1) lists approximately 22 different types of ice. The highway engineer is mainly interested in four types:

1. Frazil ice,
2. Ice floes,
3. Ridged ice, and
4. Rotten ice.

One of the most common and most difficult types to combat is frazil ice. Frazil is that ice most likely to be observed in open stretches of river during the early stages of freezing. It occurs or is produced in supercooled water just a few tenths of a degree below freezing and appears like small pieces of flowing slush. Any stream moving at about 2 feet per second (fps) or faster is a potential frazil producer as is a lake or other large body of water that might experience surface turbulence. The problem with frazil is its adhesiveness. As individual pieces collect and increase in size, it becomes more buoyant; yet, as the velocity slows, the potential for a solid ice cover increases. At the upstream edge where an ice cover ends, frazil often begins to adhere to the underside of the cover, causing what is called a hanging dam. As the water tries to pass lower under this dam, more frazil adheres to it and sometimes can, with enough frazil, create a complete ice dam in a river. The potential and often real problem should be obvious. Water will back up, causing higher water surfaces upstream, while lower flows downstream may cause ice grounding or other types of problems. Increased river bed or bank scouring can occur too, as the river tries to force its way through the ever decreasing opening under a hanging dam.

Frazil can also cause problems at hydro dams, water intakes, or at any submerged structure it might adhere to. Intakes or trash racks often become clogged solid with ice--usually frazil--and this buildup can even cause structural failures due to the added dead load. It is difficult to detect a frazil hanging dam due to its solid ice cover, but there are two possible methods. By the coring or sounding method, solid ice is first encountered, then the slush or frazil, and finally, flowing water. Another method of detection is if the ice cover is relatively thin--then the buoyant frazil will push up underneath, causing the sheet to hummock. This can be hard to detect with a snow cover, however.

An extreme example of frazil ice occurred in January 1981 on the Connecticut River near where Vermont, New Hampshire, and the Canadian province of Quebec intersect. Ice jamming caused flooding in the New Hampshire and Vermont towns as well as the raising of ice levels to within one foot of the only highway bridge over the river in the vicinity. The concern was not so much for the bridge itself but for the New Hampshire town's water line that was on the bridge. If the bridge were lost, the water supply would be lost also.

Coring through the ice on the river about a mile downstream revealed a layer of solid ice about 4 feet thick, and under that was another 8 to 10 feet of slush or frazil. Actual free flowing water was only about 2 to 3 feet deep along the bottom of the river. A hanging dam created by frazil ice adhering to the bottom of the solid ice cover was backing up water and thus raising the levels further upstream. The frazil was being generated about 5 miles upstream by turbulent supercooled water flowing over a dam spillway.

An ice jam is usually visualized as large cakes of ice or ice floes, all wedged together into a rough but solid unit. The Corps of Engineers defines a floe as a free floating piece of ice greater than 3 feet in extent (1) (Figure 1). Large floes by themselves are not normally a problem although the force of a floe hitting light objects such as small boat piers can cause extensive damage. The presence of large numbers of ice floes is an indication that, at ice jamming-susceptible locations, a jam is a distinct possibility.

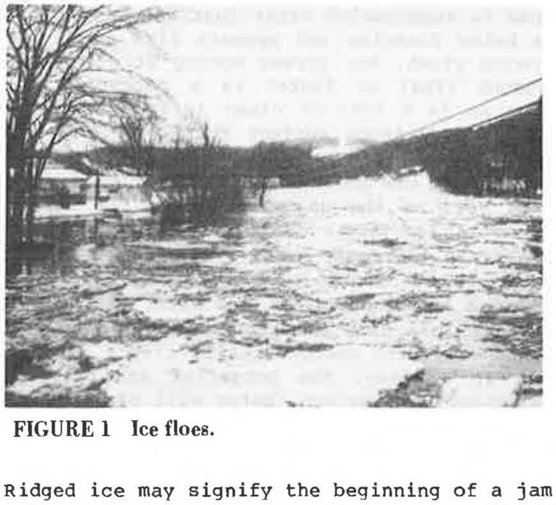
FIGURE 1 Ice floes.

Ridged ice may signify the beginning of a jam and is often mistaken for one. The terms "ridged" or "rubble" ice refer to ice floes piled or scattered haphazardly, one on top of the other, forming ridges, walls, or rough humps, although water continues to flow underneath it (Figure 2).


FIGURE 2 Ridged ice.

Rotten ice is ice in an advanced stage of disintegration. It usually contains pockets of water, may show cracks or potholes, and generally appears unstable (Figure 3). This ice may also be separated from the shore line.


FIGURE 3 Rotten ice.

Where Ice Jams Occur

An ice jam is the accumulation of frazil, ice floes, or ridged ice, wedged together thickly enough to restrict the flow of water such that a head differential is caused. Highway engineers are responsible for prevention of this or keeping the situation as minimal as possible. One aid to doing this is knowing, or being able to predict, the locations of ice jams. There are four sections of any river where jams are most likely to form, with the fourth really being a combination of the first three.

The first is a section of river where the slope or gradient decreases (Figure 4). The flatter gradient section will have a slower velocity, will freeze sooner, and will have a thicker ice cover. When ice begins to break, this area will be the last to do so and as a result, ice floes moving downstream will catch at the upper end of the ice cover. The upstream end of a lake or reservoir or the mouth of a river are all excellent places for this to happen.

Another possible jam site is at a stream constriction. The constriction can be natural, such as a canyon or other narrowing, or manmade, such as a

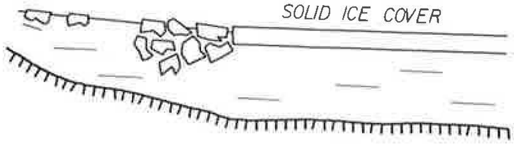

FIGURE 4 Change in gradient.

bridge (Figure 5). A short bridge, with abutments in the channel, or with piers not aligned with the flow, is an excellent ice jammer.

The third location is a shallow reach. Here, ice can either freeze to the bottom or ice floes can ground out as they move through the reach (Figure 6). Sections of rapids or wide, gravel bar areas of rivers are examples of such possibilities.

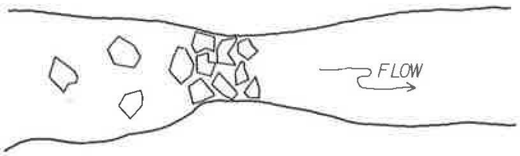

FIGURE 5 Constriction.

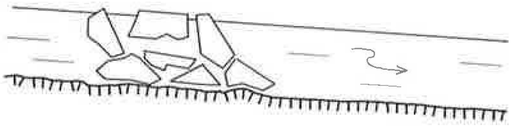

FIGURE 6 Shallow reach.

The fourth location, which may fit into any one of the first three, is at sharp bends. Here, ice builds up on the inside, where the velocity is less, creating a channel narrowing or constriction (Figure 7). Another possibility is that ice grounds on the inside due to the shallowing effect, also with constriction occurring.

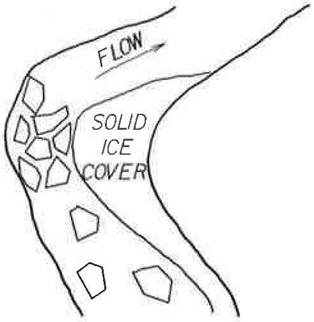

FIGURE 7 Jamming on a bend.

When the jam begins, regardless of the initial cause, water starts backing up, flattening the energy gradient, slowing the upstream velocity, and causing the jam to move even farther upstream. When this happens, flooding occurs rapidly, usually faster than during a non-ice jam flood because a regular flood increases in level based on the supply of water that is related most directly to rainfall--an important variable. During an ice jam flood, the flow rate usually does not change substantially, and the ice is in constant supply. The channel size, however, decreases (as does the capacity to convey water) and, as it decreases, the water surface rises.

Removal of Ice Jams

It is at this point that the highway agency becomes involved. An ice jam has occurred and is causing flooding of a highway or is damaging property and it needs to be removed. It should first be realized that the best time to remove an ice jam is when the water is high. There are two reasons for this: (a) water pressure is high and will help to push the ice away; and (b) the depth and flow rate will be great enough to carry the ice. If the jam is not moved at this time, then there is a chance, especially during mid-winter, that the flow will drop and so will the ice, settling on the bottom and creating a solid dam. Water may later flow over it and freeze, or else a new ice cover will be created upstream, and when that breaks, this jam will catch even more. The Corps of Engineers suggests four techniques to use in breaking a jam: mechanical removal, dusting, blasting, and using icebreaker ships. Because icebreakers are not normally used for breaking up river ice jams near bridges, nor in conjunction with highway flooding, this technique will not be discussed here.

Mechanical removal is probably the easiest and most effective, but it is also the most costly due to equipment rental costs. Bulldozers, backhoes, or draglines are used to remove the ice and create an open channel for the water. Usually the ice can be deposited on the shore but caution should be emphasized. This method was used on one river in Vermont and the owner of the property on which the ice was dumped sued the removing agency because the ice took so long to melt. It not only denied him early spring use of a portion of his field, but the material that was left when the ice did finally melt was not conducive to fertile agricultural soils.

Dusting is a relatively new method not often used, but it can be very effective. Any dark material, usually a black granite or similar type, is spread on the ice in ground-up dust-size pieces to absorb solar radiation and thus speed up the thawing process. This method is normally used before a jam begins because the rough surfaces of a wedged jam create shadows that hide much of the dust. For the same reason, dusting cannot be used if there is a thick snow cover on the ice; nor can it be used in mid-winter because the sun is not high enough in the sky. Dusting is normally done by either a helicopter or a crop duster type of aircraft. Another problem with dusting can be environmental concerns with a material such as ash or granite eventually dropping into the stream. Dusting can also be expensive.

The most popular method is blasting. Blasting is done to loosen the ice and break it into smaller pieces so that it will begin flowing as cakes again. The first consideration before blasting should be whether there is enough flow to float the ice, and then whether there is an open stretch of water downstream where the ice can float without causing problems.

An important consideration in removing a jam is not so much which method to use, but whether any method is really necessary. And if so, will it work? Quite often ice jams will break up by themselves--much of the time without causing substantial damage. Therefore, any knowledge of the performance of past jams at the site and what happened when they did break up would be useful.

There are other methods of combatting ice jams besides removal, and these consist of preventing the jam from causing any real damage. These methods include the construction of levees, both temporary and permanent to contain the higher water elevations within a certain area. By controlling the rate of water releases from a dam, a river can be raised or lowered to either carry the jam or to prevent additional ice from forming. Channels can be cleaned, straightened, narrowed, or relocated, to aid in the prevention, or lessening, of the effects of a jam. Ice booms or dams can be constructed to create the jam in a less harmful area, and finally the area can be evacuated, either temporarily or permanently.

Prediction of Ice Levels

There are two theoretical methods that may be useful in predicting how high ice jams may raise water levels. The first has been developed by the Corps of Engineers Cold Regions Research and Engineering Laboratory. This is a method used to compute flow profiles in a river covered with ice (1). In simple terms, it is the standard step method with a roof of ice over the channel. A roughness coefficient for the underside of the ice must be known or assumed, and this is combined with the channel roughness to give a composite roughness factor (Figure 8). The Cold Regions Laboratory reports that values of n for ice range from less than 0.01 to 0.045. At the downstream edge of a new and rough jam, the roughness value may be as high as 0.07, though this more likely reflects a drag coefficient. From this point on, the normal standard step methods of computing a flow profile are used. This method has been incorporated into the Hydrologic Engineering Center's Computer Program HEC-2, "Water Surface Profiles" as an optional computational sequence.

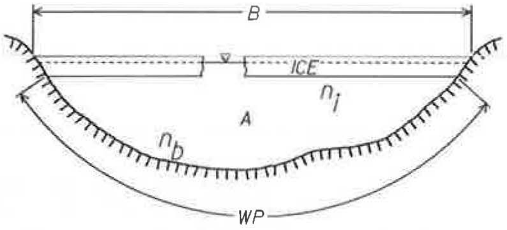

FIGURE 8 An ice-covered stream.

Why is the standard step method that reflects open channel flow used? It appears that an ice-covered stream should have a pressure flow. Actually, an ice cover usually floats and is not solid. There are expansion and contraction cracks, as well as cracks from changes in the water level so the flow really is not under pressure.

Another method, developed by an engineering firm engaged in flood insurance studies (2), may offer possibilities for use by highway engineers in predicting flood levels at bridges or along stretches of highway. The method consists of determining a stage-frequency relationship for ice jam events based on known or calculated high water-high ice levels at the location under study. Then a free flowing stage-frequency relationship is calculated and by the laws of probability of a free-flowing and ice jam event occurring simultaneously, a combined stage-frequency relationship is calculated.

If a site creates ice jams severe enough to raise concerns or complaints, there should be enough people in the area able to give one or more ice or water marks with the years they occurred. With several marks, the winter stage-frequency curve may be plotted by using one of the generally accepted methods of graphing probability distributions.

A better method may be to calculate the stage of a static ice jam based on an equation developed by Michel (3).

$$Y \geq 4.6\ (n\ Q_{max})^{0.46}/B^{0.23} \qquad (1)$$

where

Y = average water depth, feet;
B = width of prismatic channel, feet;
Q_{max} = maximum channel discharge, ft³ per second (cfs); and
n = equivalent Manning's roughness coefficient.

$$\left[n_1^{3/2} + n_2^{3/2}/2\right]^{2/3} \qquad (2)$$

where

n_1 = roughness coefficient of the ice cover; and
n_2 = roughness coefficient of the channel bed and banks.

Q_{max} is the discharge at various frequencies based on winter peak discharges, usually December 1 to April 1.

The distribution of winter peaks is normally calculated by the Log Pearson Type III method. By using Michel's equation and inserting the highest observed stage over a known period and solving for Q_{max}, a verification with the ice jam discharge-frequency analysis can be made. (Examples of ice jam discharge versus frequency and ice jam stage versus frequency are shown in Figures 9 and 10.)

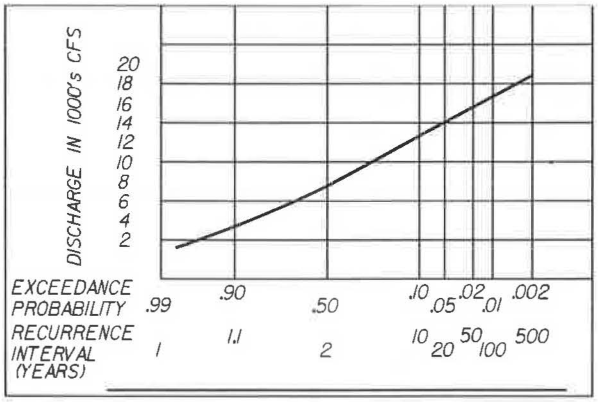

FIGURE 9 Ice jam discharge versus frequency.

The free flowing stage-frequency relationship is simpler to determine. First, the discharge frequency distribution is found by Log Pearson Type III using a record of annual peak discharges. Stage is then calculated by any backwater or flow profile method.

The combined relationship is determined from the laws of probability, which state the probability of the union of two independent events, such as an ice jam (Y_I) and a free flowing event (Y_F), is:

$$P(Y_I \cup Y_F) = P(Y_I) + P(Y_F) - P(Y_I) \cdot P(Y_F) \qquad (3)$$

The results of this are shown in Figure 11.

The highway engineer now has a stage-frequency curve considering ice jams at the site under study.

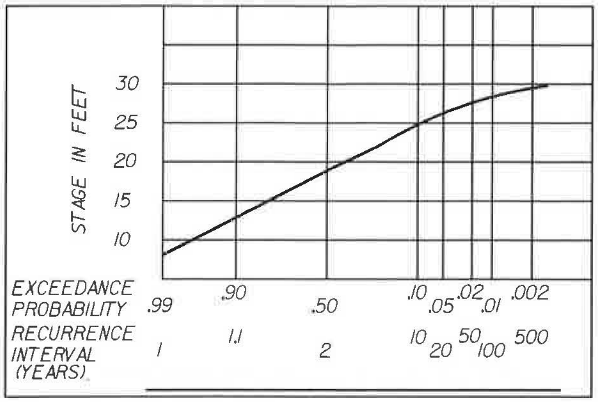

FIGURE 10 Ice jam stage versus frequency.

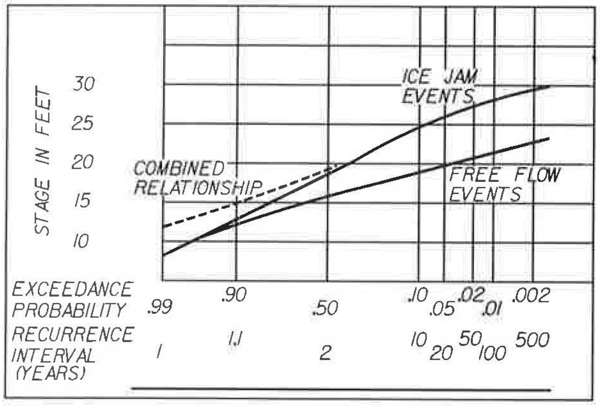

FIGURE 11 Combined stage versus frequency.

With this he can decide heights of bridges or highways necessary to prevent problems from future ice jams.

In order to use this method a record of both annual and winter peak discharges (or the ability to generate one) is required (2).

The Use of Ice-Jam Information

Now that this material is available to the highway engineer or hydraulic specialist, how can it be applied in the areas where ice jams most often affect highways and bridges?

Jamming at bridges is the most common and most critical area of occurrence. Here, ice jams can endanger the bridge as well as cause upstream flooding (Figure 12). Often the bridge is not the cause of the jamming, therefore altering the structure will not reduce the upstream flooding. The danger to the bridge can be reduced, however, by lengthening the span or by raising the superstructure. If the jamming initially begins somewhere else along the stream, the ice levels will remain the same at the bridge so lengthening the span will not help. Raising the superstructure, therefore, usually appears to be the best solution. The use of the latter method would be recommended to predict elevations of ice.

Sometimes the bridge may be the cause of the jamming and the subsequent upstream high water. If this is the case, then the Corps of Engineers' method using different channel sizes may be a better method to use in determining the ideal bridge size. Either streamlining piers or eliminating them completely may help in reducing jamming. A relocation to a crossing site less characteristic of the common causes of ice jams may also be a possibility.

FIGURE 12 Ice jams and bridges.

In designing new bridges, the design should be checked to determine if it will create one or more of the potential jamming sites mentioned earlier. Ice jamming at locations away from bridges but where the roadway is flooded is also relatively common (Figure 13). Unless the roadway has been reconstructed with side slopes projecting out into the stream creating a constriction, the roadway will not be the cause of the jamming. As with bridges, the best way to solve this problem is to raise the roadway grade. The use of the flow profile method with an ice cover is recommended in determining ice elevations. It must be remembered, however, that this method assumes a solid or static ice cover. It does not take into account pushing or humping, which may increase the actual ice levels observed. An added increase in height over that calculated may need to be made to the new roadway elevation.

FIGURE 13 Ice jams and highways.

Raising of the roadway elevation may redirect ice and water flows, causing flooding elsewhere, or higher elevations upstream. If a portion of the floodplain is cut off by this elevation increase, then another solution may have to be found.

Culverts projecting from roadway fills may snag ice floes, either causing a jam to occur, or, as a minimum, twisting or otherwise damaging the culvert end. Care must be taken in locating culvert outlets directly into streams where ice may be a problem. If outlets cannot be avoided, they should at least be angled downstream so as not to present a sharp obstacle for ice. If ice elevations can be determined, they may be able to be placed above the projected ice elevations.

SUMMARY

Ice jams have created, and will continue to create, problems for the highway engineer. Flooding of roadways and the damaging or destroying of bridges are the most common effects of ice jams, but increased bank erosion and upstream flooding caused by water backup from jams at bridges are also frequent occurrences.

In order to effectively combat ice jams, the highway engineer must first know where they might occur. Ice jams occur generally where: (a) river slope or gradient flattens; (b) stream constricts, either naturally or artificially; (c) stream depth lessens, allowing ice to bottom out; and (d) river makes a sharp bend. These sections may occur naturally, or be man-made. To minimize the chance of ice jamming, they should be avoided.

The engineer must also be able to recognize the different types of ice and what their appearance indicates. Ice forms in different ways, and therefore creates different types of jams, as follows:

1. Frazil ice or slush ice usually adheres to the bottom of solid ice covers and creates a hanging dam. These are difficult to detect and can form quickly.
2. Ice floes are easy to see and are the most common type of ice. If blocked, they continue to pile up against one another and can exert high pressures against structures.
3. Ridged ice looks like a jam, but may not create a problem. Usually water is flowing freely under the ridge with very little increase in water elevation.
4. Rotten ice is in the last stage of ice. It is decaying or disintegrating.

Once a jam forms, it may have to be removed. Although no method is completely effective, removal can help for a while. Some methods for this follow:

1. Mechanical removal is probably the most effective, but it is expensive.
2. Dusting is a relatively new, complicated, expensive method. It does work provided climatic conditions cooperate.
3. Blasting is the most common method, but it is not overly effective.
4. Ice breakers can only be used on large bodies of water where navigation needs are foremost.

Finally, the engineer must also be able to predict how high water elevations may reach during different recurrence interval ice-related events. With this information, it may be possible to raise highways and bridges above the levels of the appropriate ice events.

Methods for predicting ice levels, however, are approximate and usable only in certain cases. The derivation of a frequency-stage curve requires winter peak flows and historical ice level data. Using a stream profile or step method assumes a solid or static ice cover, which, for an ice jam event, is not usually the case.

With this knowledge, the highway engineer should be better prepared to understand ice jams, to help lessen their destructive effects when they do occur, and to design facilities that will not be affected by, or cause, ice jams.

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