FAILURE MODES OBSERVED DURING RIVER ICE BREAKUP[1]

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INTRODUCTION

Breakup of ice-covered northern rivers is a spectacular, sometimes severe and highly damaging event. Largely because of the economic impact produced by flooding and ice damage, considerable research effort has been expended on trying to understand and model the breakup process, particularly through theoretical and laboratory studies. Given the scarcity of detailed field observations, however, some of these studies have lacked focus or been misguided.

Researchers at the National Hydrology Research Institute (NHRI) and its predecessors have been studying breakup on large northern rivers since the 1960's and have compiled unique and comprehensive sets of field observations. Based on these observations, this paper attempts to characterize some of the typical ice-cover loading scenarios that leads to ice failure and subsequent breakup. It is hoped that this largely illustrative cataloguing of ice failure modes will be used in planning future research.

GENERAL BREAKUP BEHAVIOUR

In general, breakup conditions are characterized by two extremes: mechanical and thermal. The two classifications refer to specific combinations of river discharge and ice resistance. In the thermal case, spring discharge is relatively low while the ice sheet is thinned and weakened by thermal and radiative fluxes. Typical conditions leading to thermal breakups involve a low winter snow accumulation and limited spring flow. In the mechanical case, conditions involve strong competent ice resisting a large, rapidly increasing spring flood wave. Different ice failure modes precede and characterize these two types of breakup.

Both types of breakup have been observed to dominate in different years on the Liard River, a field location used by researchers of the NHRI since the 1970's to study breakup and ice jam processes (Prowse 1986). Unique sets of field observations have been compiled from this site and are the basis for the descriptions of failure modes illustrated in this report. These modes are rarely mutually exclusive, therefore an attempt has been made to indicate those processes which, in the course of deformation, can give rise to more than one type of failure. Two failure categories are presented and result from observations made at two scales. Firstly, "pre-frontal" modes represent primarily the creep or ductile failure of large (global) expanses of ice cover ($\approx$100-1000 ice thicknesses [t_i]) under the influence of increasing downstream fluid shear and gravitational forces prior to the breaking front. At an intermediate (meso) scale, "frontal" modes represent failures coincident with the flood wave and largely encompasses the brittle fracture of floes in the order of 10-100 t_i.

Although not exhaustive, it is recognized that this simple categorization applies to a broad definition of the derived failure modes and that each mode can be comprised of numerous, smaller-scale processes. For example, spalling and radial cracking are often integral to the crushing process and can control the type of ice rubble shed upon failure.

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A) PRE-FRONTAL FAILURE MODES

1) Vertical bending/buckling

Hydro-mechanical interactions produce some early types of ice failure, one of the first being hinge cracks produced primarily by vertical bending. Such cracks develop along ice-bed contacts where portions of the ice sheet are frozen to the bed or banks while the remainder of the sheet is displaced upwardly by rising water levels or by receding levels post freeze up. These are most noticeable as cracks running parallel to the banks as shown in Fig. 1 and Fig. 2. The extent of shore attachment is important because it influences the distribution of downstream forces within the cover and ultimately the type and rate of ensuing breakup.

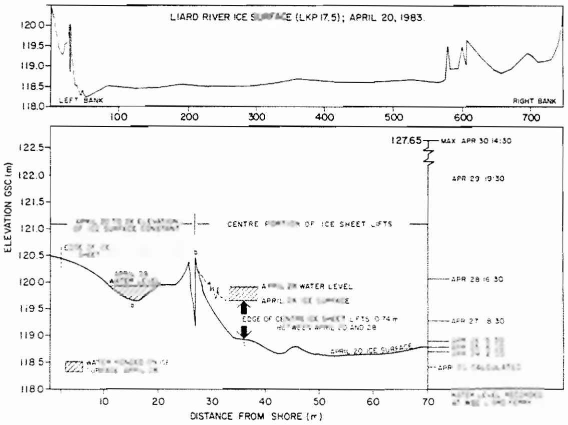

Fig. 1 Water/ice elevation history for a typical ice sheet having formed hinge cracks along its banks.

Fig. 2 Hinge crack formed at freeze-up parallel to bank.

Evidence of vertical bending has also been observed in the stream-wise direction, particularly upstream of shoal locations where an ice cover becomes grounded. Such bending results from the resistance provided by the grounded ice and an increase in downstream forces that is in turn a product of gradually increasing fluid shear on the ice bottom. The deformation associated with this bending tends to be characterized by creep buckling and the formation of large-scale waveforms in the sheet as shown in Fig. 3.

Fig. 3 Grounded ice sheet showing evidence of creep buckling and crushing.

2) Crushing failure

Crushing failure is almost always observed in conjunction with other types of failure. For example, it is evident in Fig. 3 (above) in conjunction with the vertical bending processes. It is also common during ridging and rafting processes at ice-bank interfaces (Fig. 4) and within the intact ice at ice-bed contacts (Fig. 5). It can result in the shedding of pulverized ice, large exfoliated flakes and irregular rubble. These types of processes are usually evidence of large-scale movement of the ice sheet and imminent full-scale breakup.

Fig. 4 Ridging and rafting of intact ice at the ice-bank interface.

Fig. 5 Intact ice showing signs of significant crushing action at a localized grounding site.

3) Large-scale plane-stress tensile failure

The combination of varying river planform and natural flow obstructions can result in an irregular distribution of downstream forces. This in turn leads, on the horizontal plane, to the development of tensile stresses. Transverse cracks, commonly formed at river bends (Fig. 6), are an example of tensile induced failure resulting from large-scale bending of the ice sheet in the horizontal plane (parallel to the water surface) (e.g. see Shulyakovskii, 1972 or Beltaos, 1985). Where local irregularities in ice structure or strength exist, flow and gravitational forces can also produce plane stress tensile failure (Fig. 7).

In some breakups, widening of the channel by rising water levels will permit the downstream passage of large-scale ice sheets produced by the tensile failures noted above (e.g. see Beltaos 1984). In more dynamic breakups, however, the ice sheet remains largely stationary and is only removed by fracturing and fragmentation associated with the downstream passage of a breakup front. The severity of this frontal passage depends on the competency of the ice sheet and the rate and magnitude of its deformation.

Fig. 6 Tensile-induced transverse crack spanning the full river width.

Fig. 7 Large ice sheet separating from intact cover after failing in tension.

B) FRONTAL FAILURE MODES

1) Vertical bending/buckling

Abrupt vertical bending is commonly observed at the brash-intact ice interface and is promoted by a variety of processes, the relative importance of which has not yet been ascertained. Firstly, large-scale bending can be induced by steep water slopes associated with the rapid downstream passage of flood waves. At a more local scale, vertical bending may be induced by floe interactions. As shown in Fig. 8, failure induced by upward deflection is promoted by buoyancy forces resulting from ice floes entrained beneath the intact ice cover. In the same figure downward deflection is induced by an overriding floe. Similar failure occurs where large pans begin to raft over one another (Fig. 9). Note the fracture produced in the over-riding sheet, appreciably upstream of the observed zone of overlap.

Fig. 8 Upward and downward vertical bending failure resulting from floe buoyancy and rafting processes.

Fig. 9 A large ice floe (right) overrides the intact ice (left) showing evidence of vertical bending failure.

2) Crushing failure

Crushing failure at the frontal zone takes place on a smaller scale than that produced by the pre-frontal processes. It is associated with high downstream forces, appreciably higher deformation rates and can lead to localized compressive fracture at floe perimeters (Fig. 10) and ice-channel interfaces. Crushing is particularly dominant in thermally decayed covers that offer minimal resistance to the downstream passage of the spring flow peak. Although localized cracking of the sheet can occur, there is usually no large scale propagation of cracks and much of the energy exerted by the downstream forces is consumed by crushing. The radiation-induced decay of columnar ice, a process frequently referred to as "candling", is perhaps the most dramatic example of cover weakening; its inability to accept compressive loads is illustrated in Fig. 11 and Fig. 12.

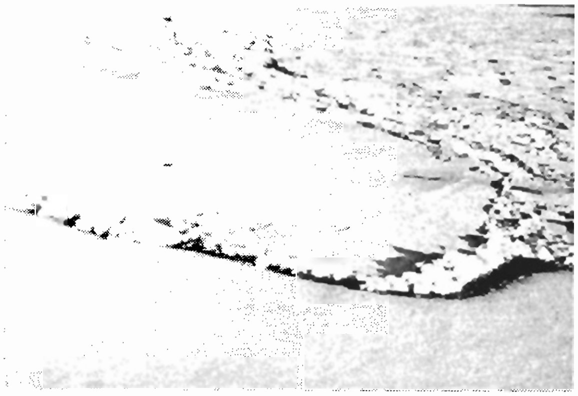

Fig. 10 A large floe (≃ 60 m ø) exhibits crushing at its perimeter as it interacts with intact ice downstream.

Fig. 11 Crushing at perimeters of highly decayed floes. Note the extrusion of crystals along the perimeter.

Fig. 12 Extremely decayed ice is shown to have lost all integrity while rafting onto shore.

Fig. 13 Complex fracture patterns are evident at the breakup front resulting from floe interactions. Note the initiation of a tearing fracture (lower left) and wide spread evidence of wedging action.

3) Plane-stress tensile failure

At the fragmentation front a complex pattern of fractures is produced by the interaction of ice pans and larger floes. Evidence of wedge-action promoting a tensile induced "opening" mode of fracture propagation is shown in Fig. 13. Also illustrated is the opening action in combination with vertical bending, leading to what might be called "out-of-plane" tearing.

DISCUSSION

The above review of failure scenarios is not exhaustive considering the numerous combinations of loading processes. Moreover, it should be noted that freeze-up history plays an important role in controlling the evolution and fracturing of floes and the routing of the fragmentation ice front. The seasonal nature of river ice coupled with the dynamic hydraulic conditions which may accompany its formation, results in ice covers typically being highly anisotropic with respect to the spatial variability of thickness, composition and strength. Observations tend to confirm that spatial variability plays an important role in the downstream-wise progression of fracturing and fragmentation. Vertical structure appears to have the greatest influence on the type of failure promoted. In particular, radiative decay can accentuate these vertical and spatial variabilities.

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