The Role of Natural Flaws and Variability in Ice-Cover Fracture During River-Ice Break-Up

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INTRODUCTION

River-ice break-up can initiate if downstream forces exceed the resistance offered by the ice cover and its boundary support zones. Two general scenarios describe break-up: i) *thermal* break-up, characterized by low downstream forces and minimal ice-cover resistance owing to extensive ice and support deterioration; ii) *mechanical* break-up (or *dynamic*), involving the failure of more competent ice covers by the high forces associated with river waves. River waves are long-period, unsteady flow phenomena resulting from rapid run-off events, ice-jam releases and dam releases. The effect of river waves is to augment the downstream forces while inherent increases in stage can reduce the resistance offered by the cover support zones.

Prowse and Demuth (1989) categorized ice-cover failures based on observations made at a variety of river scales, hydraulic and cover conditions. *Global* and *Frontal* failure modes were identified with respect to the scale of deformation and the rate of failure. This classification, in part, attempts to emphasize the crucial effects of scale and deformation rate on the forces required to overcome ice-cover resistance. To date, the fracture characteristics of river-ice break-up, during spring run-off or wave transmission, have been described by numerous investigators. For example, physical models of large-scale transverse fracture due to wave-slope flexure (Billfalk, 1982; Beltaos, 1990) and horizontal flexure arising from planform shear-stress variation (Beltaos, 1990) have been proposed. Such models assume vertical and reach-wise homogeneity in the mechanical properties of the ice cover. More recently, Ferrick and Mulherin (1989) have characterized break-up as two distinct processes which generate failure and ice-cover movement depending on hydraulic conditions: i) *Support* break-up - large ice sheets will move downstream upon failure of the bank support zone (hinge cracks); ii) *Strength* break-up- where ice-cover fragmentation takes place at a smaller scale along a distinct "rubble" front while bank shear adequately resists large translations downstream.

Of significant influence in the characterization of resistance, is the heterogeneity of the ice cover. The degree and magnitude of this variability is intrinsic in determining the dominant ice failure process and thus can largely determine the forces necessary for the initiation and progression of break-up. It is proposed that the variability itself can, at extremes, be an intrinsic part of generating an ICE-Overthrust-Flexure-Fracture sequence (ICEOFF) leading to the non-simultaneous but progressive failure of distinct zones in the intact ice sheet (Fig. 1). ICEOFF has been observed at a variety of dimensional scales and levels of downstream forcing. It can occur when large sheets begin to converge on the downstream intact cover and through overthrusting cause further fracture downstream as well as fracturing the converging sheet into smaller plates.

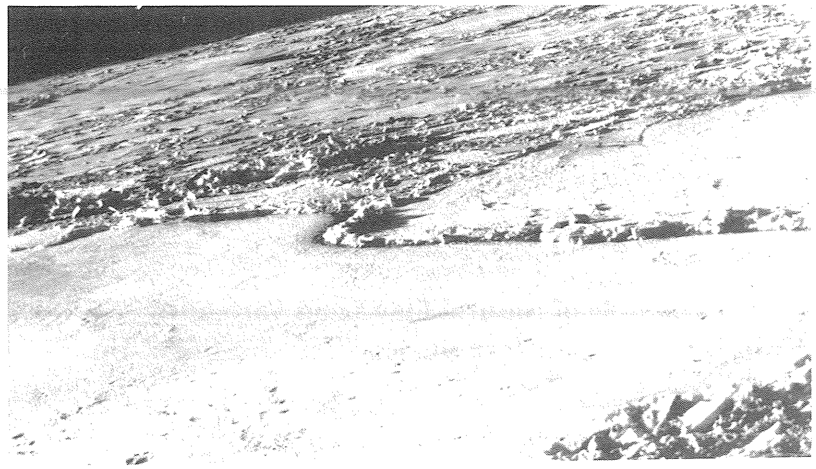

Fig. 1 The ICEOFF process during break-up, Mackenzie River, N.W.T., Canada.

ICE RESISTANCE

The resistance of an ice cover encompasses its internal strength and the boundary states (thickness, lateral extent and support conditions) which influence its kinematic behaviour and mode of failure. Observations indicate that the variability of ice-cover composition and mechanical properties plays an important role in characterizing resistance. However, defining resistance is a difficult task given the dearth of concomitant observations detailing ice failure types and the accompanying level of downstream forcing. The body of river-ice strength data, particularly that detailing the pre-break-up deterioration and its large-scale spatial variability, are limited primarily to those of Ashton (1985), Bulatov (1970), Kozitsky and Bybin (1967) and more recently by Prowse *et al*. (1989, 1990).

The effect of scale and variability on ice resistance cannot be ignored and efforts in the field of ice-structure interaction have begun to improve our understanding of large-scale ice failure. In a review addressing the perception of scale effect, Timco (1989) presents a comprehensive body of strength data and notes that their strength-scale characteristics are largely inconclusive. The principle question ultimately posed is whether the same failure modes exist, during small- to medium-scale laboratory and field testing, as in processes occurring at full-scale; and more specifically, what constitutes a flaw with respect to the evolution of failure?

Ice Cover Flaws and Variability

Flaws and variability in the context of the present discussion are limited to large-scale phenomena including: i) structural discontinuity in reaches comprised of a variety of structural ice forms, thicknesses and aerial extent, and ii) cracks or line failures resulting from thermal strain or previous ice failure (although important, micro-scale phenomena resulting in crack initiation and propagation are not discussed). The effect of these flaws may be to modify ice-cover confinement providing conditions which promote certain types of ice interaction and deformation; a common one is ice overthrust.

Structural Variability

Thermal and hydraulic freeze-up conditions strongly control the growth and distribution of ice types in the river system (Fig. 2). Types most commonly found to make up the competent portion of typical ice sheets include: i) primary and superimposed ice; ii) secondary ice, and iii) freeze-up jam/accumulation ice. Besides differing in their mechanical properties, their characteristic decay by radiation is also markedly different. For example, the decay of columnar ice structures can be significant under the influence of short-wave radiation and may result in a zone possessing little compressive or tensile strength whereas a cover having a granular white-ice surface is effectively insulated from short-wave radiation.

Extreme variations in ice thickness due to variable cover formation processes can result in localized zones of relatively thin ice. The strength of these zones can be further reduced by hydraulic erosion and surface ablation. Fragmented ice or rubble fields, produced during failure events at freeze-up or in advance of the main break-up, may provide a non-uniform line-failure possessing geometry likely to promote ice overthrust.

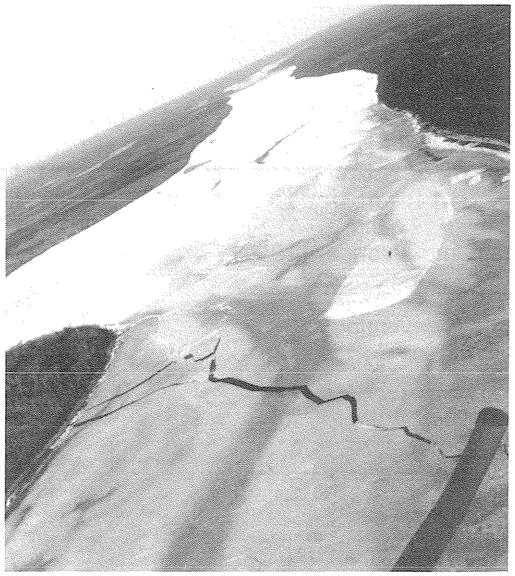

Fig. 2 Mackenzie River prior to break-up showing variability in ice-cover types.

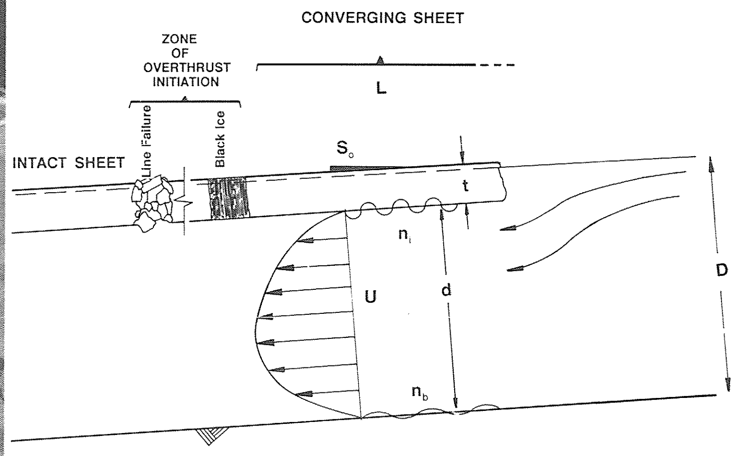

Fig. 3 A schematic of ice-cover convergence illustrating the hydro-mechanical forcing components.

Thermal Cracking

The process of thermal cracking is initiated if changes in ice temperatures induce sufficient strain. The degree to which thermal cracks become operative depends strongly on thermal conditions subsequent to their formation. In floating ice, thermal cracks may heal should infiltrating water refreeze. These flaws may re-manifest under certain thermal conditions such as radiation melt. Observations by the authors (unpublished) indicate that re-frozen thermal cracks in undeteriorated columnar ice samples subject to flexural loading, do not influence the flexural strength until warming and localized radiation melt re-manifested the flaw. This relatively uniform line-failure may have geometry likely to create a zone of ice overthrust.

OVERTHRUST KINEMATICS

It is proposed that the flaws described above, if appropriately established, could lead to an overthrust (Figs. 1,3). A zone of deteriorated black ice, for example, could fail under compressive forces and allow the upstream sheet to converge on the intact cover. In the ICEOFF scenario it is assumed that sufficient forces, due to vertical turbulence and brash-ice buoyancy, are imparted to the upstream sheet, to cause it, in most cases, to over-ride the intact cover. Field observations suggest the tendency is to overthrust rather than to underthrust. As the converging sheet overthrusts the resulting vertical- and axial-end loads (Figs. 4,5) may fail the cover in flexure.

Overthrust Uplift and Submergence

The precise mechanism of overthrust is largely unknown except that it is a highly variable process which relies on the existence of some form of line failure or discontinuity, having the geometry to promote deformation in the vertical plane along the discontinuity (Fig. 3). Nevertheless, by equating the work done during an incremental overthrusting distance to the potential energy gained by the uplifting and submerging ice covers acting against gravity and buoyancy respectively, it can be shown that the horizontal force $\Sigma F_h'$ (prime denotes per unit width) required is:

$$[1] \qquad \Sigma F_h' = \frac{\rho_i \, g \, t \, h_u \left[C + \frac{\rho_w}{\rho_i} - 1 \right]}{C + 1}$$

where ρ_i and ρ_w are the density of ice and water, g is the acceleration due to gravity, t is the ice thickness, h_u represents the height, above the hydrostatic water level (HWL), of the uplifted portion of the overthrust zone and C is the ratio of h_u to the depth below HWL attained by the submerged portion. For t = 1.0 m, $h_u \approx 1$ and $C \approx 1$, $\Sigma F_h' \approx 4.9$ kN·m^{-1}. Further details of this analysis can be found in Demuth and Prowse (1990).

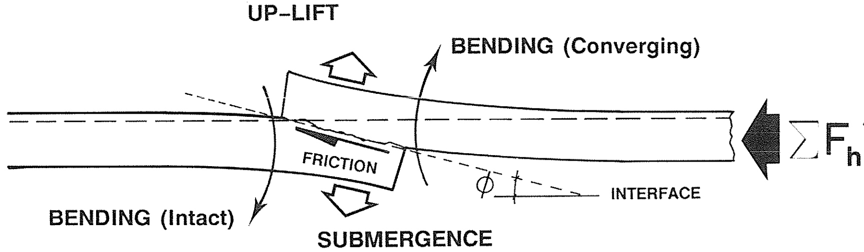

Fig. 4 The kinematic elements of ice overthrust.

<u>Overthrust Flexural Failure</u>

Flexural stresses, generated by the action of overthrust, can be described by considering the elastic deformation of an elastically-founded semi-infinite beam, subject to vertical- and axial-end loads. The differential equation governing the vertical deflection of such a beam is:

$$[2] \qquad EI \frac{d^4 z}{dx^4} + N \frac{d^2 z}{dx^2} + kz = 0$$

where E is the effective strain modulus for ice, N is the axial (compressive) load, k is the foundation stiffness ($\rho_w g$ = 10 kN·m^{-3}) and I is the section modulus of the beam which is analogous to the plate rigidity $t^3/12(1-\nu^2)$ where ν is the Poisson ratio and z represents the vertical deflection at position x along the beam length. The effect of axial load N on the bending moment magnitude and distribution is shown in Fig. 5. Once overthrust has taken place, $N \rightarrow 0$, and the vertical overthrusting force at failure P_f' can be determined from:

$$[3] \qquad P_f' = -\frac{S_{tf}}{6} \cdot \left[\frac{3kt^5}{E(1-\nu^2)^3} \right]^{1/4} \cdot \frac{e^{\pi/4}}{\sin(\pi/4)}$$

where S_{tf} (MPa) is the tensile strength of ice as measured by flexural tests (see Demuth and Prowse, 1990; Mellor, 1986 for additional details). Substituting t = 1.0 m, E = 3 GPa, ν = 0.3 and taking pre-breakup values for S_{tf} in the range of 0.1 - 0.4 MPa (Prowse *et al.*, 1990; Mellor, 1986), P_f' ranges from approximately 3.1 kN·m^{-1} to 12.5 kN·m^{-1}.

For small overthrust slopes the $\Sigma F_h'$ necessary to impart P_f can be estimated from:

$$[4] \qquad \Sigma F_h' \approx \mu_k \cdot P_f'$$

where μ_k is the coefficient of kinetic friction. Taking $\mu_k = 0.3$, we have, for the above ranges in tensile strength, $\Sigma F_h' \approx 0.9 \leftrightarrow 3.8$ kN·m^{-1}.

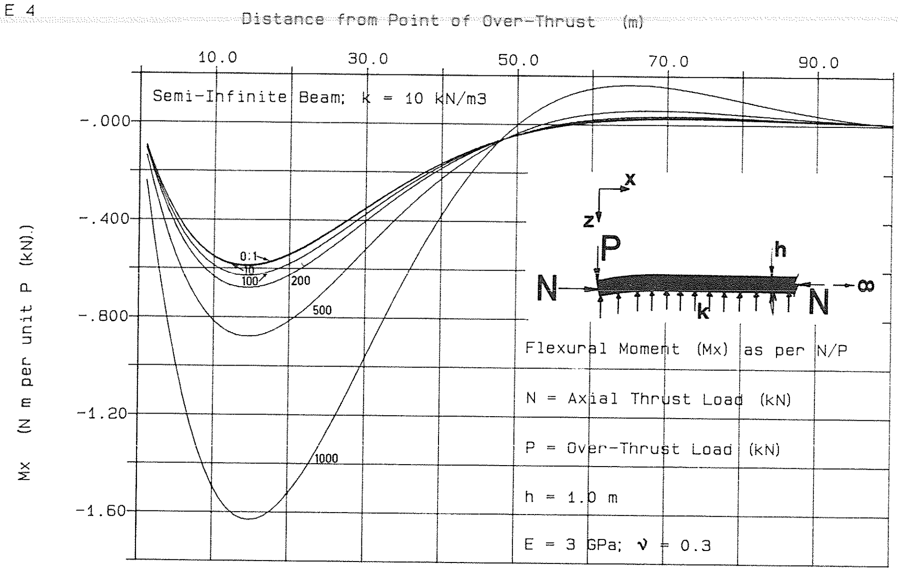

Fig. 5 Bending moment distribution of an elastically-founded beam subject to vertical- and axial-end loads.

There are a number of other related processes which can affect the transfer of forces during overthrust, whose relative importance are unknown. One example is ice roughness and its effect on the frictional resistance of the overthrust interface. Frictional resistance could increase where a zone of decayed crystals having columnar or needle-shaped structures is sheared and ploughed over as overthrust takes place. Water is often flooded on the surface due to turbulent wash or infiltration during the deflection of the intact cover; this tends to reduce the frictional resistance of the overthrust interface.

DOWNSTREAM FORCING

The above values for the required level of downstream forcing for uplift/submergence and subsequent flexural failure can be evaluated by considering the magnitude of downstream forces under typical break-up conditions. In a case study examining ICEOFF, Demuth and Prowse (1990) evaluated the role of individual ice-cover and waterway parameters and their effect on downstream forces (Table 1). Downstream forces are divided into two major categories: i) body force derived from the downstream component of the ice-cover weight (F_w); ii) hydrodynamic forces derived from leading-edge form-drag (F_t) and friction-drag (F_d), imparted to the icc cover by under-ice fluid flow (Fig. 3). These components are estimated using (Michel, 1978):

[5] $$F_w' = \rho_i \, t \, L \, S_o \, g$$

[6] $$F_t' = (1-d/D)^2 \, U^2 \, D \, \rho_w/2g$$

[7] $$F_d' = \rho_w \, d \, S_o \, n_i^{3/2} \, L \, g \, /2n_c^{3/2}$$

where L is the length of the converging ice-cover, S_o is the energy slope, d and D are the under-ice and upstream waterway depths, U is the mean under-ice velocity and n_i and n_c represent Manning's roughness coefficient for ice and the composite section.

The case study found that, under typical break-up conditions, the components of downstream forcing were of sufficient magnitude to precipitate ICEOFF. Notably, the magnitude of downstream forcing was several orders less than that required for simple elastic buckling. F_d and F_w are typically the greatest contributors, however F_t could play an important role if

U is high and when t/D increases significantly. Of pivotal importance is the role played by n_i and n_b and their obvious effect on F_d given any significant roughness variability through a reach.

Table 1
Hydro-Mechanical Forcing Magnitudes and Ice-Cover and Waterway Parameters

t	D	d	U	S_o	L	n_i	n_b	n_c	F_t'	F_d'	F_w'
1.0	5.0	4.08	3.0	0.001	100	0.028	0.028	0.028	0.08	2.00	0.90
1.0	5.0	4.08	3.0	0.001	100	0.028	0.140	0.095	0.08	0.32	0.90
1.0	5.0	4.08	3.0	0.001	100	0.028	0.006	0.019	0.08	3.58	0.90
1.0	5.0	4.08	3.0	0.001	100	0.056	0.011	0.038	0.08	3.57	0.90
1.0	5.0	4.08	3.0	0.001	1000	0.028	0.006	0.019	0.08	35.80	9.03
1.0	5.0	4.08	3.0	0.005	100	0.028	0.006	0.019	0.08	17.90	4.51
1.0	5.0	4.08	1.0	0.001	100	0.028	0.006	0.019	0.01	3.58	0.90
1.0	5.0	4.08	5.0	0.001	100	0.028	0.006	0.019	0.22	3.58	0.90
1.0	3.0	2.08	3.0	0.001	100	0.028	0.006	0.019	0.13	1.83	0.90
m	m	m	$m \cdot s^{-1}$	$m \cdot m^{-1}$	m		dmls			$kN \cdot m^{-1}$	

CONCLUSIONS

Estimates indicate that typical downstream forces during typical break-up conditions can be of sufficient order such that overthrust flexural failures are possible. Additional field data is required, describing the collective and relative magnitude of the downstream forcing with coincident observations of ice failure. The probability of an overthrust event occurring will depend largely upon the distribution and variability of ice structure and ice strength. Evidence suggests that typical river-ice covers exhibit considerable variability and possess flaws likely to promote ICEOFF. Observations of dynamic breakup indicate that knowledge of full-scale failure modes are important when applying ice strength data in an attempt to characterize the force-resistance balance.

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