INTERACTION OF LEVEL ICE WITH UPWARD BREAKING CONICAL STRUCTURES AT TWO SCALES

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ABSTRACT
Observations from centrifuge modeling are compared with those made in the field of a series of ice-structure interaction events at the Confederation Bridge crossing the Northumberland Strait in eastern Canada in March 2001. Past work has shown that ice forces on upward breaking conical structures scale in the centrifuge and this was confirmed by the tests discussed in this paper. An investigation of the process of ice rubble accumulation was conducted in parallel with the force scaling study. Ice rubble accumulations are of interest because of correlation between these events and force maxima. Following the centrifuge modeling program, ice rubble accumulations were analyzed using thin sectioning. The processes of level ice failure and rubble accumulation have been observed to be similar in freshwater centrifuge tests and the field. Fracture mechanics has been found to be the theory that most consistently explains the occurrence of ice rubble accumulations in both the field and the centrifuge.

INTRODUCTION
Field observations of a level ice floe advancing against an upward breaking conical structure show three different interaction modes. The floe may fail by a single fracture that splits the whole floe, or the sheet may fail in flexure and move smoothly around the structure, or the ice may break into numerous smaller pieces that accumulate in a rubble pile on and in front of the structure. Rubble piles are of interest due to their association with force maxima (Mayne and Brown, 2000). In addition, understanding of ice-structure interaction for the case of upward breaking conical structures is important because this geometry is often adopted in an attempt to minimize ice forces on structures. The presence of rubble on the level ice increases the forces required to fail a level ice sheet in flexure against the cone (Lau, 1999; Croasdale et al., 1994).

In order to define the circumstances under which rubble piles form and to determine the accumulation processes of the piles, the level ice interaction processes were studied in the field and at model scale in a centrifuge. This paper reports the observations at both scales, and for two ice types in the model scale. It then examines initiation of rubble piling versus the failure of an ice floe by global splitting using a fracture mechanics

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analysis. The analysis results in the identification of a criterion for rubble pile formation, and a consistent explanation for the ice accumulation process in the rubble pile.

FIELD PROGRAM
The dynamic process of ice-structure interaction was observed at the Confederation Bridge in the Northumberland Strait in March of 2001. The Confederation Bridge is situated in between the Canadian provinces of Prince Edward Island and New Brunswick and is subjected to sea ice forces annually between December and March. Velocity of the passing pack ice is influenced by the semi-diurnal tidal cycle and by wind. The piers are a series of dually sloped upward breaking cones, 56° to the horizontal at the waterline with a transition to 77° to the horizontal approximately 3 m above the waterline. The piers are approximately 10 m in diameter at the waterline.

Mean level ice thicknesses and velocities in the Strait are 0.64 m and 0.23 m/s respectively (Williams, 1996). A monitoring program is in place at the bridge to gather ice force data. The conditions in the Strait at the time of the field program were 90 % or greater ice cover with 30 % of the ice classified as medium first year ice (0.7–1.2 m thick) and the remainder of the ice classified as thin first year ice (0.3–0.7 m thick) according to the Canadian Ice Service (CIS) ice chart for the region. The on site observations were undertaken to supplement remotely acquired time-lapse video observations of ice rubble accumulation. The majority of the field observations consist of downward looking video above one of the piers typically seen in profile from the observation cameras. Several axial and lateral rubble accumulation profiles were obtained using a laser range finder.

FIELD OBSERVATIONS
Ice rubble pile formation in the Northumberland Strait typically consists of the following sequence of events:

* The floe comes in contact with the bridge pier and fails in flexure, exhibiting both radial and circumferential cracking by forming several truncated wedges of ice which are pushed up and along the cone’s surface. These wedges are macroscopic pieces, 2–3 ice thicknesses in the radial direction and approximately 1 ice thickness in width adjacent to the structure.

* Following the formation of these truncated wedges, the ice rides up the cone and ice rubble forms. The piece sizes in this part of the interaction are much smaller than those formed during the initial stages, with spans less than one ice thickness.

* The point of failure moves away from the ice-structure interface, leaving a quiescent inactive zone of rubble at the top of the pile near the structure. The active portion of the rubble pile continues to receive a supply of new ice pieces, material emerges in front of the quiescent zone and then cascades down to the leading edge of the rubble pile, extending out onto the incoming level ice sheet.

* The pile’s height and dimensions appear to reach a steady state as the floe continues past the structure. Excess ice moves away from the side and rear of the pile. Failure of the level ice sheet due to some pre-existing flaw or by downward flexural failure may occur periodically. The process then returns to the upward breaking flexural failure and accumulation stages.
When a critical portion of the floe has passed the ice-structure interface, global failure in the form of a crack to the approaching edge of the floe will occur and the rubble pile will collapse.

Initial condition: floe approaching upward breaking conical structure. Structural radius, R, is small compared to maximum dimension of ice floe, L.

Non-equilibrium ice rubble accumulation. Rubble piece size (described by maximum dimension, l) is relatively large compared to R (on the order of 0.1 R) and number of pieces is small.

Equilibrium ice rubble accumulation. 3 zones: A – inactive zone which is quiescent; little movement is observed; commonly top 1/3rd of pile. B – active zone. Pieces commonly emerge from top of zone and migrate to bottom; commonly bottom 2/3rd of pile. C – active level ice, where downward flexural failure may occur; commonly ~1 pile dimension (A+B) in front of structure. In all zones, l << R.

Collapse of rubble pile occurs most commonly when L_{past} exceeds L_{remaining} and L_{remaining} is less than 50% of L.

Figure 1: Summary of rubble pile accumulation dimensions and dynamics.

Events with no rubble accumulation were more common than rubble accumulation events. Ice rubble accumulation events were only observed 14% of the time video was collected. In some cases, an approximately triangular collection of various sized pieces of ice (typically less than 0.25 pier diameters) would occupy the zone usually associated with ice rubble accumulations and cause incoming ice floes to be deflected away from the bridge piers. Due to the discontinuous nature of pack ice, non-rubble events also occurred in many instances, because less energy was required to move a floe around the bridge pier than to initiate an interaction event. If a floe was approaching the bridge oblique to the pier, it often pivoted around the point of first contact after the failure of a small portion of the ice against the bridge. When the direction of approach was perpendicular to the bridge, global failure by cracking often occurred instead of the development of an ice rubble accumulation. These patterns were observed for a variety of ice thicknesses, velocities, and floe sizes.

Rubble accumulation events were more likely if the floe was large (over ~100 m in diameter), or if a smaller floe was surrounded by other floes at the time it came in contact with the bridge pier. If ice rubble did begin to accumulate during the interaction of the bridge pier with a smaller floe, in the majority of cases, after the initial flexural failure of the ice sheet and a small zone of ice rubble had formed, the floe would split and clear around the bridge pier without the formation of further visible fractures.
The influence of rubble accumulation under the level ice is recognized and indeed likely influences the occurrence of downward flexural failure episodes, but the amount present is difficult to quantify in the observations obtained. It is estimated from visual observations obtained during this field program that the porosity of rubble piles above the parent ice sheet is very low, contrary to previous field estimates that were on the order of 20 to 30 percent (Mayne and Brown, 2000).

An equilibrium ice rubble accumulation is exemplified by the following series of images showing the position of a dye balloon dropped onto a moving level ice sheet (Figure 2).

Figure 2: Frames showing the path of dyed ice through a field ice rubble accumulation, verifying the short-circuiting pattern observed in the centrifuge.

This sequence of frames confirms that the short-circuiting process observed in the centrifuge model thin sections occurs in the field. The dye does not emerge at the apex of the rubble pile, but rather outside an inactive zone where very little movement of the constituent ice rubble pieces is observed. This zone typically comprises approximately the top one third of the pile footprint (nearest the bridge pier) in plan view.

In addition to general observations regarding the process of ice rubble accumulation, a series of profiles of various ice rubble piles were obtained using a laser range finder (Figure 3). Video segments corresponding to these profiles were analyzed using image processing software to obtain the ice velocity, pile footprint, and percentage of the pile surface area comprised of macroscopic pieces (with respect to the structure diameter). These observations are combined with the observed pile profile and angle(s) of repose to attempt to determine if a pattern could be identified in the circumstances of rubble pile formation. Also plotted are the centrifuge observations for freshwater ice rubble piles converted to prototype units. Non-rubble events are under-represented because they clutter up the plot. In the field, non-accumulations occur for all ice velocities and for all floe diameters below 25 m.

Strength and fracture toughness measurements were not made in the field due to limited resources and personnel. Data from Northumberland Strait ice can be found in Williams et al. (1993) and Williams (1996).

CENTRIFUGE EXPERIMENTS
Centrifuge modeling has been investigated as a complementary method of investigating ice-structure interaction because it represents an opportunity to verify larger scale model theories developed in large test basins. The decreased sample ice sheet size also decreases the cost of individual tests.
Figure 3: Ice rubble accumulation observations for field and freshwater centrifuge rubble accumulations. Centrifuge observations have been converted to prototype units. Cases of zero areas or pile heights correspond to non-rubble accumulation events.

The series of centrifuge tests discussed in this paper was conducted as part of an extensive investigation into ice-structure interaction carried out at C-CORE’s large geotechnical centrifuge facility between 1998 and 2001. The specific series of tests of interest was conducted in the fall of 1999. The geometric scale was 1:120 and the structure of interest was an upward breaking cone inclined at 45°. The result of these scaling factors was a structure with a waterline diameter of 120 mm and ice thicknesses
ranging from 5 mm to 11 mm. These model conditions correspond to a prototype cone 14.4 m diameter interacting with ice ranging in thickness from 0.6 m to 1.3 m.

The interactions occurred in an insulated rectangular strongbox approximately 850 mm by 850 mm. Due to space constraints in the centrifuge, the structure moved through the ice as opposed to the field case, where the ice moves past a fixed structure. The cone was displaced through the ice sheet a distance of approximately 800 mm at a rate of 40 mm/s in all tests. Further details of the test program can be found in Barrette et al. (2000).

Immediately following the centrifuge spindown, the ice rubble accumulations were photographed and extracted from the test package. Typically, these samples consisted of up to 0.5 m² portions of both the parent ice sheet and whatever ice rubble had accumulated around the cone. These samples were bagged and stored at approximately –20 °C until thin sectioning was conducted. The thin sections were mounted on glass plates and photographed under cross polarized light (Figure 4).

Figure 4: Thin section of freshwater centrifuge ice rubble accumulation. Note the near-perpendicular orientation of columnar grains on the cone near the base and evidence of short-circuiting at approximately half the rubble pile height.

**CENTRIFUGE OBSERVATIONS – VIDEO**

A small camera with a wide-angle lens was mounted parallel to the axis of travel of the cone to record the process of ice structure interaction during centrifuge testing. Typical interaction events consisted of initial cracking, with large cracks that could be seen radiating throughout the ice sheet. These cracks were generally visible because a large portion of the ice sheet was displaced upward on the order of a few millimeters.

In the case of freshwater ice following this initial failure, ice rubble accumulation began, and this accumulation was often relatively rapid and the piece size was 1/10th of the structure diameter or less. The accumulation was generally more than one ice
thickness on the cone. The ice sheet did not fail in downward flexure due to this accumulation. In the case of saline ice-structure interaction events, ice rubble did not accumulate. Piece size was larger, with most pieces framed by circumferential and radial cracks.

**CENTRIFUGE OBSERVATIONS - THIN SECTIONS**

Thin sections, particularly in the case of the freshwater samples, revealed important features of failure of level ice during ride up on an upward breaking cone, including the shearing along grain boundaries at the point of contact between the cone and the level ice sheet, and evidence for the migration of the active zone of failure away from the interface with the structure. Both of these are evident in Figure 4. The visual evidence does not support the usual modeling assumption of flexural failure of level ice and then ride-up of intact pieces to the top of the cone. Instead, we see local shearing at the base of the cone, and a global shear line that directs material to the surface part way up the pile. Also evident from the thin sections is the low porosity of the rubble accumulation. This was unexpected due to reports of porosities in the range of 20 to 30 percent in the field (Mayne and Brown, 2000).

**DISCUSSION**

We considered similitude, friction based arguments, and fracture mechanics as possible methods of predicting and explaining the occurrence of ice rubble accumulations. The field observations, as illustrated in Figure 2, show no consistent pattern between rubble pile formation (non-zero dimensions) for any of the parameters identified through similitude analysis. Friction between the ice and the surface of the cone does not account for rubble formation. The similitude and friction analyses are discussed in detail in (Pfister, 2002). In this paper, we present the results of the fracture mechanics analysis.

Bhat (1991) examines the failure of an ice floe carried by inertia into a rigid vertical indentor. The floe is assumed to be a thin circular disk comprised of a material that obeys the Drucker-Prager criterion for failure. The stress analysis for a variety of feasible load distributions shows that in every case the maximum stresses occur in a region at or close to the indentor. At first contact, the flow fails locally due to stress concentration at the contact point. Subsequently, the floe may fail locally due to material failure in the region of maximum stress, or globally due to the propagation of a macro-crack. The analysis assumes linear elastic fracture mechanics (LEFM), but does not require any assumptions about the flaw size required to initiate the crack. The crack initiates adjacent to the structure, where local damage will accumulate until a sufficiently large flaw develops. Bhat (1991) also determined the plastic limit load and found it to be much larger than the load required for either local or splitting failure.

Rubble piles form when the ice fails locally, and do not form when the floe splits. When the inertial forces are sufficient to cause failure, the mode requiring lower force will occur. Following Bhat (1991), the global load required for local failure, \( P_L \), may be compared with the global load required to initiate splitting, \( P_s \), by

\[
\frac{P_L}{P_s} = \frac{2.1 \times r \times \sigma_t}{0.62 \times K_{IC} \times \sqrt{2R}}
\]  

(1)
Ice material properties were not measured during the field program due to limited resources and personnel. Ice properties were measured at the same location and in similar ice conditions in previous field programs, and reported in Williams et al. (1993) and Williams (1996). The ice temperatures were close to the melting point, the in situ ice density was high, and the flexural strength measured on 3-point beams was approximately 300 kPa.

Barette et al. (2000) report values of 430 and 610 kPa for the flexural strength of saline ice in centrifuge tests. Flexural strength of freshwater ice grown in the centrifuge for similar test conditions was determined to be 1.25 MPa.

In a review of fracture toughness testing, Dempsey (1989) gives a value of 120 kPa m$^{1/2}$ for the apparent critical stress intensity factor of freshwater ice, provided that the sample size is sufficiently large and other LEFM assumptions are satisfied in testing. He does not discuss the effects of temperature or loading rate.

For the fracture toughness sea ice, questions of the effect of grain size and notch sensitivity are complicated by the columnar structure and the presence of brine channels. Palmer (1991) gives a value of 80 kPa m$^{1/2}$, without reference to any particular set of measurements. Measured values using conventional 3- and 4-point specimens, over a range of temperatures and loading rates, vary from 42 kPa m$^{1/2}$ to 191 Pa m$^{1/2}$ (Urabe, 1981; Timco, 1982; Shen, 1986; Parsons, 1986, 1992; Tuhkuri, 1987). An extensive series of measurements on samples meeting the brittleness criteria of Dempsey (1989) yielded an average value of 79 kPa m$^{1/2}$ (Williams, 1993).

Based on these data, Table 1 gives representative values for the ice properties in equation (1).

<table>
<thead>
<tr>
<th></th>
<th>Flexural Strength (kPa)</th>
<th>$K_{IC}$ (kPa m$^{1/2}$)</th>
<th>$R_{crit}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>300</td>
<td>79</td>
<td>2100</td>
</tr>
<tr>
<td>Centrifuge – freshwater</td>
<td>1250</td>
<td>120</td>
<td>2.24</td>
</tr>
<tr>
<td>Centrifuge – saline</td>
<td>500</td>
<td>80</td>
<td>0.81</td>
</tr>
</tbody>
</table>

For small radii, the global force ratio is large, suggesting that floe splitting will always occur. In practice, as the field observations show, small floes are merely deflected around the structure. For large values of $R$, the $P_i/P_s < 1$, and a macro-crack will form in the inertial-driven floe. The value of $R$ for which $P_i/P_s = 1$, $R_{crit}$, is also given in Table 1.

Although the results in Table 1 represent the idealized case, they are consistent with observations.

In the field, confinement by adjacent floes in heavy pack ice will alter the stress distribution in the floe, producing the effect of a larger floe. Pre-existing flaws have the opposite effect by generating early fracture. Floes less than 2 km in radius were observed to rubble, and floes in the same range were also observed to split. The
observations and the calculation both show that large floes will produce rubble.

For saline ice in the centrifuge, the critical radius is approximately the dimension of the ice sheet in the strongbox. Once the interaction starts, ice fails locally and immediately reduces the effective radius. Global failure in the form of a radial crack follows quickly. Subsequently, the ice fails in flexure as it rides up on the structure. Hence rubble is not observed to form.

More careful analysis is required for the case of freshwater ice in the centrifuge. Although the critical radius is much larger than the strongbox dimensions, local failure occurs and rubble accumulates. In fact, splitting failure, seen as large radial cracks on the video, always occurs near the beginning of the interaction. The ice sheet, constrained by the walls of the strongbox and too stiff to deform out of plane, continues to move intact against the structure and rubble formation follows. The strongbox acts like adjacent floes in the case of heavy pack ice in the field. The same mechanism is not effective in the case of saline ice in the centrifuge because the saline ice, with lower sheet modulus, deforms out of plane around the structure.

CONCLUSION
Level ice failure at an upward breaking conical structures was observed at full scale and 1/120th centrifuge scale. Development and deformation of the rubble piles, when they occur, are similar at the different scales. Floe fracture mechanisms offer a consistent explanation for the formation of rubble in both field and centrifuge observations.

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