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Stress and Strain dynamics in a hydro-electric reservoir ice sheet

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This paper presents ice stress and strain data acquired from the Barrett Chute reservoir located in Ontario, Canada over the 2011 winter season.

Data collected from Barrett Chute showed the ice cover to be unique in a number of important ways. First, it appears that the instrumented cover behaved as a competent elastic unit over much of the winter season. Stress gauges placed in a rectangular array before the dam face presented remarkably consistent stress histories over several major thermal and water level events. This behavior differed radically from that observed at previously instrumented reservoirs, and strongly supports the utility of biaxial stress gauges in field investigations.

Secondly, the combination of a snow free ice sheet, rapid water level variations on the order of 15 cm and intense solar radiation all combined to produce diurnal stresses on the order of 300 – 350 kPa over several days. This maximum value, coupled with an average ice thickness of 40 cm, provides a calculated line load of 130 to 170 kN/m. - nearly twice that allowed by the Carter ice failure model (Carter et. al., 1998).

While no explanation presently exists to explain how an ice sheet might suffer forces well above its predicted failure limit, yet continue to act as a competent elastic material, it does point to the importance of collecting accurate, reproducible, and harmonized stress data in the field.

1. Introduction

This is the second paper presented at a CRIPE workshop on this topic. The first was called Ice forces on Dams: Harmonizing Design Criteria and Developing Means for Mitigation (Morse et al. 2009). That paper outlined the need to develop better design criteria for ice loads on dams, and introduced a collaborative research project undertaken by Université Laval (UL) and Hydro-Québec (HQ-IREQ) to measure ice loads over a wide range of conditions using a wide range of sensors. The present paper continues this collaboration, and extends it through associations with BMT Fleet Technology Inc., SUNY Cobleskill, and Ontario Power Generation (OPG).

2. Instruments deployed

This paper focuses on data obtained from January – March 2011 at the Barrett Chute reservoir, a hydroelectric facility operated by OPG on the Madawaska River (figure 1). The dam is very long (300 m) and very straight. It was instrumented near its center with 11 steel panels commonly referred to as “Carter” panels (after Carter et. al., 1998). Each of these panels was equipped with four Geokon flatjacks designed to record pressures and temperatures at four separate elevations (the top corresponding roughly to the top of the ice surface). A preliminary analysis of this data has been undertaken by Taras and Côté and will be presented at this conference (Taras et. al., 2011). These authors found that the Carter gauge data accords extremely well with in-ice flatjack measurements collected by BMT Fleet, as well as the biaxial measurements presented here.

Ice thicknesses and structural properties were obtained by integrating observations noted by all four groups working on the ice (UL, SUNY, IREQ and BMT). Further, sequential photos were acquired through the placement of two digital cameras on the dam wall. These photos were subsequently synthesized to produce time lapse movies, and were analyzed using MATLAB to quantify vertical and horizontal movements in the ice sheet. The movement of the ice sheet was also measured via a robotic total station designed to interrogate 80 prisms placed on 40 poles spread across the study area. This data set will be presented at a later date, as will water level data collected by OPG. Air temperature, relative humidity, wind speed and direction were recorded at the dam by UL to which rain and snow data from a local Environment Canada site were appended.

The bulk of the data presented in this paper comes from a set of 20 four inch biaxial gauges (figure 2) placed vertically in the ice sheet in four rows, all within 10 m of the dam face. While all gauges were initially placed at a nominal depth of 5 cm on January 18th 2011, some of the gauges were repositioned within a new snow ice layer on February 6th in order to gauge stresses in the upper part of the ice sheet. At two sites near the dam, gauges were also placed at a lower elevation in order to quantify stresses in the thickening ice sheet. Of the 20 gauges, two were not included in this analysis due to the effects of basal thermal erosion (gauges 7 and 8). A further four gauges (5, 6, 15, and 20) were only partially successful in acquiring data due to the failure of their associated data logger prior to February 8th.

Figure 1. Dam at Barrett Chute. Note flooding near dam face; artificially open section to measure levels; and instrumented section near center. Photo taken from left bank (Morse).

3. Literature review

There are some key papers describing ice forces on dams. Comfort et al. (2003) reported findings from studies at numerous locations over several field seasons. Generally, they measured line loads by integrating stresses measured at four depths in the ice sheet 30 m from the dam face. They reported that thermal events were generally slow (on the order of several days) and could build up line loads approaching 90 kN/m. Their key factor was the change in ice temperature integrated over the ice thickness. Once the ice was primed through expansion, additional line loads were induced by changes in water levels.

Stander (2006) documented the increase in stress (about 100 to 200 kPa) due to a rise in water levels for the La Gabelle reservoir, and showed that stress increased by about 4 kPa per 1 cm rise in stage height. He also noted that the process of tidal jacking led to displacement of the ice sheet away from the dam (at a rate of around 8 mm / day), and that ice growth within the fissures was the root of the process. He further noted that stresses created by this process were attenuated over short distances by the ice sheet itself.

Figure 2. Biaxial gauge no 18 held in place by 2” white PVC pipe being removed from ice on Feb. 6th.

Morse et al. (2009) as well as Taras et al. (2009) reported similar findings over subsequent winters at La Gabelle, and generally confirmed Stander’s observations. They also demonstrated a large spatial-temporal variability of stresses along the dam face. They postulated that stresses may be controlled by the rate of strain occurring in the ice sheet. Strains are generated by water level changes, with a lesser, but significant contribution from thermal expansion.

Carter et al. (1998) presented a bending and buckling mechanism in the ice sheet near dams. Based on data (covering many sites and many years) and theoretical analyses, they state that the maximum line load (kN/m) that can be passed on to the dam is about $253h^{1.5}$ where h is the ice thickness expressed in meters.

We are only beginning to analyze the Barrett Chute data set, so our presentation here must be considered preliminary. However, the present data set does generally compliment these (and other) published findings.

However, in contrast to the above reports, the 2011 ice loads at Barrett were not primarily generated by changes in water levels. Rather, they were primarily thermally generated. In addition, the events of interest did not occur over a few days (as was observed previously) but rather over 6 to 8 hour periods. Finally, the stresses generated at Barrett Chute were much greater (stresses up to 350 kPa) than those previously observed during thermal events. Taken together, and considering an ice sheet approximately 0.4 m thick, the line loads generated top out at 140 kN/m (i.e., 350*0.4). This is particularly interesting in the light of previous thermal line loads reported by Comfort et al. and those estimated by Carter’s analysis, that suggest that an ice sheet should not be able to support more than 60 kN/m (i.e., $253*0.4^{1.5}$) prior to failure.

4. Overview of the 2011 winter field season

On January 18th, we placed twenty cylindrical Geokon biaxial gages in the ice sheet. The ice at this time consisted of columnar (S2) ice 13 cm thick (figure 3). A week later, this sheet was overlain by 14 cm of snow ice. From then on, the basal columnar ice grew by 7 cm (as measured on Feb 8th). Snow and warm temperatures ensued, which led to little or no ice growth over the next period. In fact, rising air temperatures and heavy rain resulted in the formation of a slush layer about 14 cm thick by Feb 18th, at which time some of the in-ice instruments decoupled from the ice cover. Fortunately, this situation didn't remain for long, as very low air temperatures (-10 to -20 °C) followed, leading to the formation of a 46 cm thick denuded (i.e., uninsulated) ice sheet. As such, it was very vulnerable to the thermal events that occurred from Julian date 53 through 55 (February 22nd through February 24th).

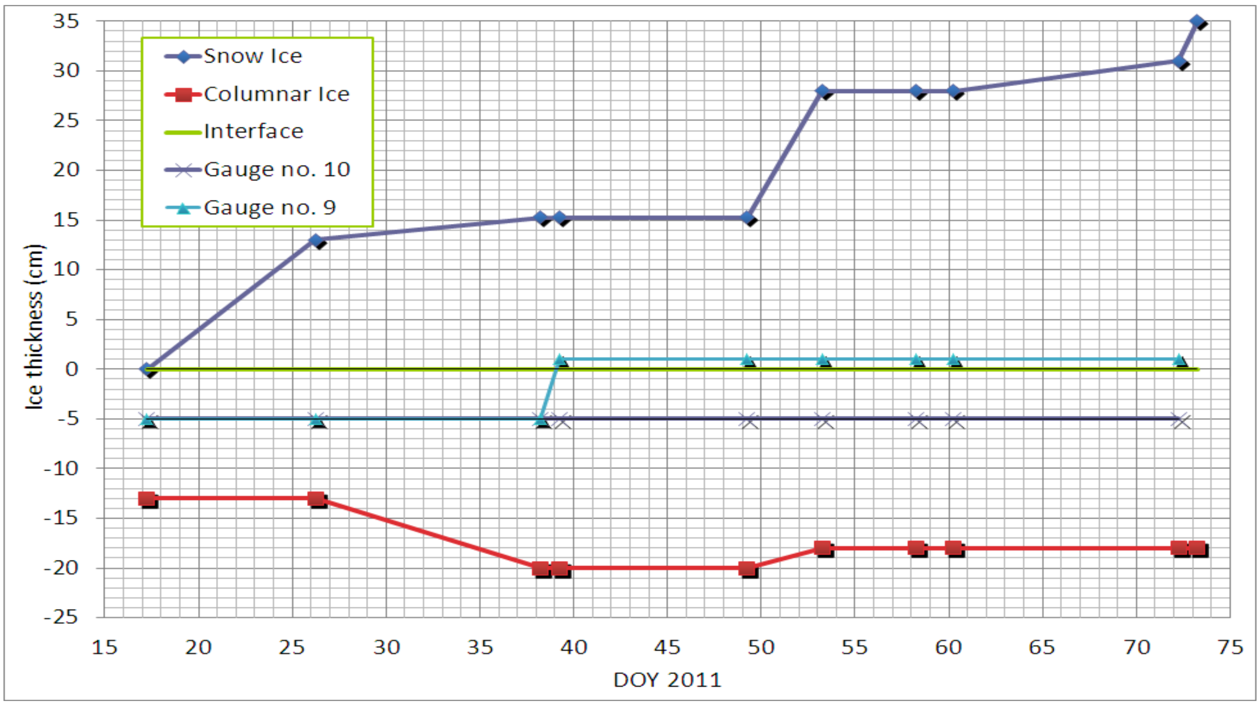

Figure 3. Ice growth separated by an interface at row no. 2 located 4.6 m from the dam face indicating biaxial gauge placement (Table 1). (DOY = Day of Year = Julian day).

The ice sheet displayed two prominent nearshore fissures over the 2011 field season. The first to form was a permanent fissure located approximately 30 cm from the dam wall (the ballycatter fissure denoted on figure 4). The second fissure subsequently developed parallel to and approximately four meters away from the wall. This latter fissure, contrary to those observed over previous seasons, migrated offshore over the course of the winter. It initially formed on January 18th, but appears to have healed shortly thereafter. By February 14th, it was located at 6.5 meters, and remained there throughout the thermal events of Feb. 22 – 25. This latter crack then healed, and reopened nearly 2 meters further afield. While the cause of this migration is debatable, we believe that it might have occurred in response to increasing horizontal stresses operating on a rapidly thickening ice cover.

5. Data Analysis

5.1 Biaxial gauge layout

Initially, the biaxial gauges were placed in four rows about 2.4 m apart. At each row, the gauges were also spaced about 2.4 m apart on a staggered grid. Of more interest to this paper is the layout following the redeployment of half the gauges on February 7th (figure 4). Note that in row 1, there are three sites. The first site located 2.4 m from the dam at a distance of 10.7 m from Carter panel no. 1 consists of gauges 1, 2 and 3 placed at three different depths. The second site consists only of gauge 4. Its location is presented in Table 1. The third site is formed by gauges 5, 6 and 11 placed at three different depths at the coordinates listed in Table 1. (Note that coordinates are in meters: X the distance from Carter panel no. 1 and Y is the distance from the dam). Data for all other rows are presented in figure 4 and table 1.

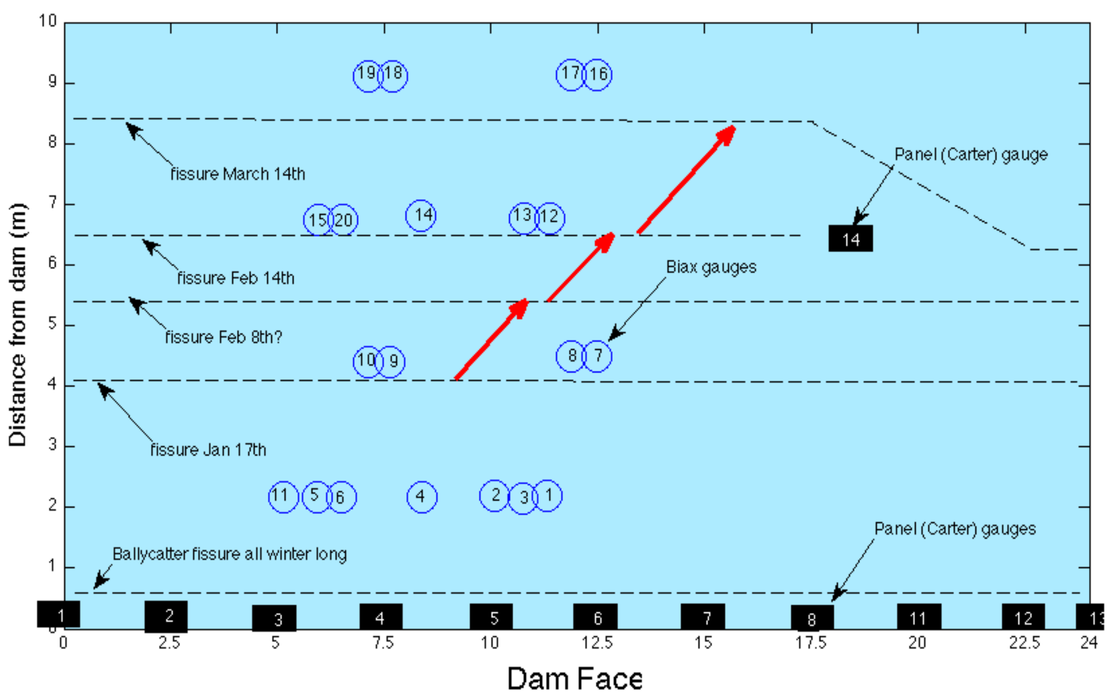

Figure 4. Location of fissures in Barrett ice sheet as well as location of biaxial gauges (circles) and Carter panels (rectangles).

Table 1. Site and biaxial gauge locations after February 8th, 2011 at Barrett Chute

Site ID	Row	Distance from dam	Distance along face	Columnar ice thickness	Snow ice thickness	Total ice thickness on Feb. 23rd	Biaxial gauge no.	Level of center of gauge
		Y	X	h_c	h_s	h		Z
		(m)	(m)	(cm)	(cm)	(cm)		(cm)
1-2-***3***	1	2.4	10.7	5	58	63	1	9
							3	21
							2	49
4	1	2.4	8.4	6	57	63	4	22
5-6-11	1	2.4	5.9	7	56	63	11	11
							5	24
							6	41
9-***10***	2	4.8	7.1	18	28	46	9	1
							10	-5
12-***13***	3	7.1	13	21	21	42	12	2
							13	-4
14	3	7.1	8.4	18	22	40	14	-4
15-20	3	7.1	6.0	15	23	38	20	3
							15	-4
16-***17***	4	9.3	11.9	25	13	38	16	3
							17	-4
18-***19***	4	9.3	7.0	21	17	38	18	3
							19	-4

Note that gauges in ***bold italics*** were those that stayed in their original placement depths and locations. The level of the gauge (Z) is in reference to the snow ice – columnar ice interface. Add the value of the columnar ice thickness to get distance of the gauge from the bottom of the sheet. For example, gauge 9 is 19 cm from the bottom of the sheet and gauge 10 is 13 cm from the bottom of the sheet.

5.2 Internal consistency of data

Data acquired from the 20 biaxial gauges placed on the ice sheet were, in general, spatially consistent. Gauges placed equidistant from the dam face and at the same depth in the ice sheet exhibited very similar stress histories, with typical discrepancies between gauges at roughly the same elevation during periods of maximum stress averaging about ± 50 kPa. This is quite remarkable, given the distance between gauges, the heterogeneity of the ice surface and the observed variations in ice thickness. In fact, it appears that the Barrett Chute ice cover generally acted as a single competent ice block in the zone covered by the biaxial gauges, with local variations in stress occurring as a function of gauge distance from the dam face, moderated by intermittently opened shore-parallel cracks, surface snow characteristics and flooding events.

5.3 The effects of stage height

Water level variations at Barrett Chute were essentially diurnal and their amplitude was generally small (typically 15 cm). The typical rise in water level over the 2011 winter season was less than 10 cm over a one-hour period. These minor adjustments in stage height were separated by prolonged periods of virtually constant water depth, the majority of which were at the low end of the spectrum.

Stresses associated with changes in water depth piggybacked atop the much larger thermal variations at Barrett Chute. Maximal stress variations were on the order of 100-150 kPa per event, providing an average increase of 3.5 – 5.5 kPa per cm rise in forebay elevation. The greatest stress rise with elevation occurred nearest the dam (figure 5). Lower values recorded further from the dam probably reflect stress attenuation by the ice cover (similar to that noted at La Gabelle in 1992 (Stander(2006)).

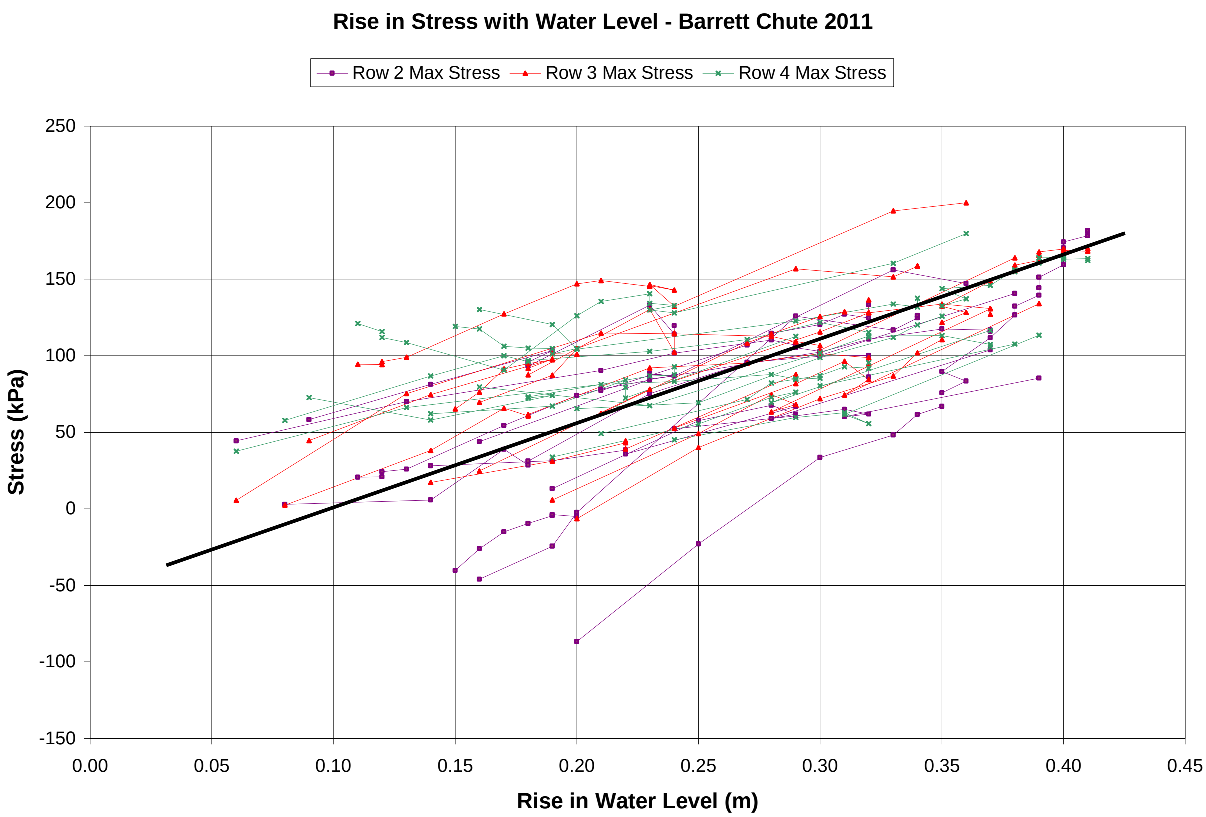

Figure 5. Increase in principal stress as a function of the rise of forebay elevation.

The observed changes in stress with increased forebay elevation appear to have been the result of new ice growth in the adjacent ballycatter fissure. This hypothesis was tested at Barrett Chute by measuring fissure dilation over the course of the winter with a set of four displacement transducers placed across the ballycatter into the floating ice cover. The results of this study showed that the fissure increased in width by about 20 cm over the winter (equal to approx. 3.6 mm per day – see figure 6), and that stress events and fissure dilation occurred simultaneously.

The mechanism by which water level affects stress is well known (see, for example, Stander (2006). In effect: the process of forming new ice along the walls of an open fissure produces moderate to high stresses by increasing the dimensions of the ice cover, making it a bit too large for its enclosing basin. As water levels subsequently rise and the fissure closes, the cover adjusts to its new girth by compressing the adjacent ice sheet.

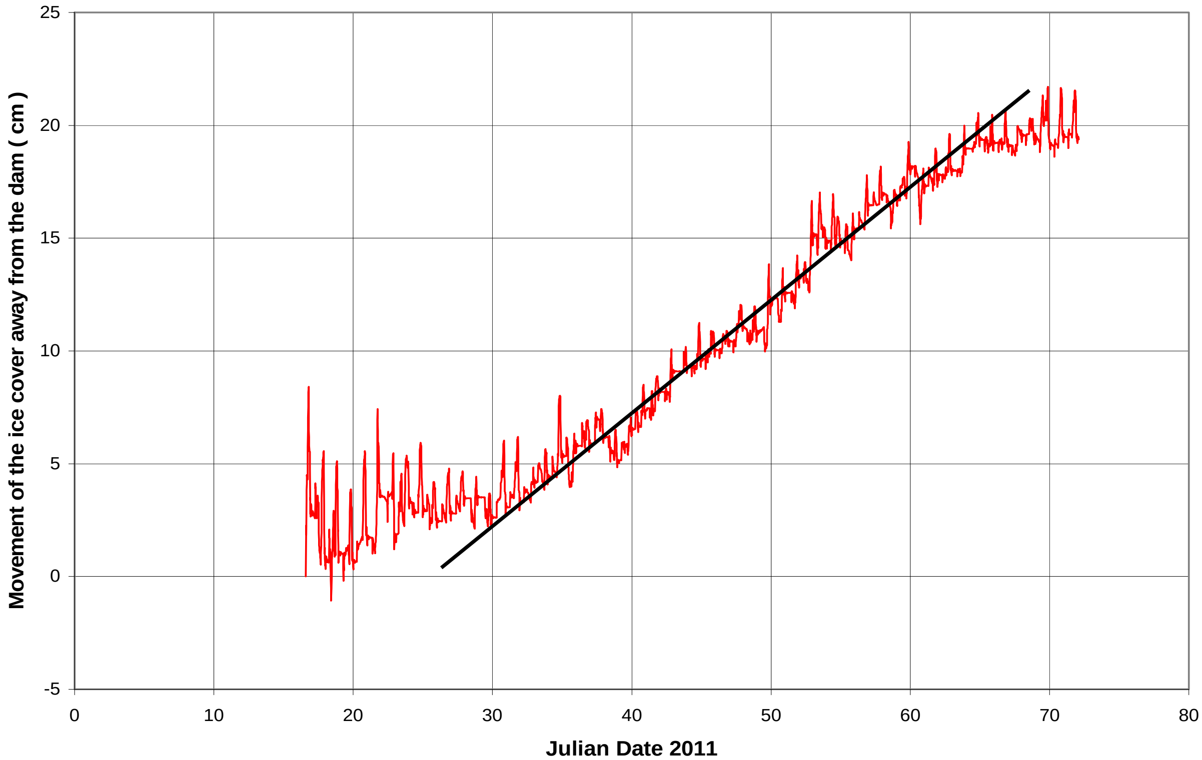

Figure 6. The offshore movement of the main ice sheet as a result of ice formation in the ballycatter fissure. Each peak marks a change in forebay elevation within the reservoir.

5.4 The effects of thermal fluctuations

The Barrett Chute ice sheet suffered two periods of major temperature fluctuation during the 2011 winter season. The first, of short duration, occurred on the morning of January 24th and was produced by the local flooding of the ice sheet in the vicinity of the dam face.

The January 24th event was important in that near-shore flooding events are common occurrences in reservoirs, and lead to extensive thickening of the ice sheet over the course of the winter. Flooding can occur whenever the principal ice sheet rises above its average stage height and impinges against the ballycatter - a triangular block of ice adfrozen to the dam face during the initial freeze-over of the reservoir. This ice block impedes the continued rise of the sheet, produces the flood event, and may initiate shore parallel fractures as the floating cover bends under the increasing vertical strain.

As water floods over the cold ice cover, it forces the surface temperature of the ice to increase, producing an expansion of the ice surface. This can lead to local flexure of the ice sheet, and wholesale ice displacement if stresses at the ice/water interface allow. It also produces internal compressive stresses which will be felt by the in-situ biaxial gauges.

The ice sheet temperature during the January 24 event rose from -10 ºC to -5 ºC. This led to a concomitant increase of stress of approximately 325 kPa in the first row gauges. Interestingly enough, the event was nearly invisible to gauges in rows 3, and 4 (numbers 12 - 20), as these gauges lay beyond the open crack that introduced much of the water to the ice sheet. Further, the bulk of the compressive force was oriented parallel to the dam face, as the open cracks located to either side of the flood zone accommodated ice expansion in those directions. Thus, it is quite possible that the dam itself felt little or no effect from this singular event.

The second large thermal event was more cyclical in nature, and followed a large period of snowmelt and rain (day 47 and 48) and refreezing (days 49-52; February 18 – 21). Following these event, several days of clear, sunny skies led to diurnal variations in air temperature on the order of 20 degrees, as well as dramatic and rapid thermal pulses in the snow-free ice sheet.

In contrast to the January event, the cyclical thermal events of February 20 – 25th produced maximum compressive stresses oriented normal to the dam face, and affected gauges in all four rows. Four diurnal thermal events were recorded during the third week of February, 2011. The first three increased in amplitude with each passing day, while the fourth produced a much smaller rise in air temperature, and led to a much slower increase in ice temperature (figure 7).

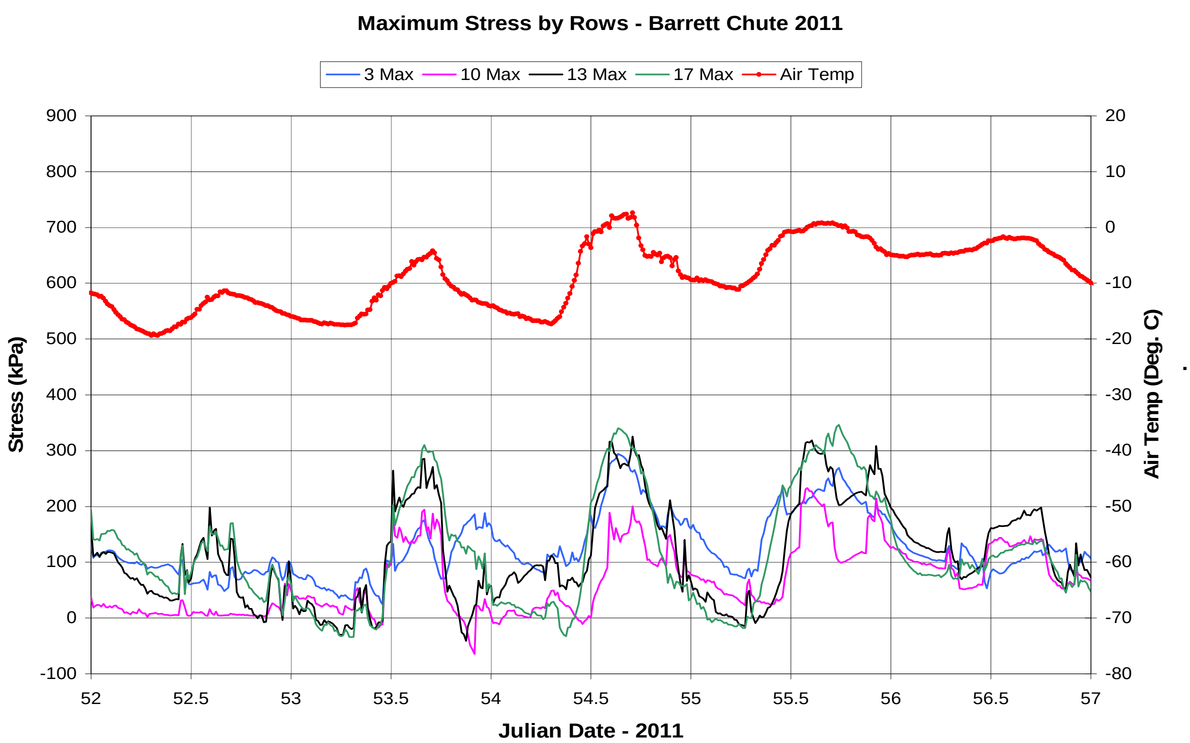

Figure 7. Variation of air temperature and principal stresses for a biax gauge no. 3 (row 1), no. 10 (row 2), no. 13 (row 3) and no. 17 (row 4).

Ice stresses produced by each of the four thermal pulses were comparable across the width and depth of the ice cover. In general, ice stress increased 80 kPa per degree Celsius of temperature rise (figure 8). The greatest thermal increase observed during this study was that of gauge no. 17 (fourth row). This gauge felt a thermal pulse of 4.5 degrees Celsius, leading to an increase in compressive stress of 350 kPa exclusive of water level effects (see figure 7).

Interestingly, the rate of thermal change did not seem to play into the maximum stress felt by any of the gauges. The value of 80 kPa per degree Celsius held for the slower events as well as the faster events, suggesting that the ice sheet behaved more or less elastically over the study period. This was unexpected, given that the strain rate of the thermal events was on the order of $1 \times 10^{-8}\ S^{-1}$. In any case, it is surely something to think about.

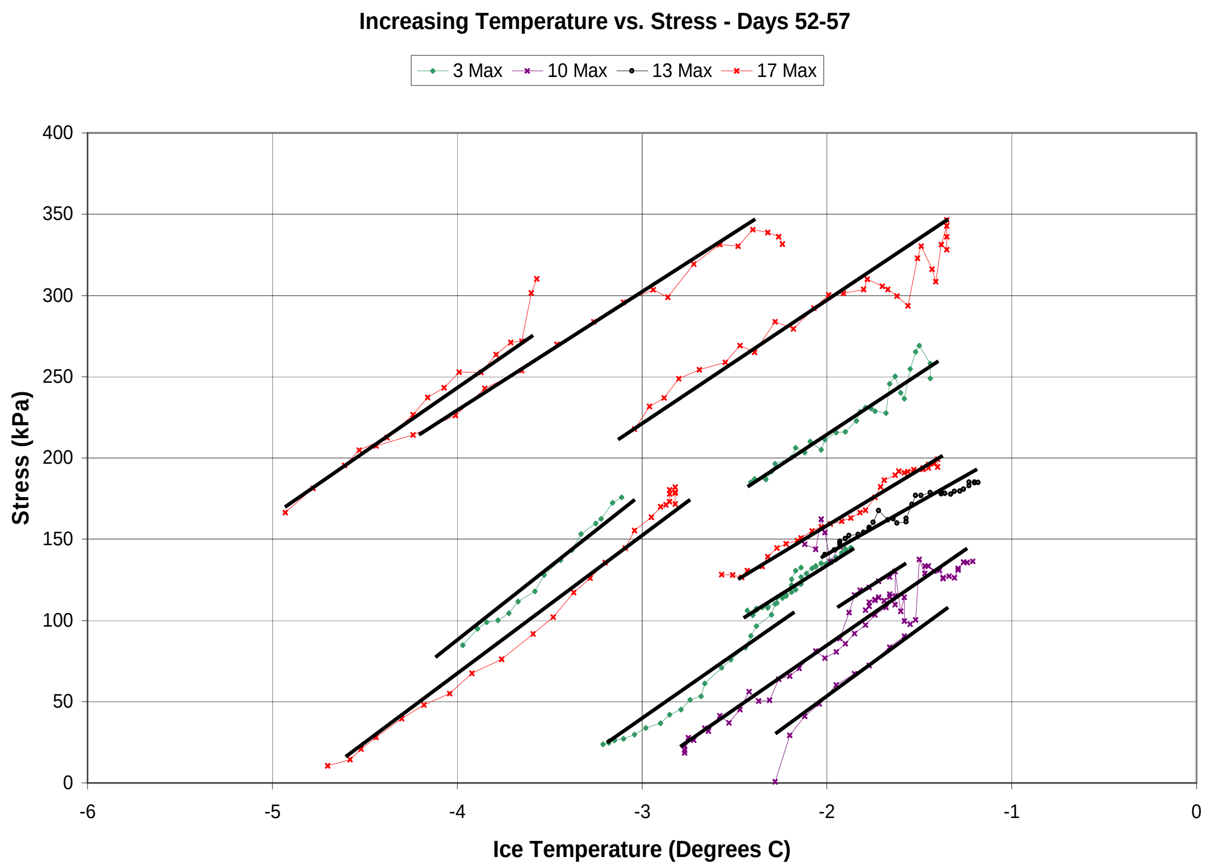

Figure 8. Increase in principal stress measured by biaxial gauges as a function of increase in ice temperature. Observed deviations from the best fit lines are primarily due to short lived fluctuations in forebay elevation.

5.5 Spatial distribution of line loads

The spatial distribution of line loads varied rapidly in time and could vary significantly in space – particularly during periods of transition. Figure 9 shows the spatial variation of calculated line load on February 24th at 10:45. These values distributed over a 0.5 m mesh are interpolated based on the values of the nine sites listed in Table 1. The perpendicular load is calculated using the stress values and directions recorded by the biaxial gauges averaged over the ice thickness (based on the number of gauges) and multiplied by the ice thickness.

The loads were calculated at 15 minute intervals and analyzed using MATLAB. In general, the spatial distribution of the maximum load was fairly uniform. For example, figure 10 shows the load distribution at the peak stress state on Feb. 23rd. In this case, the minimum value was 105 kN/m, the mean was 135 kN/m and the maximum of the nine sites was 173 kN/m measured nearest the dam.

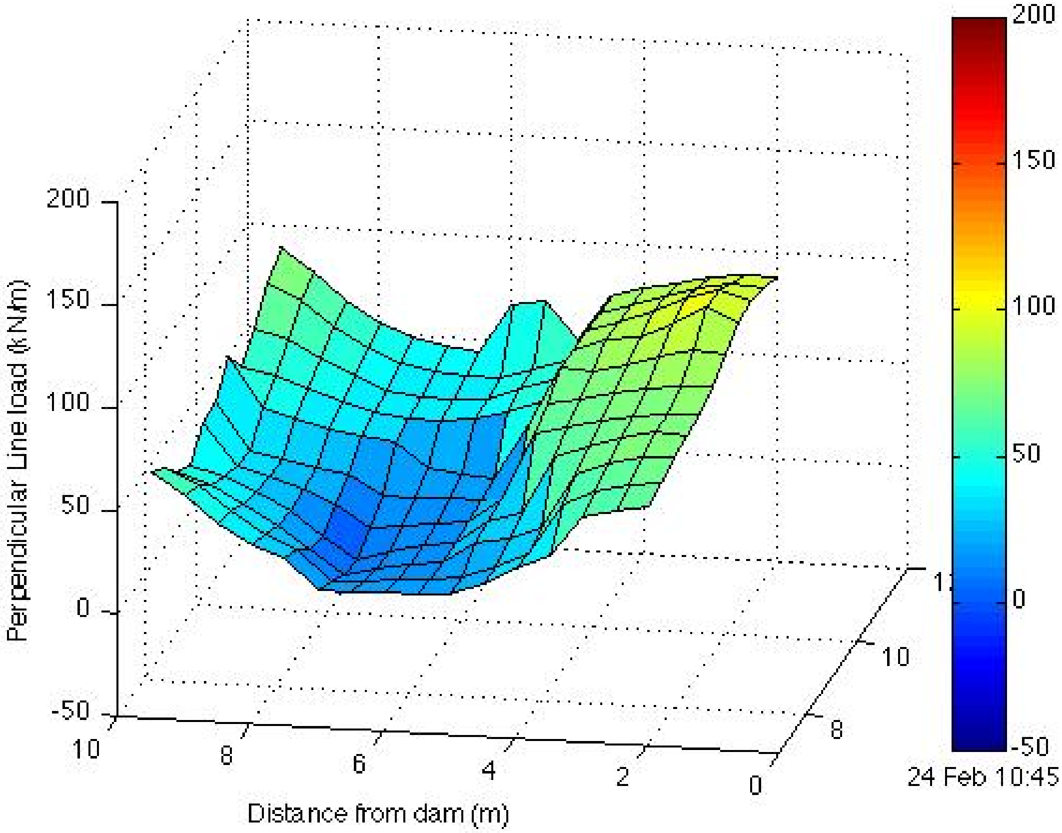

Figure 9. Spatial variation of line load during a transition period. (X-axis is distance along the dam)

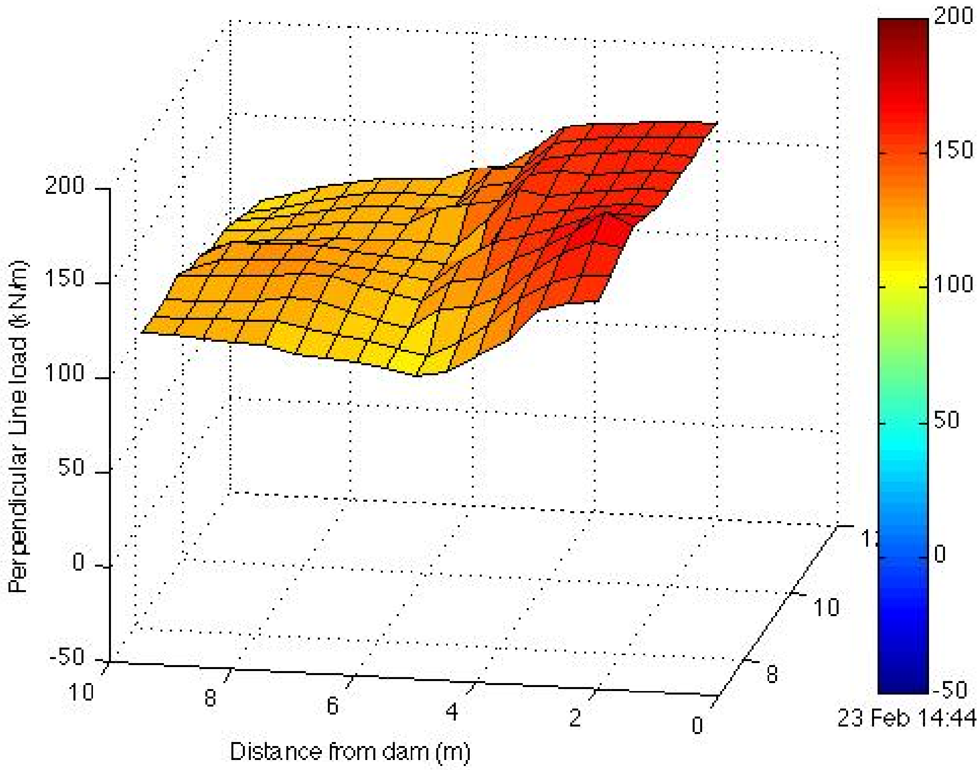

Figure 10. Spatial variation of line load at time of maximum thrust.

6. Conclusion

The 2011 data set from Barrett Chute has gone a long way towards demonstrating the reliability and consistency of biaxial gauge data. It also alludes to the fact that the biaxial data set is very consistent with measurements acquired from flatjack gauges (such as the Carter panel and BP gauges used by BMT Fleet). As such, this work represents a major step forward towards harmonizing load values acquired by these various sensors.

During periods of transition, stresses and line loads can vary significantly in space (figure 8) but at times of maximum thrust (figure 9), the spatial variation was much more uniform and calculated loads corresponded closely with values calculated using other instruments.

The data as presented supports the observation that in-ice stresses can rise as a result of increasing forebay water levels. The amount of rise measured here was on the order of 5.8 kPa/cm (as compared to 4 kPa/cm found previously at La Gabelle). However, the overall effect at Barrett is considerably less than that at La Gabelle, where water level fluctuations average four times that observed at the former site.

Similarly, it was found that the fissure near the dam face at Barrett Chute grew by about 3.6 mm per day (5 mm during the heart of winter) as compared to 8.0 mm per day at La Gabelle.

The data also show that quick thermal events (6-8 hours) can be significant (whereas previous field campaigns suggested that slow events (2-4 days) were the most important). Data here suggest a consistent rise of 80 kPa per degree Celsius rise in ice temperature. It was also shown to be independent of the rate of thermal increase. Events were generated by local flooding events, as well as global changes in air temperature. The data also suggest that the spatial variability of stress was much greater for water level induced events than to thermal events.

The calculated line load at Barrett Chute (having a peak spatially-averaged value of about 135 kN/m) was more than twice the theoretically possible value as calculated by the Carter et al. (2003). This suggests that the nature of the fissure near the dam may be very important in predicting possible maximum loads as it may affect the nature of the instability in the ice sheet.

These findings are a reminder that ice loads on dams can be significant and must be properly accounted for in the dam stability design process.

7. Disclaimer and Acknowledgements

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8. References

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