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Measurements of Ice Thrust at Arnprior and Barrett Chute Dams

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Ice thrust is an important factor to properly design safe dams. Arnprior was chosen because past measurements showed important ice loads, while nearby Barrett Chute has a straight dam face. The objective of this work was to compare near and far-field ice thrust as well as to compare different measuring systems. The three different types of sensors (Carter panels, BP gauges and Biaxial gauges) have been used by different teams to measure ice loads in the field for the last twenty years. Ice stresses were recorded at different depths in the ice sheet against or near the wall and at sites 5 m and 30 m away from the wall. At Barrett Chute a series of 11 Carter pressures panels consisting of four sensors were hung along the wall at 2.5 m intervals.

Line load obtained from the three types of sensors tracked each other quite well and values are within the uncertainties. Significant ice load values (greater than 100 kN/m) were obtained for both dams during the 2011 winter. The loads were generated during a winter that was not exceptionally cold but had small snow cover (< 10 cm). This lead to a maximum ice thickness in the field of 45 cm. Water and temperature variations influenced the ice pressure measured. Daily temperature variation coupled with the absence of snow cover yielded significant diurnal line loads variations. The averaging of loads measured over a 25 m linear face of the dam reduced the peak load but was still 30% larger than in the far field. The indentation model seems to explain to a large extent this difference. Projection of the load average over a greater linear face of the dam than actually measured tended to minimize even more the difference.

1. Introduction

There are diverging criteria for ice loading on dams. The Canadian Dam Association recommends a design value of 150 kN/m whereas some researchers seem to be recommending ever increasing design values, up to 250 kN/m. Faced with diverging criteria, Hydro-Québec Production has taken a pro-active approach to establish the maximum ice load levels and to harmonize ice load design criteria for its dams. It has assembled a joint investigative team comprised of its Research Institute, Ontario Power Generation, Laval University and BMT Fleet technologies as expert consultants. Our objectives were three fold: to determine the maximum load, to harmonize the approach in determining ice load design criteria and compare instruments.

Ice loads measurements were carried out at dams along the St-Maurice River during the previous years and yielded low load values in the ice field (Taras et al., 2009, Morse et al., 2009). In order to obtain larger loads, field measurements were undertaken in 2011 at Arnprior and Barrett Chute dams which are owned by Ontario Power Generation (OPG). The reason for this change is the historical high load recorded at Arnprior and the low level of snow precipitation in the area.

The purpose of this paper is to present the 2011 results from pressure, temperature and water level measurement recorded at Arnprior and Barrett Chute dams, and to discuss how they serve our objectives. The data were recorded from beginning of January till the middle of March 2011. Complementary data analysis from the Barrett Chute site is presented in another paper at this Workshop (Morse et al. 2011).

2. Instrumentation & Measurement Program

At both dams, field measurements of air and ice temperature, ice thickness, water level and ice stress were collected at different locations on the ice cover and along the wall. The measurements of ice stress, temperatures and water level were collected at 5 min interval while ice thickness was collected on a two to three weeks interval at different locations on the ice cover. Forebay water level variations were obtained from electronic recording meters from dam operations.

Sensors for ice pressure measurements comprised of BP circular disc sensors (Child, 1984) and Carter panels. Each panel consisted of four rectangular plate sensors (10 x 20 cm) on a 1 cm thick stainless steel plate 0.4m wide by 1 m high (Carter and Stander, 1997). They are of the flatjack type where by the ice pressure squeezes the fluid between plates into a pressure tube. The Biaxial gauges are round slugs 7 cm in diameter. Their pressure is recorded from the deformation of the circular steel casing. Morse et al. (2011) give a detailed description of the biaxial gauges as well as describe the results obtained with them at Barrett Chute. All sensors were compensated for temperature.

At Barrett Chute, eleven Carter panels were hung vertically against the wall at the beginning of December 2010, as shown on Figure 1.They were positioned at a 2.5 m interval along the wall roughly at center span with the top sensor being submerged in the water. Sensors were placed in the ice field in mid January 2011. Measurement sites were set up in the ice field at 6.5 m from the wall with one Carter panel at one site and 4 BP gauges at another site. Also there were three measurement sites at 27 m from the wall with one Carter panel as a central site and two BP sites

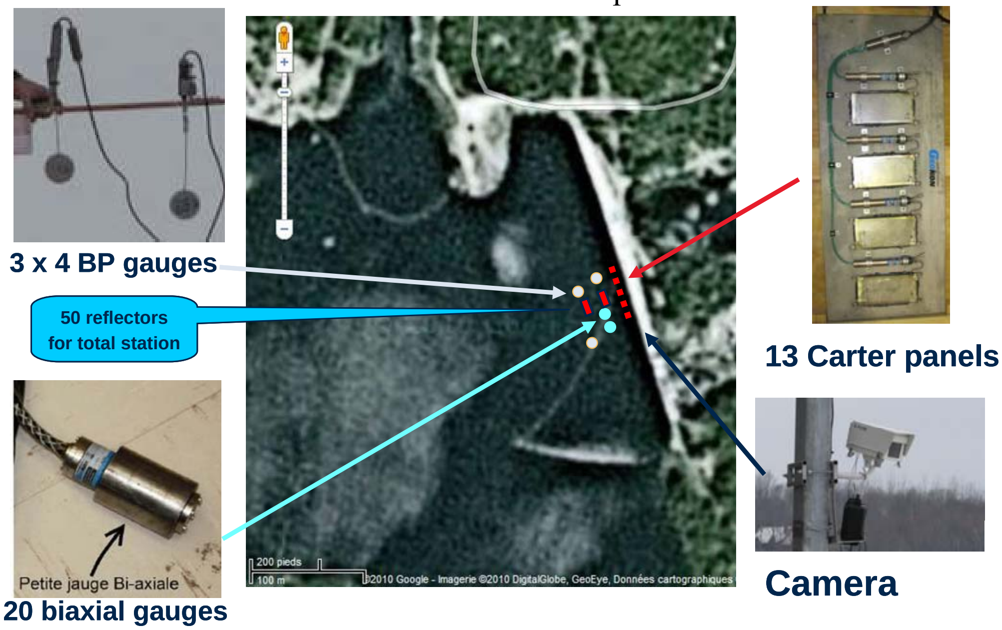

Figure 1 Layout of BP, Carter panels and Biaxial gauges at Barrett Chute dam

on each side. At each BP site, initially three sensors were installed at 3.75, 13.75 and 23.75 cm in depth; the thickness of the ice at far field reached a thickness of 28 cm at installation in January. The Carter panels were set slanted at an angle along its length in the ice such that three out of the four sensors covered the ice depth similar to the BP sensors, see Figure 2. At each measurement site, a fourth BP sensor was placed above the ice for it to be covered in ice as winter progressed and ice grew on top.

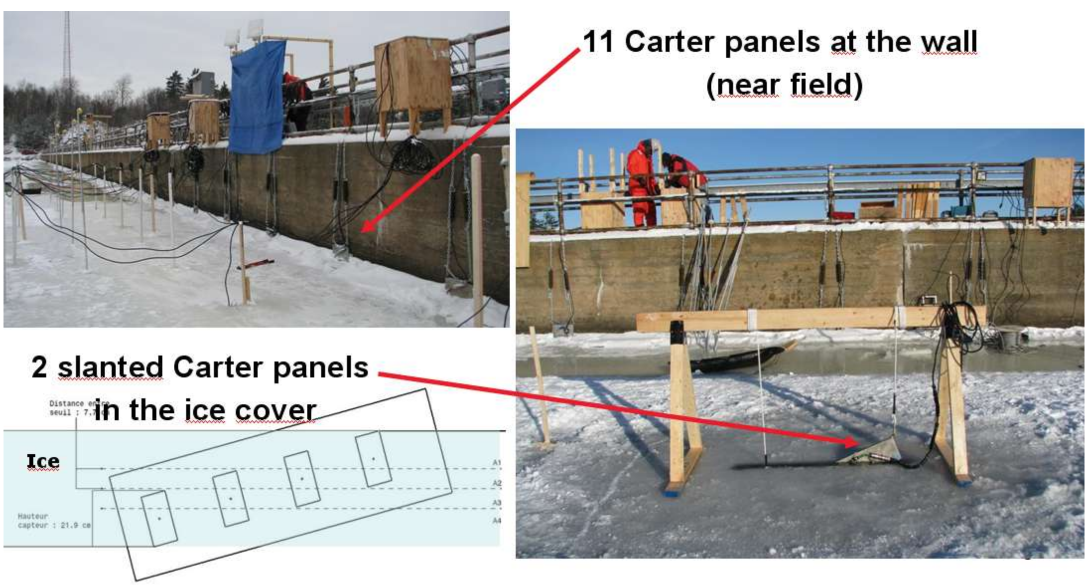

Figure 2 Carter panel on site at Barrett Chute

The layout of sensors at Arnprior was the following: none at the wall, being too short between abutments; one BP and one Carter measurement sites at 5 m from the wall; two BP and two Carter measurement sites at 30 m from the wall. Each BP site had four gauges in the ice thickness.

3. Environmental Parameters Bearing on Ice Loads

3.1 *Ice, Snow Cover & Precipitations*

Snow and ice field data were taken during each visit, at a rate of every two to three weeks from the beginning of January to mid March. Ice thickness increased over the winters with both surface and bottom growth happening. Ice surface growth occurred due to a number of mechanisms: as water level rises it can spring from the cracks and flood the ice surface, also rainfalls and warm weather can melt the snow into water and slush. Subsequently this water and slush can freeze. Measurements were taken at locations every 8 meters along the perimeter of the work area and at each measurement sites.

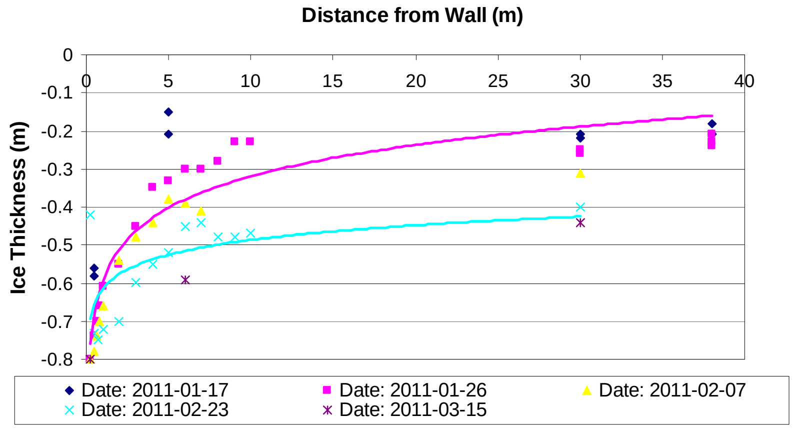

Figure 3 Ice Thickness Profile at Barrett Chute Dam 2011

The profile of the ice thickness from the dam outwards onto the ice field is presented on Figure 3. The ice thickness decreases asymptotically from the wall outwards. There are two reasons for this. One reason is that the area close to the dam is more prone to ice surface flooding due to the presence of open cracks. The other reason is that the dam wall has higher heat conductivity than the snow field. The maximum ice thickness reached at Barrett Chute out in the field was 40-45 cm.

3.2 *Ice Temperature Measurements & Precipitations*

Ice temperatures were measured with a series of 6 thermistors probes attached together at staggered lengths and inserted vertically in a hole in the ice so to measure temperatures at different depths. They were installed at a distance of about 25 m from the dam. The sixth probe was placed in the snow and a seventh probe was used to measure the air temperature attached to a pole and covered by a radiation screen. The values for Barrett Chute are presented in Figure 4.

At the beginning of February, the temperature measured in the ice hovered around the zero reading. This is explained by the constant presence of a layer of snow on top of the ice that acted as insulation. However, variations in ice temperature occurred after rain falls accompanied by a warm spell that occurred on February 15th and 20th, see Figure 4. Subsequently the temperature dropped below zero and cycled, this is when important thermally induced ice loads occurred between the 20th to the 26th of February.

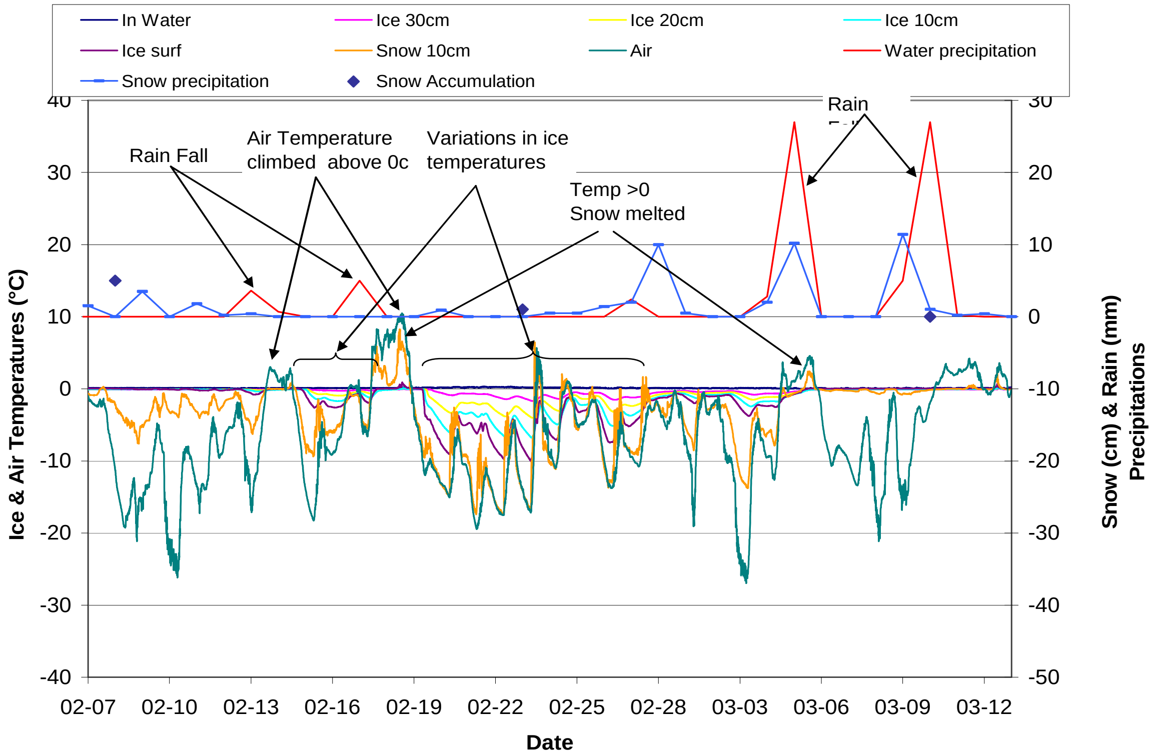

Figure 4 Ice & Air Temperatures at Barrett Chute – Snow & Rain Precipitations

3.3 *Forebay Level Fluctuations & Ice Crack Conditions*

Water level fluctuations from peak to through ranged around 15 to 20 cm at Barrett Chute and Arnprior. At both dams, the values were within the ice thickness depth of the ice cover. This is the range sensitive to generate high loads, (Comfort et al., 2003).

Water level variations create hinge effects near the wall characterized by cracks in the ice. Two important cracks were found within meters from the wall, as shown on Figure 5. They determine a segment of ice from the wall called the "crutch". As the water level changes, the ice cover moves up or down forcing the "crutch" to pivot about the "Ballycatter", a piece of ice that always stays frozen to the wall of the dam.

This effect can contribute to generate an increase in load against the dam. As water level variations pivot the "crutch" up or down, it can snag at the hinges and develop a horizontal thrust against the dam, term called "ice jacking". Conditions that favor this effect are: (a) the presence of thermal ice expansion; and (b) the profile of the ice crack, for example: a jagged crack profile as opposed to a worn and rounded one, see Figure 5.

Another effect is when water rises and seeps through the cracks and then freezes. This repetitive cycle can generate vertical layers of ice in the cracks which push gradually the ice field away from the wall. This phenomenon may be compounded to the ice thrust on the wall developed by thermal loading and ice jacking.

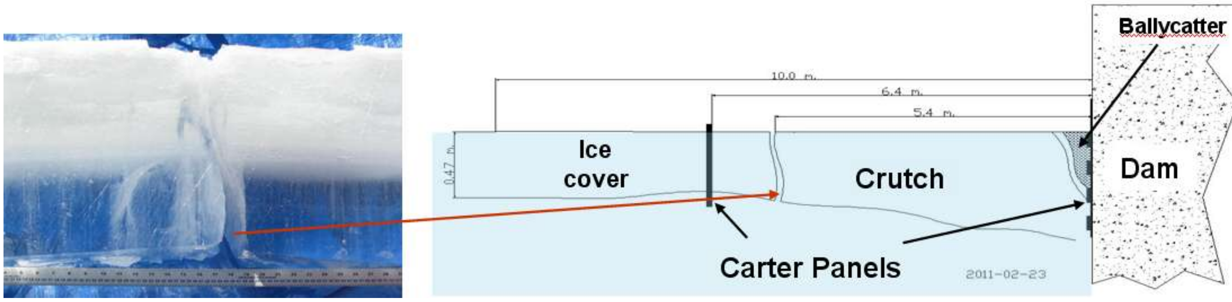

Figure 5 Ice Thickness and Crack Profile at Barrett Chute – February 23rd

4. Ice Pressures

4.1 *Ice Pressure at wall and in field*

Ice pressure values may vary through the ice thickness, along the face of the wall and with time. The pressures recorded by 11 Carter panels spaced by 2.5 m along the wall with each panel comprising of 4 pressure sensors separated by 20 cm provided a pressure grid on the wall, as shown on Figure 6. The sensor at the top layer of ice recorded most of the pressure. Also, when water level rose, ice pressures increased at the top layers.

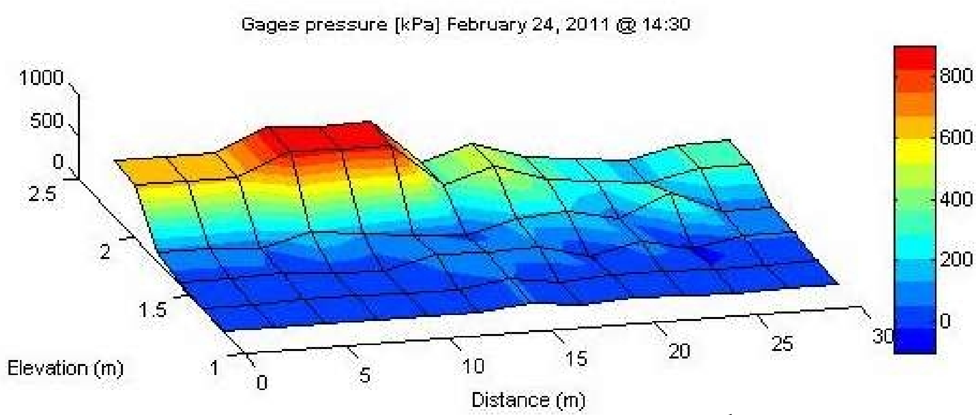

Figure 6 Pressure grid on the wall recorded at 14:30 on the 24th of February by 11 Carter panels

At the wall, the pressure distribution did not vary linearly with depth, as shown in Figure 7, where we plotted at a given time ice pressure with depth for each of the Carter panels. Moving pressure points at the crack interface induced by water level fluctuations and thermal and ice field motion could explain this phenomenon. Therefore, it is difficult to separate any bending from axial stresses.

The pressures out in the reservoir ice field were recorded by two panels at 6 m and 27 m. Also, the pressure of the top sensor was the highest through the ice sheet.

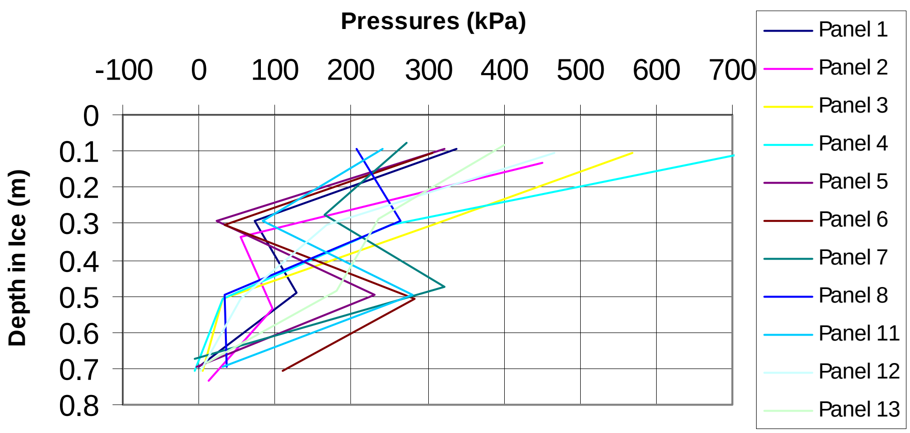

Figure 7 Pressure distribution at depth for each panel along the wall at 13:20 on Feb. 23rd

5. Ice Loads

Line loads were computed from each panel. They comprised in the stresses "σ" recorded by each of the four sensors multiplied by its attributed ice thickness "h", as shown:

$$\text{Line Load} = \sigma 1 * h1 + \sigma 2 * h2 + \sigma 3 * h3 + \sigma 4 * h4$$

For Barrett Chute, we computed at each time increment the average line load of the 11 panels on the wall. The average loads at the wall are compared to the values of the one panel at far field with their relation to "Ice Area temperature" in Figure 8. For Arnprior, the average loads of the two panels set 30 m out at far field were calculated. Figure 9 shows the comparison between the average load value at far field and that of the one panel at 9m.

Peak load values above 100 kN/m were recorded at both dams at far field. The largest peak load was recorded at a 145 kN/m at Barrett Chute wall. Table 1 summarizes the maximum line loads measured at each dam from the three types of instruments. The values were higher at the wall than at far field. They were recorded during an "average" winter where the ice thickness at far field did not exceed 45 cm, and with little snow cover.

Table 1 Maximum Line Loads recorded at Arnprior and Barrett Chute dams in 2011

Sensor type	Maximum Line Load (kN/m)		
	Barrett Chute		**Arnprior**
	Wall	**Far-field**	**Far-field**
BP	---	82	129
Biaxial	162	---	---
Carter	145	102	127

The peak loads occurred after the 20th of February where a rain fall combined with a warm spell melted the snow cover. Then a drop in air temperature below zero froze the ice again. The ice lost its snow insulation and its temperature followed the diurnal thermal fluctuations. The loads were primarily thermally induced and were well correlated to ice area temperature changes, see Figure 8. The ice area temperature is the sum of the products of the ice temperature recorded at different depth and its attributed ice thickness (Comfort et al., 2003). The effect of water level fluctuations on ice loads seem to be hidden by the thermal effect. The only clear case at hand might be a peak that occurred around the 3rd of March where the ice load increased by about 50 kN/m from 30 to 80 kN/m due to water fluctuation.

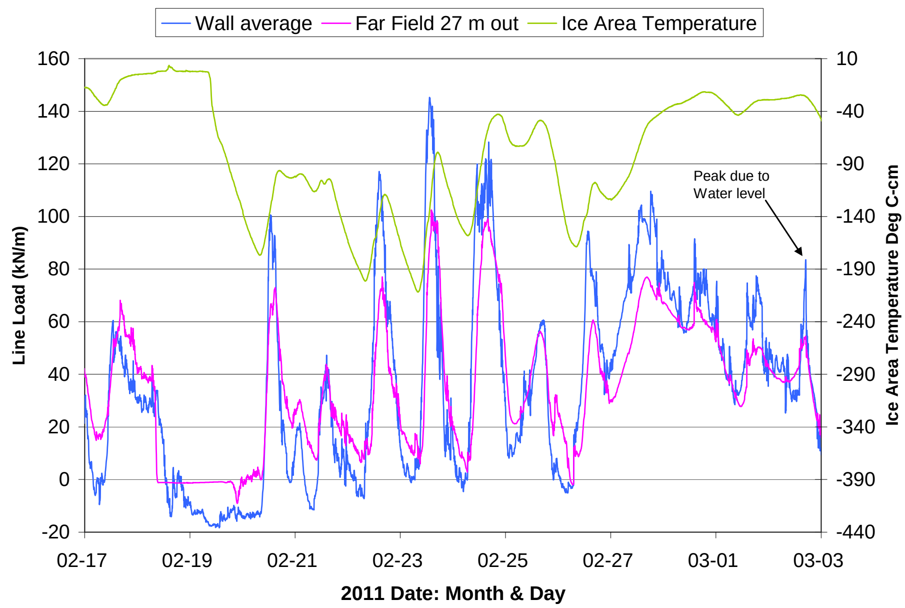

Figure 8 Line Load Far Field and at Wall from Carter Panels at Barrett 2011

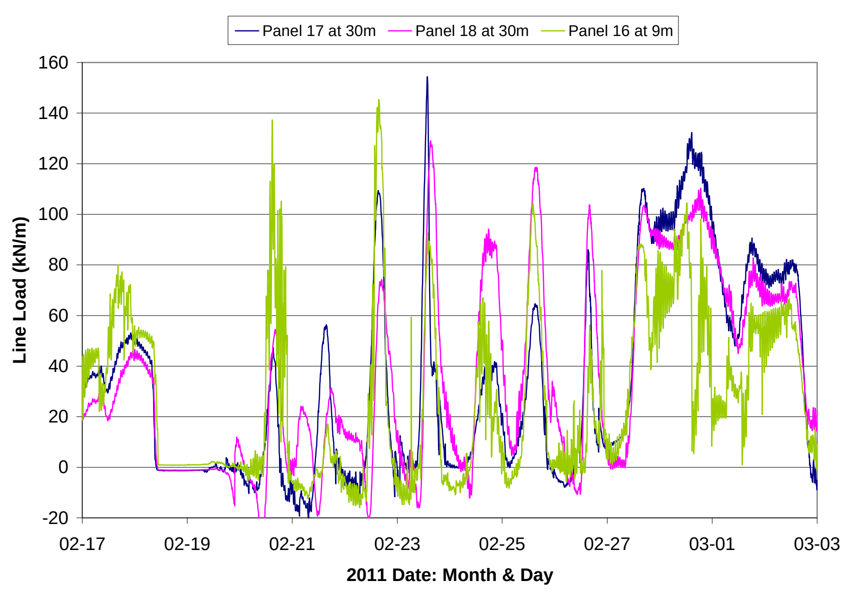

Figure 9 Line Loads at Mid Field and Far Field for Carter Panels at Arnprior 2011

6. Line Load Variation along the Wall – Indentation Factor

For piers, it is well known that the effective ice pressure diminished as the contact area increases (CAN/CSA-S471-92). Carter (2003) extended this concept of "Indentation" to static ice loads for dams. We have attempted to show that the load bearing on sufficient linear face of wall should tend to towards the load measured at far field. Measured loads were recorded with the 11 Carter panels at 2.5 m intervals over a 25 m distance along the face of the dam. We have found that ice loads vary not only along the length of the wall but also in time as shown in Figure 10. For a given peak load event, we have plotted the variation of load along the linear face of wall covered by the 11 panels for successive time frames. We see that the load values along the wall generally increased at each time frame leading to the event at 13:20 then diminished afterwards. Also, the peak load at 13:20 occurred at 7.5 m along the wall then moved to 2.5 m by 15:20.

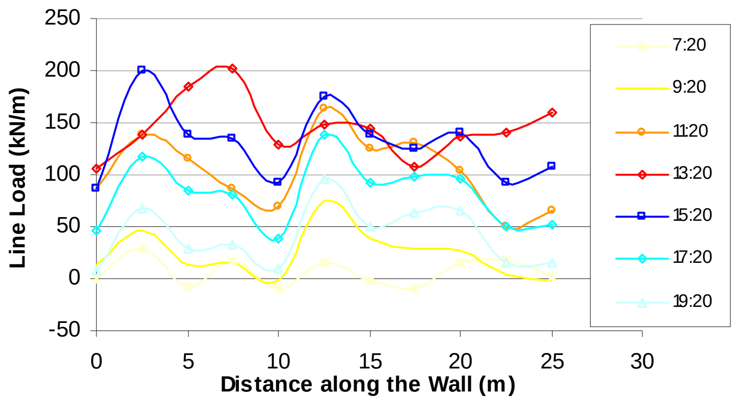

Figure 10 Ice Loads along the Wall at different times intervals around 13:20 on February 23rd

Figure 11 shows that by averaging loads over an increasingly greater linear face of the dam, the maximum average line load diminishes asymptotically, as predicted by Carter (2003). The linear face distance is expressed by the term "B/h" where "B" is the linear length along the wall and "h" the ice thickness at far field. The loads were normalized to that load at "B/h" = 62.5 which corresponds to 25 m covered by the 11 Carter panels. We note a difference of about 30% between the values at the wall versus those at far field. Even though, the Carter model prediction falls within the experimental data points, it seems that the experimental power function dependency is weaker than in the model.

A point load at the wall spreads out geometrically into the ice field. To approximate this, we have assumed the cone of influence from the wall to the far field point to be an equilateral triangle. Therefore, the ice load seen at a point 30 m out in the field is a contribution of components of point loads acting over a 60 m meter linear face of wall (B/h =150, for h=0.4 m). This is shown when extrapolating the regression curve from B/h = 62.5 to B/h = 150. The extrapolation of the wall loads comes close to match the values measured out in far field. The remaining differences may be explained by the natural variation in loads from site to site out in the field.

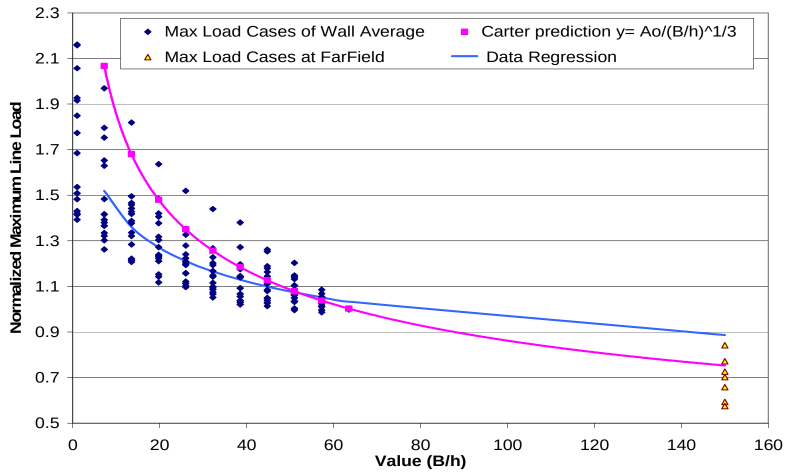

Figure 11 Reduction in Maximum Average Load with Increased Linear Face along the Wall

7. Instruments Comparison

All three instruments BP, Carter and Biaxial showed very similar load time histories at both dams, see Figure 12 and Figure 13. Comparison of BP and Carter panels at Barrett Chute and Arnprior showed that the maximum peaks recorded by both types of instrument were within 20% of each other at worst, see Figure 12. This difference probably represents variation in site conditions. The distances between the two instruments at far field were within 6m at Arnprior and 15 m at Barrett Chute. However, at Arnprior both instruments recorded almost identical maximum peak at 127 and 129 kN/m respectively, see Table 1.

Comparison of Biaxial and Carter panels at the wall at Barrett Chute showed also a very good match, see Figure 13. Two sites of Biaxial gauges were placed within 2m from the wall and at each site three Biaxial gauges were set at different depths in the ice.

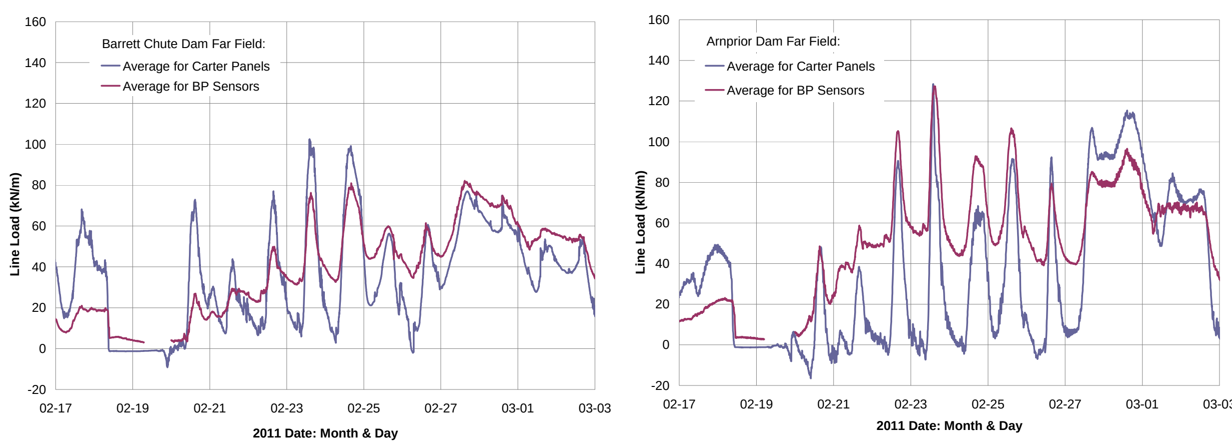

Figure 12 Loads measured by BP & Carter panels at far field, Barrett Chute and Arnprior Dams

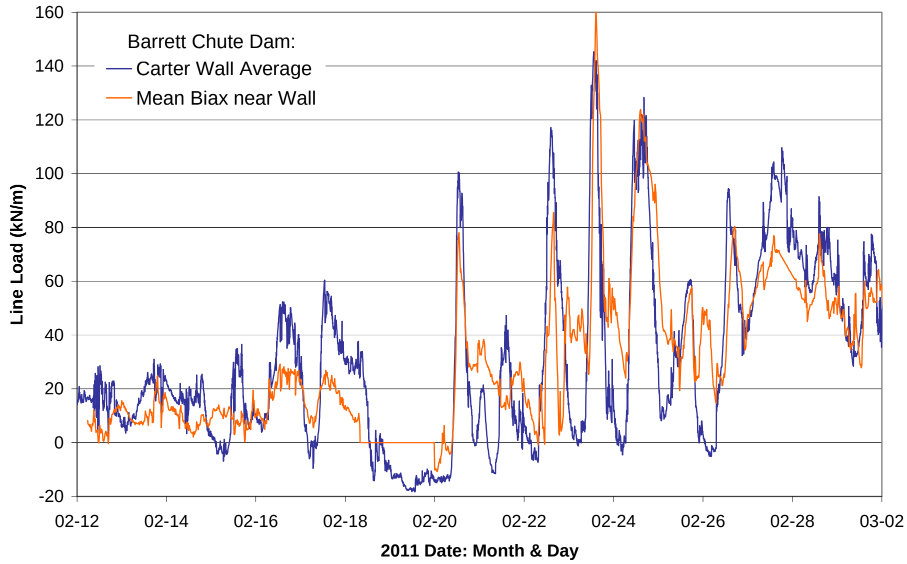

Figure 13 Comparison Biaxial gauges and Carter panels at Barrett Chute's Wall

8. Discussions

Large load values were recorded even though it was a normal winter with ice thickness of only 40 cm. Several elements contributed to high loads: a relatively small snow cover; a warming spell with rain which removed the snow cover. This was followed by a cold spell which froze the top layers. Finally temperatures cycled below zero. These diurnal temperature fluctuations created the load-generating process. Another important condition is that water level fluctuations were in the right range, of the order of 20 cm peak to trough. Also, it is interesting to note that Arnprior had a favourable wind topology to remove any snow on the ice cover thus the insulating layer

Our past measurements suggested that variations in load in the field were small. Unfortunately the related load values recorded were also small. This year with higher loads, peak load variations were of the order of 20%. Therefore, increasing the number of measurement sites at far field could have provided better statistics to compare with the wall data.

Correlation between instruments was good given the variability in site conditions and the different design of instruments. They strongly cross-validated the high loads recorded.

We observed a reduction in maximum average line load with increased linear face along the wall. This indicates that the design value for ice load should be associated to a design width. For example, rather than performing dam stability analysis based on the results of a single panel (0.5 m in width), it may be much more informative and correct to base the analysis on the average measurements over the block width of a vertical concrete section of the dam between construction joints (typically > 10 m). This notion is in complete agreement with the design concepts used for ice loads on off-shore structures (ISO-19906) where the design pressure is a direct function of surface area under consideration.

9. Conclusions

Line load obtained from the three types of sensors tracked each other quite well and values are within the uncertainties. Significant ice load values (greater than 100 kN/m) were obtained for both dams during the 2011 winter, which was not exceptionally cold. Water and temperature variations influenced the ice pressure measured. Daily temperature variation coupled with the absence of snow cover yielded significant diurnal line loads variations. The averaging of loads measured over a 25 m linear face of the dam reduced the peak load but was still 30% larger than in the far field. The indentation model seems to explain to a large extent this difference. Projection of the load average over a greater linear face of the dam than actually measured tended to minimize even more the difference. The findings of this study raise the question on whether the design value for ice load should be associated to a design width.

10. Acknowledgements

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