

STATIC ICE LOADS ON DAMS :
LOADS ALONG A LONG DAM FACE ; AND A COMPARISON OF THE
LOADS EXERTED ON WOODEN AND STEEL STOPLOGS

G. Comfort¹, Gong, Y.¹, Singh, S.¹, and R. Abdelnour¹

Abstract

A five-year field program was undertaken to measure ice loads on hydro-electric structures. The highest loads resulted from a combination of water level and ice temperature changes ; for cases where water level changes were negligible, the loads were much less (i.e., maxima of 324 kN/m [22 kips/ft] vs 69 kN/m [4.7 kips/ft] respectively). The loads were comprised of the residual load in the ice prior to the event, and the load increases associated with the ice temperature and water level changes that occurred. Methods were developed to predict each load component.

The load distribution between one pier and one gate of the Paugan dam was measured. When the maximum load on the gate occurred, the average line load on the pier was 2.4 times greater than that on the gate. The loads on steel and wooden stoplogs sections at the Seven Sisters dam were also measured. Significantly higher loads were measured on the wooden stoplogs, which is attributed to disbonding of the ice from the front face of the steel stoplogs.

Resume

Une campagne de mesure a été effectuée durant une période de cinq ans pour mesurer la poussée des glaces sur les structures hydroélectriques. La plus grande poussée mesurée a été le résultat d'une combinaison de phénomènes; le changement du niveau d'eau et le accroissement de la température de la glace. Pour les cas où le changement du niveau d'eau a été négligeable, la poussée été beaucoup moindre (un maximum de 324 kN/m [22 kips/pi] à comparé a 69 kN/m [4.7 kips/pi] respectivement). La poussée comprenait une poussée résiduelle résultant d'un événement passé et d'une poussée additionnelle associée au changement de la température de la glace et du niveau d'eau. Des méthodes ont été développées pour prédire chacune des composantes de la poussée. La distribution de la poussée entre une vanne et un pilier à été mesurée au barrage hydroélectrique Paugan. Lorsque la poussée maximale sur la vanne à été observée, la moyenne de la poussée sur le pilier était 2.4 fois plus grande que celle mesurée sur la vanne. La poussée sur des poutrelles en bois et en métal a été mesurée au barrage Seven Sisters au Manitoba. Une force beaucoup plus grande a été mesurée sur les poutrelles en bois que sur les poutrelles en métal. Celle-ci est attribuée au dégel et la séparation de la glace de la face frontale des poutrelles en métal.

Acknowledgments

The work was sponsored by the Canadian Electricity Association (CEA-R&D projects 9038 G 815 & 9502 G 2015), with partial funding from Manitoba Hydro, Hydro-Quebec, Ontario Hydro, Nfld. Light and Power Co. Ltd., and the Canadian Dam Safety Ass'n. (CDSA). The project was administered by T. Glavicic-Theberge of the CEA. The project monitors were G. Schellenberg of Manitoba Hydro, R. Lupien and Tai Mai Phat of Hydro-Quebec, G. Smith of Ontario Hydro, A. Kumar of B.C. Hydro, P. Halliday of Nfld. Light & Power Co. Ltd., and W. Pawlikewitch of Manitoba Hydro (who represented the CDSA). Assistance was provided by operations personnel at Hydro-Quebec (S. Robert, A. Pednault, R. Brazeau and A. Bond), Ontario Hydro (J. Whyte, G. James, G. McLeod, C. Stevens and J. Tremblay), and Manitoba Hydro (T. Armstrong).

Introduction And Scope Of Paper

Although dams have been built and operated in northern climates for several decades, the ice loads exerted on them and their gates and piers are not well understood. To obtain better understanding, field programs were undertaken over the 1991-92 to 1995-96 period (Comfort et al, 1994 ; 1995 ; 1996 ; 1997) to : (a) measure the loads in the reservoir ice sheet in front of the dam ; (b) measure the load distribution between a gate and pier, and : (c) compare the loads exerted on wooden and steel stoplogs. Loads in the reservoir ice sheet were measured at Hydro-Quebec's Paugan dam for 3 winters ; at Ontario Hydro's Arnprior and Otto Holden dams for 4 and 3 winters, respectively ; at Manitoba Hydro's Seven Sisters dam for 1 winter ; and in a 120 m by 60 m outdoor basin at the National Research Council (NRC) in Ottawa over one winter. Loads were measured on one pier and gate of the Paugan dam over two winters ; and on steel and wooden stoplog sections at the Seven Sisters dam over one winter.

The results obtained from 1991-92 to 1994-95 have been presented in Comfort et al, 1996. This paper : (a) updates those results with the 1995-96 data ; (b) presents the results of more detailed analyses, and : (c) presents results comparing the loads on steel and wooden stoplogs.

Loads In The Reservoir Ice Sheet : Overview

Loads at the Paugan dam and the NRC basin resulted mainly from ice temperature changes. Thirty one events occurred, with the maximum load being 69 kN/m (4.7 kips/ft). (See Comfort et al, 1996 for tabulated results). The loads at the Arnprior, Seven Sisters and Otto Holden dams were produced by a combination of ice temperature and water level changes. A total of 47, 21, and 6 loading events occurred at these respective sites, and the peak loads were 210 kN/m (14.3 kips/ft), 65 kN/m (4.4 kips/ft), and 324 kN/m (22 kips/ft), respectively. See Tables 1, 2, and 3.

Loads In The Reservoir Ice Sheet : Load-Generating-Mechanisms

As discussed in Comfort et al, 1996, the ice loads were comprised of the three components listed below, which appeared to be additive and superimposed on each other. As they are quite different ice load-generating processes, they were analyzed separately, as follows :

$$LL_{\text{tot}} = (LL_{\text{Residual}} + \Delta LL_{\text{thermal}} + \Delta LL_{\text{water level}}) + LL_{\text{contingency}} \quad [1]$$

where : LL_{tot} = the total line load produced

$LL_{Residual}$ = the initial load in the ice prior to any changes in water level and ice temperature (termed the residual load)

$\Delta LL_{thermal}$ = the increase in load associated with rises in ice temperature

$\Delta LL_{water\ level}$ = the increase in load associated with water level changes

$LL_{Contingency}$ = a contingency added to ensure that the predicted loads provide an upper bound to the measured line loads

Loads In The Reservoir Ice Sheet : Residual Loads

These loads result from stresses remaining from previous events and were present in the ice prior to all loading events. As was done during previous analyses (Comfort et al, 1995 ; 1996 ; 1997), these loads were predicted by relating them to $\Delta LL_{thermal}$ and $\Delta LL_{water\ level}$ (Figure 1). Equations [2] and [3] were developed using the whole dataset to predict average residual loads, $LL_{RESIDUAL}$.

• Total line load increase (ΔLL_{tot}) = 0 to 50 kN/m : $LL_{RESIDUAL} = 0.6 \cdot \Delta LL_{tot}$ [2]

• Total line load increase (ΔLL_{tot}) > 50 kN/m : $LL_{RESIDUAL} = 30$ kN/m [3]

where : ΔLL_{tot} = the total increase in line load produced by a change in ice temperature and/or water level (= $\Delta LL_{thermal} + \Delta LL_{water\ level}$)

Loads In The Reservoir Ice Sheet : Thermal Loads

Because currently-available methods for predicting thermal loads did not correlate well with the measured data (Comfort et al, 1995; 1996; 1997), an empirical approach was used based on the events at the NRC Basin, the Paugan dam, and the Seven Sisters dam (thermal component only - Table 4).

The thermal load was most strongly related to the ice temperature change magnitude, and it was not strongly related to the initial ice temperature, or the rate of temperature change. Snowfalls contributed greatly to the occurrence of an event as the insulation they added to the ice surface caused rapid warming through the ice thickness.

However, relationships between the thermal load and the air temperature changes, the ice surface temperature changes, and the ice temperature changes at 10 cm depth contained too much scatter to be useful. It was clear that, in order to develop an accurate thermal load predictor, the ice temperature changes that occur through the full ice thickness must be taken into account. The change in ice temperature profile area (Figure 2) was used as an index to do this. Although the thermal load was strongly related to this, it is clear that other factors are also important, as proportionately higher loads were produced for larger profile area changes (Figure 3).

Higher loads were produced for larger ice thicknesses, indicating that it is an important factor. This is due to the added confinement provided by thicker ice (which reduces the amount of cracking) and due to less stress redistribution by creep in thicker ice. Analyses were carried out to quantify the latter effect (Comfort et al, 1997), and the following equation was developed.

$$\Delta LL_{\text{Ther}} = 0.044 \bullet \Delta \text{ profile area} \bullet h_r^{0.6} \quad [4]$$

where : ΔLL_{Ther} = the line load increase, in kN/m, resulting from ice temperature changes
 Δ profile area = the change in ice temperature profile area, in °C • cm
 h_r = the reservoir ice thickness, in cm

These analyses show that the observed differences among the measured data can be explained by variations in ice thickness (Figures 4 and 5).

As the profile area change is a relatively complex parameter, equation [5] was developed (using the data collected at the Arnprior Paugan, and Otto Holden dams) to predict ice temperature changes over the full depth, for a specified ice thickness and ice surface temperature change.

$$T_{\text{Ratio}} = 1.02 \bullet D_{\text{Ratio}}^2 - 2.01 \bullet D_{\text{Ratio}} + 1 \quad [5]$$

where : T_{Ratio} = temperature change at depth d_i in the ice / temperature change at the ice surface
 D_{Ratio} = depth d_i from the ice surface / the ice thickness

The profile area changes predicted by this method were checked with the data collected at the Seven Sisters dam, which is located in a significantly different region of Canada. The predicted and measured values compare well giving confidence in the method (Figure 6).

Reservoir Ice Sheet Loads Produced By Water Level Changes

Water level changes induce ice loads by a “geometric wedging” mechanism as the ice block produced near the dam (by water level changes) is forced to rotate to accommodate vertical displacements. New ice often forms in the cracks produced, which adds another load-generating mechanism as large stresses can be generated by the volumetric expansion that occurs.

The dataset used for analysis was comprised of the events at the Arnprior, Otto Holden, and Seven Sisters dams as these loads were influenced significantly by water level fluctuations. For a few events, the ice loads resulted solely or mainly from a change in water level. (See Tables 1 and 2, which show that in a few cases, the changes in ice temperature profile area were nil, or less than zero). However, most events resulted from the combination of a rise in ice temperature with a change in water level. As a result, the measured data could not be used directly for an analysis of the loads produced by water level changes. For many of these events, the “water level” component of the total load is quite evident (Figure 7), and they were analyzed to separate this out. Datasets comprised of 51, 21, and 5 loading events were established for the results measured at the Arnprior, Otto Holden, and Seven Sisters dams, respectively (Tables 5 and 6).

The factors controlling “water level change” loads were investigated. This load is most strongly related to the area of ice compressed when ice movements occur due to water level changes. It is not very sensitive to the rate of water level change, nor to the magnitude of the ice temperature rise (versus the temperature magnitude itself, which is an important factor, as discussed below).

$\Delta LL_{\text{water level}}$ increases with the compressed area (Figure 8), although there is considerable scatter. The Otto Holden dam events produced much lower load than did those at the Arnprior and Seven Sisters dams. This variation is likely due to differences in ice cracking conditions and patterns, as the cracks at Otto Holden were much “looser” and “hinge-shaped”. The cracks at the other two sites were vertical and more confined (Figure 9). They also contained more new ice growth. The variation in ice cracking conditions is likely due to differences in water level fluctuation patterns (as water level changes were larger and more regular at the Otto Holden dam) although more information and analyses are required to quantify the effect of this on the loads produced. Differences in ice temperature likely contributed to the observed differences in ice cracking conditions. The ice was significantly warmer at the Otto Holden dam, and the loads appear to decrease with warmer temperatures (Figure 10). Warmer ice temperatures are probably an indicator of reduced new ice growth in the cracks ; however, this parameter was not included in the current modelling procedure because the process is not fully understood.

Predictor equations were developed (in Comfort et al, 1997), to relate the load to the compressed area, which, due to space limitations, can only be summarized here. Because higher loads are of more interest, functions were only fitted to the data for the Arnprior and Seven Sisters dams.

- Arnprior Dam : $\Delta LL_{\text{Water level}}, (\text{in kN/m}) = 0.7 \bullet A_{\text{tot}}, (\text{in cm}^2)$ [6]
- Seven Sisters Dam : $\Delta LL_{\text{Water level}}, (\text{in kN/m}) = 3.1 \bullet A_{\text{tot}}, (\text{in cm}^2)$ [7]

where : A_{tot} = the total compressed area (= $A_{\text{start to horiz}} + A_{\text{horiz to end}}$) [8]

$A_{\text{start to horiz}}$ = the area of ice compressed by movements of the two ice blocks at the end of the ice sheet from their initial position to the horizontal during a water level change

$A_{\text{horiz to end}}$ = the area of ice that is compressed by movements of the two ice blocks at the end of the ice sheet from the horizontal to the end of the water level change

Reservoir Ice Sheet Loads : Predicted Vs Measured Total Loads

For the case where the load was purely thermal, the average ratio between the predicted and measured loads was 1.27 +/- 0.52 for all events producing line loads exceeding 40 kN/m (2.7 kips/ft). See Figure 11. For the case where ice loads resulted from a combination of water level and ice temperature changes, the average ratio was 1.25 +/- 0.50 (Arnprior dam dataset), and 1.04 +/- 0.20 (Seven Sisters dam dataset). See Figure 12.

“ $LL_{\text{contingency}}$ ” was evaluated by comparing the total predicted and measured loads. Two methods were considered (i.e., by multiplying all predicted loads by a safety factor, or by adding a fixed value to the predicted loads regardless of magnitude). As the discrepancy between the measured and predicted loads does not appear to increase with the load magnitude (Figures 11 and 12), the latter approach is considered to be more appropriate. A higher value is required for “ $LL_{\text{contingency}}$ ” for the case where ice loads result from a combination of water level and ice temperature changes than for purely thermal loading events, as the discrepancy was significantly greater for the former case. Values of about 75 and 20 kN/m are indicated for “ $LL_{\text{contingency}}$ ” for these respective cases.

Load Distribution : Gate Vs Pier ; And Wooden Vs Steel Stoplogs

This project has produced the first, and only, field data to define this, to our knowledge. As the Paugan dam data have been previously reported (Comfort et al, 1996), they are only referred to here, and summarized in Table 7. At the Seven Sisters dam, the peak line loads across the full widths of the instrumented pier, and the wooden and steel stoplogs on either side of that pier, were 560 kN/m (38 kips/ft), 93 kN/m (6.3 kips/ft), and 21 kN/m (1.4 kips/ft) respectively. See Figures 13 and 14 for sample results and Table 8 for tabulated data. Key results are summarized below :

- **Loads On The Pier Versus the Gate Or Stoplogs** - At both sites, much higher loads were measured on the pier than on the gate or stoplogs. At the Paugan dam, the line load across the face of the pier was 2.4 times greater than that on the gate at the time when the peak line load occurred on the gate. The average ratio between the line loads on the pier and the gate was 3.3 for all events in which the line load on the gate exceeded 15 kN/m. At the Seven Sisters dam, much higher load ratios were measured between the line loads across the face of the pier and the stoplogs, indicating that a greater proportion of the load was carried by the pier. The load across the front face of the pier was 27 times and 6.0 times higher than that on the steel and wooden stoplogs respectively at the time when the peak line loads occurred on these respective structures.

The variation between the two sites can probably be explained by differences in the spans of the gates and stoplogs (i.e., 15.2 m at the Paugan dam versus 6.1 m at the Seven Sisters dam), and pier length (i.e., 6.7 m, measured from the front face of the gate, at the Paugan dam versus 2.1 m, measured from the front face of the stoplog, at the Seven Sisters dam). As a result, more arching is expected to occur from pier to pier at the Seven Sisters dam (based on finite element analyses which can not be reported here due to space limitations - see Comfort et al, 1997 for information). As a result, more load is expected to be carried by the piers at the Seven Sisters dam.

- **Loads In The Reservoir Ice Sheet Versus Those Applied Across The Combination Of The Pier And Gate Or Stoplogs** - At the Paugan dam, these two line loads “track” each other and the variation between them when the thermal events occurred averaged 15 kN/m (about 1 kip/ft). This indicates that the load “seen” by the dam was similar to that produced in the reservoir ice sheet away from the dam. At the Seven Sisters dam, the load in the reservoir was significantly greater than the average across the pier and the stoplogs. This imbalance can be explained by load transfer along the sides of the pier (which was not measured).

It is believed that this variation can be explained by differences and in pier length and gate or stoplog span. As the gate at the Paugan dam had a larger span, less arching from pier to pier is expected, which allows more load to be applied to the gate. This would cause load transfer by shear along the sides of the pier to be less significant at the Paugan dam.

- **Loads On Wooden Vs Steel Stoplogs And The Behaviour Of Wooden Vs Steel Structures** At the Seven Sisters dam, higher loads were consistently measured on the wooden stoplog section than on the steel one (Table 8). This is believed to be due to disbonding of the ice attached to the steel stoplogs during loading events. During the four events that produced zero or tensile loads on the steel stoplogs (Table 8), the air temperature rose to above-freezing, and remained there for a significant time period. This, in combination with solar heating, was probably sufficient to cause disbonding of the ice at the steel stoplogs. However, because the wooden stoplogs have higher

thermal conductivity, this process probably would not have occurred there. As a result, the ice likely remained bonded to them throughout the event.

Disbonding was not observed at the gates at the Paugan dam, which are also steel. This may be attributable to the fact that the Paugan dam events were of much shorter duration, and often, the air temperature did not rise above zero, or remain above zero for an extended time period.

Conclusions And Recommendations

Significant progress has been made towards understanding ice loads on dams, and their piers and gates or stoplogs. However, the developed ice load predictors are subject to a number of limitations and further work is required before changes to current design practices can be recommended with confidence.

More field data should be collected to define the loads arising from a combination of water level and ice temperature changes, which is considered to be the most serious gap in the present database. Also, more data should be collected to define the load-sharing between a pier and steel or wooden stoplog. Additional numerical analyses are also recommended to better define the loads produced by water level changes, the probabilistic distribution of thermal loads, and the load-sharing between a pier and steel or wooden stoplog.

References

- [1] Comfort, G., and Abdelnour, R., 1994, Field Measurements Of Ice Loads : Thermal Loads On Hydro-Electric Structures, proc. CDSA conf., Winnipeg.
- [2] Comfort, G., Abdelnour, R. Gong, Y., and Dinovitzer, A., 1995, Static Ice Loads On Hydro-Electric Structures : Ice Loads Monograph, CEA Project 9038 G 815.
- [3] Comfort, G., Abdelnour, R. Gong, Y., and Dinovitzer, A., 1996, Static Ice Loads On Hydro-Electric Structures : Field Measurements And Analysis, proc. CDSA conference, Niagara Falls, Ont.
- [4] Comfort, G., Abdelnour, R, Gong, Y., Dinovitzer, A., and Singh, S., 1997, Static Ice Loads On Hydro-Electric Structures : Ice Loads Monograph No. 2, CEA Project 9052 G 2015.