

## PREDICTING STATIC ICE LOADS ON DAMS

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### ABSTRACT

An eight-year field program was undertaken from 1991-92 to 1998-99 to : (a) measure the loads in the ice sheet near the dam ; (b) measure the load distribution between a gate and pier, and : (c) compare the loads on wooden and steel stoplogs. The most significant finding has been to show the importance of water level changes on ice loads. Ice loads are much higher and more variable (compared to purely thermal loads) when significant, but not excessive, water level changes occur. Ice load predictors have been developed, and they predict thermal loads well. They are less accurate for loads produced by a combination of water level and ice temperature changes.

### INTRODUCTION AND SCOPE OF PAPER

Ice loads exerted on hydro-electric dams are not well understood although dams have been built and operated for many years in northern climates. A field program was undertaken from 1991-92 to 1998-99 to : (a) measure the loads in the ice sheet near the dam ; (b) measure the load sharing between a gate and pier, and : (c) compare the loads on wooden and steel stoplogs. Results are presented and analyzed in detail in Comfort et al, (1996; 1998a ; 1999). The 1991-92 to 1995-96 results are summarized in Comfort et al (1997 and 1998b) among other papers as well as in the annual field reports, which are available from the Canadian Electricity Association (CEA). This paper describes methods that have been developed for predicting ice loads. A companion paper describes the factors controlling ice loads in more detail (Comfort et al, 2000). In view of the significance of water level changes, the following cases were analyzed separately.

- Case 1: Water Level Changes are Negligible – in this case, ice loads are generated thermally.
- Case 2: Combined Thermal/Water Level Regime – water level changes affect the ice loads significantly here. See Comfort et al, 2000 for further information.

## PREDICTING THERMAL ICE LOADS (NEGLIGIBLE WATER LEVEL CHANGES)

### General Approach

These ice loads are comprised of two parts: (a) residual loads, which are loads that were present before the start of the loading event, and ; (b) line load increases produced by ice temperature rises – these result from air temperature rises ; and/or from precipitation, particularly snowfalls. The most rational analysis approach (which also provided the best fit to the data) was to predict these two load components separately (equation [1]). The analyses were based on events producing line loads greater than 30 kN/m (2 kips/ft) because they are of greater interest for design. Also, these data are more reliable because larger loads can be resolved more accurately.

$$LL_{\text{total}} = \Delta LL_{\text{ther}} + LL_{\text{Residual}} + LL_{\text{contingency}} \quad [1]$$

where :  $LL_{\text{total}}$  = the total line load

$\Delta LL_{\text{ther}}$  = the line load increase produced by ice temperature changes

$LL_{\text{Residual}}$  = the residual load in the ice sheet before the thermal event occurred

$LL_{\text{contingency}}$  = a load contingency that was added to ensure that the predicted line loads provide an upper bound to the measured line loads.

### Predicting Residual Loads

Lower residual loads are to be expected for events starting in cold ice than for warm ice, because the previous stresses are less likely to be fully decayed in warm ice. The data support this (Figure 1 and Eq'n 2), although there is scatter due to variations in the time elapsed between events.

$$LL_{\text{Residual}} \text{ (in kN/m)} = -0.0528 * A_i + 21.37 \quad [2]$$

where :  $A_i$  = the ice temperature profile area, in °C\*cm, at the start of the event. (See Comfort et al, 1998b for a definition of the ice temperature profile area).

### Predicting Line Load Increases Due to Ice Temperature Rises

The best-fit equation for  $\Delta LL_{\text{ther}}$  in equation [1] was determined as given below.

$$\Delta LL_{\text{ther}} \text{ (in kN/m)} = 0.064 * \Delta A^{0.6} * h^{0.88} * Dur^{[\text{Min}(\log 160/\Delta A, 0)]} \quad [3]$$

where:  $\Delta A$  = the change in ice temperature profile area, in °C\*cm

$h$  = the ice thickness, in cm

$Dur$  = the event duration, in days

## Measured vs Predicted Thermal Loads and the Load Contingency Required

The predicted loads (obtained by summing  $\Delta LL_{ther}$ , and  $LL_{Residual}$ ) were compared with the measured total loads to evaluate the load contingency ( $LL_{contingency}$ ) required. See Figure 2. The predictive error (defined as the measured load minus the predicted load) can be approximated by a normal distribution with a mean of -7 kN/m (0.5 kips/ft), and a standard deviation of 13 kN/m (0.9 kips/ft). The overall range between the predicted and measured values is +/- 23 kN/m. A value of 25 kN/m for  $LL_{contingency}$  would ensure that the predicted loads bound the measured loads for all events. A value of 13 kN/m (0.9 kips/ft) for  $LL_{contingency}$  would ensure that the predicted loads exceed the measured loads for 90% of the events analyzed.

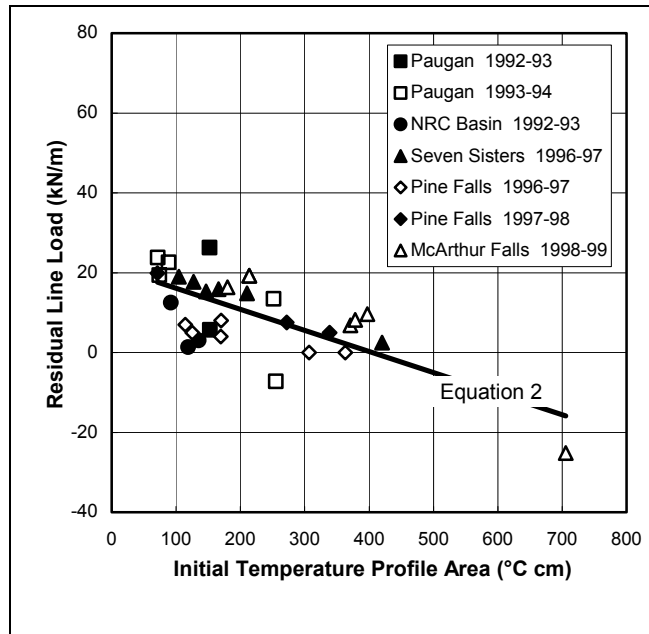


Figure 1: Residual Loads

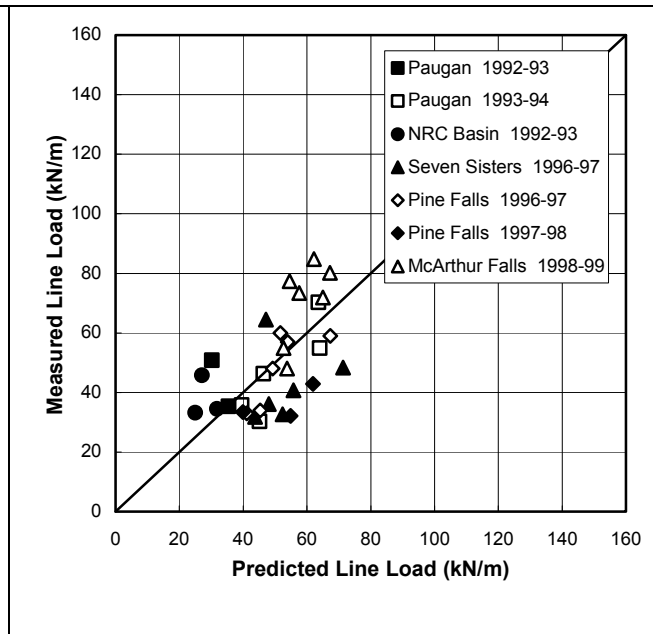


Figure 2: Measured vs. Predicted Total Loads

## Range of Applicability for the Thermal Load Predictors

Table 1 Ranges of Variation in the Thermal Load Database for the Key Parameters

Parameter	Max. Value	Min. Value
Total Load, " $LL_{total}$ ", (kN/m)	85	6
Residual Load, " $LL_{Residual}$ ", (kN/m)	26	-25
Line Load Increase due to Thermal Effects, " $\Delta LL_{ther}$ ", (kN/m)	110	8
Ice Thickness, " $h$ ", (cm)	80	15
Change in Ice Temperature Profile Area, " $\Delta A$ ", ( $^{\circ}C \cdot cm$ )	418	17
Event Duration, " $Dur$ ", (days)	9.2	0.2
Ice Temperature Profile Area at the Start of Event, " $A_i$ ", ( $^{\circ}C \cdot cm$ )	705	56

## PREDICTING LOADS AT SITES WITH SIGNIFICANT WATER LEVEL CHANGES

### Introduction and Review of Loading Events

This is the most important case because it has generated the highest loads (Comfort et al, 2000). Unfortunately, it is difficult to analyze because many parameters affect the loads produced. A review of the loading events (Figure 3) indicated the following:

- Water Level Changes: Although events typically lasted several days, water level changes had the most significant effect in the last 2-3 days leading up to the peak load when they produced large load “spikes”. The early part of the event was dominated by thermal effects.
- Interaction Between Ice Temperature and Water Level Changes: Although some events occurred in which no ice temperature rises took place, the largest loads were produced by a combination of ice temperature and water level changes. The highest loads were produced after ice temperature changes had “pre-stressed” the ice initially.
- Effect of Ice Temperature Magnitudes: Higher loads were produced when the ice was colder at the start of the event, as this affected the “interaction” loads described above.
- Effect of Ice Temperature Changes Before the Event: Lower loads were produced when the ice temperature had been decreasing prior to the event start compared to the case where the ice temperature had been stable for some time before the event occurred.

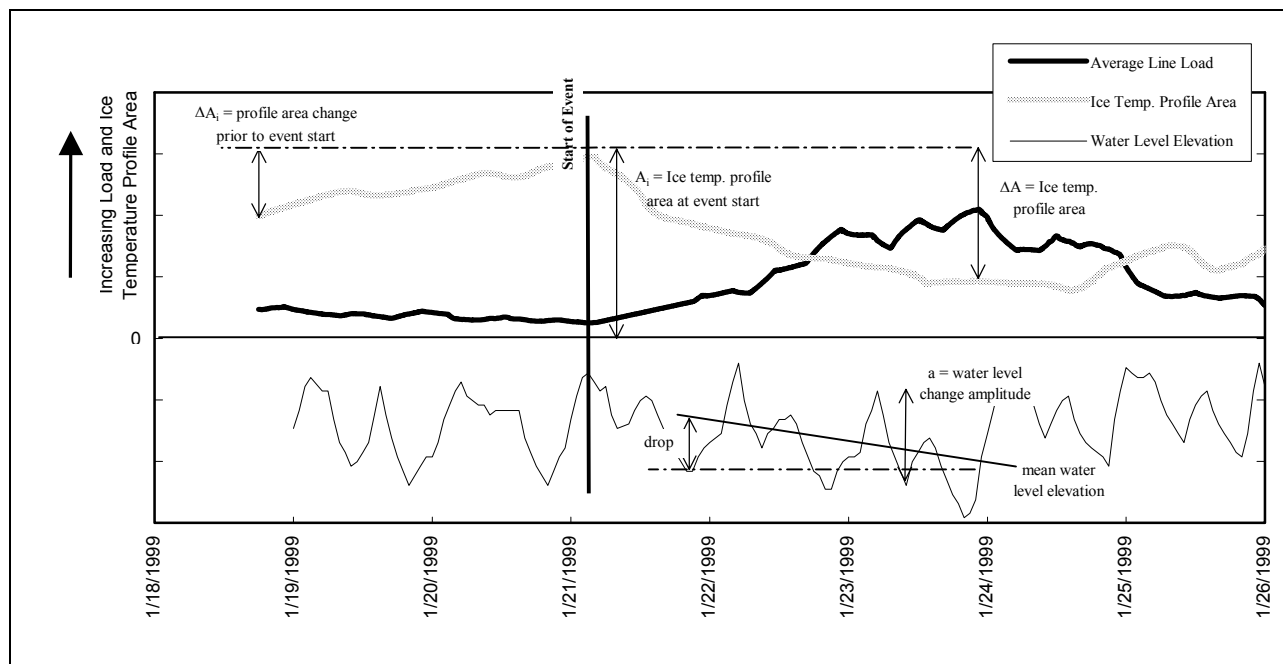


Figure 3 Schematic for a Combined Water Level Change/Thermal Loading Event

### Overview of Analysis Approach

The following form was adopted for modelling the total load,  $LL_{total}$ :

$$LL_{total} = LL_{Residual} + \Delta LL_{Thermal} + LL_{Water Level} + LL_{Contingency} \quad [4]$$

- where :
- $\Delta LL_{Thermal}$  = the “pure thermal” load, as defined by equation [3].
  - $LL_{Water Level}$  = the “water level change” load, which is produced by water level changes.
  - $LL_{Residual}$  = the load in the ice prior to the loading event, termed the residual load
  - $LL_{Contingency}$  = an additional line load that was added to the predicted load to ensure that the measured load did not exceed the predicted load

## Predicting “Water Level Change” Loads: Trend Analysis

Key parameters were identified by comparing them to the “water level change” load (“ $LL_{\text{water level change w/o contingency}}$ ” – eq'n [5]). This is related to several factors as listed below:

$$LL_{\text{water level change w/o contingency}} = LL_{\text{total}} - LL_{\text{Residual}} - \Delta LL_{\text{Thermal}} \quad [5]$$

where:  $LL_{\text{total}}$  = the total line load measured during the event

$LL_{\text{Residual}}$  = the residual line load measured during the event

$\Delta LL_{\text{Thermal}}$  = the thermal line load predicted using equation [3]

- (a) water level change amplitude and ice thickness – these had the most significant effect. For all dam sites, the ice load reduced greatly as the ratio between the water level change amplitude, “a”, and the ice thickness, “h”, increased (Figure 4). The “a/h” ratio was defined based on the average water level change amplitude for the 2-3 day period prior to the peak load (Figure 3).

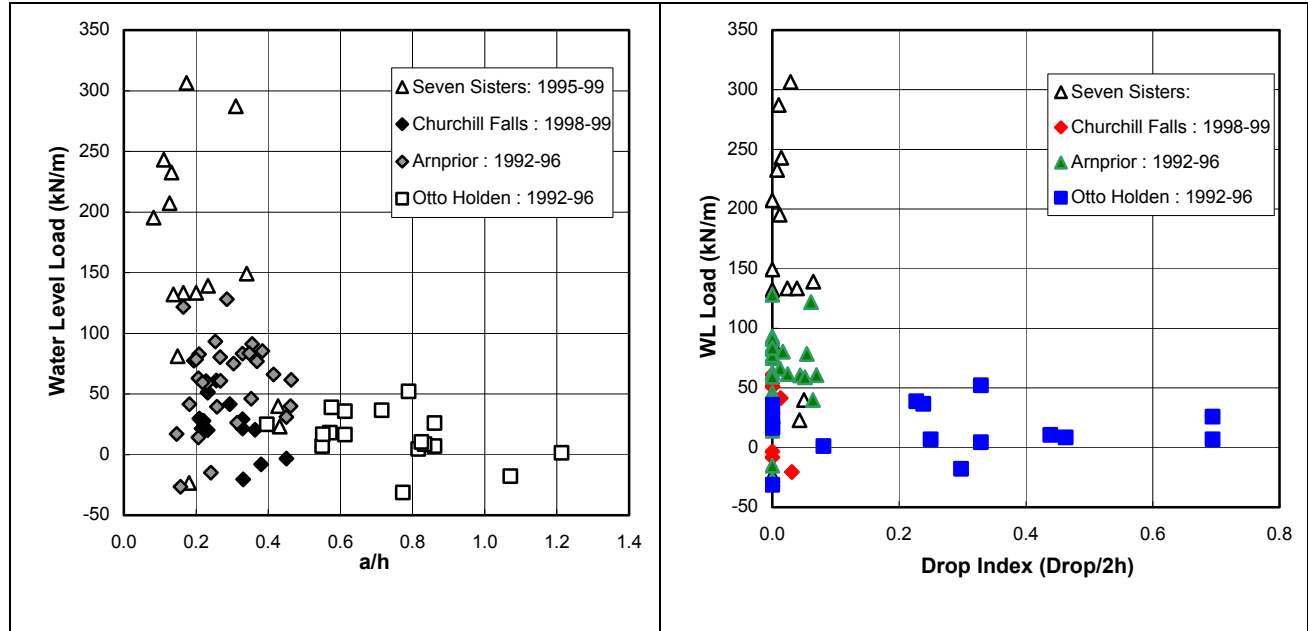


Figure 4 Water Level Change Load vs a/h      Figure 5 Water Level Change Load vs Drop Index

- (b) water level change frequency (defined as the number of cycles per day) – this was not included in the ice load equations because water level change loads were not dependent on it.
- (c) a drop or rise in mean water level – higher loads are expected when the water level is cycled about the same mean level, versus cases where drops or rises in mean water level occur. This effect is related to the ice thickness as well. Water level drops or rises of more than two ice thicknesses would cause the water level change loads to decrease to nil or to a very low value because the ice sheet would lose contact with the dam. The water level change load decreased with the Drop Index (defined in Figure 3, and equation [6] below). See Figure 5.

$$\text{Drop Index} = |\text{drop or rise}| / (2 * h)$$

[6]

where : | drop or rise | = the absolute value of the drop or rise in mean water level over the 2-3 days preceding the peak load, in cm  
 h = the ice sheet thickness, in cm

- (d) change in ice temperature profile area – higher loads were produced when large ice temperature changes occurred in combination with water level changes (Figure 6).
- (e) duration of loading – long duration events produced lower water level change loads, which is similar to the trend observed for purely thermal loads.
- (f) ice temperature at the start of an event – This had a significant effect as larger water level loads were produced by colder ice than warmer ice.
- (g) ice temperature profile area change before the start of an event – higher loads tended to be produced if the ice temperature had been stable for several days before the event. Reduced loads occurred if the loading event was immediately preceded by a drop in ice temperature.

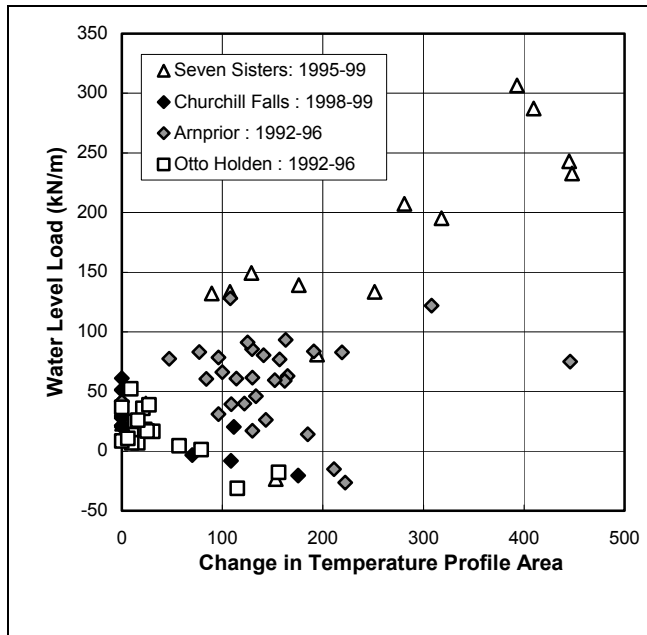


Figure 6 Effect of Profile Area Change

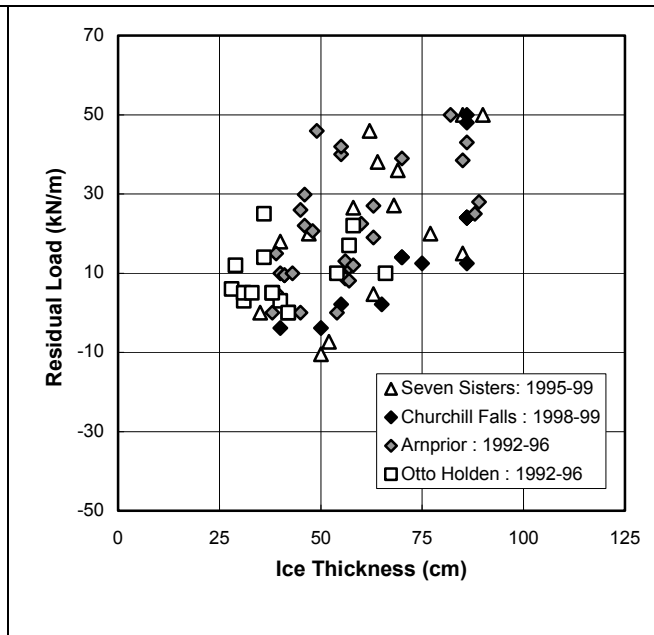


Figure 7 Residual Load vs. Ice Thickness

### Predicting “Water Level Change” Loads: Equations Developed

The following equations were developed based on the observed trends and an error minimization analysis. “ $LL_{\text{Water Level}}$ ” contains the two components below, in keeping with the trends observed.

- (a) the “pure water level change” load – this is the load produced solely by a water level change.
- (b) the “interaction” load - this is the second term. It models the observed interaction effects with higher loads being produced when water level and ice temperature changes both took place.

$$LL_{\text{water level}} = f(\text{temp \& water level changes}) * (5 + 7.5 \times 10^{-8} * \Delta A^2 * A_i^{1.2} / \text{Dur}^{0.4}) [7]$$

where:  $f(\text{temp \& water level changes}) = f(\Delta A_i) * f(\text{drop}) * f(a/h)$  [8]

$f(\Delta A_i) = \text{the maximum of: } 0 \text{ or } 1 - 4(\Delta A_i/A_m)^{1.4}$  [9]

$f(\text{drop}) = \text{the maximum of: } 0 \text{ or } 1 - 20 * (\text{drop}/2h)^2$  [10]

$f(a/h) = 0.22 \text{ for } a/h < 0.22, \text{ and; } 1 / (a/h)^2 \text{ for } a/h \geq 0.22$  [11]

Dur = Duration of the event, in days

a = the average water level change amplitude (absolute value), in cm, over the 2-3 days leading up to the peak load (Figure 3)

h = reservoir ice thickness, in cm

$\Delta A$  = profile area change (absolute value), in  $^{\circ}\text{C} * \text{cm}$

$\Delta A_i$  = initial profile area change (absolute value) prior to the start of the event, in  $^{\circ}\text{C} * \text{cm}$

$A_i$  = ice temperature profile area (absolute value) at the start of the event, in  $^{\circ}\text{C} * \text{cm}$

drop = drop or rise (absolute value) in mean water level during the event, in cm

$A_m$  = the maximum ice temperature profile area, in  $^{\circ}\text{C} * \text{cm}$ , (defined as  $20 * h$ , in cm [12])

### Predicting Residual Loads: Trend Analysis and Equations Developed

Although residual loads are affected by several parameters, the ice thickness and the “a/h” ratio were found to have the greatest effect (Figures 7 and 8, respectively).

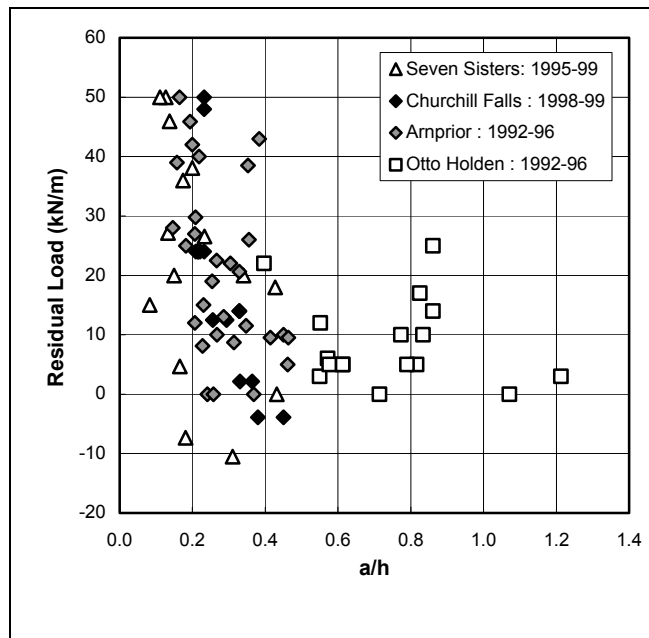


Figure 8 Residual Load vs a/h

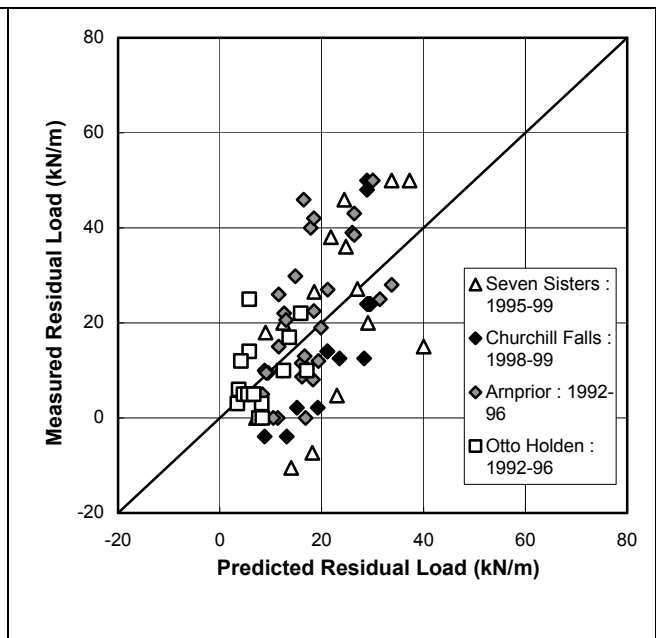


Figure 9 Predicted vs Measured Residual Loads

The best-fit equation for the residual loads with respect to these parameters is shown below. Equation [13] predicted the measured residual loads within 29 kN/m (2 kips/ft). See Figure 9.

$$LL_{\text{Residual}} \text{ (in kN/m)} = 0.37 * f(h) + 1.47 / (a/h) \quad [13]$$

Where:  $f(h) = h - 25$ , for  $h > 25 \text{ cm}$  For  $h \leq 25 \text{ cm}$ , equation [13] is not applicable. [14]

## Predicted vs Measured Loads and the Load Contingency Required

The required contingency load, (i.e., “ $LL_{Contingency}$ ”) was evaluated by comparing the predicted loads (which were calculated by summing “ $LL_{Residual}$ ”, “ $\Delta LL_{ther}$ ”, and “ $LL_{Water Level}$ ”), with the measured loads (Figure 10). The required load contingency is a measure of the prediction error. It is normally distributed with a mean of zero, and a standard deviation of 45 kN/m. The probability that the required contingency load will be less than 60 kN/m (4 kips/ft) is 90% (Figure 11).

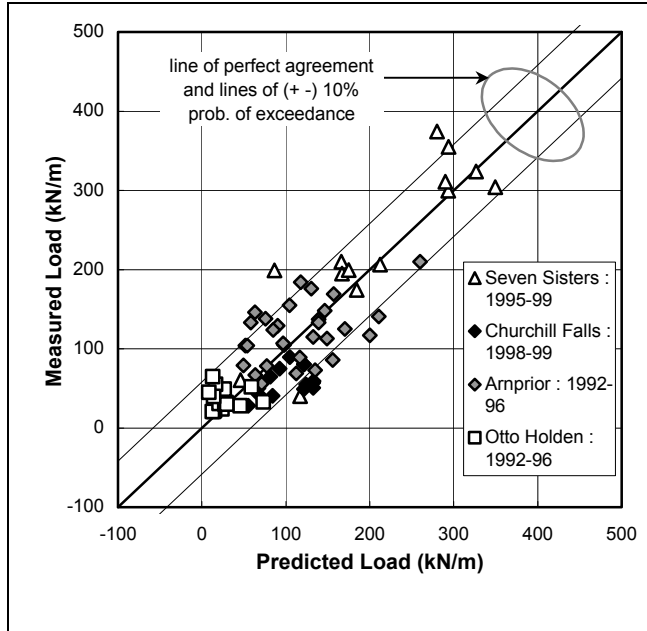


Figure 10 Predicted vs. Measured Loads

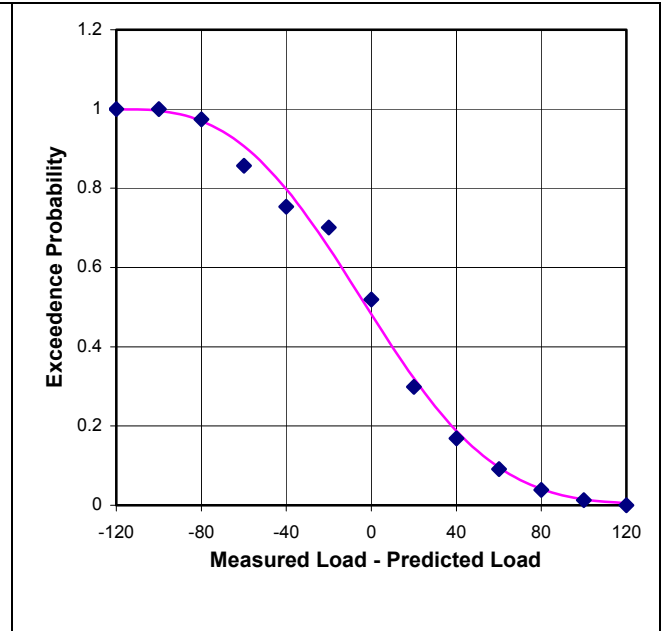


Figure 11 Load Contingency Distribution

## Range of Applicability for the Combined Water Level Change/Thermal Load Predictor

Table 2 Ranges of Variation for the Events in the Combined Water Level Change/Thermal Load Database

Parameter	Max.	Min.
Total Line Load, “ $LL_{total}$ ”, (kN/m)	374	21
Residual Line Load, “ $LL_{Residual}$ ”, (kN/m)	50	-10
Reservoir Ice Sheet Thickness, “ $h$ ”, (cm)	90	28
Water Level Change Amplitude “ $a$ ”, (cm)	51	7
Water Level Change Amplitude/Ice Thickness, “ $a/h$ ”	1.21	0.08
Forebay Mean Level drop, “drop”, (cm)	50	-50
Forebay Level Drop Index, “ $ \text{drop} /2h$ ” – equation [6]	0.69	0
Water Level Change Frequency (cycles/day)	2.25	0.25
Event Duration, “dur”, (days)	14.2	0.15
Ice Temperature Profile Area Change During the Event, “ $\Delta A$ ”, ( $^{\circ}\text{C}\cdot\text{cm}$ )	448	0
Ice Temperature Profile Area Change Before the Event, “ $\Delta A_i$ ”, ( $^{\circ}\text{C}\cdot\text{cm}$ )	530	0
Ice Temperature Profile Area at the Start of the Event, “ $A_i$ ”, ( $^{\circ}\text{C}\cdot\text{cm}$ )	608	0

## CONCLUSIONS

Much progress has been made towards understanding static ice loads on hydro-electric structures, and the mechanisms generating them. Methods have been developed to predict the ice load. The algorithms predict thermal loads well as a load contingency of 13 kN/m (0.9 kips/ft) would be adequate for 90 % of the loading events. Loads produced by a combination of water level and ice temperature changes cannot be predicted as well, as the required load contingency to cover 90 % of the events is 60 kN/m (4 kips/ft). Further work in this area would be useful.

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## REFERENCES

- Comfort, G., Gong, Y., and Singh, S., 2000, The Factors Controlling Static Ice Loads on Dams, proc. IAHR Symposium on Ice Problems, Gdansk, Poland.
- Comfort, G., Abdelnour, R., Gong, Y. Singh, S., And Dinovitzer, A., 1999, Update No. 2 to Static Ice Loads On Hydro-Electric Structures : Ice Loads Monograph No. 2, CEA projects EG 910012 and T992700-0204 .
- Comfort, G., Abdelnour, R., Gong, Y. Singh, S., And Dinovitzer, A., 1998a, Static Ice Loads On Hydro-Electric Structures : Ice Loads Monograph No. 2, CEA proj. EG 910012.
- Comfort, G., Singh, S., and Gong, Y., 1998b, Static Ice Loads On Dams : Loads on the Dam Face, and on Wooden vs Steel Stoplogs, CDA Conference, Halifax.
- Comfort, G., Gong, Y., Singh, S., And Abdelnour, R., 1997, Static Ice Loads On Hydro-Electric Structures: Loads Exerted Along A Dam Face ; And A Comparison Of The Loads Exerted On Wooden And Steel Stoplogs , CDSA conference, Montreal.
- Comfort, G., Abdelnour, R., Gong, Y. And Dinovitzer, A., 1996, Static Ice Loads On Hydro-Electric Structures : Ice Loads Monograph, CEA project 9038 G 815.