THE FACTORS CONTROLLING 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 identify the importance of water level changes on the resulting ice loads. Ice loads are much higher and more variable compared to purely thermal loads when significant, but not excessive, water level changes occur. The maximum measured line loads for these two cases are 85 kN/m and 374 kN/m, respectively. Preliminary analyses have shown that ice loads can be affected significantly by the reservoir shape when the reservoir sides are significantly softer than the dam.

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 distribution 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, (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 is focussed on ice loads for dam safety analyses. The ice loads measured in the reservoir ice sheet are most applicable for this case. A companion paper describes methods that have been developed to predict the ice load (Comfort et al, 2000).

ICE LOADS IN THE RESERVOIR ICE SHEET: MAXIMUM MEASURED LOADS

Probably, the most significant finding of the work to date has been to identify the importance of water level fluctuations on the ice loads produced. Ice loads are much higher and more variable compared to purely thermal loads when significant, but not excessive, water level changes occur (Tables 1 and 2 – see also Figure 1).

Table 1 Thermal Load Database Summary (Negligible Water Level Changes Occur)

Site & Owner	Winter	Total No. of Events	No. of Events: Loads > 30 kN/m	Max Line Load (kN/m)
Paugan Dam (Hydro-Quebec)	1992-93	12	2	51
	1993-94	9	5	70
120 m by 60 m basin (Nat. Res. Council)	1992-93	10	3	46
Seven Sisters (Manitoba Hydro)	1996-97	9	6	64
Pine Falls Dam (Manitoba Hydro)	1996-97	8	6	60
	1997-98	7	3	43
McArthur Falls (Manitoba Hydro)	1998-99	7	7	85

Table 2 Combined Water Level Change/ Thermal Load Database (Significant Water Level Changes Occur)

Dam & Owner	Monitoring Period		No. of Events	Peak Load, kN/m (kips/ft)
	Winters	No. of Yrs.		
Arnprior (Ont. Hydro)	1992-93 to 1995-96	4	30	210 (14.3)
Otto Holden (Ont. Hydro)	1993-94 to 1995-96	3	17	65 (4.4)
Seven Sisters (Man. Hydro)	1995-96, 1997-98, & 1998-99	3 (note 1)	15	374 (25.4)
Churchill Falls (Nfld. & Lab Hydro)	1998-99	1	15	80 (5.4)

Notes:

1. The 1996-97 data were not included in this database because water level changes were “small and slow” in 1996-97 (Figure 1). The 1996-97 events at Seven Sisters were included in the thermal load database (Table 1).

DEFINING SIGNIFICANT WATER LEVEL CHANGES

Although forebay level fluctuations follow a complex pattern, they can be divided as follows. It should be noted that the information presented here applies to ice that is about 0.3 to 0.7 m thick.

- steady reservoir drawdown - this breaks the ice away from the dam, producing low ice loads.

- a large one-time drop or rise (i.e., more than the ice thickness) – This will reduce ice loads if the ice does not refreeze strongly to the shore or dam. Large one-time drops reduced loads at:

(a) the Otto Holden dam – no more ice loading events occurred each year after the water level was lowered by 2 to 3 m in late February.
(b) the Seven Sisters dam - a large water level drop in early January, 1997 contributed significantly to the much lower ice loads measured there during the 1996-97 winter.

- cyclical water level changes – Their effect is related to the average water level frequency and amplitude, and they can be generally classified as follows (Figures 1 and 2):

(a) "Small and Slow" – water level changes have a negligible effect, and the loads are primarily thermally-induced. This produces relatively low, quite uniform loads (Figure 1 and Table 1).
(b) "Large and Frequent" – This case produces low ice loads (Figure 1) because these water level changes inhibit the formation of a strong bond between the ice and the dam. Hinge-shaped cracks are produced which prevent high ice loads from being developed at the dam.
(c) "Intermediate" – This causes the highest ice loads because these water level changes produce ice crack and ice cover conditions that greatly resist ice sheet movements (Figure 1). The ice cracks produced are vertical, or near-vertical, with a great deal of new ice growth in them.

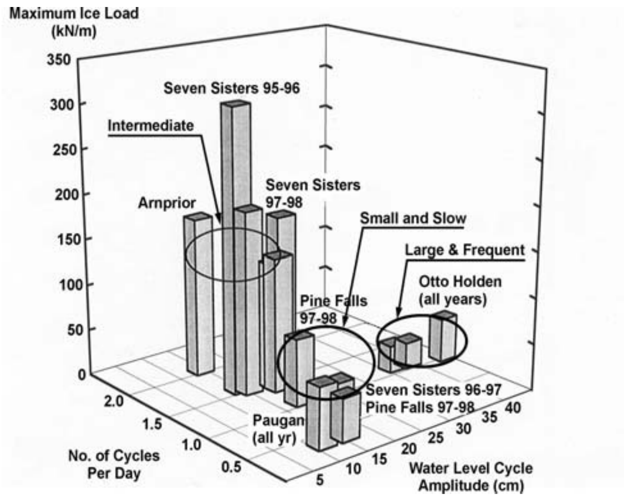

Figure 1: Ice Load Vs Water Level Changes

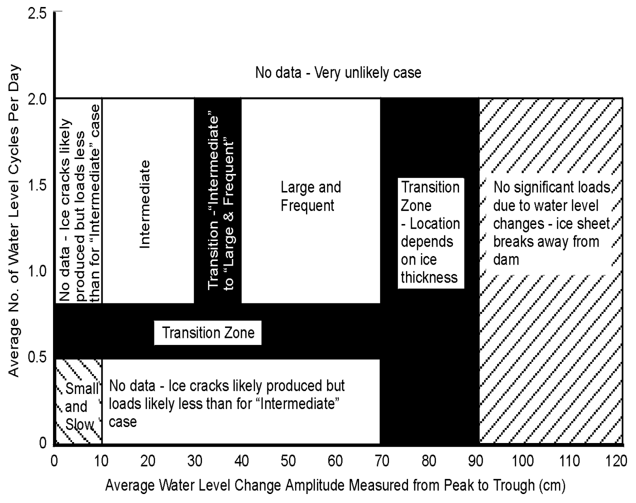

Figure 2: Water Level Change Regime Map

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. This case covers all other parts than "Small and Slow" (Figures 1 and 2).

REVIEW: THE ICE LOADING EVENTS AT THE SEVEN SISTERS DAM

These field data are of great interest because the highest loads have been measured here. As well, the loads have varied significantly from year to year, due to various factors (Table 3).

- 1995-96 and 1998-99-High loads (of 324 and 374 kN/m, respectively) were measured due to:

(a) Large ice temperature changes - 1998-99 and 1995-96 were the two coldest winters and they produced the largest maximum ice temperature profile area changes (Table 3).
(b) Forebay level changes – Water level changes were in the "intermediate" range which causes high ice loads. As well, the forebay was cycled within a narrow range over the whole winter.

- 1996-97 - The maximum line load (i.e., 62 kN/m) was much less than those for 1995-96 and 1998-99, despite the fact that 1996-97 was a relatively cold winter as well. The much lower loads in 1996-97 can be traced to two differences in water level fluctuation patterns:

(a) a large one-time drop occurred near the start of the winter which broke the ice free from the dam. This may have created a “hinge” mechanism that would relieve ice loads (Figure 3).
(b) water level fluctuations were in the “Small and Slow” category which does not produce significant ice loads due to water level fluctuations (Figure 1).

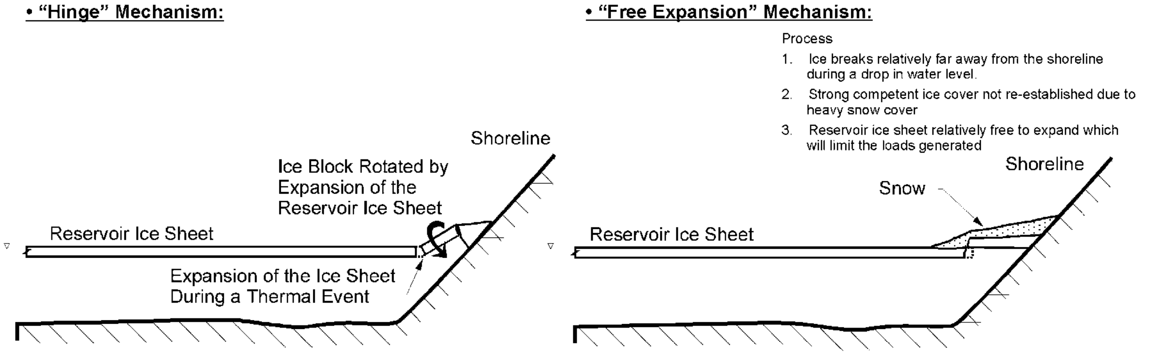

Figure 3 Hinge Mechanism Created by a Large One-Time Drop in Water Level

- 1997-98 - the maximum line load (i.e., 199 kN/m) was also much less than those for 1995-96 and 1998-99. This is mainly due to the fact that 1997-98 was a mild winter, as water level fluctuation patterns in 1997-98 were generally similar to those in 1995-96 and 1998-99.

Table 3 Summary Of Results At The Seven Sisters Dam

Ice Loads	Air & Ice Temp.	Water Level Changes	
1995-96 winter			
Very high loads measured Max. Load = 324 kN/m	Cold winter - Large ice temperature changes Max profile area change = 445 °C*cm	Drop in early winter ? Fluctuation amplitude Fluctuation frequency Fluctuation pattern	No +/- 5 to +/- 7.5 cm Peaked every 12 to 24 hours Quite regular
1996-97 winter			
Low loads measured: Max. load = 62 kN/m	Cold winter - Large ice temperature changes Max. profile area change = 351 °C*cm	Drop in early winter ? Fluctuation amplitude Fluctuation frequency Fluctuation pattern	Yes - 45 cm over Jan. 3-6,1997 +/- 5 to +/- 10 cm Peaked roughly every 4 days Irregular
1997-98 winter			
Lower loads measured Max load = 199 kN/m	Warm winter - small ice temperature changes Max. profile area change = 92 °C*cm	Drop in early winter ? Fluctuation amplitude Fluctuation frequency Fluctuation pattern	No +/- 7.5 to +/- 12.5 cm Peaked every 12 to 24 hours Sometimes irregular
1998-99 winter			
Very high loads measured: Max load = 374 kN/m	Cold winter - Large ice temperature changes Max. profile area change = 448 °C*cm	Drop in early winter ? Fluctuation amplitude Fluctuation frequency Fluctuation pattern	No +/- 7.5 to +/- 10 cm Peaked every 12 to 24 hours Sometimes irregular

This comparison shows that:

(a) very high ice loads will develop if large ice temperature changes occur in combination with "Intermediate" forebay level changes. This occurred twice (in 1995-96 and 1998-99) with the same result (regarding the loads produced) which adds reliability to the measured results.
(b) effect of ice temperature vs water level changes - in 1997-98, significant ice loads (i.e., >150 kN/m [10 kips/ft]) occurred due to the effects of "intermediate" water level change patterns despite the much smaller ice temperature changes in that winter (than 1995-96 and 1998-99).
(c) the ice loads will be greatly reduced if forebay level fluctuations follow the pattern that took place in 1996-97. Although large ice temperature changes also occurred in 1996-97, the water level change pattern below more than "compensated" for this, which produced low loads.
    (i) the water level was dropped significantly, and held there for the rest of the winter, and
    (ii) subsequent water level fluctuations were in the "small and slow" range.

EFFECT OF RESERVOIR SHAPE

Introduction and Purpose of Analyses

The Arnprior and the Seven Sisters dams are the only ones where ice loads exceeding 150 kN/m (10 kips/ft) have been measured in the eight years of monitoring done to date. Higher maximum loads have been measured at Seven Sisters by about 2 (Table 2) despite relatively similar ice temperature and water level changes at each dam. The reservoirs at the Seven Sisters and Arnprior dams are "lake-shaped" and "river-shaped", respectively (Figures 4 and 5). Preliminary finite element analyses were used to assess whether this difference may have contributed to the observed variation. To make the analyses more general, basic cases were analyzed (Figure 6).

Figure 4 Seven Sisters Dam and Reservoir

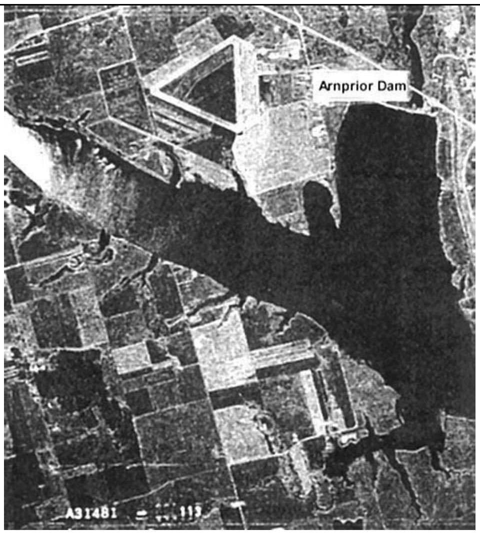

Figure 5 Arnprior Dam and Reservoir

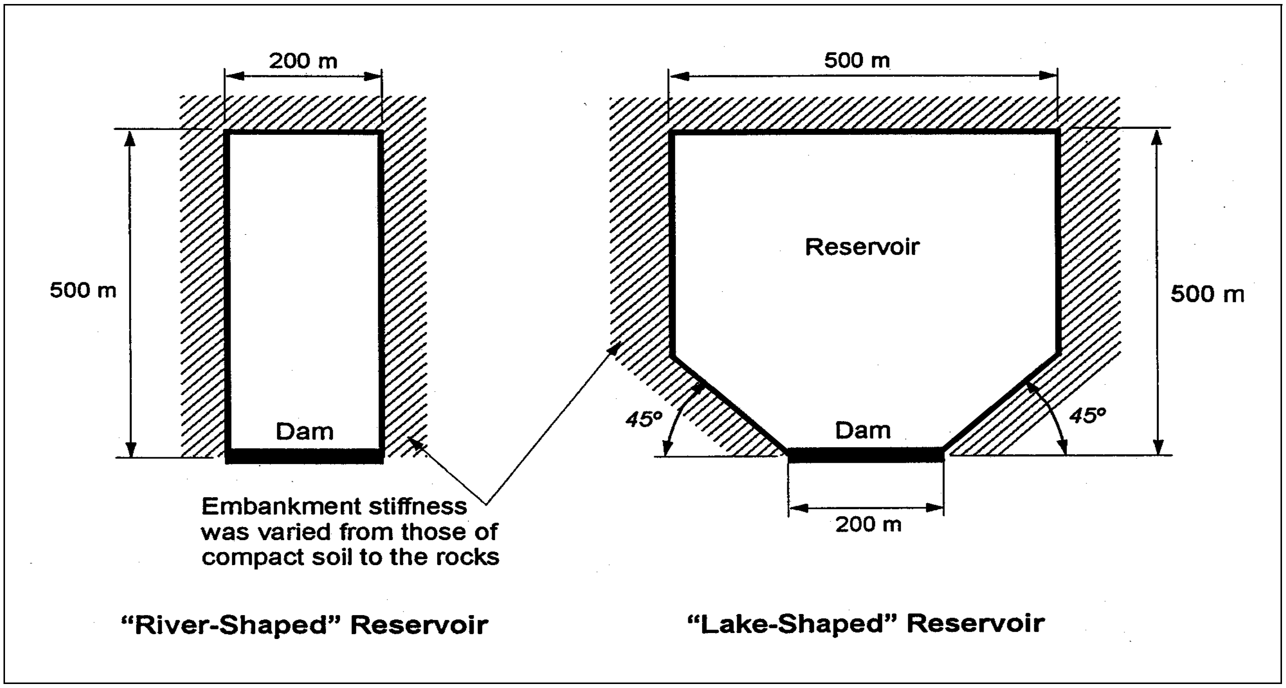

Figure 6 Reservoir Geometries Selected for Analysis

Approach

Plane stress conditions were assumed, as well as linear-elastic deformations in the ice sheet, the dam, and the reservoir sides. See Table 4 for material properties. The reservoir was assumed to be frozen over with a uniform 1 m thick ice sheet that underwent a uniform temperature rise of 10C°. The dam stiffness was taken to be uniform along its length. Local variations, such as those produced by stoplogs and piers, were not included. The reservoir embankment around was assumed to have uniform stiffness throughout its perimeter. The boundary conditions were selected to represent those for an ice sheet that is not bonded at the reservoir edges (due to cracks that normally form at the reservoir edges), but is in contact with it. In plane ice sheet displacements perpendicular to the boundary (due to thermal expansion) were resisted by springs, whereas any movement parallel to the boundary was unrestricted.

Table 4 Material Properties Used for the Dam, the Ice and the Embankment

Material	Properties
Dam	Stiffness: 2000 MN/m
Ice	Young's Modulus(E): 4 GPa Poisson's Ratio: 0.3
Embankment	Ranged as follows to cover range of materials: • Compacted soil to loosely packed rock: Stiffness = 20 to 200 MN/m/m – see text below • Rock face: Stiffness = 10,000 MN/m/m – see text below

The reservoir stiffness was estimated by assuming that the ice stresses were dissipated in a length equal to two times the loading width, and that the applied ice stresses were applied uniformly through the ice thickness. Hence, the stiffness per unit length of reservoir, K, is:

$$K = (\text{area}_{\text{loaded}} * E) / \text{active length} \qquad [1]$$

where: $\text{area}_{\text{loaded}}$ = the area loaded by the ice sheet
E = the elastic modulus
active length = the length over which stresses are dissipated in the material (assumed to be two times the loading width)

For a 1 m ice thick ice sheet, and a 2 m "active length", equation [1] produces a reservoir side stiffness per unit length equal to half of the Young's modulus for the reservoir material.

Results: Effect of Reservoir Shape

The results (Figures 7 and 8) show that reservoir shape is an important factor influencing the ice loads when the reservoir sides are significantly softer than the dam. In this case, differences in ice loads of up to a factor of about 2 could possibly be expected due to variations in reservoir shape.

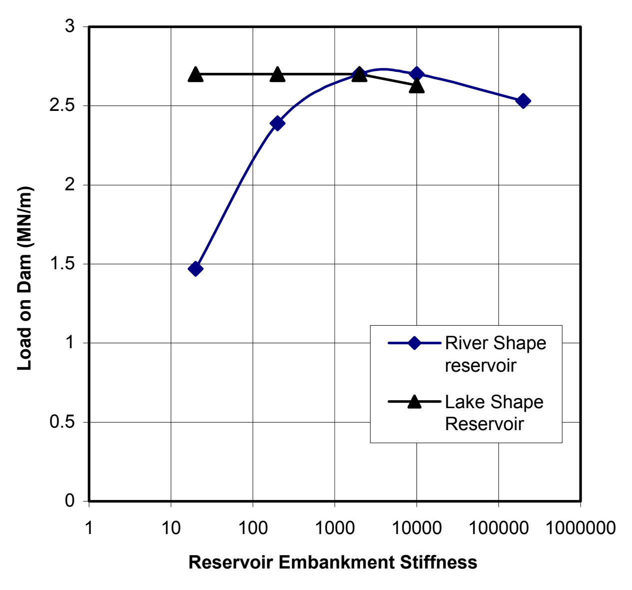

Figure 7 Results in Engineering Units

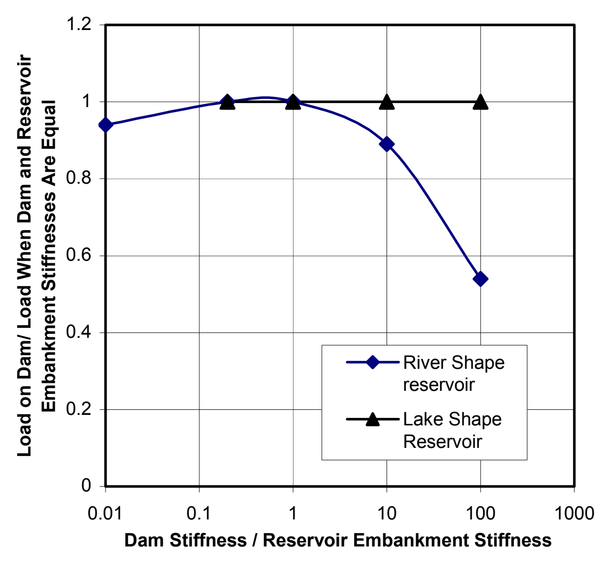

Figure 8 Non-Dimensional Results

Unfortunately, direct conclusions (comparing the expected loads at Seven Sisters and Arnprior) are not possible because the reservoir and dam stiffnesses at these sites are not known. However, because the reservoir sides at each of these dams are berms, it is likely that they are significantly softer than the dams at these sites. These calculations suggest that part of the observed ice load variations between these two sites (Table 2) may be attributable to variations in reservoir shape although further analyses are required to verify this. The work should also be followed up with more detailed analyses that take ice creep into account.

CONCLUSIONS

The ice load database has been expanded, and now contains 8 years of measurements. Progress has been made towards understanding static ice loads on hydro-electric structures, and the mechanisms generating them. The most significant finding of the work has been to identify the importance of water level changes on the resulting ice loads. Ice loads are much higher and more variable compared to purely thermal loads when significant, but not excessive, water level changes occur. The water level fluctuation patterns that induce relatively high, and low, ice loads have been identified. Preliminary analyses have shown that loads in a lake-shaped reservoir may higher than those for a river-shaped reservoir by a factor of up to about 2 when the reservoir sides are significantly softer than the dam. It would be useful to investigate the effect of reservoir shape further with field data collection and more detailed analyses.

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