Static Ice Loads on Wooden and Steel Stoplogs at Seven Sisters Generating Station

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There is interest in replacing the wooden stoplogs commonly used on dams with steel ones. A three-year field program was conducted to measure the static ice loads on wooden and steel stoplog sections at the Seven Sisters Generating Station. The loads on the steel stoplogs were determined based on ice stress measurements and also using strain gauges. The line loads measured by the two systems are in reasonable agreement.

1. Introduction And Background

Ice loads on dams and their gates and piers can be of great importance to designers and operators of dams in northern climates, especially for low-head dams. However, only limited information is available to define ice loads and, as a result, many uncertainties still remain.

The ice load distribution along the dam face is one such uncertainty. This issue is of importance because there is interest among the hydro utilities in using steel stoplogs to replace the commonly-used wooden ones. Steel stoplogs are expected to last longer than wooden ones, thereby reducing overall costs.

The research described in this paper was undertaken to compare ice loads on wooden and steel stoplogs, which was one important factor affecting the relative merits of each stoplog type. At first glance, one would expect the steel stoplogs to sustain higher ice loads due to their higher stiffness. One of the objectives of the work was to test this assumption, and this paper summarizes three years of ice load data to compare wooden versus steel stoplogs.

Another objective of this paper is to present ice load data for the steel stoplogs that were measured over one winter season using two independent systems and approaches. This information is useful for assessing the accuracy of the ice load measurements.

2. Information Base and Scope of Paper

The information presented in this paper comes from two main sources :

(a) an 8-year field program conducted from 1991-92 to 1998-99 to measure ice loads that was sponsored by the Canadian Electricity Association (CEA), with partial funding from the hydro utilities. This project was carried out by deploying stressmeters in the ice to measure the in-situ stress. This program had two main objectives :

(i) to obtain information to define ice loads for use in Dam Safety Evaluations - Loads were measured in the reservoir ice sheet 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, Pine Falls and McArthur Falls dams for 4, 2 and 1 winters, respectively ; the Churchill Falls-Labrador Corp'n.'s dam at Churchill Falls, Lab. for 1 winter ; and in a 120 m by 60 m outdoor basin at the National Research Council in Ottawa for one winter.

(ii) to obtain information to define the load distribution along the dam face - Loads were measured on one pier and gate of Hydro-Quebec's Paugan dam over two winters. Loads were also measured at Manitoba Hydro's Seven Sisters dam on adjacent steel and wooden stoplog sections, as well as on the pier between them, over three winters.

The results obtained up to the 1998-99 winter are presented and analyzed in detail in Comfort et al, 1999, and much of this information has been published previously in papers by Comfort et al 1998; 1997; and 1996, among others. All of the available stoplog data (which is the subject of this paper) are analyzed in Comfort et al, 1999.

Although all three years of data are summarized in this paper, only the 1995-96 data are discussed because ice-induced loads from the strain gauge data (described below) are only available at present for that winter.

(b) A parallel research program conducted by the University of Manitoba (on behalf of Manitoba Hydro) to measure ice loads on the steel stoplogs at Manitoba Hydro's Seven Sisters dam using strain gauges fixed to the steel stoplogs (Penner, 1998). Data were collected for three winters, from 1995-96 to 1997-98. Only the 1995-96 data are presented in this paper because only these data have been fully analyzed as of now. The data for the other 2 winters are currently being analyzed.

The objectives of this paper are to :

(a) compare the loads on the wooden and steel stoplogs for the 1995-96 winter.

(b) present the ice loads determined from the strain gauge data for the steel stoplogs for the 1995-96 winter.

(c) compare the ice-induced line loads measured on the steel stoplogs using the two measurement systems (i.e., the stressmeters and the strain gauges).

3. Background And Site Description

The work was carried out at Manitoba Hydro's Seven Sisters Generating Station, which is located on the Winnipeg River about 150 km from Winnipeg. One set of steel stoplogs was installed by Manitoba Hydro in 1995, which made this an ideal site for comparing wooden and steel stoplogs (Figures 1 and 2).

4. Ice Load Measurement Approaches

Ice loads were measured using two general approaches as follows :

(a) Ice loads determined from measurements of in-situ stresses – The "CEA" programs were conducted by installing BP stressmeters (termed so because they were developed by British Petroleum Ltd.- Duckworth and Westermann, 1989) in the ice sheet within 15 cm of the stoplog sections to measure the in-situ ice stress. These sensors consist of 7.5 cm diameter, mercury-filled flatjacks that are connected to an electronic pressure transducer.

Data were collected for three winters, from 1995-96 to 1997-98. The data collection period for each winter usually commenced in early January (when the sensors were installed) and it extended to early April (when the stressmeters were removed from the ice).

A total of 18 BP stressmeters were installed each year to measure stoplog loads. Nine of them were deployed in front of section #18 (which was the steel stoplog), while the other 9 were deployed in front of section #19, which was an adjacent wooden stoplog (Figure 1). The stressmeters were divided into three groups across the width of each stoplog section. Each group consisted of three sensors that were positioned at centreline depths of 7.5 cm, 22 cm, and 41 cm.

The stresses were also measured in front of the pier between the two instrumented sections using a total of six stressmeters, deployed in two groups.

(b) Strain Gauge Measurements - The top two steel stoplogs of section #18 were instrumented with strain gauges at strategic locations (Figure 3). Four groups of gauges were used to monitor bending, longitudinal, and shear strains. Strain gauges placed at location ST1 and ST2 were used to monitor the strain of the stoplog due to bending.

The strain gauges at locations ST3 and ST4 were in a region of minimal bending moment. Consequently, these rosette strain gauges provided information concerning the shear at the supports and any longitudinal strains in the stoplogs. The strain gauges at sections ST3 and ST4 were used to monitor the reactions at each end of the stoplog.

The measured strains were temperature-corrected as recommended by the strain gauge supplier based on stoplog temperature data that were collected during the field monitoring periods.

The instrumented stoplogs were calibrated prior to installation at the University of Manitoba's Structural Engineering and Construction Research and Development facility during November, 1995. This was done by applying known loads to the stoplogs for pinned-end conditions.

The stoplogs were installed at Seven Sisters Generating Station on Dec. 20, 1995. All strain gauges were zeroed immediately prior to installation.

The strain gauge data were collected using the same data acquisition system used for the ice stressmeters over the same data collection periods (described above).

5. Results From the Ice Stressmeter Data

Method for Calculating the Line Load Through the Full Ice Thickness

The line load acting through the full thickness of the ice sheet was calculated at each sensor group by assigning depth ranges in the ice sheet to the stresses measured by each of the three sensors in the vertical array. The results from the three sensor groups were averaged to determine the average line load across the full width of the stoplogs.

Results

Line Load Magnitudes - Figure 4 shows the line load time history for the steel and wooden stoplog sections for the whole monitoring period during the 1995-96 winter. A total of 18 loading events occurred over the 1995-96 to 1997-98 period (Table 1). The peak line loads recorded during these events is summarized below :

- Pier : 1995-96 Winter - 560 kN/m (38 kips/ft)
  1996-97 Winter - 202 kN/m (13.7 kips/ft)
  1997-98 Winter – 527 kN/m (36 kips/ft)
- Wood Stoplogs : 1995-96 Winter - 93 kN/m (6.3 kips/ft)
  1996-97 Winter - 47 kN/m (3.2 kips/ft)
  1997-98 Winter – 111 kN/m (7.6 kips/ft)
- Steel Stoplogs : 1995-96 Winter - 21 kN/m (1.4 kips/ft)
  1996-97 Winter - 50 kN/m (3.4 kips/ft)
  1997-98 Winter – 57 kN/m (4.0 kips/ft)

Line Load Time Histories for the 1995-96 Winter - Figure 4 shows that the line loads on the wood and steel stoplogs were both non-steady over the 1995-96 winter. As has been stated previously (e.g. Comfort et al., 1998), this is due to the combined effects of the two main factors generating the ice loads :

(a) ice temperature rises which induce thermal loads - Ice temperature changes occur relatively slowly, and as a result, the ice load time histories exhibit low-frequency rises that generally follow the ice temperature changes (Figure 4).

(b) water level changes – water level changes occur considerably faster than ice temperature changes and they superimpose "load spikes" on the thermal load "baseline" for an event (Figure 4).

The contribution of these two ice load-generating mechanisms produced line load time histories during the events that can be characterized as higher frequency line load fluctuations superimposed on a steadily increasing baseline.

Table 1 - Summary of Loading Events at the Seven Sisters Dam During the 1995-96 to 1997-98 Winters : Loads Determined Based on the Ice Stressmeter Measurements

1995-96 Winter :

Event	Date	Peak Line Load (kN/m) Across The :		
		Pier	Steel Stoplogs	Wood Stoplogs
1	Jan. 17	46	-5 (tension)	-7 (tension)
2	Feb. 10	96	-4 (tension)	5
3	Feb. 24	146	5	18
4	Mar. 13	281	-1 (tension)	45
5	Apr. 1	560	21	52
6	Apr. 10	560	-3 (tension)	93

1996-97 Winter :

Event	Date (note 1)	Peak Line Load (kN/m) Across The :		
		Pier	Steel Stoplogs	Wood Stoplogs
1	Feb. 20	42	17	21
2	Feb. 25-26	94	21	18
3	Mar. 1-4	76	23	24
4	Mar. 9-11	60	25	26
5	Mar. 13-14	17	37	47
6	Mar. 20-24	202	50	40

1997-98 Winter :

Event No.	Date (note 1)	Peak (note 1) Line Load (kN/m) Across The:		
		Pier	Steel Stoplogs	Wood Stoplogs
1	Jan. 17	23	25	2
2	Jan. 23	39	22	31
3	Jan. 27-28	95	21	111
4	Feb. 15-16	147	33	65
5	Mar. 13	452	33	28
6	Mar. 16-17	527	57	57

Notes :

1. The above values are the peaks that occurred during the indicated time period. However, usually the peak line loads across the pier, the wood stoplogs, and the steel stoplogs did not occur at the same time.

Wood vs Steel Stoplogs – A full discussion of these results is beyond the scope of this paper. However, it can be stated that in all cases, the loads on the steel stoplogs were less than or equal to those on the wooden ones.

Because ice-induced loads have been determined for the steel stoplogs for the 1995-96 winter (described next), it is of interest to consider the 1995-96 data. For 1995-96, the line loads on the steel stoplogs were slightly tensile for the events in January and February. Compressive line loads were measured during the events in March and April. The loads on the wooden stoplogs were always compressive.

Higher loads were consistently measured on the wooden stoplog section than on the steel one. As has been discussed in Comfort et al, 1998, this is attributed to the effect of the different thermal conductivities of the steel and wood stoplogs, and ice disbonding in front of the steel stoplogs. Above-freezing air temperatures were recorded at the end of 4 of the 6 events (which is the time when the peak loads were produced). These warm temperatures, combined with solar heating, were probably sufficient to cause partial disbonding of the ice at the steel stoplogs. This likely would not have occurred to the same degree at the wooden stoplogs, which have lower thermal conductivity.

6. Results From the Strain Gauge Data

Method for Calculating the Line Load Applied to the Steel Stoplogs

The uniformly distributed static ice load acting on each Hollow Structural Section (HSS) of the steel stoplogs was obtained by multiplying each temperature-corrected bending strain, $\varepsilon_{BENDING}$, from sections ST1 and ST2 by the proper regression coefficient. The averages of all resulting calculated static ice loads for each individual HSS section were summed up to obtain the total applied static ice load applied to the top two stoplogs. Finally, the total static ice load was determined by summing the load resisted by the top and second stoplogs (which were both in contact with the ice).

Table 2 summarizes the calculations that were performed on the strain gauge readings throughout the winter to obtain the static ice load acting on the stoplogs.

Table 2 - Summary of Stoplog Loading Calculations

	Top Stoplog	Second Stoplog
Top HSS	$\frac{\sum_{4}^{1} K_n \varepsilon_n}{4} = w_{TT}$	$\frac{\sum_{4}^{1} K_n \varepsilon_n}{4} = w_{T2}$
Bottom HSS	$\frac{\sum_{9}^{6} K_n \varepsilon_n}{4} = w_{BT}$	$\frac{\sum_{9}^{6} K_n \varepsilon_n}{4} = w_{B2}$
Stoplog Static Ice Load:	w_T	w_2
Total Static Ice Load:	w_{TOTAL}	

where: K = Appropriate regression coefficients for strain gauges at sections ST1 and ST2.

ε = Appropriate strain gauge readings for sections ST1 and ST2.

w_{TT} = Uniformly distributed static ice load applied to the top half of the top stoplog.

w_{T2} = Uniformly distributed static ice load applied to the top half of the second stoplog.

w_{BT} = Uniformly distributed static ice load applied to the bottom half of the top stoplog.

w_{B2} = Uniformly distributed static ice load applied to the bottom half of the second stoplog.

w_T = Uniformly distributed static ice load applied to the top stoplog.

w_2 = Uniformly distributed static ice load applied to the second stoplog.

w_{TOTAL} = Total uniformly distributed ice load applied to the top and second stoplogs.

Results for the 1995-96 Winter

Line Load Magnitudes - Figure 5 shows the total loading on the top two steel stoplogs for the entire 1995-96 winter period.

It should be noted that the line loads shown in Figure 5 include the hydrostatic line load because the strain gauges were zeroed immediately prior to installation. Thus, these values are the sum of the applied ice and hydrostatic loads. This must be kept in mind in making comparisons with the ice stressmeter data, which do not include the hydrostatic component.

The hydrostatic line load on the stoplogs was computed based on the average water level elevation at the stoplogs during the testing period. The hydrostatic line load was determined to be approximately 8 kN/m.

During the monitoring period, the combined maximum line load experienced by the top and second stoplogs was 50 kN/m. After subtracting the hydrostatic force, the peak static ice load measured during the testing period was 42 kN/m. The peak load occurred on April 6.

Line Load Time History – Figure 5 shows that the line load on the steel stoplog section was non-steady. As was the case for the line loads calculated from the stressmeter data, the line load time history determined from the strain gauges is related to :

(a) ice temperature changes, and

(b) forebay level fluctuations.

7. Comparison : Ice-Induced Loads on the Steel Stoplogs Determined From the Strain Gauges and the Ice Stressmeters

Presentation of Results

The ice-induced line loads on the steel stoplogs determined from the strain gauges and the ice stressmeters are compared directly in Figure 6.

Line Load Magnitudes

The ice-induced line loads indicated by the strain gauges were in reasonable agreement with those determined from the ice stressmeters (Figure 6). The loads inferred from the strain gauges were consistently higher than those determined from the ice stressmeters. The variation between the two line loads averaged 17 kN/m (1.2 kips/ft) for the whole monitoring period. The maximum variation was 33 kN/m (2.3 kips/ft).

The variation between the loads measured by the two systems could come from a number of sources :

(a) non-uniform ice stresses resulting from partial disbonding between the ice and the upstream face of steel stoplogs.

(b) the loads calculated from the strain gauge readings were based on a moment diagram determined by assuming a uniformly distributed load along the full length of the stoplog. The ice stressmeters showed that this is not the case as the load distribution along the stoplog was non-uniform. Arching of the load between the piers, as well as cracking of the ice are two potential reasons for an uneven load distribution.

Line Load Time Histories Measured by The Two Systems

The time histories measured by the two systems generally "track" each other (Figure 6). Furthermore, both measurement approaches show that, during the events, the line load time history was non-steady with "load spikes" being superimposed on a steadily increasing baseline. As has been discussed previously, this load pattern is believed to be due to the combination of the two mechanisms generating the ice loads : (a) ice temperature changes, and (b) forebay level fluctuations.

Both measurement systems show that the loading events occurred at about the same times although there were discrepancies. For example, the peak line load determined from the strain gauges occurred on April 6 whereas the peak inferred from the stressmeters occurred on April 1 (Figure 6). The reasons for these variations are unclear.

8. Conclusions

The Seven Sisters Generating Station provides a god site for comparing wooden and steel stoplogs, and field data have been collected over three winters to define the ice loads on steel and wood stoplogs. The loads on the steel stoplogs were measured using two independent measurement systems (i.e., using strain gauges on the stoplogs and by measuring the stress in the ice within 15 cm of the stoplog).

The loads on the steel stoplog were found to be less than or equal to those on the wooden one.

The line load time histories measured with both systems were similar. This indicates that both measurement systems responded to the two mechanisms believed to be responsible for generating ice loads in this case (i.e., ice temperature changes and forebay level fluctuations).

The line loads measured by the two monitoring methods were within 17 kN/m (1.2 kips/ft) on average for the whole monitoring period. The line loads determined from the strain gauges were consistently higher than those calculated from the ice stressmeter data.

Acknowledgements

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(a) Ice loads determined from in-situ ice stress measurements - sponsorship was provided by the Canadian Electricity Association (CEA-R&D projects 9038 G 815 ; 9502 G 2015, EG 910012 & T992700-0204), with partial funding from Manitoba Hydro, Hydro-Quebec, Ontario Hydro, Nfld. Power Co. Ltd., Nfld. and Labrador Hydro, and the Canadian Dam Safety Ass'n. (CDSA). These projects were 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 and P. Bhat of Ontario Hydro, A. Kumar of B.C. Hydro, P. Halliday of Nfld. Power Co. Ltd., R. Barnes and E.G. Piercy of Nfld. and Labrador Hydro, 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), Manitoba Hydro (G. Ferguson, P. Roach), and the Churchill Falls Labrador Corp. (D. Hodder, G. Tucker).

(b) Ice loads on the steel stoplogs determined from strain gauges placed on the stoplogs - sponsorship was provided by Manitoba Hydro to the University of Manitoba.

References

Comfort, G., Abdelnour, R., Gong, Y. Singh, S., And Dinovitzer, A., 1999, 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 Versus 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, Ice Loads On Dams : Field Measurements And Analysis, CDSA conference, Niagara Falls.

Duckworth, R., and Westermann, P., 1989, Stress and Strain Instruments Developed for Ice, IEEE Journal of Oceanic Engineering, April, 1989, vol. 14, no. 2.

Penner, R., 1998, Static Ice Loading On Steel Stoplogs, Report On Instrumentation And Analysis During Winter Of 1995/96 submitted to Manitoba Hydro.

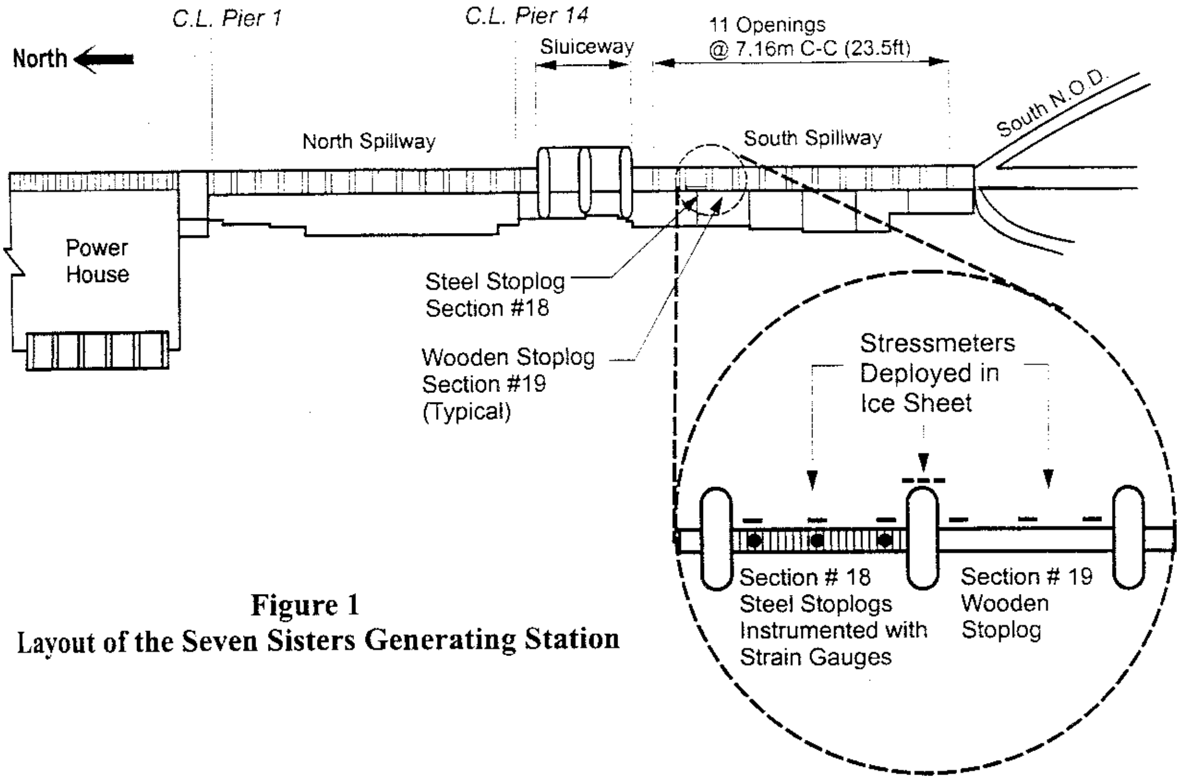

Figure 1
Layout of the Seven Sisters Generating Station

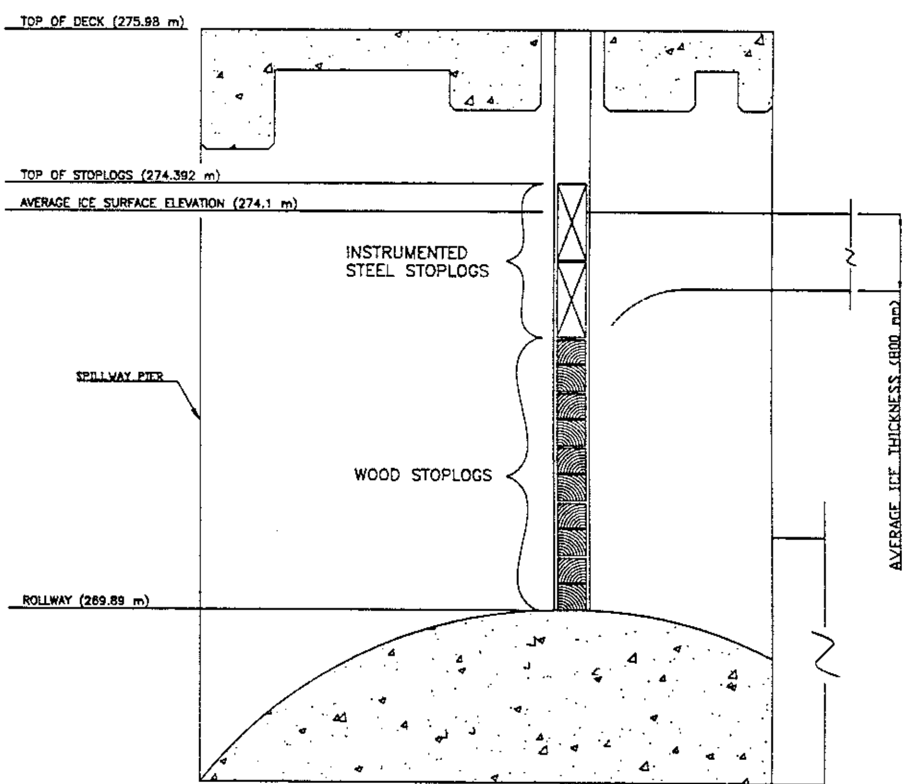

Figure 2 Spillway Stoplog Section #18 Configuration

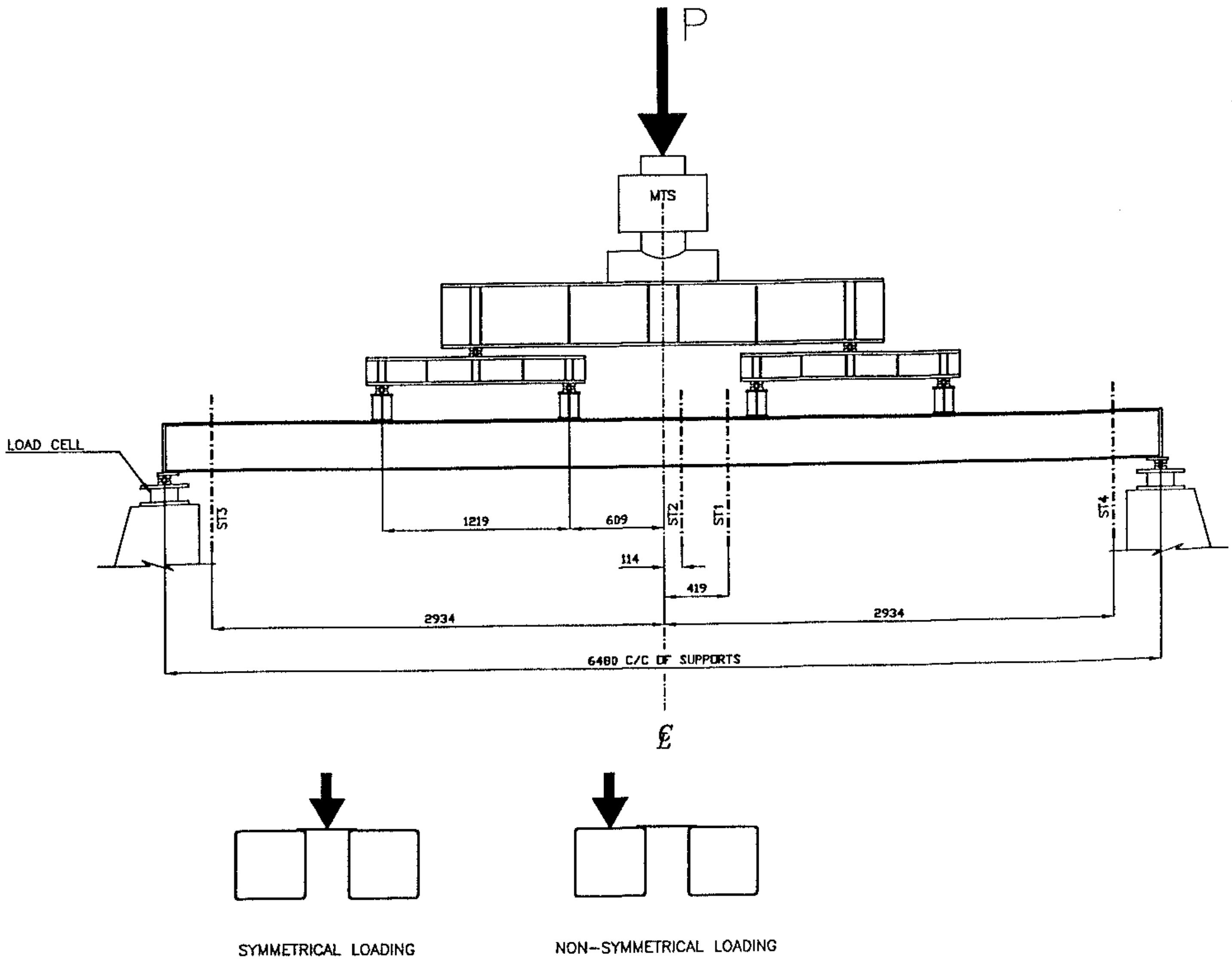

Figure 3 Calibration Apparatus Arrangement And Strain Gauge Locations

Figure 4
Ice Stressmeter Results

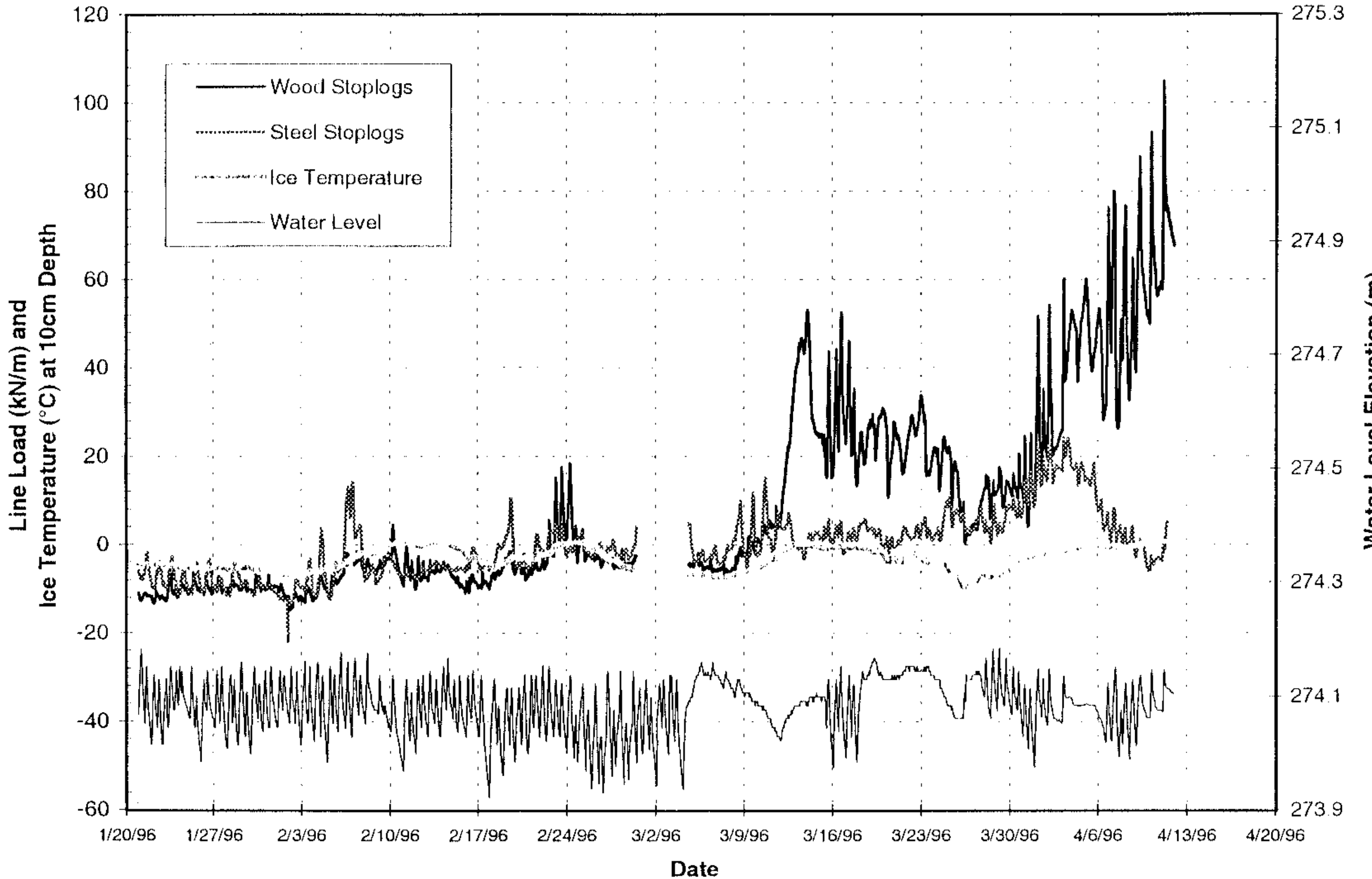

Figure 5
Strain Gauge Results

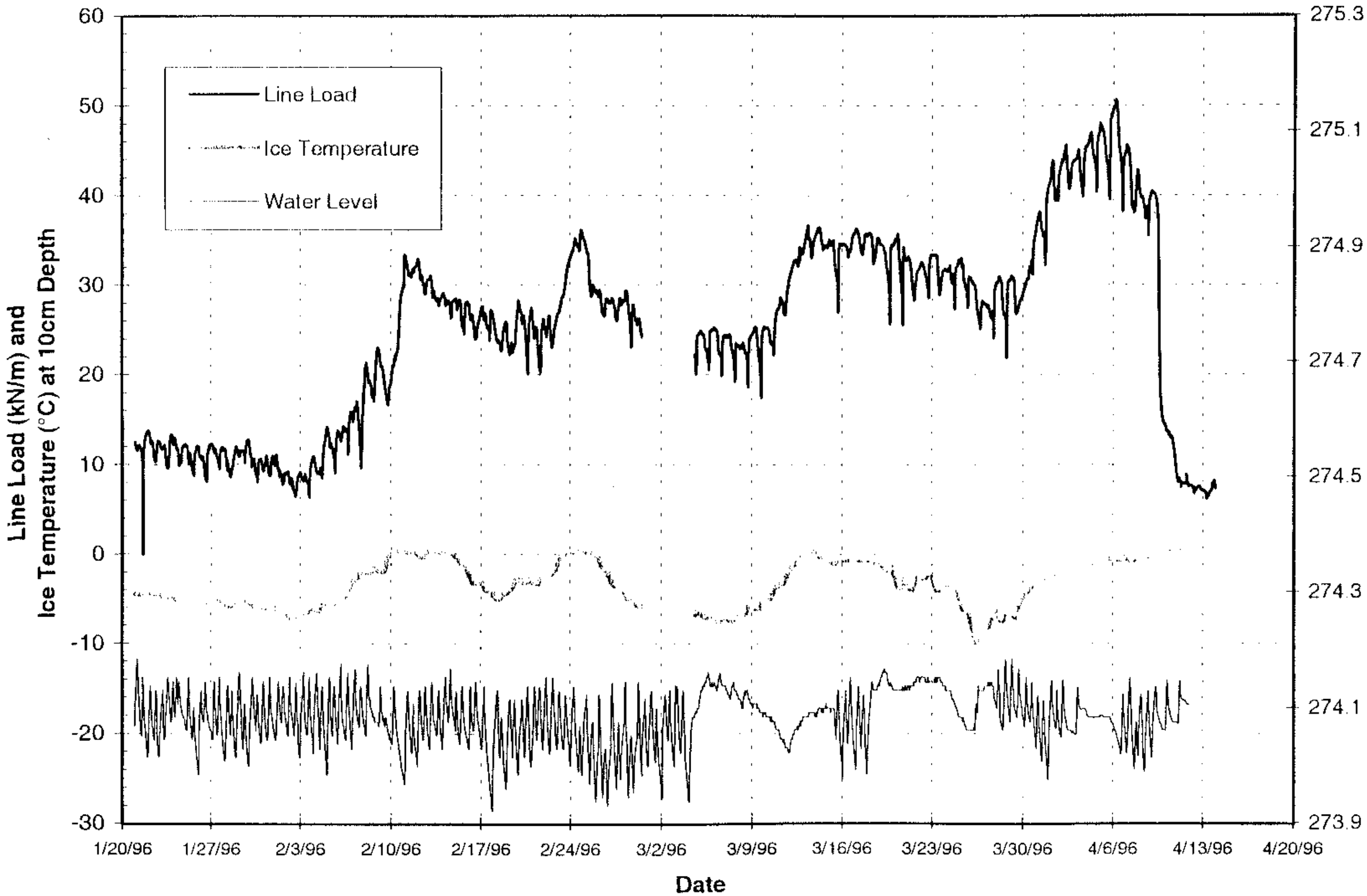

Figure 6 Comparison: Ice-Induced Line Load On The Steel Stoplogs Measured Using Strain Gauges And Determined From The Ice Stressmeters