An Icing Study for a
Future Suspended Bridge at Montmorency Falls

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ABSTRACT

The site chosen by SÉPAQ (Société des établissements de plein air du Québec) for a pedestrian bridge over Montmorency falls is particularly exposed to icing from droplet spray. ROCHE Ltd, responsible for the design of the bridge, has required a study to estimate the probable ice loads prior to the design of the suspended bridge.

A 12.5-mm-diameter steel cable was installed on existing towers at the location site of the future bridge. A load cell measured the end tension in the cable. Measurements of icing rate temperature, wind velocity and direction were also collected on site during the 1992-1993 winter, and compared with AES (Atmospheric Environment Service) meteorological data to establish an estimation valid over a longer period of time.

Results have shown that a maximum 5 kg of ice collected can be attributed to droplet spray from the falls. In fact, two freezing events 4 and 22 Jan. 1993, have resulted in glaze icing loads from atmospheric sources of 3 to 4 times that amount. These results appear to be related to two factors. Firstly, most of the time the spray droplets do not appear to be in the supercooled state essential for their adhesion to the structure. Secondly, the random direction of the droplet cloud results in a low water content impinging locally on the cable. A numerical simulation has shown that in such a case the icing rate on a structure would be small and only very soft rime would form. This type of atmospheric icing would not constitute a hazard for the planned bridge.

In conclusion, the additional icing due to the presence of the fall is small and therefore the design has been based on other estimated loads such as wind and glaze icing loads.

1. INTRODUCTION

SÉPAQ (Société des établissements de plein air du Québec) is presently creating a public park around Montmorency falls, near Québec city. Within this project a pedestrian bridge is being constructed over the falls and the chosen site is particularly exposed to droplet spray clouds from the falls. ROCHE Ltd, responsible for the design of the bridge, has required a study to estimate the possible icing loads prior to the design of the suspended bridge.

Montmorency falls are quite unique in that they have an important height (85 m) and are located at a latitude where the ambient temperature is below the freezing point during a few months every winter. Also, since it is very unusual to choose voluntarily, for attraction purposes, to build a bridge on the most exposed site to the supercooled droplet spray, a research project was initiated.

Two types of atmospheric icing have similarities with this situation and are the basis for this research. First, atmospheric icing of cables (Makkonen, 1984) has to do with atmospheric icing of structures, in particular the in-cloud icing of cables, important for power transmission lines. This phenomenon is also similar in a way to the droplet spray icing from waves on ships or off-shore structures (Zakrzewski and Lozowski, 1987). For this reason, a review paper published by Horjen (1989) was largely used for the basis of the analysis used to predict the icing of the bridge. Measurements were taken on the site using a cable crossing the river at the site of the future bridge. Measurements were conducted with procedures similar to work done on the icing of transmission lines. (McComber et al., 1987).

2. INSTRUMENTATION

A data acquisition system was installed on the site and the data were transmitted to the laboratory via telephone. Also a GOES satellite transmission system was available for reliability. The instrumentation was installed by Hydro-Québec, and the data acquisition and analysis was the responsibility of École de Technologie Supérieure. The following variables were measured : wind velocity and direction, air temperature, cable icing and finally icing rate. The site and the location of the cable with respect to the fall is shown in Fig. 1.
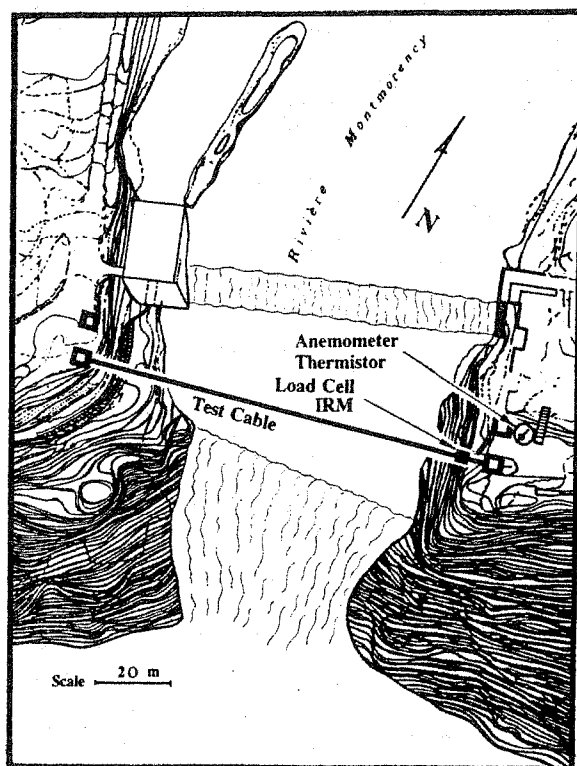

Figure 1 Instrument location on the site

A 12.5-mm-diameter steel cable, 112 m in length, was installed on existing towers at the location site of the future bridge. A load cell (Intertechnology T62H-3K-10P1), maximum load of 1350 kg, measured the end tension in the cable. Assuming that the load is uniformly distributed on the cable, a geometrical relationship shown in Fig. 2. is used to transform the end tension into a vertical load (kg) (McComber et al. 1987). Since this conversion depends largely on the angle of the cable at the end, this angle (21.3°) was measured accurately
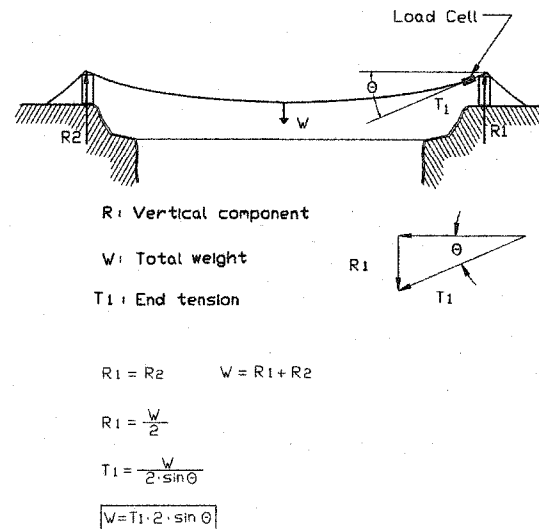

R : Vertical component

W : Total weight

T₁ : End tension

$R_1 = R_2$ $W = R_1 + R_2$

$R_1 = \dfrac{W}{2}$

$T_1 = \dfrac{W}{2 \cdot \sin\Theta}$

$$\boxed{W = T_1 \cdot 2 \cdot \sin\Theta}$$

Figure 2 Load calculation from the end tension

($\pm$ 0.1°) on the site with a Mitutoyo Digimatic Digital Protractor, soon after the installation of the cable.

The anemometer (HANDAR 430A and HANDAR 431 A) and the thermistor (Handar 432A) are standard meteorological instruments with no de-icing provided. These instruments were installed on top of a 17 m pole on the east side of the fall. Measurements of temperature, wind velocity and direction were also collected during the 1992-1993 winter, and compared with AES (Atmospheric Environment Service) meteorological data to establish a relationship for using the AES measurements over a longer period of time.

An icing rate meter (IRM), developed by Hydro-Québec, was also installed on the east side 10 meters from the shore above the stream. This icing rate meter records the occurrence and duration of the icing events. It uses a Rosemount 871 probe as a sensing device. An oscillator forces the sensing probe to vibrate longitudinally parallel to its axis. Ice accretion will cause a shift in the oscillation frequency. After a small preset thickness of ice has accumulated, the control circuit emits a signal and the sensor is de-iced by heating. This corresponds to approximately 0.5 mm of ice accumulated on the sensing cylinder. The number of signals are continuously added to the total. The number counted over a period of time gives an indication of the icing rate (McComber et al., 1993).

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3. ICING LOAD MEASUREMENTS

Measurements were taken from 30 November 1992 to the end of January 1993. Vertical loads measured were between 0 and 5 kg, except for two known freezing rain events, for the duration of the measurement period. These amounts are small, and because the accuracy of the measurement system is low at the end of the scale, it is difficult to make the distinction between the measured loads and errors on the signal. Also, these loads do not remain for long periods on the cable which prevented ice from accumulating to a significant degree. Considering the ambient temperature, the load appears sometimes to be water that has collected on the cable strands.
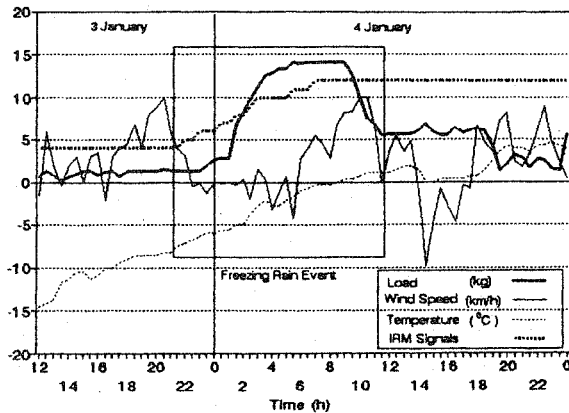

Figure 3 Measurements for the freezing rain event 3-4 Jan. 1993.

Two freezing rain events resulted in the maximum ice loads measured. These freezing rain events are important for two reasons. Firstly, they show that the measurement system did work satisfactorily and could measure any significant icing from the falls. Secondly, they confirm that freezing rain events are responsible for much larger loads on the future bridge than those resulting from droplet spray from the falls.

The first freezing rain event took place 4 Jan. 1993 between 0:30 h and 18:00 h. The temperature was close to the freezing point and rising. The freezing point was reached at 12:00 h and the temperature decreased again in the afternoon. Measurements give an icing load of 16 kg for the cable, corresponding to 140 g/m if the load is uniformly distributed. Unfortunately the ice did not stay long

enough on the cable to permit a corresponding estimate of the accretion thickness. The eight (8) IRM signals would give 80 g/m when using the conversion factor suggested by McComber et al. (1993). Figure 3 shows measurements recorded for this event.

The second event took place 23 Jan. 1993. There were 7 IRM signals and a load of 12 kg was measured, corresponding to about 110 g /m. Glaze remained on the cable until the freezing point was reached 26 h later. The conversion of the IRM signals gives 70 g/m. It should be mentioned that for Hydro-Québec, 7 IRM signals during an icing event constitute the minimum number of signals necessary to cause an icing alarm which translate to potential damage on their power transmission lines. As a basis for comparison, the design standard used by Hydro-Québec for ice loading of power transmission lines is 45 mm equivalent radial thickness on a 12.5 mm cable or 7.3 kg/m.

4. ANALYSIS AND SIMULATION OF THE BRIDGE ICING.

A simulation of the cable and bridge icing was performed. Since important parameters used in this simulation could not be measured, results are only approximate. However, the main purpose of these calculations is to establish a comparison between measured icing on the test cable and probable icing on the bridge structure. A certain number of assumptions explained below were necessary to compute the icing rate.

Most of the necessary equations to describe the physical process were taken from the review paper by Horjen (1983). The icing rate, kg/m can be found for a two-dimensional structure with the following equation:

$$\frac{\delta M}{\delta t} = 3.6 \, E \, w \, V \, D \, f \qquad (1)$$

In Eq. (1), E is the collection efficiency, w the liquid water content, g/m³, V the normal wind speed, m/s, D the accretion size, m, and f the icing fraction. The icing fraction is the fraction of the impinging water forming the ice accretion.

The ice load over a period can then be calculated by a time integration of the icing rate.

$$M_{i+1} = M_i + \frac{\delta M}{\delta t} \cdot \delta t \qquad (2)$$

The accretion size, D, in Eq. (1) becomes a feedback variable and a variable density should be used to determine the accretion diameter, D_i, at each time step (Jones, 1990). However, the comparison of cable and bridge icing was done for the respective icing rates.

In using these equations, one must make the assumption of steady state and average values used for the variables which is obviously a very wide assumption. Only the random spatial distribution of the liquid water content was considered.

Collection efficiency

The collection efficiency for droplet spray icing must be calculated, since it depends on wind velocity and accretion diameter. The collection efficiency is calculated from the consideration of droplet trajectories following the approach of Langmuir and Blodgett (1946).

The icing fraction, f, is evaluated from a heat balance on the surface of the ice accretion. The approach suggested by Horjen (1983) has been used in this paper. Only the significant terms of the heat balance are included. The heat resulting from the freezing of the ice must be transferred to the ambient air by convection and by evaporation and must warm the impinging water up to the freezing point. The frictional heating of the accretion by the air, the kinetic energy of the water droplet impinging on the accretion and the radiation heat losses are all considered negligible. The heat transfer by conduction to or from the cable is also negligible.

Droplet size

The droplet diameters are given by a probability distribution. However, the median volume diameter dvm can be used, this is defined as the diameter corresponding to the cumulative probability of 0.5 (Finstad et al. 1988). The dvm is better known for clouds. In the case of droplet spray the estimation of 70 μm dvm for droplet spray from waves was used (Finstad et al., 1988).

Liquid water content

This important variable is the most difficult to estimate. For in-cloud icing or freezing rain, an assumption of uniform liquid water content is usually made. In the case of the falls such an assumption cannot be made. The droplets are formed when the water hits a solid object, a rock or previously formed ice. It is carried afterwards by the wind, so that only droplets small enough to be carried will rise to the bridge level. Finally, the droplet cloud is quite limited in size. It can depending on the wind speed and direction move to the right left, up or down with respect to the cable centre. This droplet cloud is obviously much smaller in size than the cloud or fog that can be observed resulting from meteorological conditions.

First, the liquid water content is assumed to be approximately the same for the droplet spray cloud as that observed in clouds. Based on 577 observations taken over a 20-year period on top of Mt Washington, Jones (1990) estimated this liquid water content at w = 0.5 g/m³. Horjen (1983) estimates the liquid water content in an icing fog at ten times less: w = 0.055 g/m³. Since no measurements were taken, the highest value was chosen to be on the conservative side. Another problem with the liquid water content is the limited size of the spray cloud and its random flow direction. Based on visual observation at the site the droplet cloud size was estimated to be a rising column with a cross-section approximately 5 m in diameter. The intersection of the droplet cloud with the structure depends on many factors. The most important is the random wind direction, but also the location of formation of the droplets. Therefore a Gaussian distribution of probability for the intersection of the droplet cloud with different parts of the bridge was used to determine the local liquid water content.

For the bridge width, the assumption is made that 99.9 % of the liquid water content is distributed over the 112 m span of the bridge with the maximum probability in the center of the span. The standard deviation of the Gaussian distribution is:

$$\sigma_x = 112/6 \qquad (m) \qquad (3)$$

Vertically, with the assumption that the maximum probability is 12 m above the fall, the level of the future bridge, and that a height of 24 m intersects 99.9 % of the droplet flux from the droplet cloud.

$$\sigma_y = 24/6 \quad (m) \qquad (4)$$

therefore consider the maximum droplet flux to be in the center of the span. On the site, from visual observation it seems that the east side of the river is more exposed to prevailing winds. However, this was not measured and the cable icing was too small to permit a visual observation of a distribution on the cable.
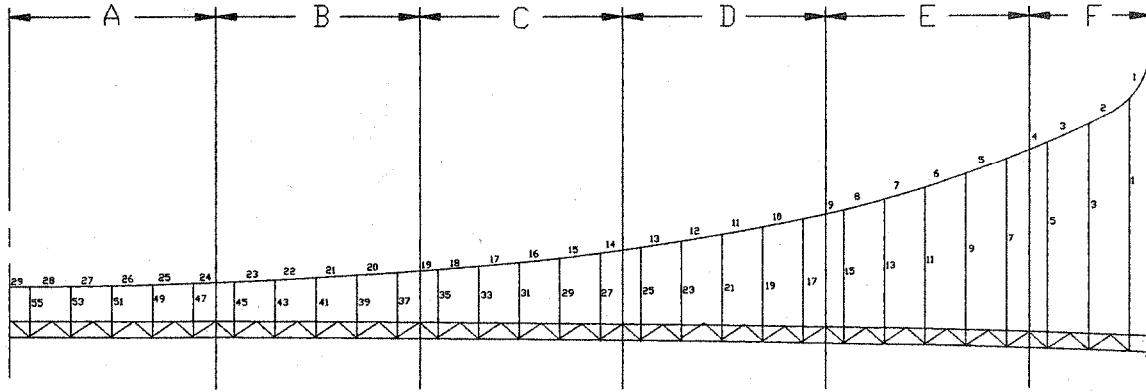

Figure 4 Division of the bridge into 6 parts for icing rate simulation

The average local liquid water content w_f is calculated for each window of the simulation of the different parts of the bridge. For a window of area A_f :

$$A_f = (x_2 - x_1)(y_2 - y_1) \qquad (5)$$

and the average liquid water content used in the simulation is :

$$w_f = \frac{w_p A_p}{A_f} \left[F(x_2/\sigma_x) - F(x_1/\sigma_x) \right] \left[F(y_2/\sigma_y) - F(y_1/s_y) \right] \qquad (6)$$

where F(z) is the Gaussian cumulative probability distribution.

In Eq. (6) w_p and A_p are the liquid water content (w = 0.5 g/m^3) and the droplet cloud area ($A_p = \pi 5^2/4$). The use of these assumptions results in the fact that 99.9 % of the droplet flux will intersect the bridge horizontally, but vertically the spray cloud can flow above or below the bridge so that the total probability is less.

These assumptions do not take into consideration the effect of the prevailing wind direction, and

Simulation results

The simulation was done for the 12.5 mm cable using an approximate two-dimensional profile of the bridge, shown in Fig. 4. Because of symmetry, the simulation was performed on half the cable and bridge, divided into 6 parts A to F, in Fig 4. In the case of the bridge each element in a part is considered to be a ribbon, with its width and length, or a cylinder, with its diameter and length. The resulting calculated icing load was summed on all elements for each part and summed again to find the results for the complete bridge. Table 1 summarizes results for each section and the total icing rate obtained for the cable and bridge.

This simulation was done for a normal wind velocity of 3.0 m/s or 10.8 km/h. In Table 1, the ratio between the calculated load on the bridge and the test cable is 4.402/0.0511 = 86.1. For example, a load of 5 kg is measured on the test cable it would correspond approximately to a load of 430 kg on the bridge structure.

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Table 1. Simulated icing rate for test cable and bridge

TEST CABLE			BRIDGE		
Sect.	w g/m³	icing load kg/h	Sect.	w g/m³	icing load kg/h
A	1.99E-2	0.0219	A	1.84E-2	1.9665
B	1.38E-2	0.0152	B	1.22E-2	1.3206
C	9.80E-3	0.0108	C	7.70E03	0.84454
D	2.35E-3	0.0026	D	1.78E-3	0.2003
E	4.70-4	0.0005	E	5.20E-4	0.0605
F	2.30E-5	0.00002	F	1.18E-4	0.0087
Total		0.0511	Total		4.402

5. DISCUSSION

Icing measurements

Results indicate that no significant ice accretion mass can be attributed to the droplet spray. On the other hand, from a thermodynamic analysis, it can be verified that droplets would be in a supercooled state when reaching the cable, so that it could be expected that an icing rate would be measurable. However, two conditions must be met in order to obtain significant ice accretions. First, the droplet must still be in the supercooled state when they collide with the structure, and second the cohesion of the ice formed must be high enough to permit a fairly solid and resistant accretion. Hence, one explanation for the small measured load might be that only very soft rime is formed and therefore it would continuously break and be shed from the cable.

However, the ice accretion from the droplet spray can be compared with the freezing rain icing obtained twice. In this case, the liquid water content is much higher and also the ice formed has a much larger density and cohesion permitting an accretion until the melting temperature is obtained.

Local liquid water content

The droplet spray from the fall forms a spray cloud which has a random direction resulting from the wind. When the wind blows from the St Lawrence, the droplet cloud is in the direction of the test cable. However, when the probability of intersection with a part of the bridge is taken into consi

deration, the droplet flux and the average local liquid water content is much smaller than would normally be found in a uniform cloud.

Supercooled droplets

Observations show that the droplet spray might either form supercooled droplets or ice crystals. This can be observed, by the small ice hill formed at the foot of the fall which is called an "ice loaf" . This small hill is formed largely of ice crystals. So it is possible that the droplet might freeze before making contact with the structure and therefore in such a case would not stick on the structure.

Type of ice formed

The density of the atmospheric icing formed is very important for the cohesion of the ice accretion and therefore for the resulting total ice load. The type of ice formed for a low water content, with a low average wind speed and low temperature is a very soft rime. Calculations based on the heat balance for a spray droplet and following the approach suggested by Personne (1989), have shown that typically a droplet has time to freeze before the next droplet hits the same spot. In such a case a very soft rime of feather type would form. However, in the case of a flexible structure such as a cable, it is easily broken, shed and does not accumulate enough to become a hazard.

On one occasion however, it was possible to observe on the cable a visible amount of soft rime caused by the droplet spray. On this occasion, one IRM signal was recorded. This very soft rime disappeared rapidly, either broken by the wind or sublimated by the combined effect of the sun and wind.

Recommendation for the bridge design

Following this research project, it was recommended to the engineering firm responsible for the design to consider as negligible the added amount of rime resulting from the presence of the fall and therefore to base the design on the usual load limits for wind and ice loading of the structure in the Québec area.

6. CONCLUSIONS

1- Measurements of ice loading on an instrumented cable across the river show that the icing due to the spray cloud from the falls is small. An ice mass of less than 5 kg was measured on the load cell and the IRM has measured only isolated signals. However, on two occasions more significant loads from glaze icing were recorded on the load cell as well as with the IRM.

2- The droplet spray from the falls forms a spray cloud which depending on the wind takes a direction given by a statistical distribution. When the wind blows from the St Lawrence, the droplet cloud is in the direction of the test cable. However, when the probability of intersection with a part of the bridge is considered, the droplet flux and the average local liquid water content is much smaller than would normally be found in a uniform cloud. This reduces significantly the icing rate.

3- A numerical simulation for the icing rate yields an icing rate of 50 g/h for the total of the cable, which corresponds to the right order of magnitude, even if conservative estimates were used for the parameters. This simulation gives a comparison of the icing rate calculated for elements of the test cable and of the suspended bridge. The icing on the bridge structure in 86 times the icing of the single cable for an icing rate of 4.3 kg/h, with half this amount in the central part (20 m).

4- The type of ice formed with a low average water content and low wind speed is a very soft rime. This type of rime is easily broken, especially on a flexible structure such as a cable and hence does not usually permit accretions large enough to create a hazard for the structure.

5- The major hazard from an icing overload on a structure requires the ice accretion to have the cohesion that is usually found in glaze and wet snow. This was verified twice by glaze accretions from freezing rain that resulted in ice loads that were three times greater than those caused by the droplet spray cloud.

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