Gate failure, numerical and physical modelling at Gouin dam

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Abstract

Gouin dam is the main structure on the Saint Maurice river. A gate failure in 2002 prompted this study. Over the years, many modifications and attempts to correct the problems and obtain smooth operation of the bottom outlets were carried out, but with limited success. The numerical results gave a good representation of the flow conditions in the zone of pressure flow before the separation and free surface flow zone but in this latter regime the results were less satisfactory. As a result, a new physical hydraulic model was requested and built. The solution retained has significant advantages when compared to the previous one. In summary, the numerical simulation, due to the power of a strong graphics display, allowed a good preliminary evaluation of the problems. However, a physical model was an essential tool in studying aspects such as air-water mixture and the free surface instability as well as giving information on the vibration and cavitation problems associated with the interaction of high velocity flow and the gate structure. A final solution was found.
Keywords: gates, separation, vibrations, cavitation, dams, sluice, physical and numerical models.

1 Introduction

Bottom gates are very often located at sites where difficult flow conditions are present. High pressures and velocity, excessive turbulence and aeration need to be considered in their design. A poor concept can lead to gate vibrations that can lead to gate failure. For the case of high pressure bottom gates the standard design is of two types: the first one, the gate is on the upstream face of the dam.

In the second one, the tunnel type, the gate is placed in the tunnel where upstream and downstream of the gate stable conditions of flow exist.

Unfortunately the Gouin gate does not fit any of the two standard designs indicated above. We do not know the reason why the designer did not follow a more secure approach. Maybe it was the fact that the gate was just moderately high head since the maximum operating head over the gate never exceeds 25 meters or at that time, 1917, the technique was not defined (Naudascher et al [1]).

The fact is that the original design is a kind of hybrid between the two standard types. This causes a problem since we have the separation point jumping from the gate to the limit of the mask wall of the gate well depending on the flow and opening conditions at the gate outlet. Even if today the gate is equipped with air vents to limit the cavitation and vibration problem those vents were added later around 1930 during refurbishment to improve the operation of the gate. We do not know if air availability (Ismail [2]) as provided by the vents is good enough.

With the actual design the gate well also participates in the aeration process, finally with respect to the gate failure as one can see on figure 1, the cross bottom beam was torn apart due to the separation and reattachment of the free streamline causing the vibrations and solicitations on the gate structure. Information relevant to this aspect of the problem is found in Kolkman [3], Naudascher [4] and Wang and Naudascher [5].

2 Context

The Gouin dam is located at the outlet of Gouin Reservoir, approximately 400 km from the city of Trois-Rivières, Québec. Built in 1917, the development consists of a concrete gravity dam, a free surface spillway and ten bottom outlets which release flow to the St. Maurice River downstream.

During a period of many years, Hydro-Québec personnel have experienced problems operating the bottom gates. Severe gate vibrations at large gate openings have led to restrictions on operations, limiting their flow capacity to approximately half.

In 1999, the first recent model study was carried out. The solution coming out of this study was implemented on gate 8. Eleven months later, during an inspection with bottom outlet no. 8 dewatered (Figure 1), it was observed that the horizontal beam near the bottom of the gate had failed. This failure prompted the present study.

The first physical model study showed that the outlet intake geometry was one of the reasons that the gates vibrated. Figure 2 shows the intake of the outlet as it was prior to the study. The following modifications were implemented to correct the problem: (a) elimination of the upstream beams, (b) raising the elevation of the upstream wall of the gate well, (c) filling part of the upstream gate slot and (d) adding a concrete block in the gate well to damp water level fluctuations. All these changes are indicated as black filling on figure 2.

The upstream wood beams had no real structural importance: these beams were redundant. The removal of the beams resulted in a more uniform flow and less turbulent profile and a reduction in gate vibrations.

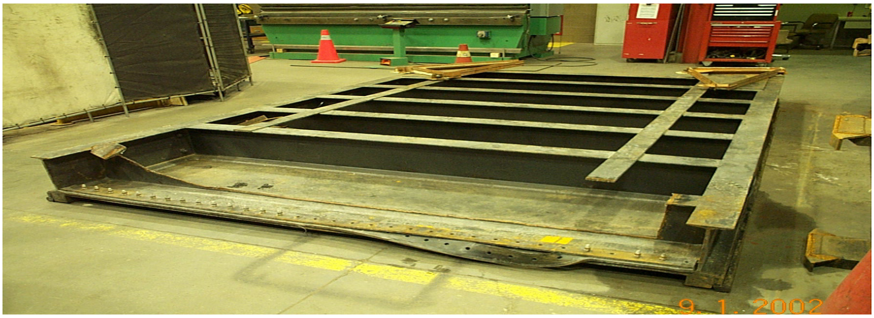

Figure 1: Failed dewatered gate.

Following the (a) modification, a well defined spring point was established at the upstream edge of the gate well mask wall. Downstream of this point the flow occupied approximately half of the outlet cross section. To increase flow capacity, the mask wall was raised so that the flow filled almost the full section.

With this (b) modification, flow capacity increased from 95 m^3/s to 124 m^3/s, but resulted in less uniform flow and depending on the gate opening, two possible separation points; one at the lip gate and the other at the edge of the upstream mask wall.

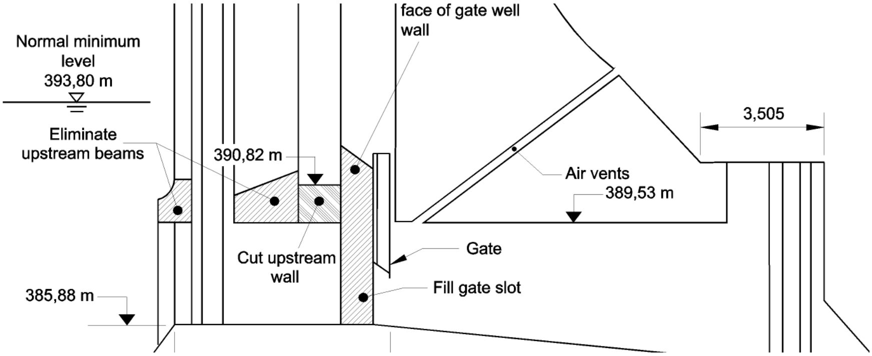

Figure 2: View of gate outlet with gate partially closed.

The (c) modification consisted of reducing the width of the gate slots. Initially, the gate slots occupied the full length of the gate well. When the high velocity jet entered the gate well, it was redirected vertically after hitting the downstream face of the slots, forming large rooster tails. These rooster tails, situated in the same direction as the course of the gate, were in part responsible for the gate vibrations.

The final modification consisted of installing a concrete block in the gate well, the block, which acted as a flow throttle, reduced water level fluctuations in the gate well from 3 m to 5 m. The proposed modifications significantly reduced the pressure fluctuations that were causing the gate to vibrate. The later failure of the gate was the object of the present study and this paper. Since a physical model was already done, the first move was to verify by numerical model the condition leading to the gate failure, what is described in the following chapter.

3 Numerical modelling

The numerical model to predict the flow field close to the gate of the dam was carried out using Phoenics [6], as a preliminary exercise by the second author in view of awarding a research contract if the preliminary results were conclusive.

Phoenics [6] is a commercial CFD (Computational Fluid Dynamics) code based on the finite volume method. After concluding that the two-dimensional model could produce a reasonable flow field prediction, the initial outlet configuration was modeled with all the obstacles in place (original gate layout), as shown on figure 2. . This model confirmed the 1999 study by Villeneuve [7], and showed the overriding influence of the wood beams, previous (a) modification, on blocking and generating an uneven and skewed turbulent flow. Figure 3 presented below shows the distortion on the flow field caused by the beams, on 2D model. Even with preliminary results, the distortion on the flow caused by the transversal beam is very important. The flow reaching the gate will never be as predicted by the design of the outlet because of the obstacles presence.

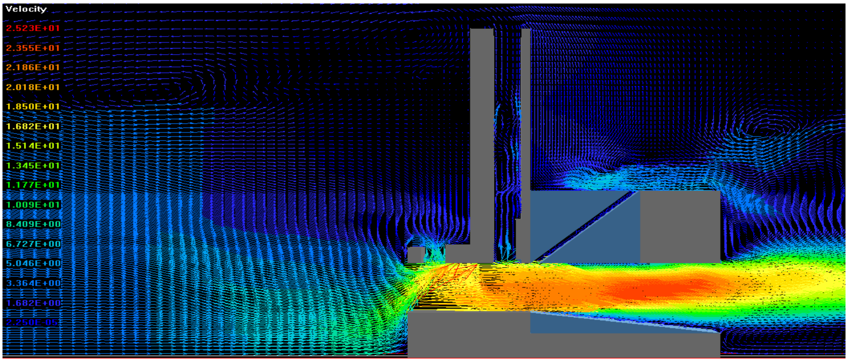

Figure 3: 2D velocity field for the outlet without any modifications; gate completely open.

These results validated the conclusion of the 1999 study by Villeneuve [7] concerning (a) modifications. To further verify the study results, we set up a 3D numerical model of the outlet to see if any clue concerning the failure of the gate could be obtained. The outlet is modelled with a three-dimensional technique incorporating all modifications from the 1999 study by Villeneuve [7].

The model is implemented using the Cartesian coordinate system. The geometry of the dam structure and the gate was imported into the domain as solid blocks

from AutoCAD. These blocks are recognized in the model as solid boundaries.

To achieve a more reliable prediction of the flow field at the curved boundaries and to reduce the effect of 'stair-stepping', a denser grid was provided close to the solid boundaries. In addition, the grid cells were concentrated at the water passage to capture the dynamics of the flow passing under the gate at high velocity.

The time step of the simulation was set to satisfy the condition of Courant number less than 1.0.

Some of the simulation results from the three-dimensional model are presented.

The grid dimension of '104 x 40 x 56' cells was used to discretize the physical domain dimension of 80.0 m x 20.8 m x 30.0 m. Figure 4 shows the predicted free surface and velocity fields for the case when the gate is fully open.

The results show that the model is capable of predicting the gate-water interaction in general. However, the model also shows a limited capability predicting the water and air interface precisely, particularly involving the cavitation phenomenon and flow separation streamline.

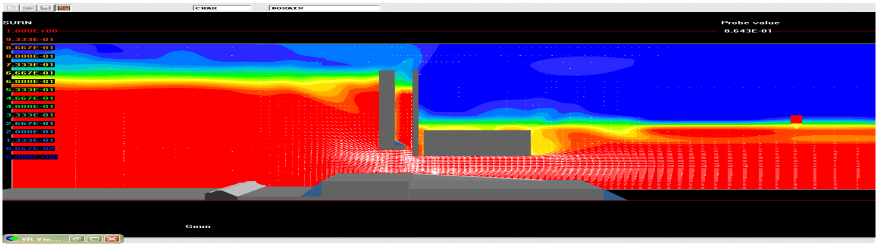

Figure 4: 3D free surface and velocity fields at middle section.

3.1 Remarks

In spite of the numerical effort, we could not determine the reason for the failure of the gate from the numerical model studies, even using 3D. The reason was that we were not able to replicate the results of the 1999 physical model study by Villeneuve [7] because the behaviour of the free surface streamlines is of paramount importance with respect to finding a solution to the problem. The flow oscillations in the gate well and the mixed water surface composed of air and water was beyond the capability of the 3D model approach, as well as the behaviour of the flow at gate lip. From the post-mortem analysis of the gate it was evident that only violent pressure fluctuations could provoke such damage.

Concerning the inability to operate the gate, the oscillation of the separation point from the gate lip to the mask wall was also a factor that contributed to the failure. This effect will be less important since the modification following the 1999 study by Villeneuve [7]. For the above reasons it was concluded that the preliminary numerical modelling effort was inadequate and provided an insufficient basis to proceed further to define the final design of the gate outlet, a physical model was again recommended

4 Physical modelling

The model was constructed, Holder et al [8], in a glass walled permanent flume at the LaSalle Consulting Group's laboratory in Montreal, Canada. A model scale of 1:20 was selected to ensure that air entrainment was adequately reproduced. The model consisted of a representative slice of the dam containing one bottom outlet. The dam and outlet were constructed out of clear acrylic plexiglas (Figure 5) so that flows in the model could be followed using red dye tracer. Water levels and pressures were measured in the model at the locations shown in Figure 6.

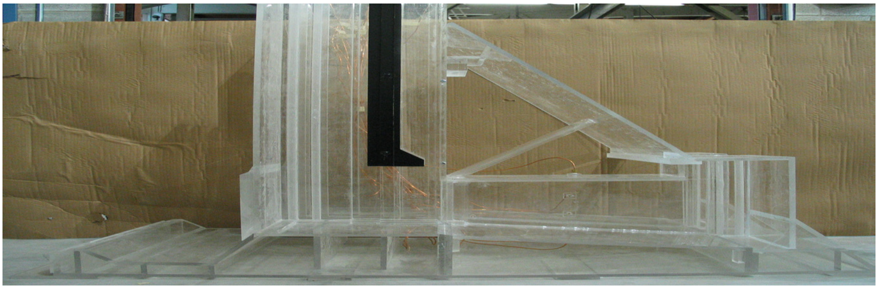

Figure 5: The model.

In order to study the influence of the gate geometry on the pressure fluctuations acting on the bottom of the gate, two different types of gates were tested and the results compared. The first gate tested was the gate that failed, this gate had no upstream skin plate and the cross beam members were exposed.

The knife edge consisted of the projection of the downstream skin plate below the bottom cross beam. The second was the gate installed in the other outlets, equipped with an upstream skin plate and 45˚ knife edge. The mean pressure as well as pressure fluctuations were obtained from pressure taps installed in the lower beam of the gate that failed and the 45˚ knife edge of the second gate tested. The results showed that the gate with the 45˚ knife edge was subjected to a higher uplift pressure and lower pressure fluctuations than the failed gate.

However, even though the other nine outlets had a 45° knife edge they had not been modified and could still not be operated over the full range of gate openings.

With the gate that failed, the spring point was unstable and the flow control was jumping between the upstream beam flange and the gate lip, as predicted by Naudascher [4] and Wang and Naudascher [5]. The resulting pressure fluctuations that developed along the lower face of the web of the beam were responsible for the failure of the gate.

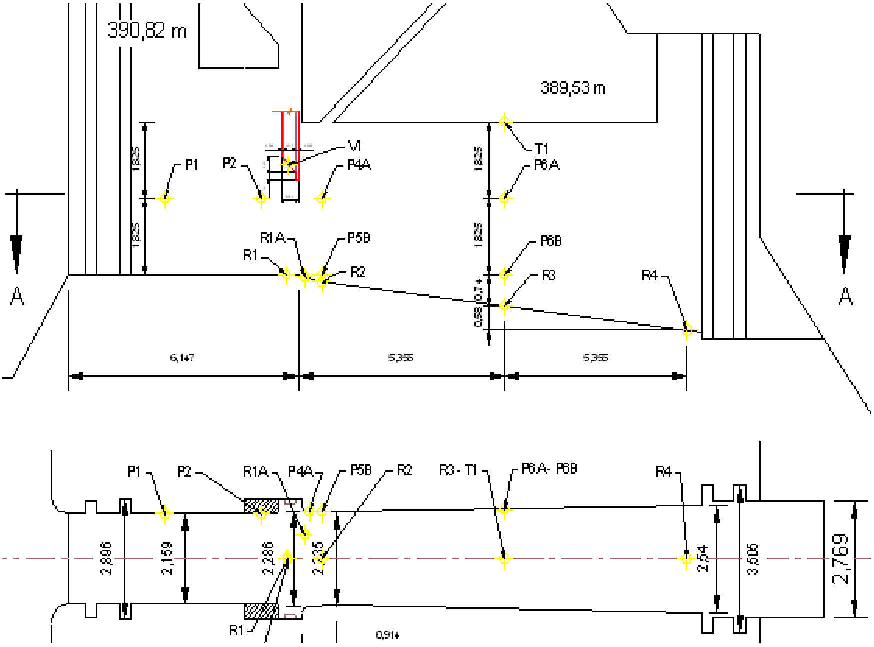

Figure 6: Pressure tap locations.

To reduce the risk of negative pressures and cavitation, on a previous retrofitting, around 1930, three air vents were added to each outlet, venting to the atmosphere on the downstream side of the dam, to supply air to the back of the gate. Venting was also provided when the downstream water level was below the roof of the outlet, but this did not happened for all flow conditions.

For the majority of gate openings, the air vents were shown to have no effect on the mean pressure at the knife edge. However, for gate openings greater than 85%, the pressure dropped when the vents were closed.

The only impact that the drop in pressure had on the gate with an upstream skin plate and 45° knife edge was that the flow capacity increased and the uplift on the gate decreased. However, in the case of the gate in bottom outlet number 8, the gate that failed, the force acting on the lower beam increased.

Pressure fluctuations were also found to be influenced by a lack of aeration, maximum pressure fluctuations on the model increased from ± 2.5 m with the air vents opened to ± 5.5 m with the air vents blocked.

Figure 7 shows the effects of the air vents on the pressure fluctuations at different gate openings.

4.1 Operation of the gate under just submerged conditions

When the gate is fully open, the flow is controlled upstream of the gate with the spring point of the jet located at the upstream corner of the gate well wall. In the first model study, the elevation of the spring point was set such so as to maximize flow capacity. However, due to flow fluctuations, the upper nape of the free surface jet can hit the lintel, choking off the air supplied via the air vents to the back of the gate. Even when the jet just cleared the lintel at the outlet of the gate well, little space was left for the air to pass from the air vents downstream to the gate well. As a result, air was supplied to the high velocity free surface jet via the gate well shaft. This situation is undesirable and should be avoided as much as possible. Fluctuations measured at the gate knife edge are presented in figure 7. The 2000 inset on figure 7 refers to the 1999 model by Villeneuve [7].

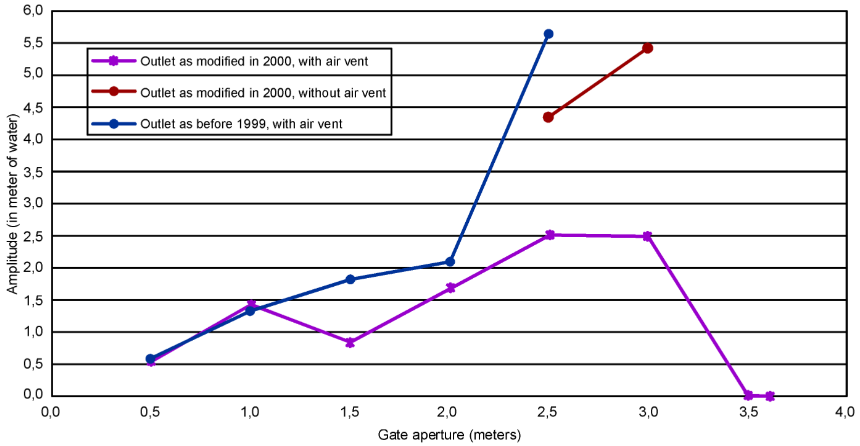

Figure 7: Pressure fluctuations at gate knife edge.

It should be noted that the combined effect of a slightly submerged gate and blocked air vents produce a highly undesirable situation (Figure 8). Pressure fluctuations are up to ten times higher than what they would be under normal operating conditions. In addition, the high intensity and unstable jet occasionally impacts on the upstream side of the gate, inducing additional vibrations.

4.2 Final solution definition

The previous results showed the importance of providing an adequate air supply to the gate. It was also shown that the gate should not be just immersed in the flow but either opened fully or adequately submerged. However, both of these requirements were problematic because of the draft of cold air with the gate fully open, the reduced flow capacity with the gate submerged and always the poor definition of the free surface caused by the abnormal length of the gate well.

Figure 8: Slightly submerged gate and blocked air vents.

The (b) modification rising of the mask wall edge increases the flow but also turbulence, making the shift of the spring point from gate to the mask wall more problematic. For that reason a solution with a more uniform flow distribution was sought. The solution is depicted on figure 9.

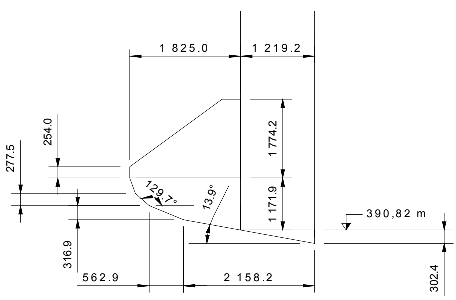

Figure 9: Retained solution for intake geometry.

To overcome these problems, modifications to the intake geometry were realized as follows.

Several parabolic intake profiles were tested in the model with different horizontal and vertical aspect ratios. The profile adopted consisted of a parabolic curve approximated by a series of five straight lines (figures 9 and 10). To maintain a well defined and stable jet, the last straight line was extended under the mask wall of the well. This approach with the rounding of the flow entrance reduced the problem but the length of the well still allowed the upper nape to oscillate and created a poorly defined free surface. Since convergence is always paramount to stability as far as flow is concerned, a slight convergent straight line was added to the bottom of the mask wall to stabilize the jet. The resulting smooth free surface (figure 10) jet dipped well below the lintel, removing the gate lip from the zone of turbulence and allowing air to reach the back of the gate. Air was no longer being supplied via the gate well shaft.

Tests carried out on the model showed that the air vents could supply the increased air discharge without exceeding the normally accepted velocity criteria of 45 m/s. The maximum flow capacity with the gate fully open was slightly reduced from 124 m^3/s to 118 m^3/s.

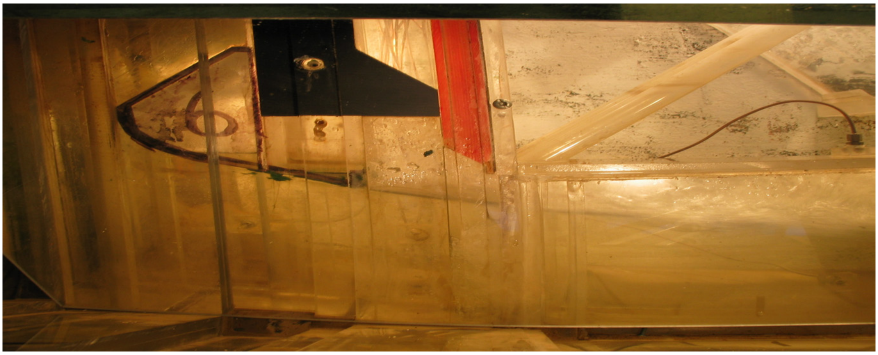

Figure 10: Final solution retained.

5 Conclusions

The problem with the operation of the Gouin bottom outlet gates and the subsequent gate failure is that they do not conform to a standard design; the length of the gate well is too big.

The solution retained provides a stable solution for all possible configurations of discharge and gate openings at minimum cost.

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