Sluiceway Deflector Design as part of the Boundary TDG Abatement Program

by

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ABSTRACT

The high pressure sluice gates at the Boundary Project have been modified to accommodate throttled flow by addition of steel deflector plates at the sluiceway exit to direct flow away from the gate slots to prevent damage to the gate system.

Boundary Dam is the City of Seattle, Seattle City Light department's (SCL) major hydroelectric generating resource. Facilities include a 340-foot high concrete arch dam, two spillways, seven low-level sluices through the dam, and a 6-unit powerhouse with 1,040 MW capacity. Air entrained in the spillway flow plunges to depths of over 100 feet in the tail water, driving generation of excessive total dissolved gas (TDG). In support of their license application, SCL is investigating ways to mitigate the generation of TDG in the project tailrace during flood passage.

The sluice gates are under a head of approximately 190 feet. The sluice gates are fixed-wheel gates, 17ft wide by 21ft high, operated by cable hoists. The sluice gates were designed and constructed to operate either fully opened or fully closed. A TDG mitigation option is to operate a number of sluice gates in a throttled position that reduces the plunge depth of water entering the plunge pool. Testing of the sluice gates in the throttled position has led to damaged gate slot heater covers due to exit flow impinging on the gate wheel slots. Further testing of this potential TDG mitigation was halted until a means of preventing flow into the gate slots was found.

Major components of the work under this project include:

- *Computational fluid dynamic testing to model flow, loading and hydrodynamic effects;*
- *Structural design accommodating the sluiceway geometry and gate seals;*
- *Fabrication of the deflectors;*
- *Field adjustment and installation into the sluiceway, directly welding to the steel lining;*
- *Testing to confirm the reduction of side spray when the gate is in a throttled position; and*
- *Operation of the sluice gates in the throttled position to test TDG performance.*

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INTRODUCTION

The City of Seattle, Seattle City Light department (SCL) recently received a final, new FERC license (FERC 2013) for the Boundary Hydroelectric Project (Boundary Project) initiating new license implementation activities including water quality improvement measures. The Pend Oreille River has a total maximum daily loading (TMDL) for total dissolved gas (TDG). TDG is the amount of air held in saturation in the water and is quantified in the standards in terms of percent of saturation pressure relative to ambient barometric pressure. A TDG Attainment Plan (which is part of the new license) describes the proposed process for complying with the 110 percent TDG saturation standard. SCL is required to identify all "reasonable and feasible" (Ecology 2005) improvements that could be used to meet the state of Washington's 110 percent TDG saturation standard by evaluating operational and/or structural modification alternatives at the Boundary Project. The standard is waived for conditions where incoming TDG is greater than that leaving the project and for flow exceeding the 7-day, 10-year (7Q10) flow event, which is 108,300 cubic feet per second (cfs) for the project (SCL 2006).

Development of one of the simpler structural mitigation alternatives for TDG has proven to be more complicated than expected. This paper describes the process that resulted in design and installation of deflectors in the sluiceways and demonstrates the complex interactions involved with alternatives that use structural and mechanical systems to address a water quality issue.

THE PROJECT

The Boundary Project is located on the Pend Oreille River in northeastern Washington State, one mile south of the Canadian border, as shown in Figure 1. The Boundary Project is the third of five dams on the Pend Oreille River. Seven Mile and Waneta dams are located downstream in Canada. Box Canyon Dam is immediately upstream of the Boundary Reservoir, and Albeni Falls Dam is 50 miles farther upstream near Newport, Washington.

The Boundary Project, shown in Figure 2, consists of an arch dam, reservoir, and underground powerhouse. Boundary Dam is a variable-radius concrete arch dam with a structural height of 340 feet, a crest length of 508 feet, and a total length of 740 feet with both spillways. The gross head of the project for power generation purposes is 261 feet. On each abutment there is a 50-foot-wide spillway with a 45-foot-high radial gate. The two spillways have a combined total maximum discharge capacity of 108,000 cubic feet per second (cfs). In addition, there are seven low-level sluices through the dam under a head of 190 feet that provide 252,000 cfs of capacity. Boundary Project powerhouse flow capacity is approximately 55,000 cfs, through six generating units, Units 51 through 56 (two equipped with 200-MW Francis turbines and four equipped with 160 MW Francis turbines). Flows through the Boundary Project powerhouse discharge into the tailrace immediately below the dam. The Boundary Project operates in a load-following mode, generating power during peak-load hours and curtailing generation during off-peak hours.

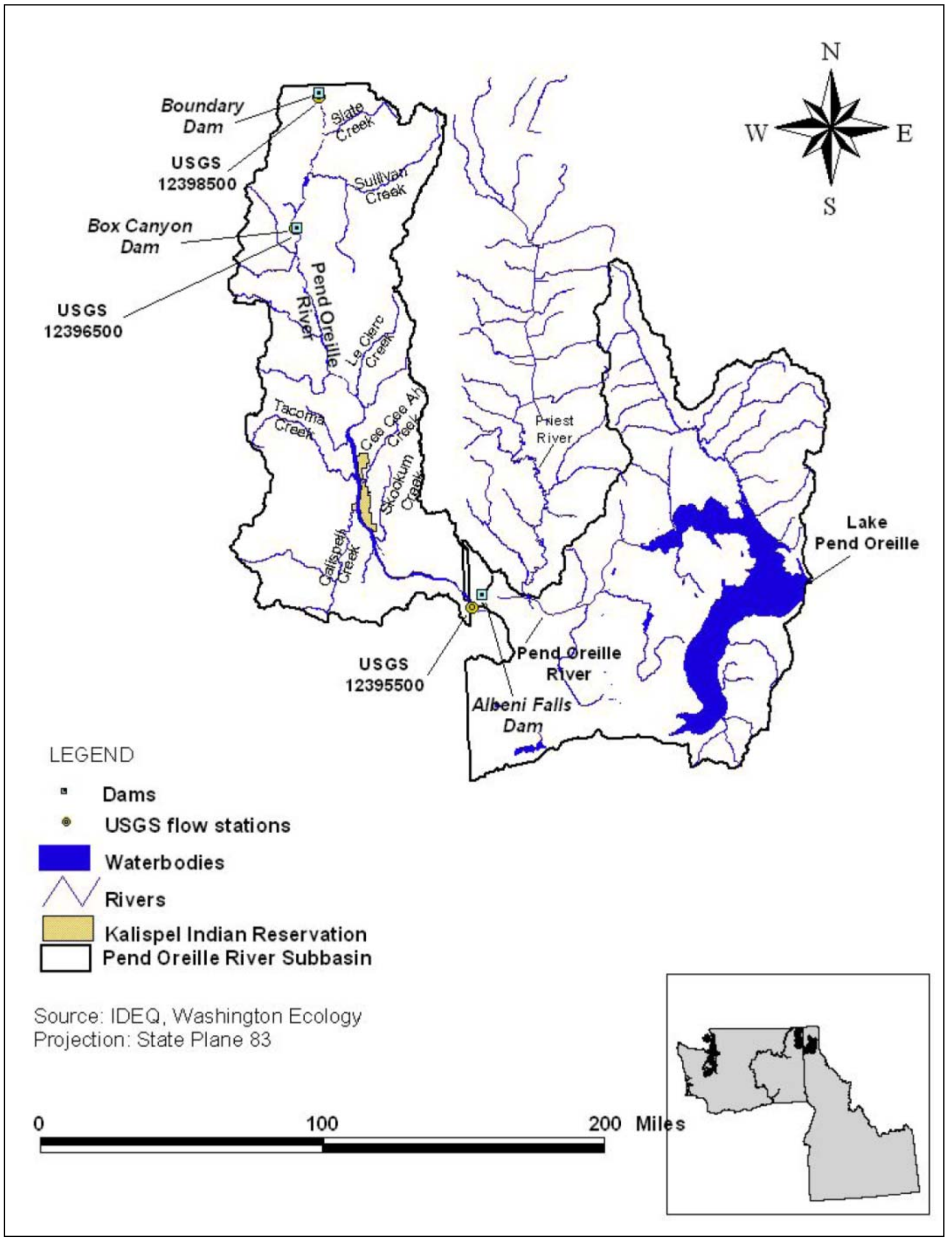

Figure 1. Boundary Project Site Map

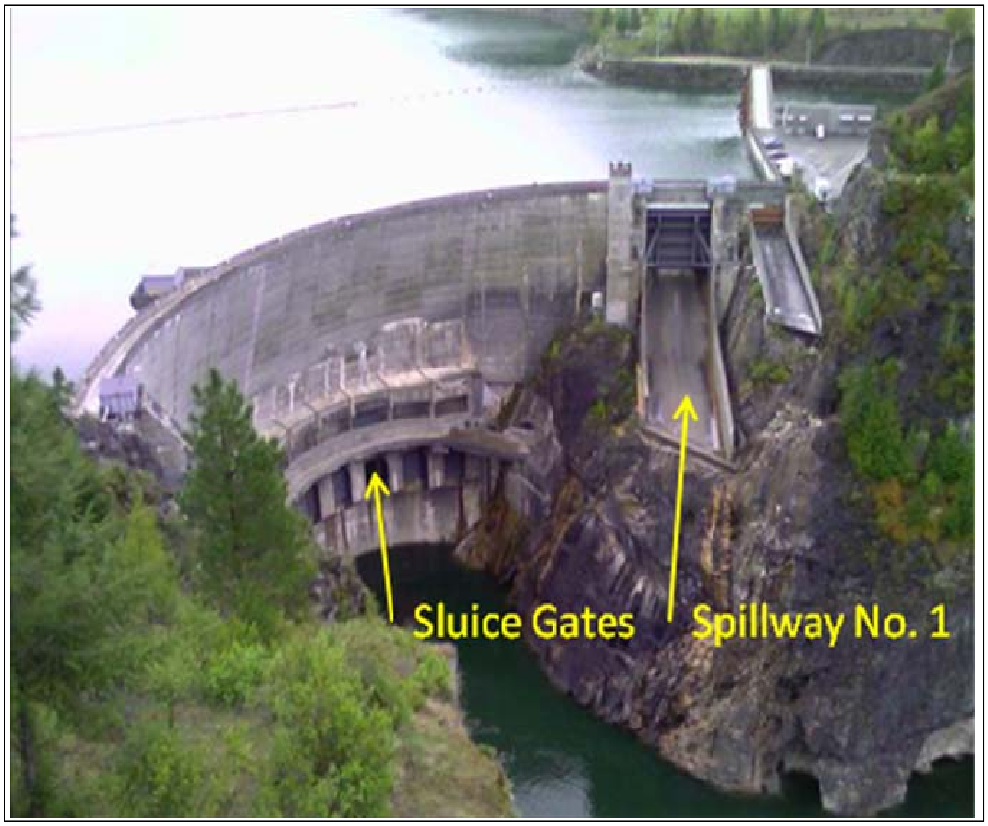

Figure 2. Boundary Project Overview

TDG PRODUCTION AT THE PROJECT

High TDG concentrations at the Project during spill are caused by the configuration of the project spillways. Flow is released into the air as a jet; this jet entrains a substantial quantity of air as it falls. This air is carried deep into the plunge pool by the jet, the air goes into solution in the water at depth and returns to the surface with a high TDG content.

Studies of TDG operational changes and structural modification alternatives have been going on for several years and are continuing. These studies included testing of various gate operations during spill in combination with physical and numeric modeling. Three primary alternatives, listed below, were selected for more detailed examination.

1. Throttle Sluice Gates, which involves modification of the sluice gate sealing system so they can be operated in partially open positions (see Figure 3).
2. Roughen Sluice Flow, which entails modification of the sluice gate outlets to break up and spread flow.
3. Spillway Flow Splitter/Aerator, which entails modifying the spillways to aerate, break up, and spread flow.

This paper describes the series of events and adventures associated with the first of these alternatives, which is to modify the Sluice Gates to allow operation with the gates partially open, allowing “throttled” flow and break up of the jet, which reduces plunge and thus reduces TDG.

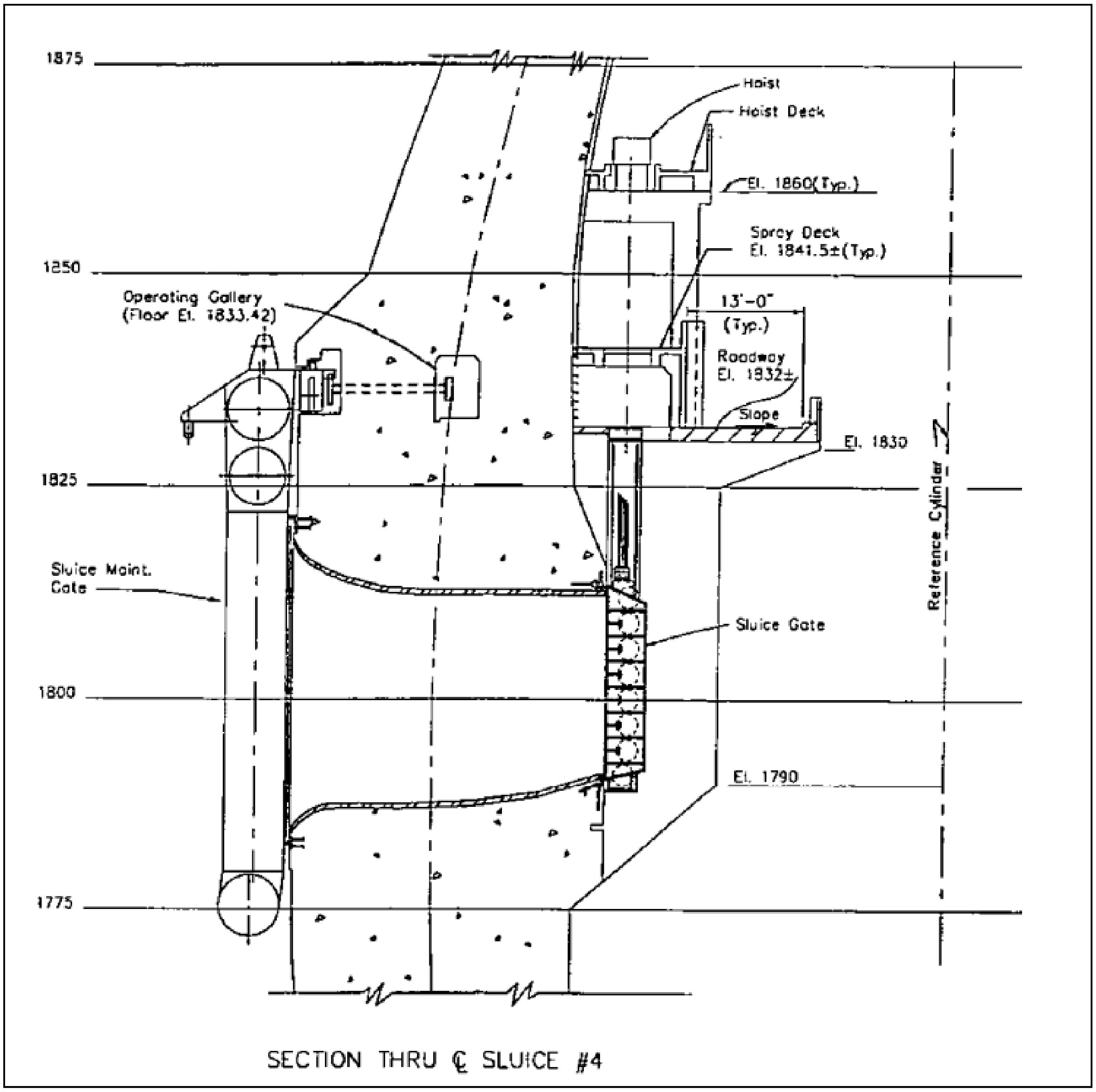

Figure 3. Section Through Sluice Gate

BUMPS IN THE ROAD

Dam Safety Concerns

As part of the regularly scheduled FERC dam safety inspection, the operation of the sluice gate in throttle position was considered as a potential failure mode (PFM) due to reports of perceived vibration during operation.

The failure mode was considered as a Category II failure with no monitoring required. Category II - Potential Failure Modes are termed “Considered but not Highlighted”. These are judged to be of lesser significance and likelihood. However, even though these potential failure modes are considered less significant than Category I, they are also described and included with reasons for and against the occurrence of the potential failure mode. The reason for the lesser significance is noted and summarized in the documentation report or notes. The notes mention that the use of gates to throttle flow is discouraged. The possibility of an operational method of avoiding the failure mode may have contributed to the hazard classification as Category II instead of Category I. This is significant as throttled operation of the sluice gate is integral to two of the TDG abatement alternatives currently being developed.

The full extent of mechanical, structural, and hydraulic analysis on the sluice gate as part of the TDG program was not considered prior to the PFMA.

Sluice Gate Closing Issues

The sluice gates have been throttled during three spill seasons (2006, 2008, and 2009). No sluice gate testing was performed in 2010 with the exception of load cell testing during May and June of 2010. There were some tests of a fully open Sluice Gate 4 in 2011, and no sluice gate testing in 2012. In 2006 Sluice Gates 3, 4, and 5 were throttled for a total duration of approximately 36 hours each. In 2006, problems were identified when closing Sluice Gate 4. The problem was identified as broken welds in the sluice gate heater slots.

In 2008, an improved welded design was applied on the gate slot heater covers for Sluice Gate 4. Gates 2 and 6 had their gate slot heater covers removed for throttle testing to avoid problems. In 2008, Sluice Gates 2 and 6 were throttled for a total of 64 hours and Sluice Gate 4 was throttled for a total of 401 hours (16.7 days).

During testing on June 19, 2008, problems were identified when closing Sluice Gates 2 and 6. These gates had not yet been modified with seal plates, and the gate slot heat covers had been removed. An unusual noise was reported from Sluice Gate 4, and problems were also identified with closing Sluice Gate 4. At this point, all further testing was cancelled. Details of the sluice gate slots are shown in Figure 4.

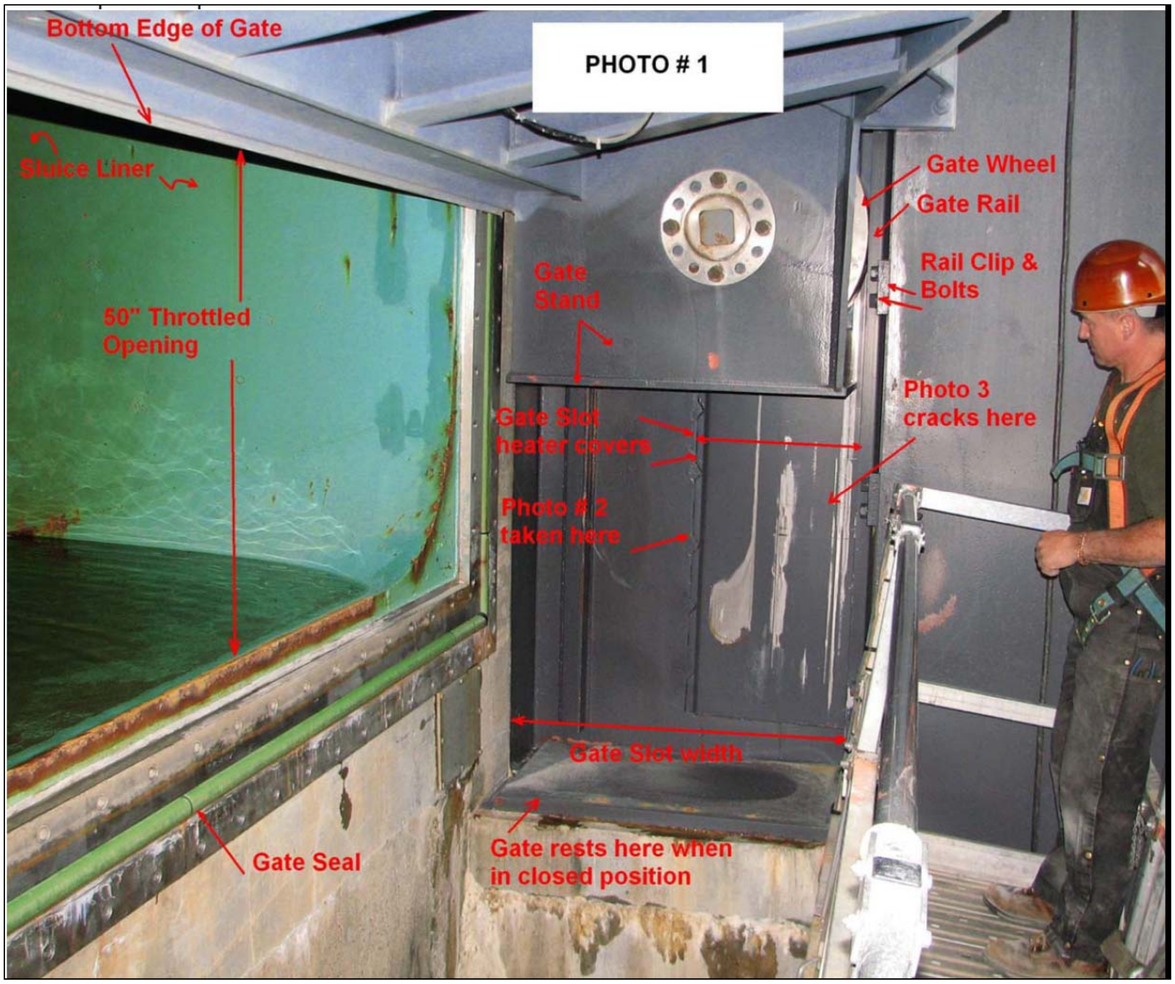

Figure 4. Details of Sluice Gate Slot

Inspections identified that the Sluice Gate 4 gate slot heater cover welds had failed, which explained the trouble with closing. Sluice Gate 6 was also inspected and no problems could be identified as to why it would not close.

Sluice Gate 4 was to be the only gate used in the 2009 testing plan. The gate slot heat covers were removed, and the gate was inspected prior to testing. Gate 4 performed nine tests and had difficulty upon closing after the last test. Each test's duration was four hours in length, for a total of 36 hours of throttled operation.

A detailed visual inspection of the gate, gate guides, gate slot, and seals was performed. No explanation for Gate 4's inability to close could be identified. A detailed examination of the gate slot and guides for evidence of debris revealed no evidence. All paint scrapes were compared to pre-testing photos, and all visible paint scrapes had existed prior to the 2009 throttle testing. Photos were reviewed of the discharging jet of water from the gate when the gate was not closing properly. The flow patterns and spray of water were normal. It is considered unlikely that large debris was holding the gate open. It is possible that a small piece of debris wedged within the gate slot and prevented the gate from lowering, but it is unlikely debris would have remained through three cycles of the gate opening and attempted closing. No obvious external cause was uncovered for the gate's closure issues.

INVESTIGATIONS OF THE GATE SYSTEM

Sluice Gate System

A series of analyses were initiated to investigate potential causes of the gate's closure issues associated with the mechanical systems. The sluice gates are fixed-wheel gates, operated by cable hoists. The mechanical systems include the gate hoist, cables, gate wheels, rails, gate seal, and gate seal heaters and gate slot heaters.

The following analyses were undertaken on the sluice gates:

- Hoist operations including load cell tests were performed and the measured data integrated in analysis of the hoist system;
- Roller friction;
- Fatigue due to pressure fluctuations; and
- Measurements of the gate position and alignment (metrology).

Hydraulic modeling of the sluice gates has been performed using both physical and numeric modeling techniques. The physical models are:

- Current (active) Alden 1:25 model; and
- Original Albrook Hydraulic Laboratory (1963) 1:65 scale general model. This model was used to develop rating curves for the sluices and spillways.

Computational fluid dynamics have also been applied to develop a detailed examination of the expansion of flow as water exits the sluice gates as well as examination of the throttled jet as it interacts with the plunge pool.

Hoist Operation

The hoist capacity to raise and lower the gate was examined. SCL collected load data in May and June of 2010. Data were analyzed to extract the actual gate weight, the coefficient of friction in the wheel bushings, and other unknown vertical forces acting on the gate (see Figure 5). Hoist system analysis was updated to reflect load tests.

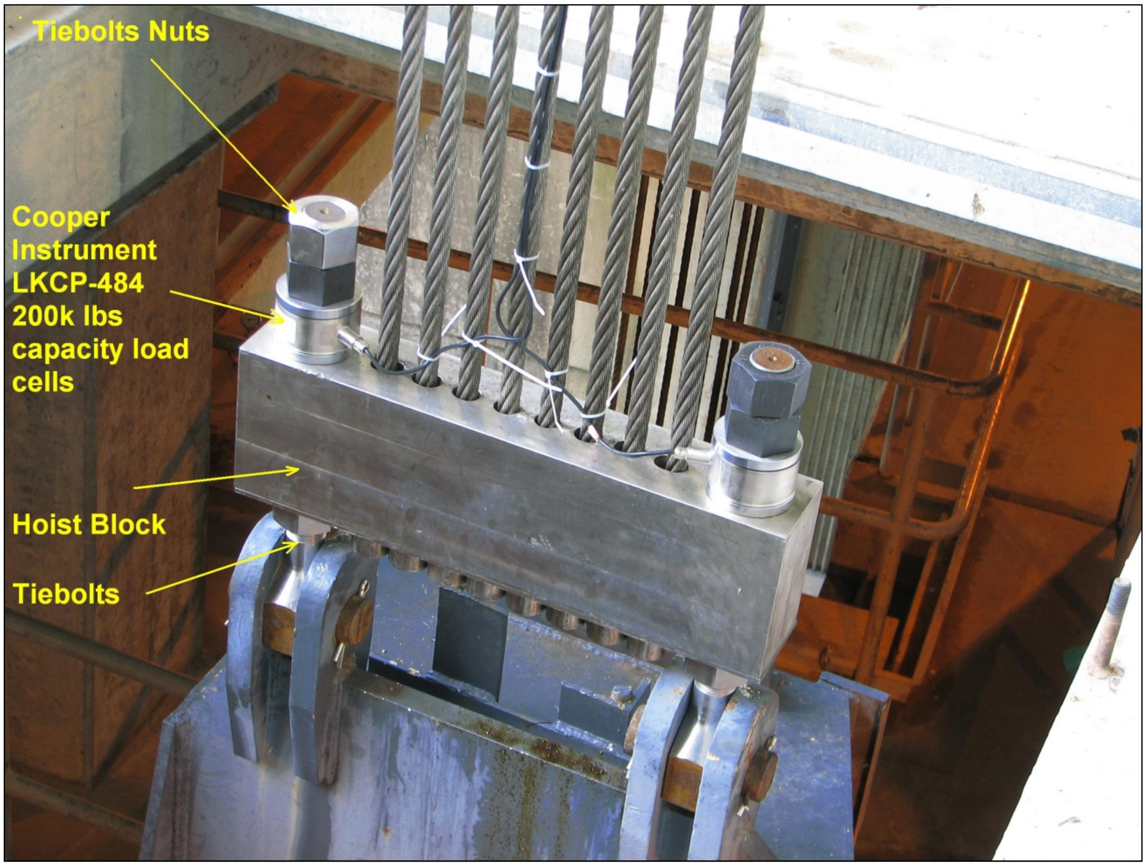

Figure 5. Hoist Load Cell Placement on Sluice Gate Lifting Block

Hoist Capacity - It is important that the gate wheel bearings be kept in good condition in order to maintain the low friction level to avoid exceeding the rated hoist capacity. The lowering requirements for the gate do not relate to the capacity of the hoist; they are only a function of the gate weight and the resisting frictions.

Open Gearing - The bending strength of the teeth for the open gears were checked and found to be acceptable, but very close to allowable loading.

Wire Ropes - The wire ropes have been checked and found suitable for the rated hoist capacity.

Wire Rope Drum and Shaft - The wire rope drum and shaft have been checked using the hoist rated capacity. These components were found to be acceptable.

The gate hoist load is sensitive to the friction between the wheel bearing and the steel pins. The factor of safety found in the analysis indicated that the gate wheel bearings need to be kept in very good condition in order to maintain low friction level.

Wheel Bearing Friction

An analysis of the effects of wheel-bearing friction on lifting and lowering was conducted to determine if high wheel-bearing friction could cause a failure to lower from an intermediate open position. Based on this analysis, a check was performed to determine if wheel friction could be the cause of the slack cable limit switch stopping the gate's downward operation. The sluice gate wheel bearings are self-lubricated "Lubrite" bearings riding on 6.5-inch diameter chromium plated steel pins. The gate weight is 60 tons (120,000 pounds). The horizontal force when the gate is closed due to hydrostatic pressure is 4,725,000 pounds. If each wheel is evenly loaded, then a static friction coefficient of only 0.13 would prevent the gate from closing. However, the hydrostatic force decreases as the gate opens as the area of the gate slider under hydraulic pressure reduces. Conversely, the hydrostatic force increases as the gate closes because the area of the gate slider under hydraulic pressure increases. If the gate were throttled at a relatively small opening then the relatively high hydraulic pressure could induce a high static friction force, which could prevent the gate from closing under its own weight. This effect becomes more pronounced if there is a high static friction factor at the wheel bearings. For example, if the sluice gate is two feet open and the average coefficient of static friction at the wheel bearing is 0.142, then static friction force would prevent the gate from closing. Since a static friction factor of 0.15 is regularly used in Lubrite bearing design calculations, it appears that high friction in the wheel bearings is an operational concern.

The sporadic nature of the failure of the sluice gates to close could be due to unevenness in the wheel race and uneven friction among the Lubrite bearings. If a wheel bearing with a higher-than-average friction factor comes to rest on a high point on the wheel race (which increases the load on the bearing), then the friction force may prevent further lowering of the gate.

Since three different gates have failed to close, with no obvious mechanical obstructions, (Gates 2 and 6 in 2008 and Gate 4 in 2009) the failures were probably caused by a feature that is common to all sluice gates. Among these common features, wheel friction and debris interference are the most reasonable explanations. Debris interference is unlikely, due to the depth of the gates (190 feet) and the apparent absence of contact marks or unusual spray patterns.

Analysis to date has been inconclusive as to the cause of the failure to close. It is noted that the preliminary load cell measurement data used in the analysis was obtained for lifting and lowering operations after the gate had been "exercised" up and down. For subsequent analyses, operational load measurements should be taken for conditions similar to those leading up to the failure to close events. That is, the data should be collected over a duration that includes the opening to a throttled condition, intermittent measurements while the gate is in the throttled position, and measurements during the first and subsequent (if necessary) attempts to lower the gate from the throttled position. Most critical is measurement of the initial loads for the first attempt to lower the gate from a sustained throttle position.

The mechanics of the gate system is thought (or assumed) to be understood with all variables and parameters included and correctly calculated in the analysis model. Although it has not been shown by the analysis to date (using the preliminary load cell measurement data), upper range friction in the gate wheels is the prime suspect for the failure to close. However, some more subtle and yet undiagnosed behavior may be an operative that adds sufficient resisting force against lowering such that the gate remains immovable.

Fatigue Due to Pressure Fluctuations

Pressures on the sluice gate were measured during spill flow in 2008. Data was collected with the gate opened to various positions in order to determine the magnitude of pressure fluctuations acting near the bottom of the gate. One minute of data at a rate of 100 samples per second was taken at four test points. Each data set has 6,000 samples in the one-minute data acquisition period. The maximum pressure fluctuation was found to be 2.36 psi peak-to-peak, which occurred while the gate was opened to 64 inches. This pressure fluctuation was used as the applied load to the lower gate girder assembly and the corresponding maximum tension stress fluctuation or range was found to be 0.34 psi. Cyclical loading causes fatigue, which can cause structural failures.

Tests have shown that, when opened, there is fluctuating pressure distribution acting on the lower portion of the gate. The purpose of the fatigue analysis is to determine if the variable pressure loading will result in any fatigue damage (fatigue cracks to failure) over the operating life of the gate.

This fatigue stress is negligible compared to the allowable fatigue stress of 3 ksi for a Category E detail at Load Condition 4 (more that 2,000,000 stress cycles), as specified by American Institute of Steel Construction (AISC 89). Therefore, the measured pressure fluctuations do not pose a fatigue problem for the gate structure.

Metrology

OASIS was engaged to use 3D metrology and optical alignment to check the center Sluice Gate 4, (See Figure 6). The object of the exercise was to check if there are any interferences that could be causing the gate to jam when being lowered under full hydrostatic and hydrodynamic loading, particularly just before the gate fully lowers.

The results of the Metrology were not entirely conclusive however the conditions observed on site did not point to a geometry or alignment problem. The measured face alignment of the wheels indicated some “toe-in” as the gate is lowered that could result in increased lateral wheel loading which would somewhat hinder lowering. Interference was eliminated as an issue.

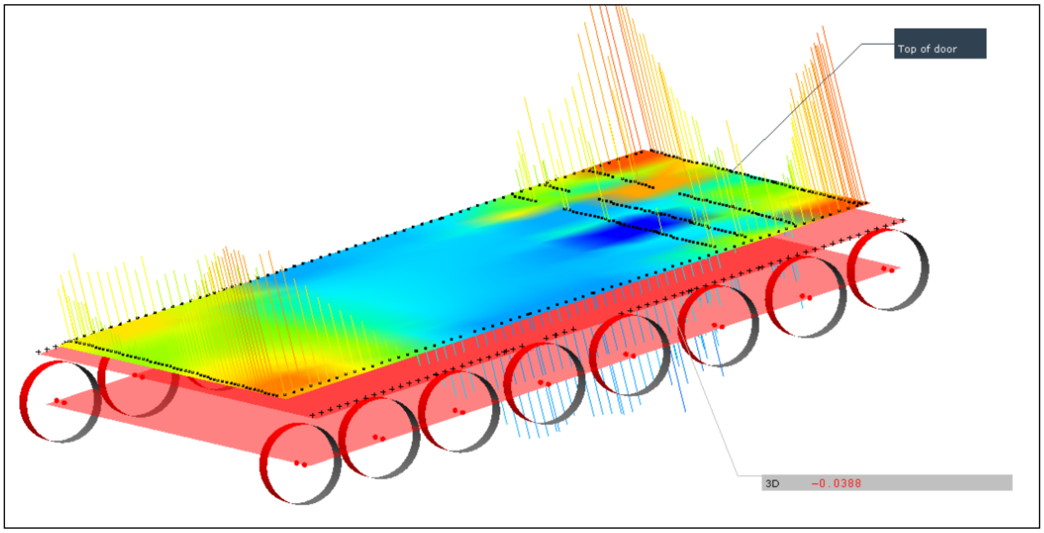

Figure 6. Metrology Measurements of Gate Alignment

MODIFICATION OF THE SLUICE GATES SYSTEM

Seal Plates

A series of stainless steel plates have been added to Sluice Gates 2, 4 and 6 to improve hydraulic performance of these gates during throttled flow. The outer sluice gates (Gates 1 and 7) have the greatest chance to include unwanted interference with the dam foundation, so they are less desirable. The logical gates to select for testing while avoiding use of the outermost gates are Gates 2, 4 and 6.

The seals provide a means to seal the gate at intermediate positions and should help minimize vibration during throttled openings of sluice gates. Given that the space below each sluice gate is limited, the viability of use of throttled flow is expected to be limited to only a portion of the gates. The design and operation of this modification will not significantly alter the structural integrity, design function or operation of the sluice gates. The seals consist of 3/8-inch-thick by 8-inch-wide stainless steel (SS-304L) plates.

The Sluice Gate 4 plates were installed during October/November 2007. The seal plates' locations correspond to the following gate openings and flow levels:

- Gate 30" open (20" orifice opening flow rate 2200CFS);
- Gate 50" open (40" orifice opening flow rate 4500CFS); and
- Gate 64" open (54" orifice opening flow rate 6000CFS).

Testing was performed with Sluice Gate 4 during 2008 with sealing plates in place. The performance was better than without the sealing plate in place (see Figure 7). The water no longer leaked in the space between the gate and the seal. The expanding jet, however, impacts the gate slot. Further modifications are required to keep the flow away from the gate slot before the system is ready for long-term reliable use. Use of deflectors within the sluice gates has been examined as the preferred method to direct the water away from the gate slots.

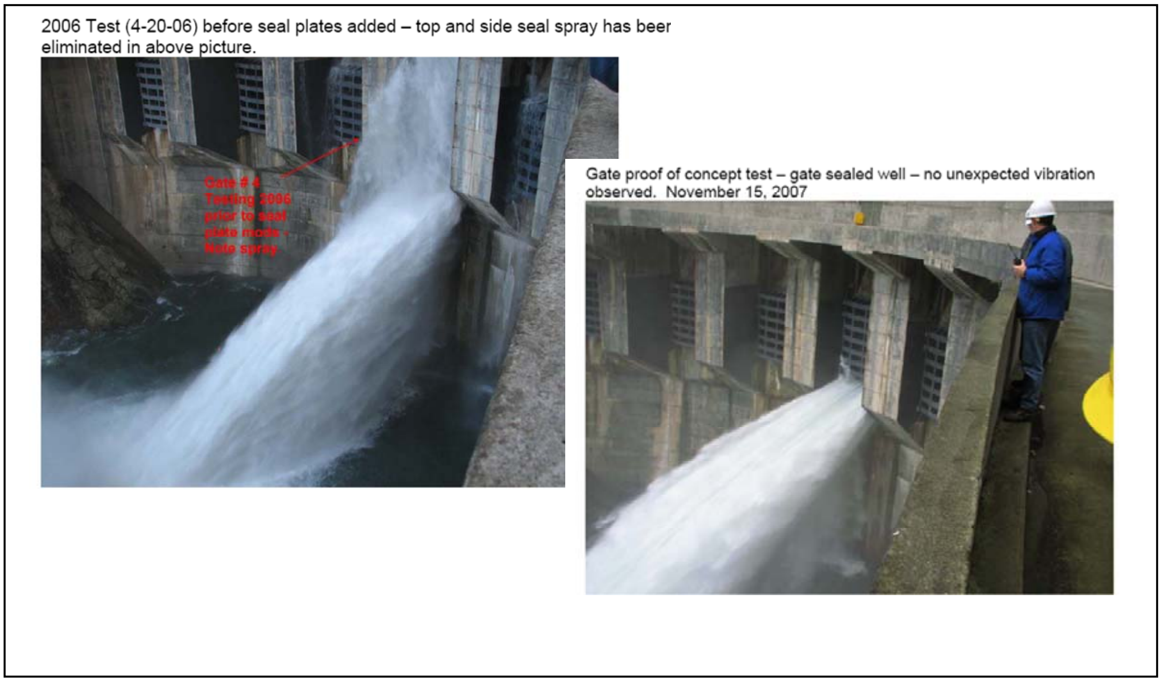

Figure 7. Throttled Sluice Gate Operation (Before and After Seal Plates)

Figure 7 highlights two photographs. The left photograph shows gate discharge before seal plates were added to Sluice Gate 4. The right photograph shows gate discharge after seal plates were installed. Note the decrease in spray.

The 2008 testing indicated that the TDG performance of the throttled sluice gate only justified the addition of two seal plates each to Sluice Gates 2 and No. 6. These plates were installed in late September and October 2009:

- 30”gate opening (20" orifice opening flow rate 2,200 cfs); and
- 50” gate opening (40" orifice opening flow rate 4,500 cfs).

Gate Slot Heater

The original Bechtel design included one 100-foot long electric heater per gate slot. These heaters heat the sides of the gate and the gate rails and therefore indirectly the gates’ wheels. These heaters failed within the embedded sections of the gate slot and cannot be removed or repaired because of corrosion and calcification. New gate slot heaters were installed as part of the1999-2002 gate rehabilitation program and consist of stainless steel “covers” that are welded over the original embedded slot heaters. Their intention was to replace the original gate slot heaters.

As discussed above, after throttled gate testing, the redesigned gate slot heater covers were found to have cracks over the covers. These cracks included weld cracks and there were fatigue cracks in the plates from vibration caused by the edges of the jet impinging within the gate slot. This damage was the result of the equivalent of 16.7 days of operation.

The original sluice gate heaters failed after a couple years and the retrofit options were not ideal. Currently, winter operation of the gates is addressed by winterization of the gates to prevent leakage (that can freeze and hinder gate operation) by applying gate sealing material after gate is operated (silvacell). This is currently the primary means to ensure gates are operational when freezing conditions are present. As a backup, temporary heating could be applied on the sluice gate structure to melt the ice in the unlikely event that sluice gates would be required for spill during freezing condition.

Deflectors in Sluice Water Passage

The sluiceway flow deflector is intended to deflect the flow horizontally inward such that the flow does not impinge on the gate slots when the sluice gate is at its partial (up to four feet) open position.

CFD analysis was performed to determine shape (see Figure 8). Field tests and old physical model study tests show that the high velocity jet can expand to impact on the downstream gate guide. Numerical models showed a similar trend. Runs were undertaken to evaluate the possible implementation of "deflectors" to shield the guides. The gate was assumed to be restricted to a four-foot opening.

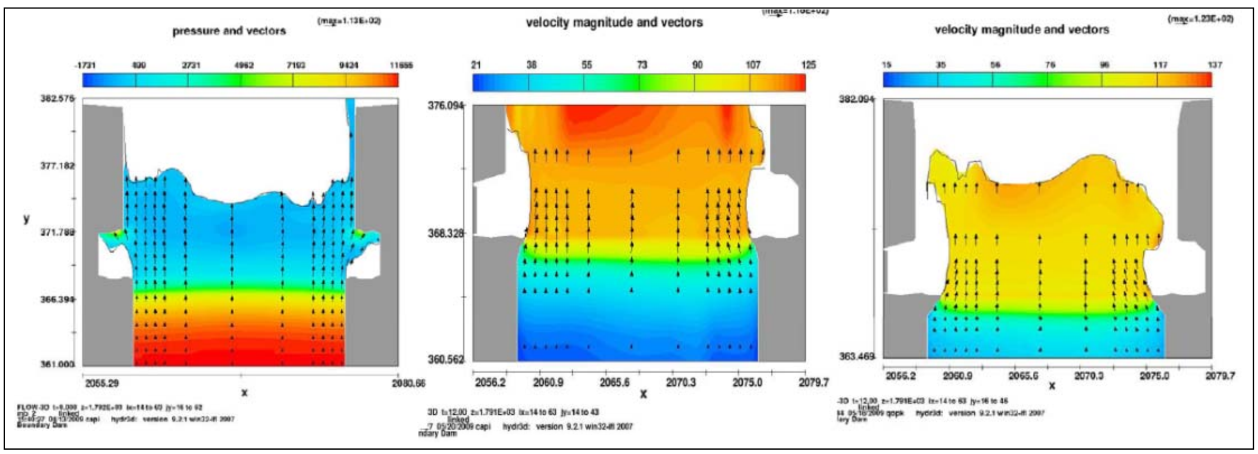

Figure 8. Sluice Deflector CFD Modeling Results

The deflector profile is a flat 1.33:1 sloped plate, with a nine-inch high trailing edge. The deflector profile is integrated into the geometry sluiceway side wall, up-sloping invert, and the nine-inch fillet radius in between. The height of the deflector is 60 inches at the downstream opening of the sluiceway. The top of the deflector is capped with an upward sloping cover plate that blends into the vertical sluiceway wall. To prevent flow separation and potential cavitation damage, the leading edge weld is finished with a smooth profile blended into the deflector plate. The deflector is configured as a welded steel structure that is then welded to the sluiceway liner. In order to avoid fit-up and connection difficulty that would be encountered with a completely assembled shop fabricated deflector assembly, the deflector is configured as three components that are field welded to the sluiceway liner. The shop-fabricated components consist of the main deflector (skin plate and rib assembly), the lower deflector-to-fillet plate, and the top closure plate.

The flow deflectors are located at the outlet of the sluice water passage. The final deflector installation is shown in Figure 9. The deflector was field-welded to the sluiceway liner. The skin plate was welded to the back plate, and the upstream leading edge was welded to the steel liner and ground smooth and painted to obtain a good flow profile.

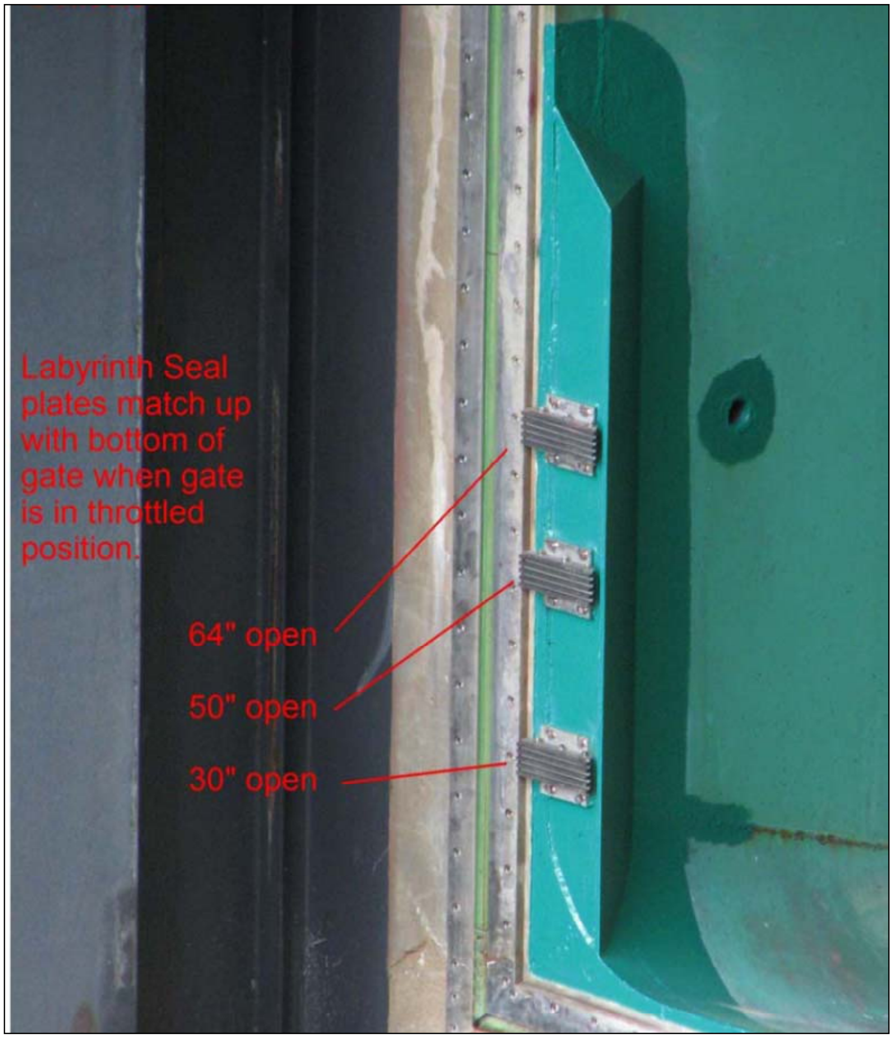

Figure 9. Sluice Deflector Installation

Water Bag System

Because of the failure to close incidents, an augmented or backup closure method was provided. Various systems were considered including addition of permanent weights, a device that can be deployed to push the gate down (such as a hydraulically-powered device), and addition of temporary weights as needed to start downward closing motion. Water bags weights were selected for development.

From a standard operating procedure aspect, it is thought that if the gate would not initially lower from a sustained throttle position, it can be lowered by first lifting the gate (no history of failure to lift) to some position above the sustained throttle position and then lowering the gate such that it moves at full speed through the "sticking" zone. Such an operation would serve to relieve the initial high wheel friction condition developed during sustained stationary loading of the wheel bearings. This is how the sluice gates have been closed during past failure to close incidents. If, after three attempts of this procedure, the gate cannot be lowered, the water bag backup lowering method would be initiated.

The water bag system consists of:

- 27.6 kip capacity commercially available water bag (yypically used for load testing, see www.canflexinc.com);
- Structural frame that hooks over the top girder flange and supports the water bag on the downstream face of the gate;
- Hoist system capable of handling the empty water bag and support frame (assume some residual water in the bag);
- Stowage and deployment mechanization; and
- Water filling and emptying system including a water meter to estimate the added water weight.

The selected water bag capacity compensates for about an equivalent of 0.033 increase in wheel coefficient of friction.

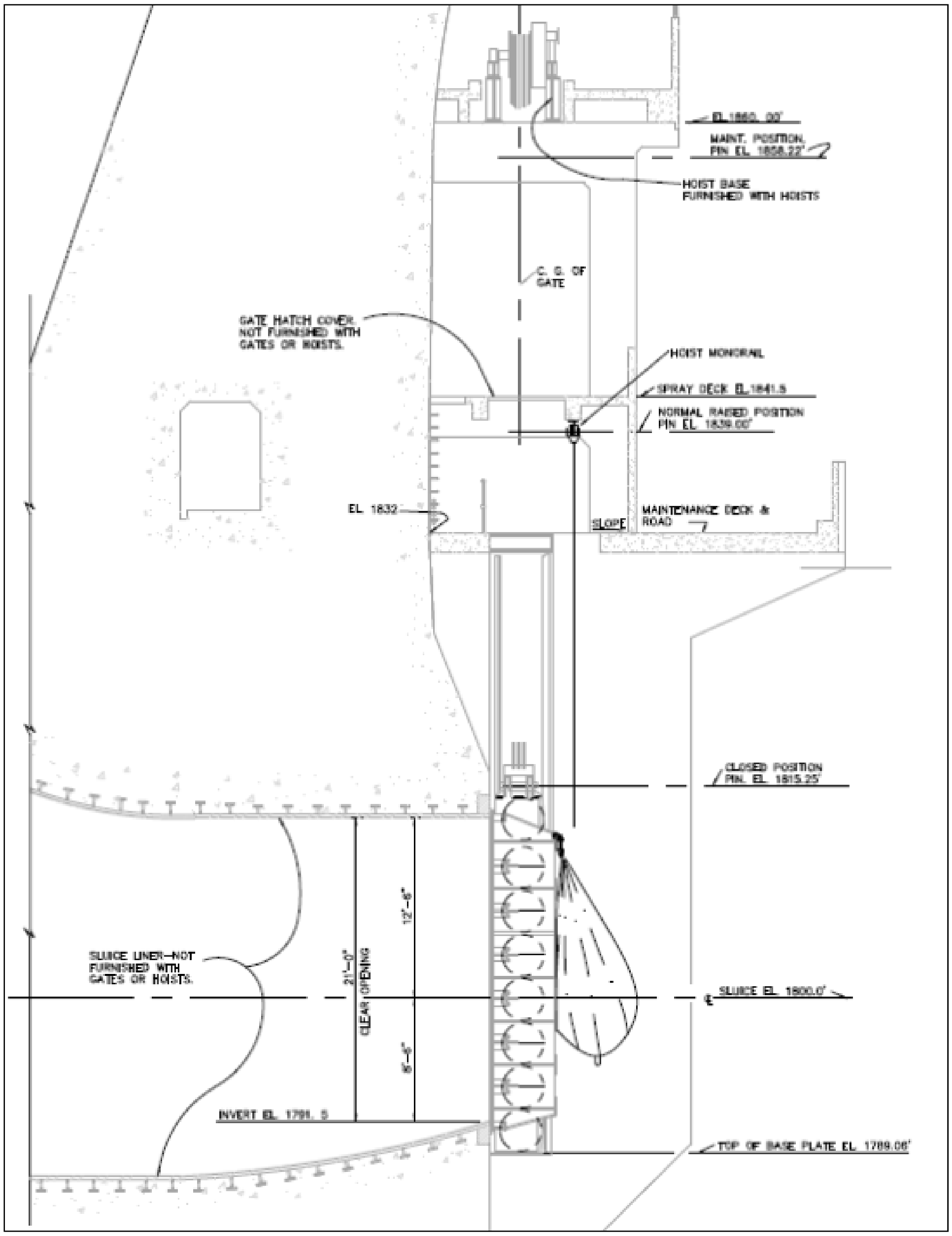

Figure 10. Water Bag Configuration Deployed on the Sluice Gate

CONCLUSIONS

The testing and analysis performed on the sluice gate have not indicated any conditions during throttle flow that have demonstrated vibrations that could lead to damage of the gate structure or hoists. The area of concern for throttled operation is primarily the structures within the gate slot, which includes the heater covers and gate rails. The retrofitted gate slot heaters are particularly susceptible to damage, and have caused difficulty lowering the gates in the past.

Hydraulic modeling evidence confirmed that the mechanism that causes damage is flow expansion downstream of the gate exit impacting the slots. Modeling has shown that it is possible to modify the water passage to deflect the water away from the gate slots.

The retrofitted gate slot heaters and heater covers have a high potential for damage and little perceived value. For the life of the project, there has not been an operational need to utilize gate slot heaters for over 40 years of operation and there are alternative means to seal the gates and heat as required to allow winter utilization.

Use of seal plates for intermediate openings of the sluice gates provides improved performance by preventing high pressure water flowing out from between the gate skin plate and the upper seal.

There are currently no definitive determinations as to the cause of the difficulty lowering the gate after throttled use, but the most likely scenario is associated with wash out of the lubricant in the Lubrite bearings and development of a set within the bearings after long periods of throttled use in a single position. This phenomenon should continue to be examined to develop a more definitive explanation of the cause and potential solutions to prevent difficulties closing gates. Additional field tests with load cells and gate position data during prolonged throttled flow will provide insight into the functionality of the entire sluice gate system.

Use of the water bag system as a backup closure aid provides additional weight, which help overcome friction resistance on the bearing. The position of the water bag load will include an eccentric loading on the downstream face of the gate which will have the effect of reducing the load on the lower gate wheels, which see the greatest hydrostatic load under throttled conditions.

With the analysis, testing and modifications in place, use of the gates in the throttled position is better understood and a more viable option for TDG mitigation.

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AUTHORS

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