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Managing Water in the West

Hydraulic Laboratory Report HL-2014-04

Gate Catcher Pins – Physical Hydraulic Model Study

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14. ABSTRACT

A physical model study was performed to investigate newly developed pins to catch low-head radial spillway gates. These "gate catcher pins" are cylindrical steel rods embedded in the concrete pier wall downstream of the radial gate leaf. Their purpose is to catch the gate if the trunnion arms or pins were to fail, preventing the gate assembly from plunging downstream and causing damage and/or an uncontrolled flow release. Testing was performed to determine hydraulic effects caused by the pins as well as estimated maximum dynamic load on the pins from a gate failure. Results showed that there was no significant affect to gate discharge capacity for most pin sizes and that cavitation on the pins is not an issue for most low-head gate applications. Dynamic failure testing showed that the impact force of the gate on a catcher pin can be about 20 times greater than the hydrostatic force on the gate. Findings from this study will hopefully provide general guidance to future gate catcher pin installations.

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Gate catcher pins, radial gates, spillways, impacts to discharge, head loss, cavitation, dynamic load

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GLOSSARY OF SYMBOLS

F	= maximum force on gate catcher pin (lb)
$F_{hydrostatic}$	= hydrostatic force of water on gate (lb)
W_{gate}	= total weight of radial gate assembly and trunnion arms (lb)
g	= acceleration constant (ft/s^2)
m	= mass used in impact force calculation, includes mass of gate assembly and water force on gate (slugs)
a_{mean}	= mean acceleration of gate over the impulse time as it impacts the pins (ft/s^2)
σ	= cavitation index number
P_o	= reference pressure (lb/ft^2)
P_a	= atmospheric pressure (lb/ft^2)
P_v	= vapor pressure of water (lb/ft^2)
ρ	= density of water ($slug/ft^3$)
V_o	= reference velocity (ft/s)
δ	= boundary layer thickness (ft)
x	= distance from downstream from end of plate (ft)
v_o	= velocity (ft/s)
ν	= kinematic viscosity (ft^2/s)
$Re_{bl} = \frac{v_o x}{\nu}$	= Reynolds number based on *x* (-)
C_D	= drag coefficient of a smooth cylinder (-)
D	= diameter of cylindrical gate catcher pin (in)
$Re_{cyl} = \frac{v_o D}{\nu}$	= Reynolds number based on gate catcher pin diameter (-)

Executive Summary

Hydraulic modeling results are available for gate catcher pins designed to catch low-head radial spillway gates in the event of a failure of the trunnion arm or pin. The 1:12-scale model simulated gate catcher pins 6 inches in diameter and spaced 1 ft vertically immediately downstream of the radial gate leaf. The model study investigated flow conditions for the gate and catcher pins and dynamic loading on the pins during a full gate failure. Hydraulic testing was repeated with four different lengths of gate catcher pins (3.5, 5.5, 7.5, and 9.5 inches), while only the 3.5 inch pins were tested for dynamic loading. Data were collected with an upstream reservoir elevation of 17 ft relative to the crest of the spillway. Gate discharge capacity of every pin length was compared to a baseline condition with no pins behind the gate. Primary results and conclusions include:

- There is no reduction in gate discharge capacity for catcher pins less than 7.5 inches in length when the gate opening is at least 2 ft. At gate openings less than 2 ft significant head losses were caused by every pin length which would reduce the gate's discharge capacity for the same reservoir elevation. These results are illustrated in Figure 12. (pg. 14). Results from the 9.5 inch pins showed significant head loss at the 1 ft gate opening and some head loss at all gate openings.

- At gate openings less than 2 ft there is a significant flow split around the exposed pin that causes a vertical jet to shoot up and over the pin. While the jet's impacts to the gate leaf and pier wall are unknown, it is obviously an undesirable flow condition that can be handled by minimizing operational time at lower gate openings. Photos in Figure 13 show visual observations of the flow split (pg. 15).

- Dynamic load testing of a full gate failure on the pins showed that the dynamic load on the pins can be about 20 times the hydrostatic load of the gate (Table 3 and Figure 16, pg. 19). While the results from these tests are believed to be conservative, accuracy is unknown due to model scaling limitations. Results provide an order-of-magnitude estimation.

Introduction

A physical model study was performed to investigate newly developed pins to catch low-head radial spillway gates. This study was requested by Reclamation's Structural Analysis Group of the Technical Service Center (TSC). These "gate catcher pins" are cylindrical steel rods embedded in the concrete pier wall on the downstream side of a radial gate leaf. Their purpose is to catch the gate if the trunnion arms or pins were to fail, preventing the gate assembly from plunging downstream and causing damage and/or an uncontrolled flow release. These gate catcher pins have already been installed on a few of Reclamation's spillways but have not been observed during a spill event. While details of each design and installation are different, the general configuration of the pins is similar for each site. It is anticipated that results from a general pin configuration in this lab study will be applicable to various site designs.

There were two main objectives for this study:

1. Determine hydraulic effects caused by the pins.
2. Estimate the maximum dynamic load on the pins from a full gate failure.

Since the gate catcher pins protrude from the concrete wall into the flow field downstream of the gate, there were some hydraulic concerns. These concerns included reduced discharge capacity, increased head loss, cavitation potential, and any hydraulic irregularities caused by the pins. Also, an accurate prediction of the dynamic load on the pins caused by a gate failure is difficult to calculate. Measurements were made during a simulated full gate failure of the model to estimate this load which will be used for future pin design and sizing.

Experimental Setup

The hydraulic model study was performed in Reclamation's Hydraulics Laboratory in Denver, CO. A 1:12 (model/prototype) Froude – scale model of a radial gate between two pier walls was constructed in a laboratory flume. Dimensions from Reclamation's Echo Dam were used to scale the gate, pier walls, and gate catcher pin diameter. While existing dimensions were used, this was not a direct model study of Echo Dam as a different gate catcher pin configuration and different pin sizes were tested. Seventeen gate catcher pins on each side were set into the pier walls immediately downstream of the gate leaf to represent a general configuration (Figure 1). A middle gate with piers on each side was used to allow symmetrical flow conditions at the gate and pins (Figure 2 and Figure 3).

The model was installed at the tail end of the flume (3 ft wide and 60 ft long) which allowed a uniform flow approach. Flow immediately fell away from the gate as it was discharged, maintaining a free-flow condition expected for radial gates on a spillway (Figure 4). No spillway geometry was included in the model.

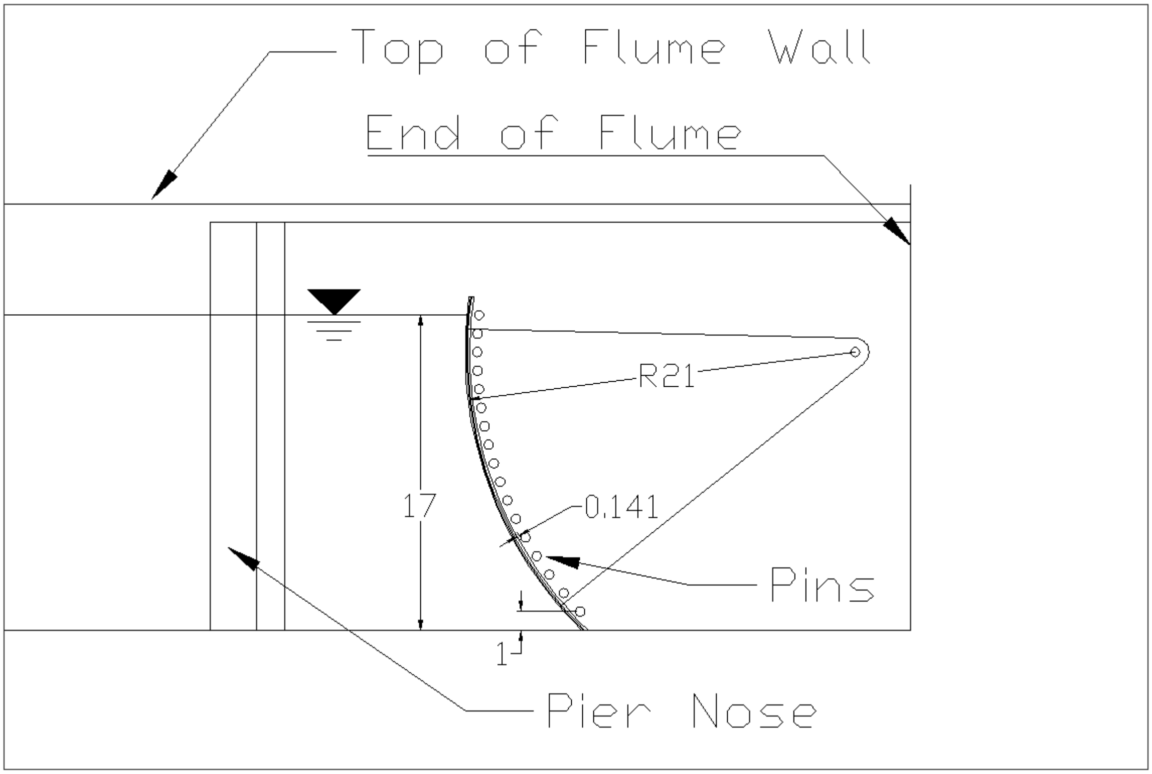

Figure 1 Profile view of model gate, pier walls, and gate catcher pins. Dimensions are in model inches and prototype feet. Dimensions of the gate and pier walls were scaled from radial gates at Echo Dam.

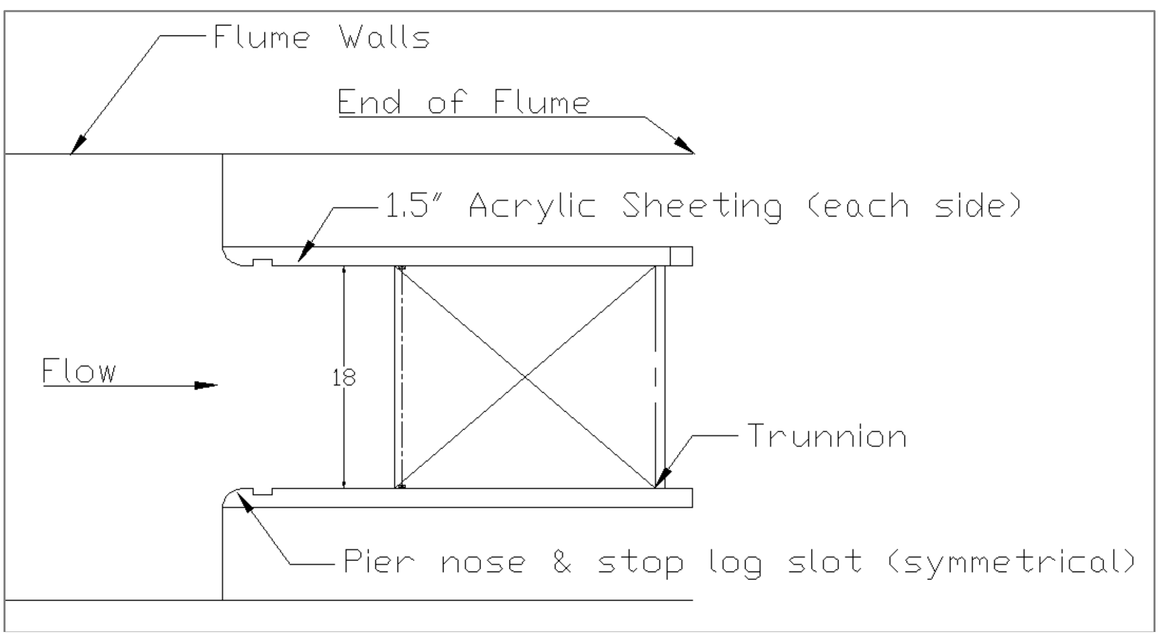

Figure 2 Plan view of model gate and piers. A middle gate was modeled with symmetrical piers on both sides, including scaled nose and stop logs slot dimensions for accurate flow conditions at the gate. Gate width dimension is in model inches and prototype feet.

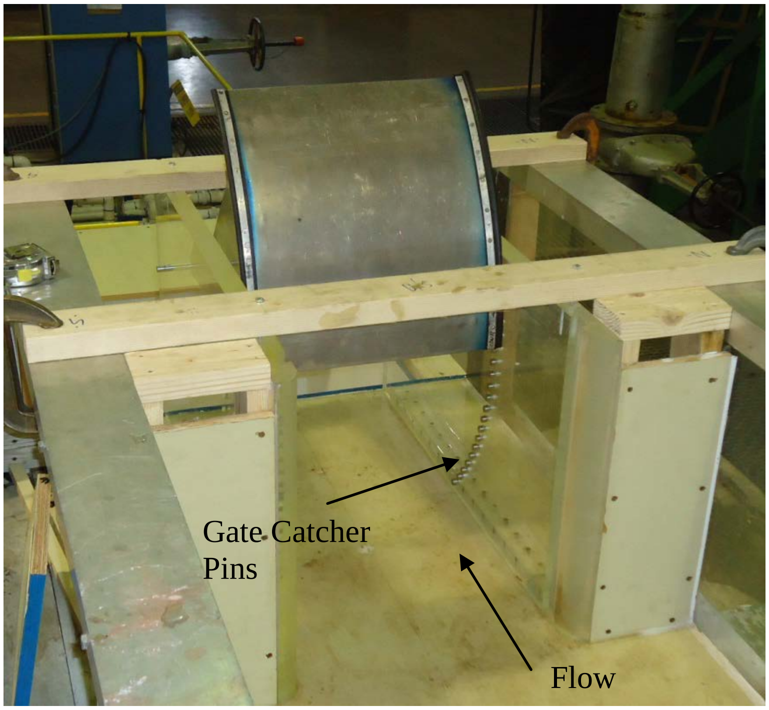

Figure 3 Gate model with catcher pins in the pier wall. Rubber seals were used during hydraulic tests to prevent flow between the sides of the gate and walls. Pier walls were made out of clear acrylic for visual observation.

Figure 4 Model of gate and piers at the tail end of the laboratory flume (60 ft long, 3 ft wide). This allowed flow to immediately fall away from the gate to maintain a free-flow condition observed at spillway gates.

Hydraulic Modeling

Hydraulic testing consisted of comparing upstream water surface elevation measurements with gate catcher pins to a baseline condition without pins for the same gate discharge. Head loss caused by the pins was quantified by the difference in water surface elevations for the same discharge. Flow around the pins at the wall was observed through the clear acrylic walls and documented with photographs and video. Gate discharge was measured using laboratory venturi meters calibrated to an accuracy of ± 0.25%. The upstream water surface was measured 26.5 ft (model) upstream using a stilling well with a MassaSonic M-5000 ultrasonic sensor sampling at 10 Hz. The water surface measurement was corrected by adding the velocity head component of the flowing water in the flume. Taking into account error from the sensor, survey instrumentation and human error an uncertainty analysis indicated that the accuracy of water surface measurements was ±0.13 ft prototype.

Test comparisons were made with no gate control (gate completely out of the flow) and with control at various gate openings. Five different flows were tested with both free-flow and gate openings of 1, 2, 4, 6, 8, 10, and 12 ft prototype. For each test the flow was allowed to stabilize for at least 30 minutes before taking a reading. Water surface and discharge measurements were averaged for one minute. Testing was repeated with four different pin lengths (*L*), which is defined as the distance between the pier wall and edge of the pin (Figure 5). *L* represents the portion of the pin that protrudes into the flow.

Figure 5 Model scale gate catcher pin lengths that were used in the hydraulic model testing (*L* = 3.5, 5.5, 7.5, and 9.5 prototype inches).

Dynamic Load Modeling

Dynamic modeling was used to predict the maximum dynamic impact force of the gate on the gate catcher pins. This testing utilized the same model gate (weight modified), and pier walls used in the hydraulic tests. Only the 3.5 inch pins were used for dynamic modeling. A full gate failure was simulated by simultaneously pulling both trunnion pins using pneumatic cylinders, allowing the gate to freely fall back against the gate catcher pins (Figure 6). Modeling a "full gate failure" is intended to test the worst case condition of the entire weight of the gate assembly impacting the pins under a full hydraulic load (maximum upstream water surface).

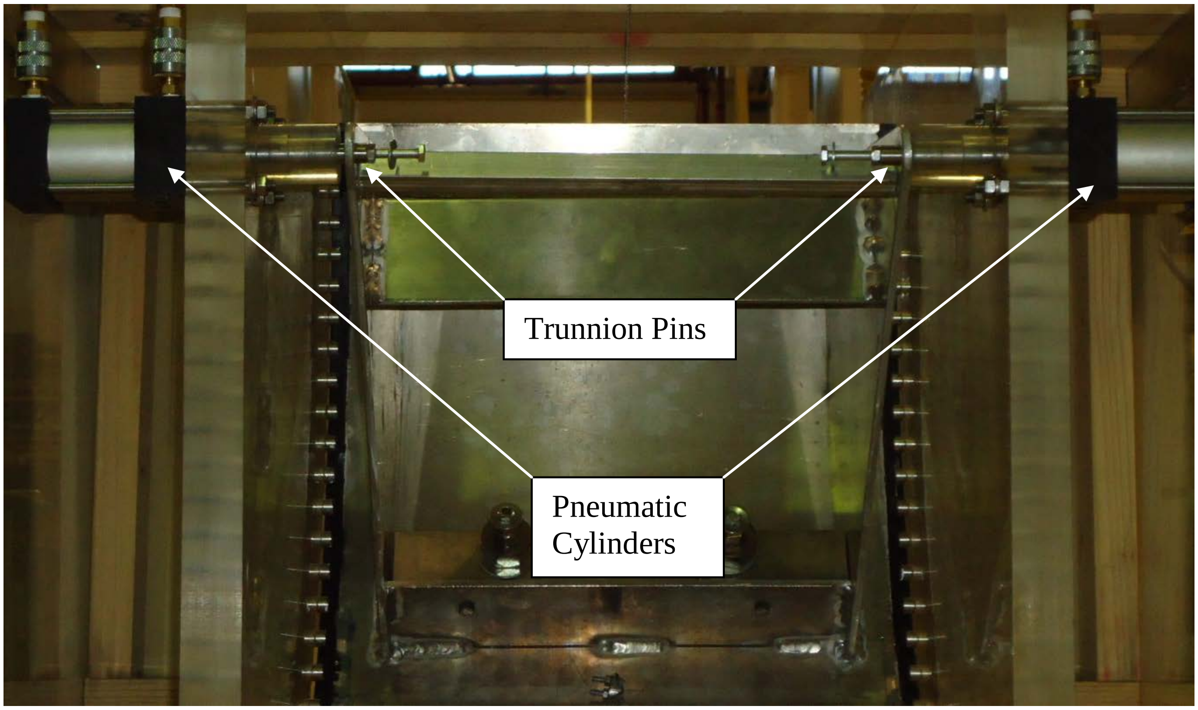

Figure 6 Pneumatic cylinders used to simultaneously release both trunnion pins to simulate a full gate failure (back side of gate looking upstream).

Dynamic Model Scaling

This model cannot be used as a true dynamic structural model since the material properties and weight distribution of the radial gate assembly are not properly scaled. The same is true for the gate catcher pins and their connection to the pier walls. Therefore, no accurate predictions of the vibration or dynamic response of the gates and pins can be made using the existing setup. However, an estimation of the maximum dynamic load of the gate impact on the pins can be made by assuming a rigid pin connection to the pier wall and properly scaling the overall weight of the gate assembly. This was done by adding weights to the backside of the model gate (47,300 lbs. prototype, 27.37 lbs. model). Froude scaling can be used to model both the hydraulic and dynamic forces of the gate on the pin since gravity is the dominant force. Froude similitude provides the following relationship for force at a 1:12 scale.

Force ratio: $L_r^3 = 12^3 = 1{,}728:1$

This approach is likely conservative for various reasons; friction between the gate leaf and pier wall was eliminated in the model (no rubber seals), the model gate is more rigid than the prototype, and a true gate failure would likely be caused by a single arm buckle, not simultaneous failure of both arms as performed in the model test. While results from these tests are believed to be conservative, accuracy is unknown due to model scaling limitations. Results, therefore, provide an order-of-magnitude estimation.

Dynamic Load Measurements and Analysis

Impact forces were estimated indirectly from the impulse of the gate on the pin (equations 1 - 3). A direct force measurement was not used due to difficulty finding and installing instrumentation on the relatively small pins of the model. With this approach, the only measurements required were upstream water surface (hydrostatic load on the gate) and gate acceleration upon impact with the pins (Figure 7). Water surface measurements were made similar to those of the hydraulic testing, using the stilling well and a point gage. Acceleration was measured using two Model 1000 VibraMetric accelerometers mounted on the upstream side of each end of the gate as shown in Figure 8. It was assumed that the force acted in only 1 direction and uni-axial accelerometers were used. The accelerometers had a range of ±500g and a frequency response within ±5% up to 15 kHz. Acceleration data were collected at 80 kHz and the mean acceleration over the impulse was used in the force calculation.

$$F\Delta t = m\Delta V \tag{1}$$

$$m = \left(\frac{W_{gate}}{g} + \frac{F_{hydrostatic}}{g}\right) \tag{2}$$

$$F = m(a_{mean}) \tag{3}$$

Where: F = impact force (lb)

m = mass (slug), includes the mass of the gate assembly and the hydrostatic force of water on the gate

a_{mean} = average acceleration over impulse time (ft/s^2), accounts for the Δt and ΔV terms of equation 1 (see Figure 7).

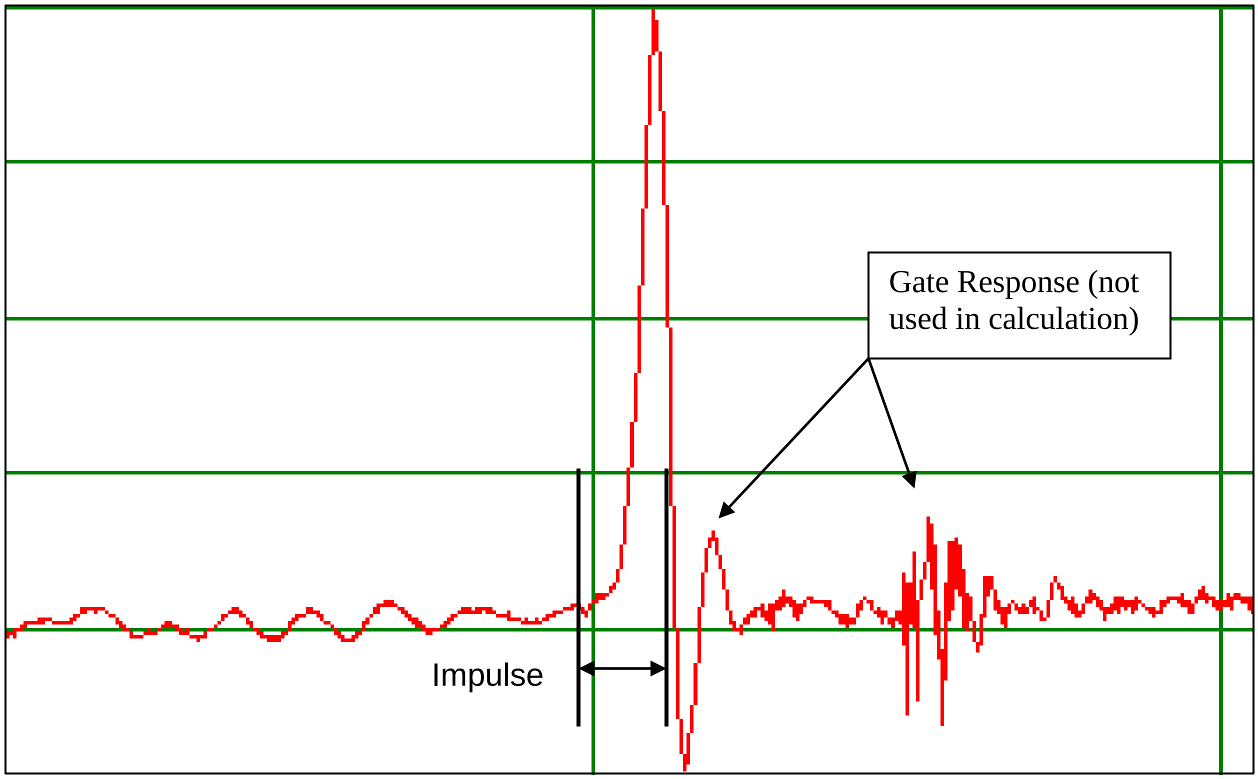

Figure 7 Example of impulse signal measured with an accelerometer (acceleration vs. time). Acceleration measurements were averaged over the impulse which is the initial gate impact with the pin.

Initial impact testing was performed using all 17 pins per side and with a sampling rate of 10 kHz. These tests produced impulse results that were difficult to interpret since the gate was impacting several pins at once and distributing the load. Only results from a 10 ft vertical gate opening from the initial tests are reported here. The model was modified by reducing the number of pins and increasing the sampling rate to 80 kHz.

For impact testing only three pins were used on each side that were spaced far enough apart vertically to ensure that the full force of the gate impact was taken by only one pin at a time. Tests were conducted with gate openings of 0 ft (fully closed), 0.9 ft, and 5.5 ft. Before measuring acceleration, high-speed video (2,000 frames per second) of each gate opening test was used to review gate motion and verify the location of first impact. For each gate opening the accelerometers were positioned directly opposite to the gate catcher pin that saw the first impact from the gate (Figure 9). This allowed the signal to be read at the rigid impact of the pin and reduced effects from the dynamic response of the gate.

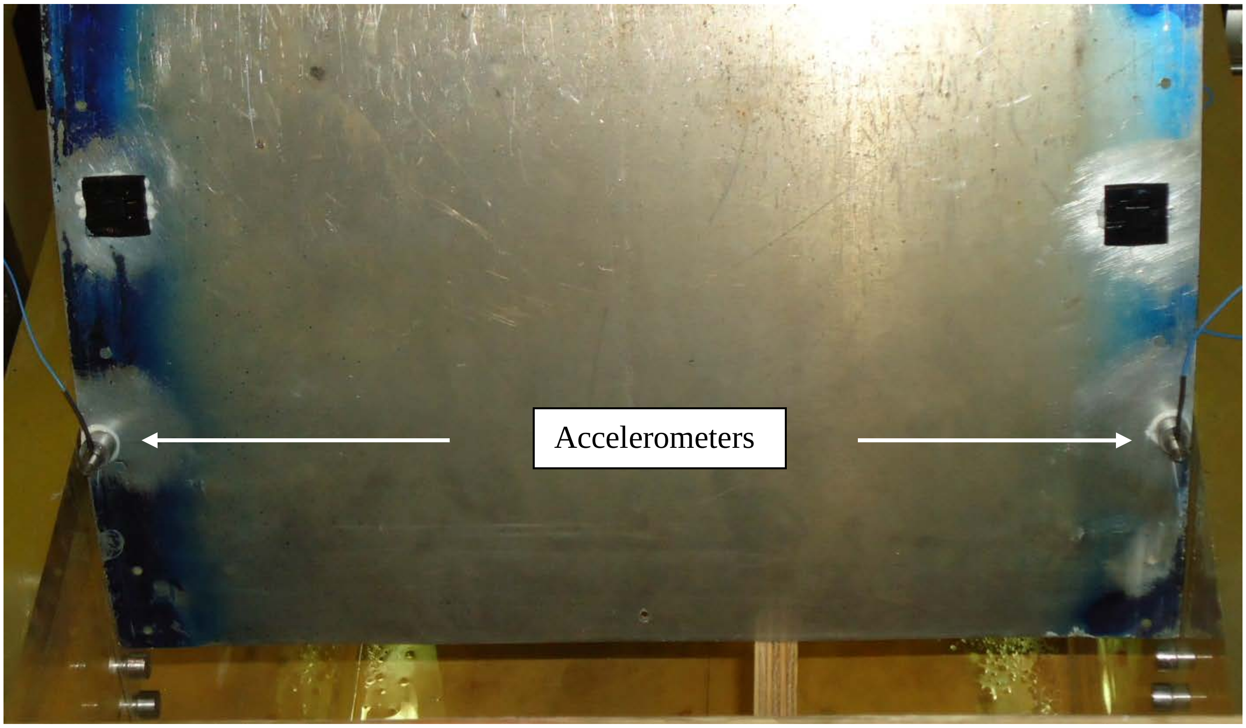

Figure 8 Accelerometers mounted on the upstream side of the gate on each side for impact load testing (looking downstream).

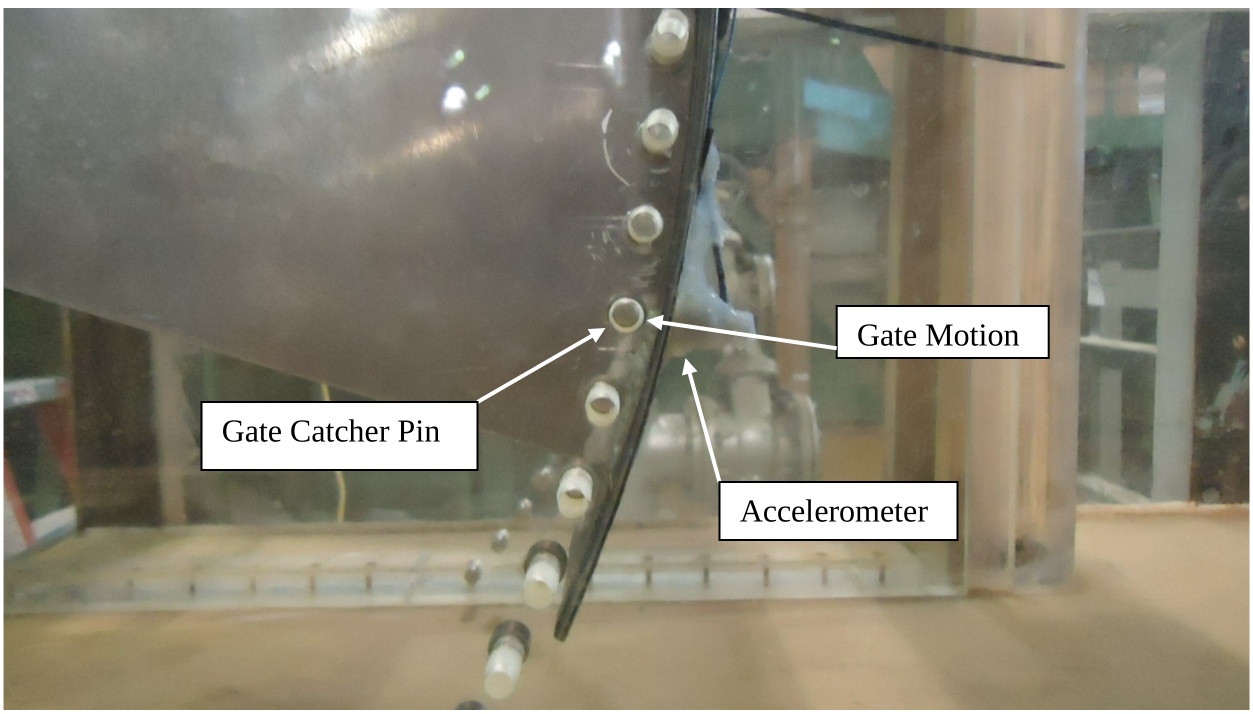

Figure 9 Accelerometer mounted on upstream side of gate directly opposite of the gate catcher pin that saw the first impact. Accelerometers were waterproofed with an RTV silicone coating.

Results and Discussion

Hydraulic Modeling

Head Loss

Gate discharge and upstream water surface measurements were made to compare gate catcher pin results to a baseline condition without pins. The first set of tests was made with the gate completely out of the water, and only the 3.5 and 9.5 inch pins were tested. Figure 10 shows that there was no measurable head loss due to the pins even with the worst case of 9.5 inch pins. Therefore, the other pin sizes were not tested with a no-gate condition.

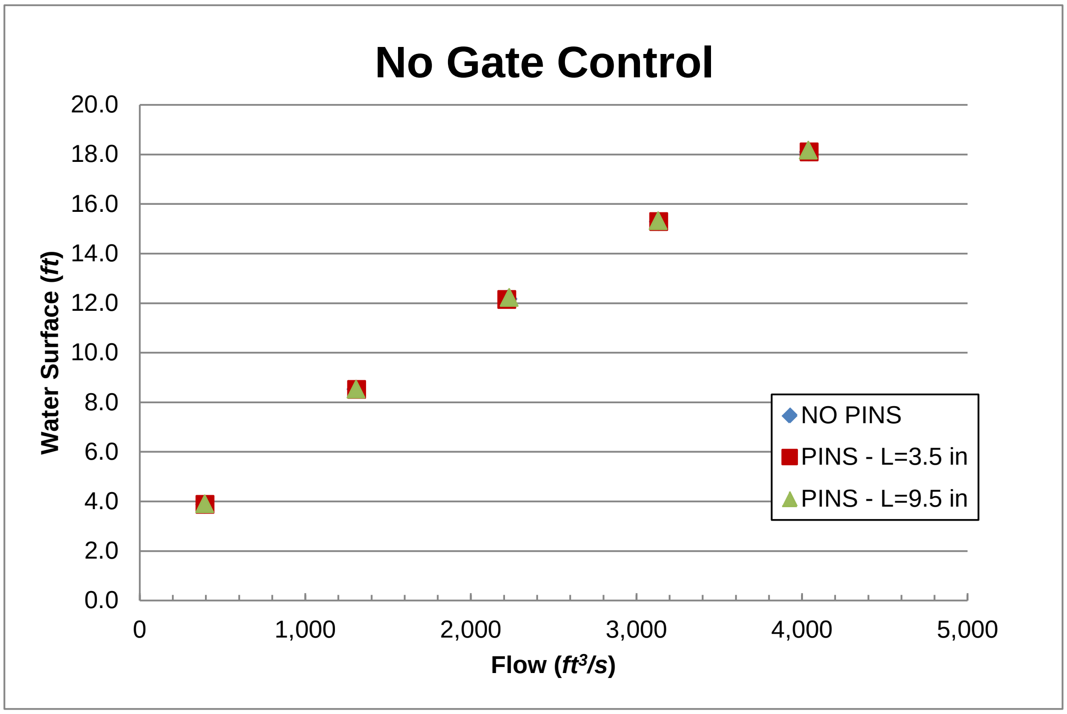

Figure 10 Test results of 3.5 and 9.5 inch pins with the gate out of the flow.

Tests were repeated with gate control at gate openings of 1, 2, 4, 6, 8, 10, and 12 ft prototype. The upstream water surface was set near 17 ft at the baseline condition which was compared to results with different gate catcher pin lengths at the same gate discharge. At the 12 ft gate opening (3,700 ft^3/s) it was necessary to set the water surface to over 18 ft to maintain gate control. Figure 11 shows that there were no significant differences with the pins except at the 1 ft gate opening (500 ft^3/s).

The comparison to baseline results is shown in greater detail in Figure 12 which defines head loss caused by the pins as the difference in water surface from the baseline test. With the exception of the 1 ft gate opening, pin lengths of 7.5 inches or less caused minimal head loss. Most of these results were within the uncertainty of the measurement and are not significant. Differences with the 9.5 inch pin were seen at all gate openings but were significantly greater at the 1 ft gate opening.

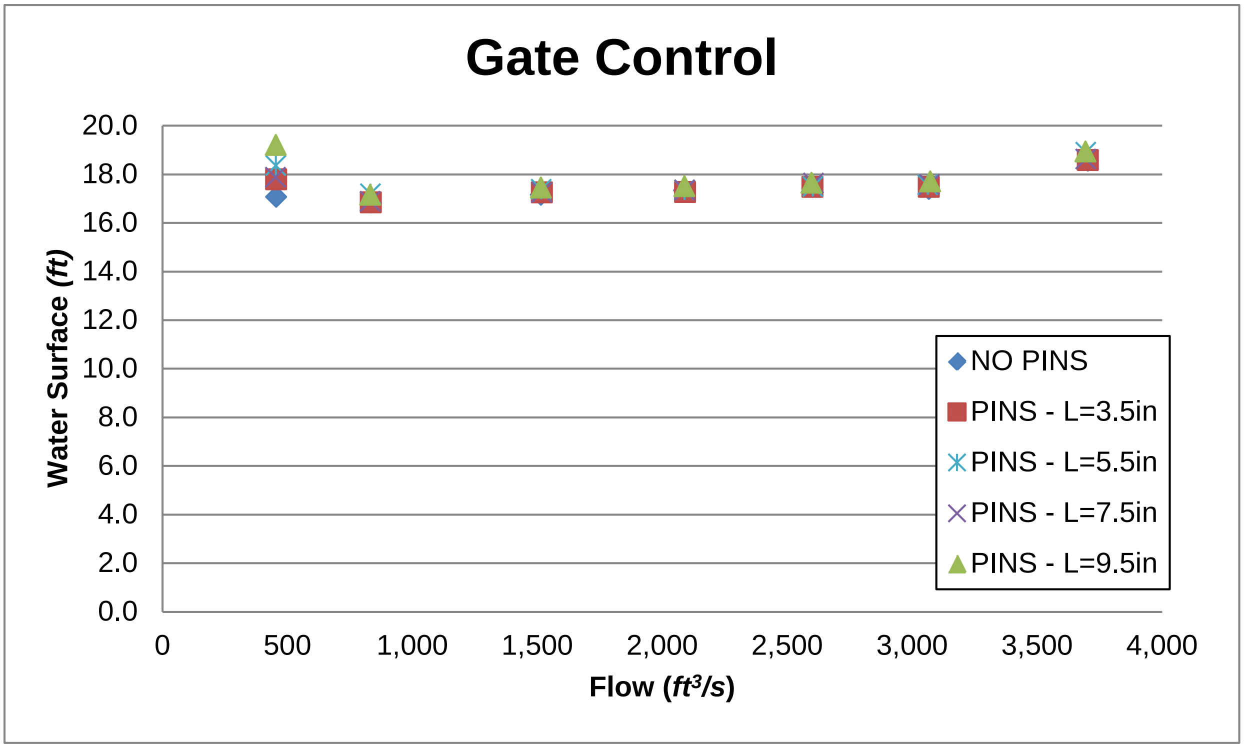

Figure 11 Water surface vs discharge results for all pin lengths compared to the baseline. Each flow rate corresponds to a different gate opening.

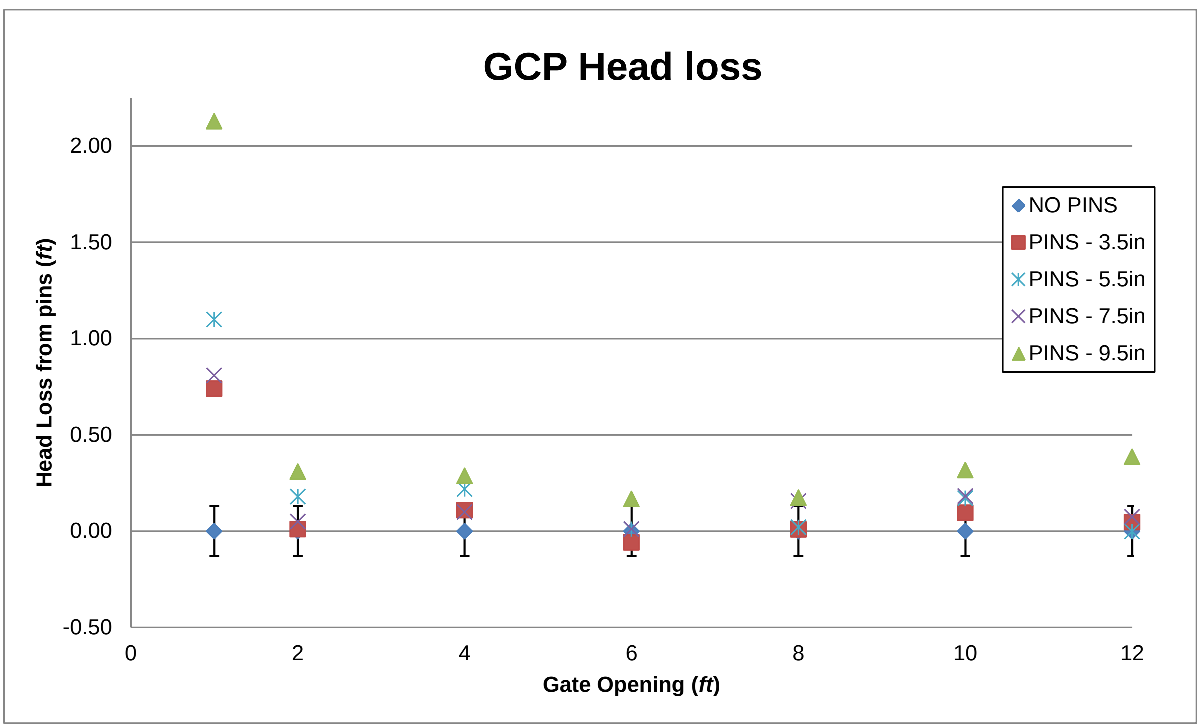

Figure 12 Head loss caused by the gate catcher pins for all pin lengths when compared to the baseline for the same discharge. Head loss is shown in prototype feet. Error bars show the water surface uncertainty of ± 0.13 ft prototype.

It is unclear why there was a drastic increase in head loss at the 1 ft gate opening for all pin sizes. Average velocities, using area of the gate opening and discharge, were not significantly greater at 1 ft than those for larger gate settings. Similarly, the reduction in flow area caused by the exposed pins at the 1 ft gate opening is similar to and even less than the larger gate openings. However, a difference in flow conditions at the 1 ft gate opening was observed.

Visual Flow Observations

Visual observations of the flow around the gate catcher pins were made through the clear acrylic pier walls and were helpful in identifying differences in flow conditions at various gate openings. The primary difference observed was a significant flow split around the top exposed pin that caused a jet to shoot up vertically around the pin. This "rooster tail" jet, which did not exist at the baseline condition with no pins, was most pronounced at the 1 ft gate opening and then decreased as gate opening increased (Figure 13). At gate openings greater than 4 ft the rooster tail was hardly visible.

The pronounced rooster tail at the 1 ft gate opening may be related to increased head losses that were measured for the same gate setting. The rooster tail may have formed because the flow stream lines have a greater horizontal component coming off the gate lip at a 1 ft opening (due to the radius of the gate) compared to larger gate settings. This allows the flow to strike the top exposed pin at a flatter angle that splits a greater portion of the flow over the top of the pin, causing a greater head loss. Stream line effects on a prototype spillway are unknown and may vary with spillway crest geometry which establishes the stream lines of the flow.

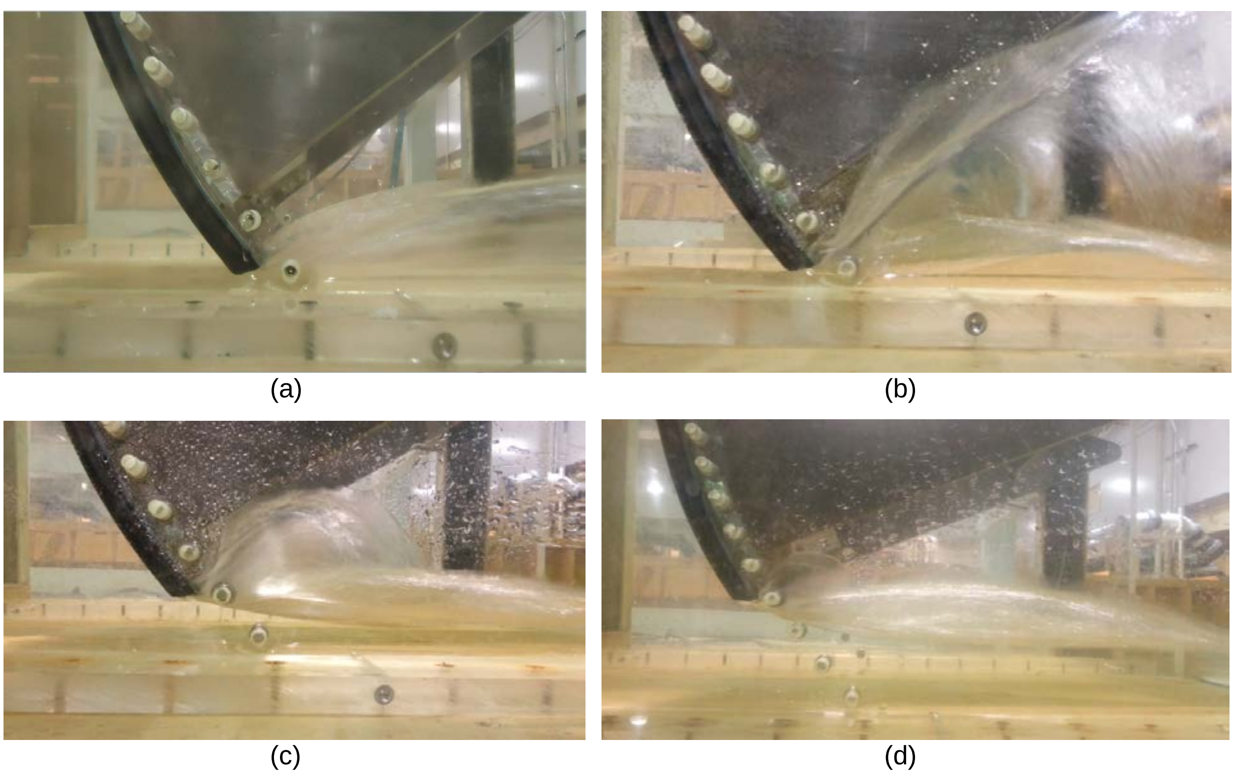

Figure 13 Visual observations of gate catcher pin impacts to flow near pier wall. The photographs show configurations of Go=1 ft, no pin (a), Go=1 ft, pin (b), Go=2 ft, pin (c), and Go=4 ft, pin (d).

Cavitation Potential

A basic analysis was performed to determine the cavitation potential of the gate catcher pins. Hydraulic conditions of the Echo Dam spillway with 3.5-inch gate catcher pins were assumed. Using a reference velocity of 25.7 ft/s (greatest velocity from model testing), the cavitation index was determined to be 2.7 (equation 4).

$$\sigma = \frac{P_o + P_a - P_v}{\rho {V_0}^2/2} \tag{4}$$

Engineering Monograph 42 (1990) was used to determine an incipient cavitation index for a cylinder protruding into the flow. Since no data were available for the specific geometry of the gate catcher pin, an index range was determined using assumptions from data available in the monograph in which incipient cavitation was likely to occur for the pin geometry. This resulted in an incipient index range of 1.75 to 1.0 which corresponds to a velocity of 32 – 42 ft/s respectively. Since this is not possible at Echo Dam, cavitation is not likely to be a problem with the pins for this case (or for most low-head radial gates). This analysis provides general conclusions to be considered for various sites and configurations. However, site-specific analyses may be necessary depending on the range of gate heads and discharges as well as geometry of the gate catcher pin. Cavitation characteristics of specific pin geometries can easily be determined from testing in the Hydraulics Laboratory if necessary.

Boundary Layer and Drag Considerations

Investigation of the boundary layer of the flow near the pier wall provides insights into hydraulic impacts of the gate catcher pins as well as potential differences between model and prototype. Due to potential size-scale effects near the boundary, this investigation was necessary to ensure that model results can confidently be used for prototype applications. Flow approaching the pins along the pier wall can be considered to behave similar to uniform flow along a flat plate. For a more detailed discussion of boundary layer characteristics, see Munson *et al* (2006). Using Equation 5 (Naudascher, 1991), the approximate boundary layer thickness was estimated for both model and prototype flow conditions, assuming flow was in the turbulent range.

$$\delta = \frac{0.377}{(Re_{bl})^{1/5}} x \quad where\colon Re_{bl} = \frac{v_o x}{\nu} > 5x10^5 \tag{5}$$

Table 1 shows calculations for the approximate boundary layer thickness for both model and prototype gate catcher pins. The main difference between model and prototype is that the model pin (L = 3.5 inch) likely does not protrude past the boundary layer into the region of uniform flow since the pin length in the model is only 0.29 inches. The opposite is true for the prototype pins which would protrude approximately 1 inch past the boundary into the uniform flow region. This may produce model results that underestimate the head losses of the prototype pins. However, testing additional pin lengths that are greater than the boundary layer thickness in the model (L = 0.46, 0.63, and 0.79 model inches) helped bracket the expected head losses expected for the prototype. As previously shown in Figure 12, the lack of significant differences in head loss results from longer pins in a similar flow condition as the prototype (protrusion through boundary layer) help confirm that model results will accurately represent prototype conditions.

Table 1 Boundary layer calculations along pier wall

	PROTOTYPE	MODEL		NOTES
x	18.22	1.52	*ft*	Distance along pier wall to gate catcher pin (bottom pin)
v_o	25.5	7.36	*ft/s*	Greatest flow velocity seen from model testing
v	1.22E-05	1.22E-05	ft^2/s	Kinematic viscosity of water
Re_{bl}	3.8E+07	9.2E+05		Reynolds number based on distance along plate
δ	2.51	0.44	*inch*	Boundary layer thickness at *x*

Drag is another consideration for differences in model and prototype flow conditions around the pins. Data are available which characterize the drag coefficient of a smooth cylinder (Figure 14, see Munson *et al* (2006)). These data are applicable to the cylindrical pins on the pier wall assuming they protrude past the boundary layer. As shown in Figure 14 and Table 2, the differences in *Re* number produce a significantly lower drag coefficient for the prototype pins than those of the model. This is due to the location of flow separation near the backside of the cylinder for more turbulent flow (Munson, Young, & Okiishi, 2006). The fact that there is less drag on the prototype pins compared to the model adds confidence that model results will not underestimate head loss due to drag for the prototype.

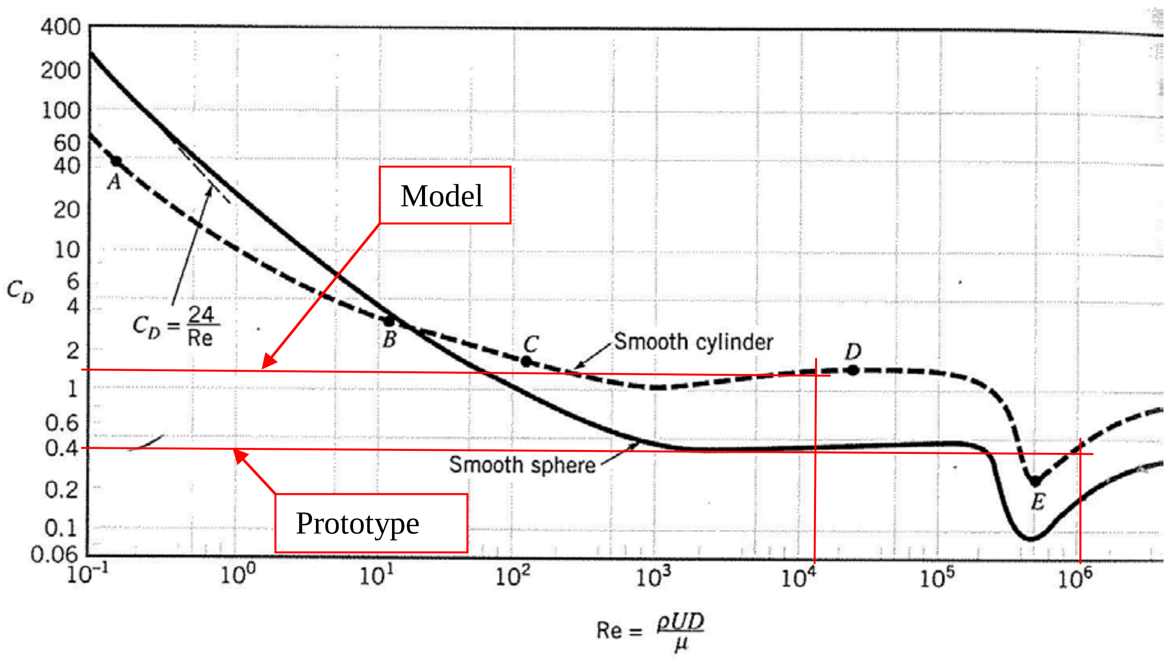

Figure 14 Plot from Munson *et al* (2006) that shows the relationship of the drag coefficient with Reynolds number for a smooth cylinder. Note the decrease in drag coefficient as Re approaches $1x10^6$.

Table 2 Drag coefficient estimations for model and prototype gate catcher pins.

	PROTOTYPE	MODEL		NOTES
D	6	0.50	*inch*	Diameter of gate catcher pin
v_o	25.5	7.36	*ft/s*	Greatest flow velocity seen from model testing
v	1.22E-05	1.22E-05	ft^2/s	Kinematic viscosity of water
Re_{cyl}	1.0E+06	2.5E+04		Reynolds number based on pin diameter
C_D	0.4	1.75		Approximate drag coefficient around a smooth cylinder

Dynamic Load Modeling

Impact force on the pins was predicted for a full gate failure at four different vertical gate openings using the impulse of the gate on the pins. Figure 15 shows a typical gate impulse where the left side consistently made the first impact causing the right side to swing around and impact the pins with a greater force. This sequence was the same for every test run which consistently caused a force that was 2 – 4 times greater on the right side. It was assumed that this type of failure was highly unlikely in the prototype for two reasons: first, most failures would likely involve only one side of the gate assembly; and second, if both sides did fail they would likely happen at different times and the gate motion of the second impact would be slowed by arm buckling and friction. Therefore, only results from the left side of the gate were used in the analysis since it always made the initial impact.

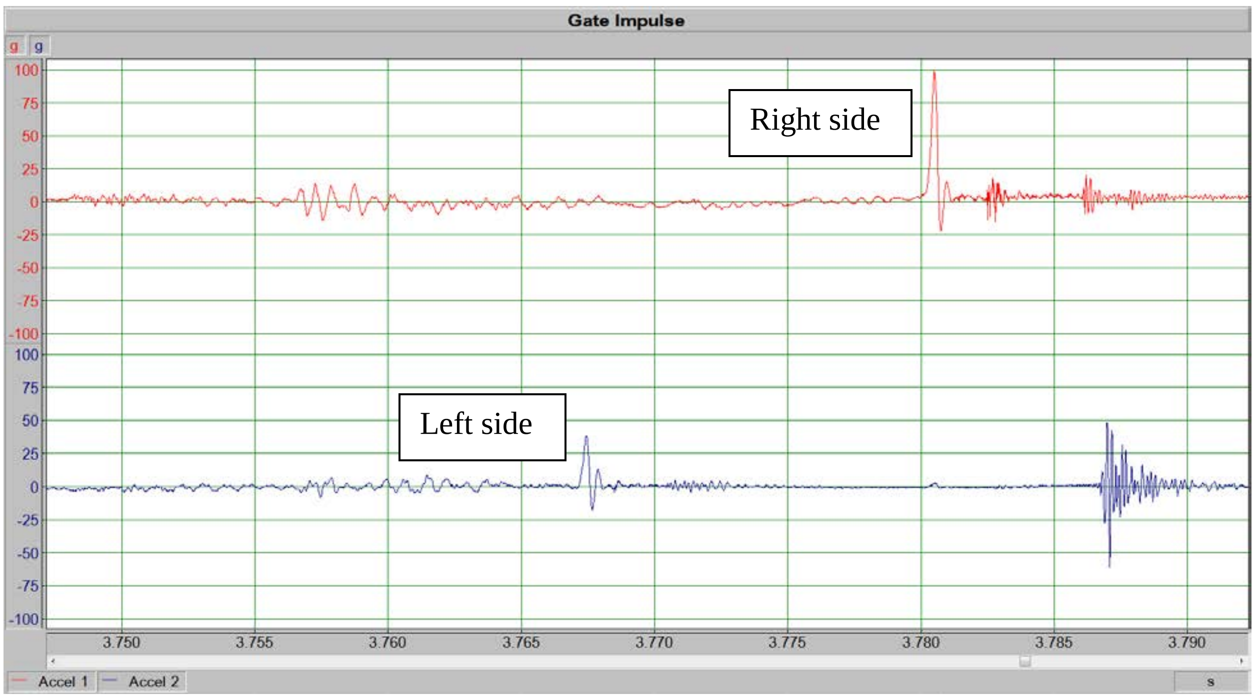

Figure 15 Impact signals from accelerometer on left and right side of the gate. The left side of the gate consistently impacted before the right side and was used in the impulse calculations.

Table 3 shows averaged dynamic impact force predictions for each of the gate openings that were tested which range from approximately 600,000 to 4.3 million pounds. The force trend increased with smaller gate openings as would be expected since there is greater upstream head on the gate for smaller openings. An interesting finding is that the average dynamic force on the pins for each gate opening was consistently about 20 times greater than the hydrostatic force on the gate.

Table 3 Impact force predictions for each of the four gate openings tested.

Go	Average Impact Force	Average Dynamic/Hydrostatic Force Ratio
ft	*lb*	-
0	4.33E+06	22
0.9	2.69E+06	16
5.5	1.47E+06	19
10	5.80E+05	21

Individual impact test results are shown in Figure 16 for each gate opening. For most gate openings, results were fairly consistent with exception to test runs made at the 0.9 ft gate opening. Scatter in the data may be caused by inconsistency in how the trunnion pins are released to cause the gate failure and slight differences in gate position which affects the location of accelerometer impact. However, the primary cause of scatter at the 0.9 ft opening is likely differences in reservoir elevations used for each of the test runs. Data used for force calculations are shown the Appendix.

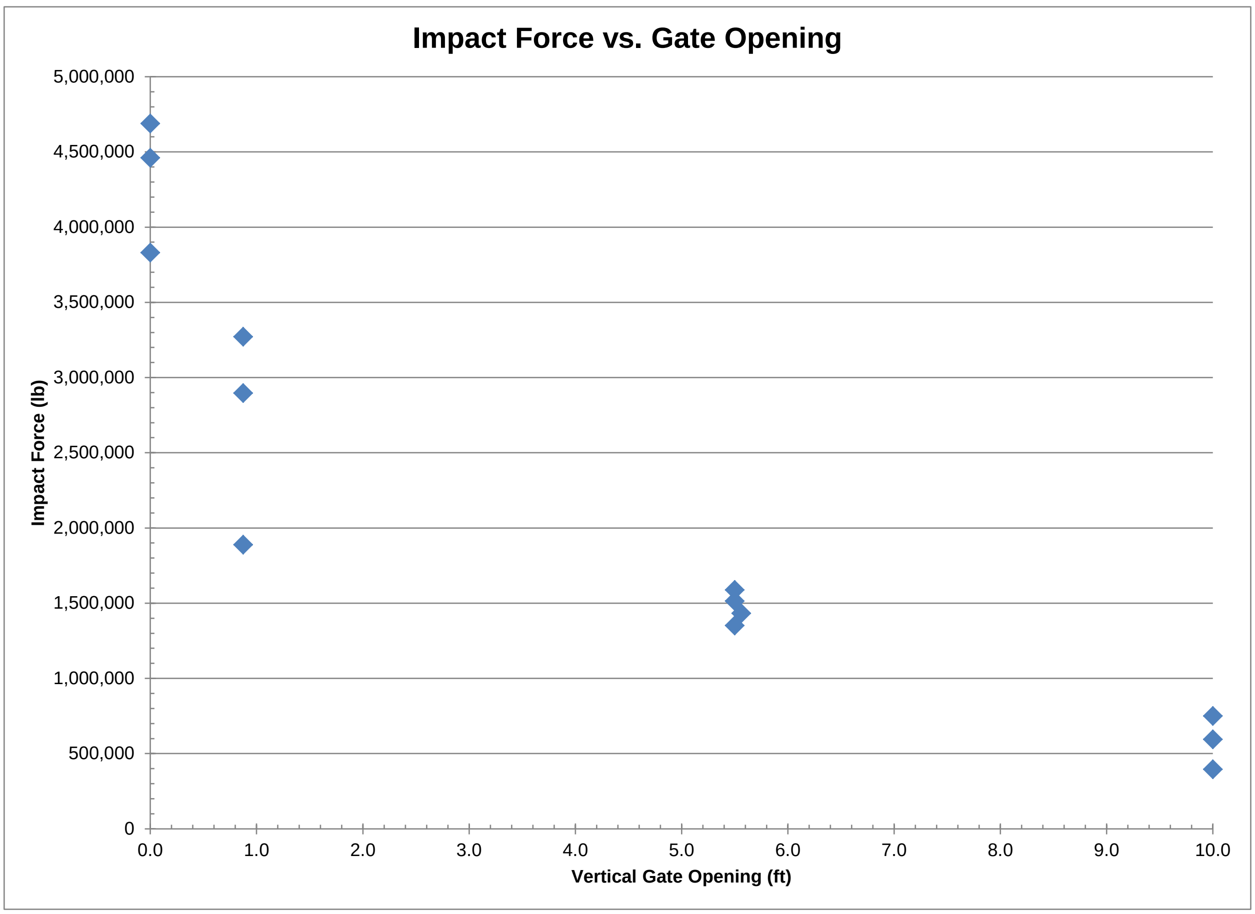

Figure 16 Impact force predictions of each run for the four gate openings.

High speed video verified that the gate always makes contact with the pins from bottom to top. After the gate is in contact with all the pins it then bounced off the pins at least once before coming to rest. The force of the water was sufficient to hold the gate in place on the pins without the hoist cable holding it open. For the 10 ft gate opening tests, after initial contact with the pins the gate flipped over the top of the pins instead of being arrested in place. It is not known if this would happen in a prototype gate since the center of mass of the gate assembly is different than that of the model gate. Also, both trunnion arms would have to be unattached for the gate to flip over the top of the pins. However, it should be pointed out that, depending on the prototype gate assembly, it may be possible for the gate to flip over the top of the pins if failure occurs at a higher gate opening. Photos from the 10 ft high speed video test of the gate failure are included in the Appendix.

Conclusions and Recommendations

Hydraulic Modeling

Physical measurements of upstream water surface and gate discharge for four gate catcher pin lengths (3.5, 5.5, 7.5, and 9.5 inches) were compared to a baseline condition with no pins. Results showed that there were no adverse hydraulic effects caused by the pins with the exception of increased head loss at very low gate openings. At a gate opening of 1 ft, each pin length increased the head loss and created a significant flow split around the pin shooting a vertical jet of water up over the top exposed pin. However, this flow split was reduced with greater gate openings and the head loss significantly decreased at gate openings of 2 ft and greater. For pin lengths less than 7.5 inches, results showed that head loss was not significant at gate openings greater than 2 ft. Cavitation was not measured in the model and is not expected to be an issue for the pins since the maximum velocity (25 ft/s) was not sufficient to cause incipient cavitation (32 – 42 ft/s required). However, further analyses may be necessary for each site depending on the range of gate heads, discharges, and pin geometry.

While results showed favorable flow conditions for multiple pin lengths, it is recommended that the standard pin length of 3.5 inches be used whenever possible. Pin lengths should not exceed 7.5 inches to keep head loss at a minimum. Also, for any pin length gate openings for long-term discharge should exceed 2 ft to prevent excessive head losses and a vertical flow split around the pin. This will ensure that the gate discharge capacity is not reduced. If it does not affect the structural design, another option may be to install the lowest pin at least 4 ft off the floor to reduce the vertical flow split around the bottom pin.

Dynamic Load Modeling

Impact force from a full gate failure simulation on the gate catcher pins was predicted for four different vertical gate openings using the impulse of the gate on the pins. A worst case scenario was tested in which the load of a free-falling gate assembly was taken by one pin on each side of the gate. While results varied with gate opening they showed that the dynamic impact could be up to 4 million pounds force on the pins. The dynamic force was approximately 20 times the hydrostatic force on the gate for each of the openings tested. High-speed video showed that the gate always contacted the bottom pin first and that the gate bounces off the pins slightly before coming to rest.

References

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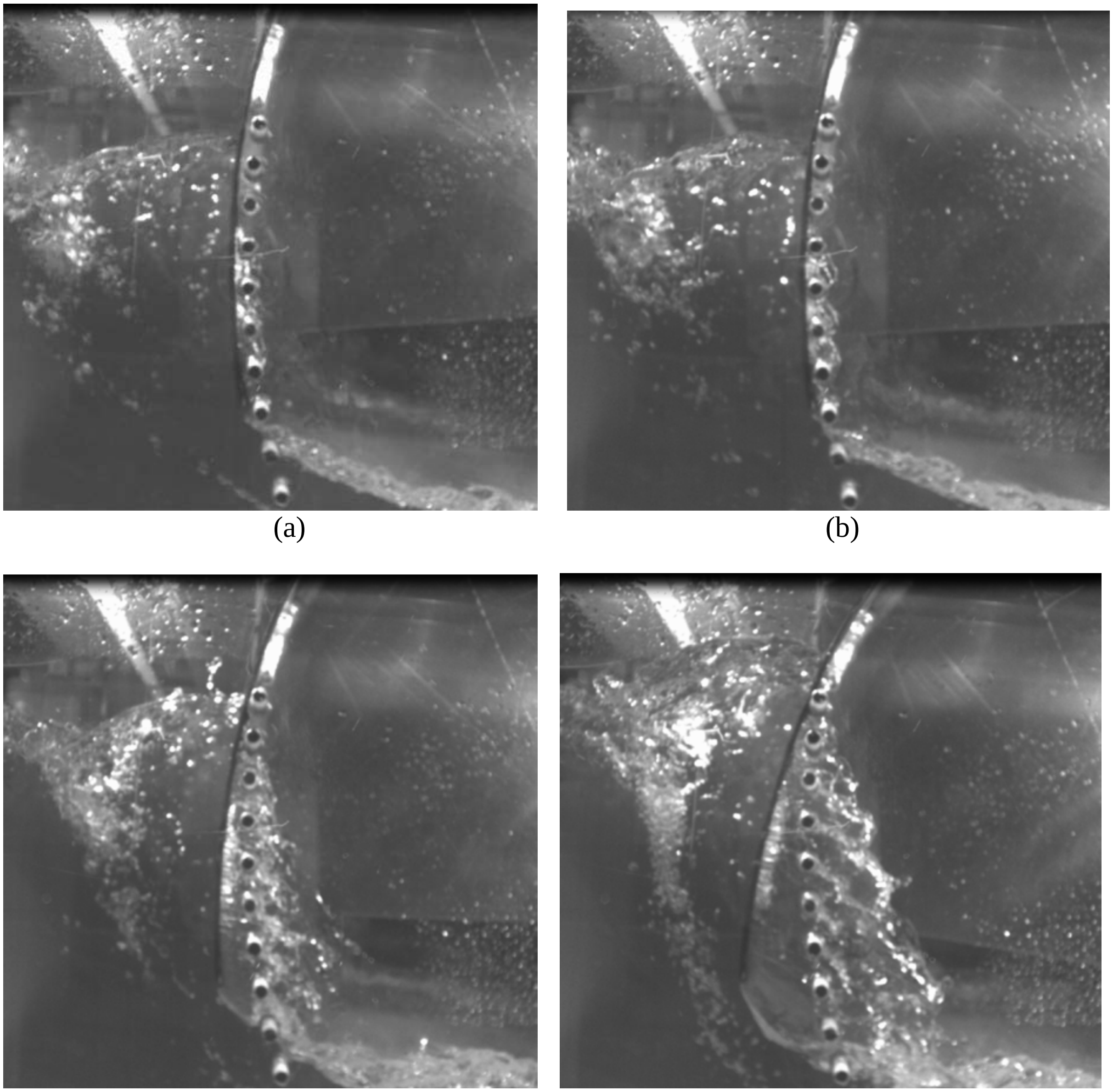
APPENDIX

Table 4 Data used for used for hydrostatic and dynamic force calculations.

	Prototype (calculated prototype force from scaled model dimensions - matches model force estimates)											
Go	**H**	**Hc**	**θ**	**Ah**	**Av**	**Fh**	**Fv**	**Fhydrostatic**	**Mean Accel**	**Impact Force**	**Dynamic/Hydrostatic**	**Avg. LS**
									LS	**LS**	**LS**	
ft	*ft*	*ft*	*deg*	*ft2*	*ft2*	*lb*	*lb*	*lb*	*g*	*lb*	-	
0.0	17.08	8.54	50.9	332	77.3	176,958	85,892	196,702	19.21	4,687,913	24	22
0.0	17.04	8.52	50.9	332	77.3	176,585	85,892	196,367	15.72	3,830,037	20	
0.0	17.18	8.59	50.9	332	77.3	178,078	85,892	197,710	18.21	4,460,537	23	
*0.9	17.10	8.11	47.7	311	63.8	157,569	70,880	172,777	23.68	*5,210,313	30	16
0.9	16.91	8.02	47.7	311	63.8	155,704	70,880	171,078	8.65	1,888,963	11	
0.9	17.06	8.09	47.7	311	63.8	157,219	70,880	172,458	14.88	3,270,252	19	
0.9	16.99	8.06	47.7	311	63.8	156,520	70,880	171,821	13.22	2,896,504	17	
5.6	17.16	5.80	32.5	212	18.7	76,739	20,742	79,493	11.30	1,432,169	18	19
5.5	17.10	5.80	32.5	212	18.7	76,755	20,742	79,509	11.94	1,514,017	19	
5.5	17.06	5.78	32.5	212	18.7	76,517	20,742	79,279	10.68	1,351,292	17	
5.5	17.02	5.76	32.5	212	18.7	76,200	20,742	78,972	12.57	1,587,546	20	
10	16.99	3.50	19.4	127	3.8	27,617	4,255	27,942	9.96	749,569	27	21
10	17.05	3.53	19.4	127	3.8	27,854	4,255	28,177	7.88	594,814	21	
10	16.80	3.40	19.4	127	3.8	26,858	4,255	27,193	5.30	394,722	15	

*Impact force was an outlier and not used in the analysis. This failure occurred somewhat differently than the others which is believed why it produced a significantly different result.



(a) (b) (c) (d)

Figure 17 Photo sequence of a gate failure at a 10 ft gate opening from before the gate is released (a) to when the gate begins to flip over the top of the gate catcher pins (d).