ERDC/CHL TR-21-5

Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
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Rough River Outlet Works Physical Model Study

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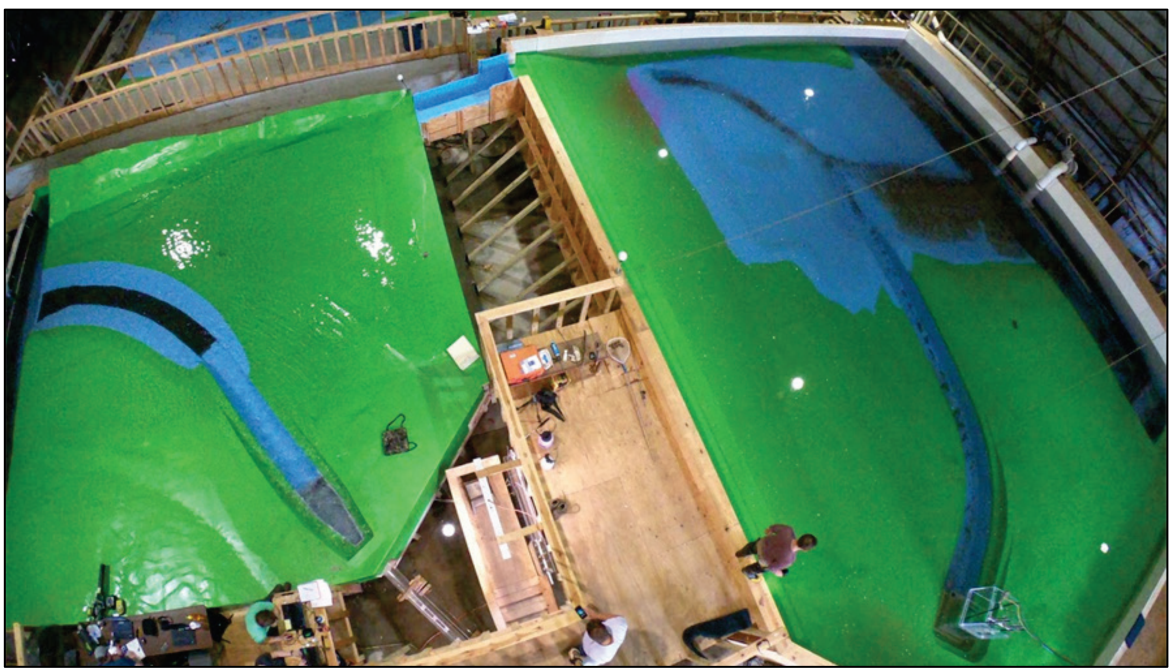
April 2021



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Final report

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Louisville, KY 40201-0059

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Abstract

The US Army Corps of Engineers, Louisville District, requested the support and assistance of the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL), in the evaluation of the hydraulic performance of the replacement Outlet Works for Rough River Dam. To support the design effort, CHL constructed a 1:25.85 scale physical model. The proposed features of the model in the domain are the curved approach channel, intake structure, transition, curved conduit, stilling basin, concrete apron, and retreat channel. Tests performed to evaluate the hydraulic performance illuminated a few design concerns. To address these issues, several key design changes were made. These included the retreat channel slope, end sill design, and transition design.

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Preface

This study was conducted for the US Army Corps of Engineers, Louisville District (LRL), under project identification “Rough River Outlet Works Physical Model Study,” MIPR W22W9K91624272. The technical monitor for the LRL was Mr. Jake Allgeier, H&H Rough River Lead.

The work was performed by the River and Estuarine Engineering Branch of the Flood and Storm Protection Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Mr. David P. May was Branch Chief; Dr. Cary A. Talbot was Division Chief; and Dr. Julie D. Rosati was the Technical Director for Flood & Coastal Risk Management Research and Development. The Deputy Director of ERDC-CHL was Mr. Keith Flowers, and the Director was Dr. Ty V. Wamsley.

The Commander of ERDC was COL Teresa A. Schlosser, and the Director was Dr. David W. Pittman.

1 Introduction

The US Army Corps of Engineers (USACE), Louisville District (LRL), requested the support and assistance of the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), in the evaluation of the hydraulic performance of the replacement Outlet Works for Rough River Dam. The project vicinity map and location are shown in Figure 1. To support the design effort of the newly proposed outlet works, CHL constructed a 1:25.85 scale physical model to validate and refine the proposed design.

This ERDC CHL report describes the process to determine refinements associated with the LRL design and operation for the new Rough River Dam Outlet Works, which includes the following structures: the Approach Channel, Intake Tower, Transition, Conduit, Stilling Basin, and Retreat Channel.

1.1 Background[1]

The Rough River Dam is located on the Rough River, 89.3 miles east of the confluence with the Green River (Figure 1). The existing outlet works at Rough River Dam were constructed between November 1955 and January 1958. The dam and spillway were constructed between May 1957 and December 1958. The dam was placed into service in 1960.

A Potential Failure Mode Analysis (PFMA) completed in 2008 indicated the dam foundation posed unacceptable risks from internal erosion failure modes at unusual and extreme reservoir loading conditions. The PFMA confirmed the results of a previous risk assessment, and the dam maintained a Dam Safety Action Classification (DSAC) 2 rating within the

[1] USACE LRL News Release February 13, 2018 (December 15, 2020)

USACE inventory[1]. In general, the PFMA identified four potential failure modes associated with concentrated leak erosion at various locations across the dam abutments and valley center: upper-left abutment, lower-left abutment, lower-right abutment, upper-right abutment, and internal erosion of the compacted embankment along the outlet conduit. A Dam Safety Modification Report (DSMR) was completed in 2012 that recommended implementation of an exploratory grouting program and a future cutoff wall to reduce risks associated with the dam. The cutoff wall was to go over and around the conduit followed by grouting from within the conduit and installation of a downstream filter.

The Dam Safety Modification Project consists of two major phases that have been broken into multiple contracts. The first contract, Phase 1A, consisted of relocating existing State Highway 79 to the upstream slope of the dam. The second contract, Phase 1B, utilized old Highway 79 on the crest of the dam to conduct exploratory drilling and grouting. Approximately 150 holes were drilled through the embankment to grout the foundation bedrock below the dam. Grout was observed exiting into the stilling basin through several weep holes during a period when the stilling basin was dewatered. The grout was being advanced from the dam centerline in a grout stage targeting the karstic Beech Creek Limestone. The grouting event confirmed the presence of an interconnected karst network below the dam with the potential for an undetectable, unfiltered exit during normal reservoir releases. Embankment cracks were also noted during drilling above the left and right Beech Creek Limestone. The Haney

[1] The Dam Safety Action Classification (DSAC) system is defined in USACE ER 1110-2-1156 as a system that provides guidance for appropriate actions to address dam safety issues and deficiencies within USACE. The five action classes within this system depict the range of dams from those critically near failure (DSAC 1) to those considered to have very low risk and which meet all essential USACE guidelines (DSAC 5). Classification 1 is for dams where progression towards failure is taking place under normal operations and the dam is almost certain to fail within a few years without intervention; these structures are given very-high urgency. Classification 2 is for dams where failure could begin during normal operations or be initiated by an event; these dams are given high urgency. Life-risk for Classifications 1 and 2 is considered by USACE to be unacceptable except in extraordinary circumstances. Classification 3 are dams that have moderate incremental risk, and USACE considers this level of life-risk to be unacceptable except in unusual circumstances. Classifications 4 and 5 represent progressively lower risk dams. Additional information regarding the DSAC system can be found in ER 1110-2-1156, section 3.2.4 and Appendix G.

Limestone in the upper left abutment encountered clay-filled solution features up to 50 ft[1],[2] wide and 50 ft deep.

A Semi-Quantitative Risk Assessment (SQRA) was completed in early 2016, which indicated the internal erosion had likely already initiated and progressed. The SQRA confirmed risks to the dam warranted a cutoff wall. The condition of the dam foundation posed significant risks to the structure, and a contract modification was implemented to almost double the scope of the project and fully complete both the upstream and downstream grout lines for slurry control in advance of the future cutoff wall.

During design for the cutoff wall in 2017, the existing outlet conduit was found to be structurally inadequate to support placing the cutoff wall around the conduit as proposed in the 2012 DSMR. In November of 2018, a DSMR Supplement was endorsed by the Dam Safety Senior Oversight Group (DSOG), which recommended a new left abutment outlet works design measure to complete the tentatively selected plan and safely install the cutoff wall across the dam foundation. During the meeting, DSOG voted to change the DSAC for Rough River Dam from DSAC 2 to DSAC 3 based on instrumentation that indicated the foundation of the dam had been temporarily stabilized. The DSOG noted in the memorandum that the foundation conditions at Rough River Dam will degrade over time and that foundation grouting is not a permanent solution.

In the time since grouting has been completed, the foundation at Rough River Dam continues to be monitored, and the dam still poses a very high Annual Probability of Failure exceeding tolerable risk guidelines at reservoir levels as low as 508 ft in elevation. Instrumentation indicates that piezometric pressure is higher near the conduit which suggest enhanced permeability in this area. The upstream dam crest has settled more along the right abutment, and the downstream dam crest has settled more than the left abutment. Expedient completion of the Phase II design

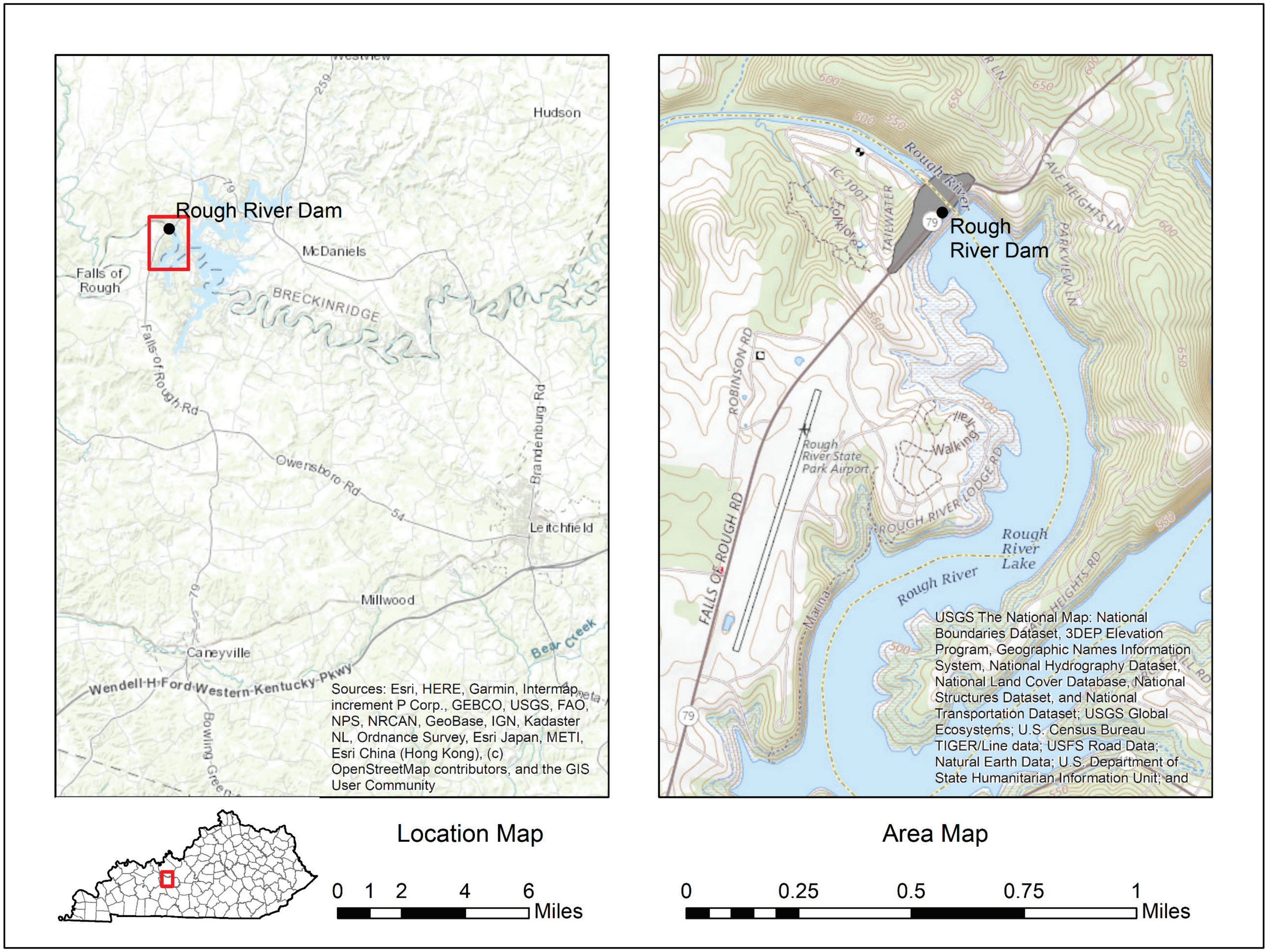
[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

and installation of the cutoff wall and outlet works are essential to maintaining the integrity of the structure during construction and for the long term.

The LRL Project Delivery Team (PDT) has completed the final design for the new outlet works at Rough River Dam based on the results and findings from the Rough River Outlet Works Physical Model Study. This study was completed by ERDC in a joint effort with the PDT and the Dam Safety Modification Mandatory Center of Expertise and the Lakes and Rivers Division Dam Safety Production Center. The new design alternative includes the construction of an entirely new outlet works for Rough River Dam.

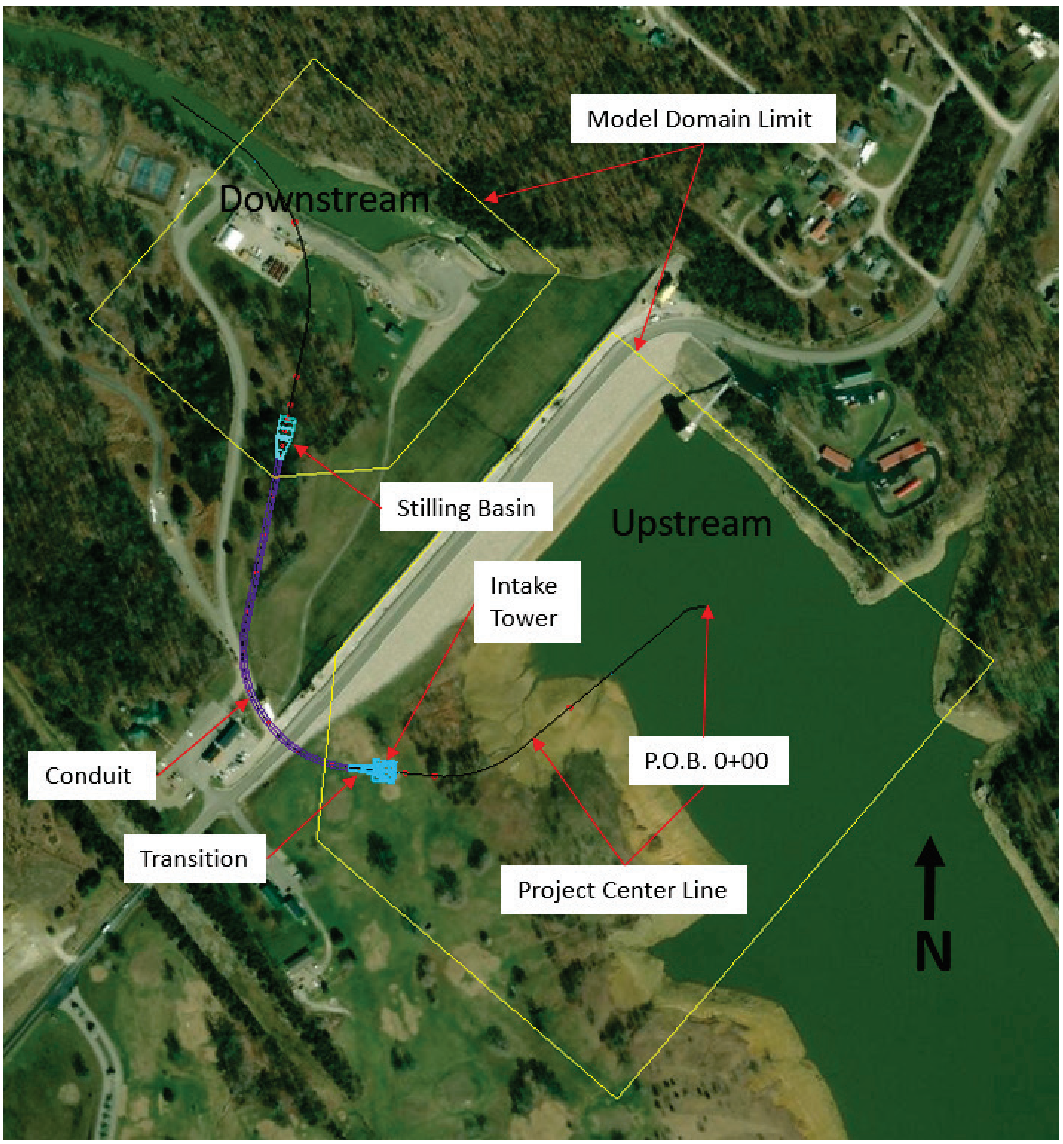
Figure 1. Site location as shown from final design submittal.



1.2 Objective

The objective of the study is to determine the optimum design and associated operational performance for the proposed Rough River Outlet Works (RROW). Specifically, the physical model evaluated the vortex potential of approach flow, refinement of the gate and conduit rating curves, performance of the transition monoliths, pressure to gravity flow transition in the conduit, stilling basin performance, and retreat channel performance (Figure 2).

Figure 2. Physical model domain and key features.



1.3 Approach

The physical model need was shown prior to this effort in the LRL computational fluid dynamics modeling. Furthermore, the numerical modeling assisted in determining the domain limits of the physical model. The physical model was simulated with varying boundary conditions as well as design alternatives in order to optimize the structure's design. Note that CHL has provided LRL with data separate from this report to include pictures, videos, monthly progress reports, and velocity data.

2 Process and Setup

2.1 Rough River Outlet Works (RROW) model design

The RROW physical model is a Froude-scaled 1:25.85 undistorted model (Table 1) with a domain that incorporates a portion of the Rough River Reservoir and Rough River retreat channel (Figure 3). The upstream or pool/reservoir section of the model is approximately 1280 ft by 1470 ft. The large upstream area or pool was desired to ensure that any flow circulation or eddies that formed in the reservoir would be present in the model. The downstream section or tailwater of the model is approximately 820 ft by 875 ft. The scale provides a fully turbulent flow with no surface tension influences on the model for the selected flows. Note: the fractional scale was selected for the facilitation of using a commercially available acrylic pipe size (6.5 in. inside diameter [ID], 7 in. outside diameter) for the model's conduit.

The construction method employed for RROW Physical Model bathymetry is the Waterways Lightweight Modeling System (WeLMoS). This is a new construction technique, and the RROW is the third physical model recently built with this method. The first model using WeLMoS was the Red River (Bell et al. 2020), and the second was the Low Sill Structure model[1]. The roughness of WeLMoS surface, for this study, is equivalent to a Manning's n of 0.015 (the value is based on a normal depth flume study). RROW structures are fabricated of acrylic with an equivalent roughness Manning's n of 0.009.

Table 1. Physical model scale conversions.

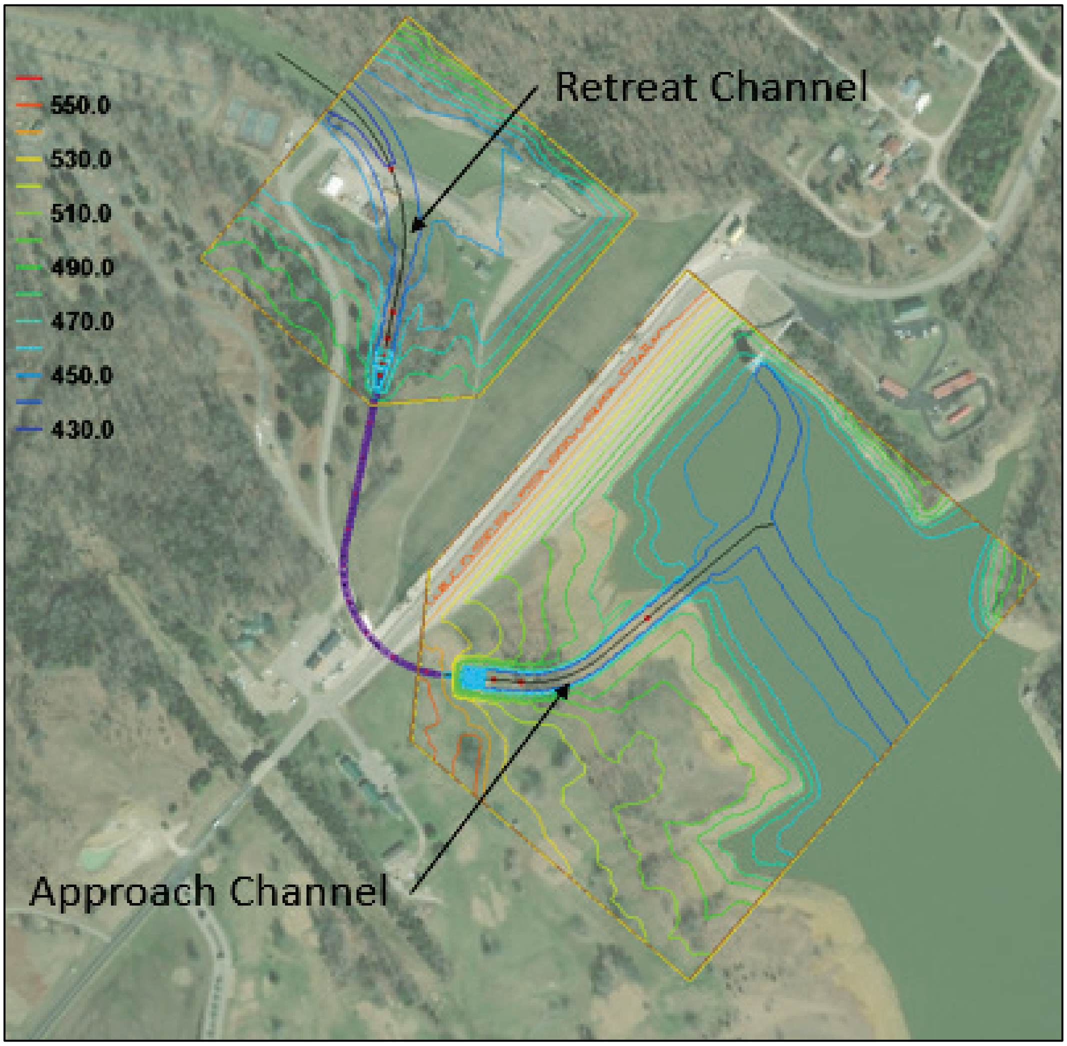
Variable	Froude Similitude Scale
Length	L_r = 25.85
Velocity	$L_r^{0.5}$ = 5.084
Time	$L_r^{0.5}$ = 5.084
Discharge	$L_r^{2.5}$ = 3397
Volume	L_r^{3} = 17,273

[1] Sharp, J. A., D. B. Bryant, and G. Savant. In preparation. *Low-Sill Control Structure Gate Load Study*. ERDC/CHL Technical Report. Vicksburg, MS: US Army Engineer Research and Development Center.

Bathymetry data, provided by LRL (Figure 3) established both the existing terrain and proposed features for the RROW physical model bathymetry. The bathymetry was trimmed to the physical model domain limits. Note that the horizontal datum is North American Datum 1983, State Plane Kentucky South Federal Information Processing Standards (FIPS) 1602 (US feet), and the vertical datum is National Geodetic Vertical Datum of 1929 (US feet). The conversion from NGVD29 to NAVD88 at the project location is -0.476 ft.

The model used two inflow lines for testing, nominal 12 in. and 8 in. diameter pipes, each controlled with a vertical gate valve. Supply for the inflow lines come from the facility's constant head tank. The turbulent flow at the head bay into the model was baffled through a discharge manifold and baffling material. Control vanes were used to achieve the proper inflow conditions. The 8 in. line controlled lower flow events while the 12 in. line controlled higher events and was employed during initial flood up. The tailwater in the model utilized a 22.5 ft long vertical lift gate with 49.54 ft of equivalent prototype vertical control. Tailgate settings, for repeatability, utilized a Leroy Type A Point Gauge with 0.001 ft resolution.

Figure 3. Bathymetric contours used in the construction of the RROW physical model.



2.2 Key feature locations

A stationing alignment (or project centerline, Figure 2), designed by LRL establishes the configuration of all key features of the RROW (Appendix A: Center Line Alignment and Model Layout). Model pictures with key features are in Figure 4 – Figure 6. The point of beginning is at X = 1423438.693, Y = 2109326.112, and is identified as station 0+00 with a total station length for the alignment of 30+69.058 ft. The project's key features are the following. The RROW has 2 – 6.25 ft wide by 14 ft tall mitered bottom vertical lift gates siting in the intake tower. The sill elevation is at 440 (NGVD29) while the invert elevation (el) of the approach channel at the base of the intake tower is at 435 ft. The intake tower upstream face is at station 9+36.9, and the physical model station is 9+36.80. The intake tower upstream face is 0.1 ft off due to program conversion issues; ERDC CHL uses Auto Cad Civil 3D. Thus, at model scale, the difference is 0.004 ft and makes no measurable impacts to model results. The el of 440 ft carries through the invert of the intake and into the transition section. The transition (Figure 2) length is 59.1 ft and starts at Station 09+96.9 and connects to the conduit at station 10+56. The conduit, 14 ft ID, is on a slope of 0.00299. The conduit curves and transitions into a straight section before the stilling basin. The conduit point of curvature is at station 10+56.7, and the point of tangency (PT) is at station 15+59.7. The radius of the conduit curvature is 300 ft and is a simple curve. Constructed of straight mitered sections, the conduit is comprised of sections that are typically 10 ft long. Where the conduit connects to the stilling basin, the station is at station 19+92.7. The stilling basin is a USBR Type-III basin, and the end of the basin is at station 21+11. From the end of the stilling basin, a monolithic concrete apron continues (Figure 4) downstream approximately 300 ft until the retreat channel joins the Rough River.

Figure 4. Downstream view of model, tailwater/retreat channel.

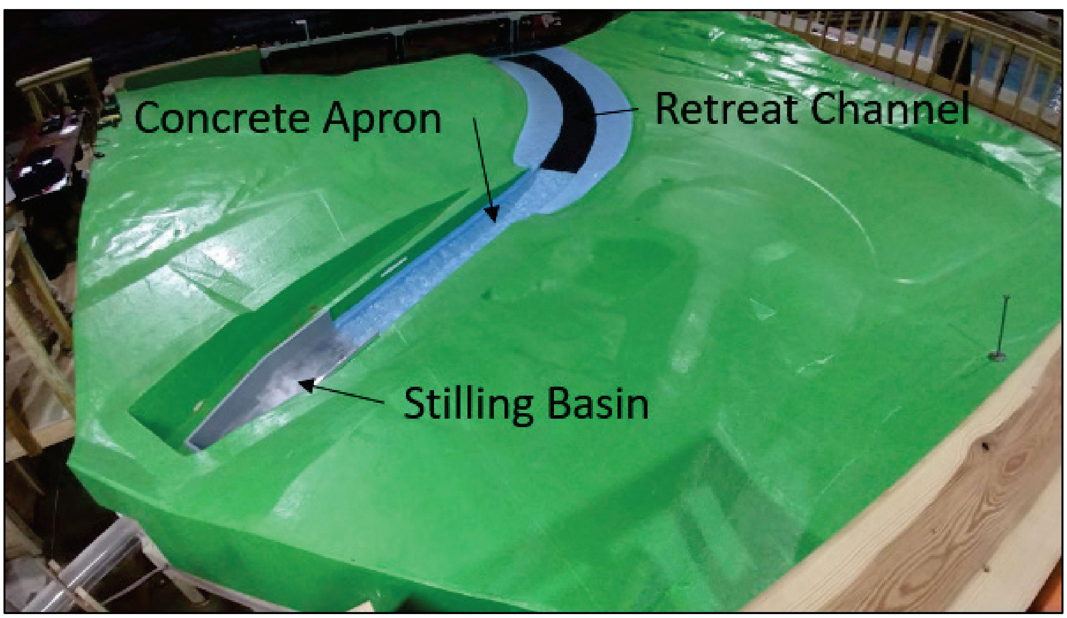


Figure 5. Upstream and downstream view of model.

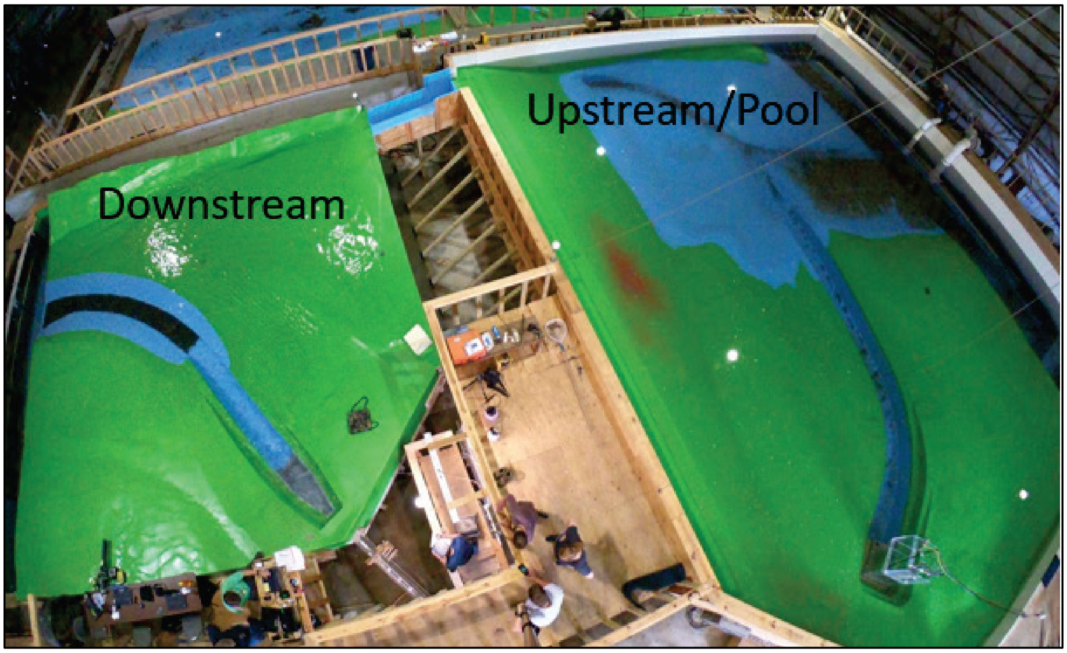
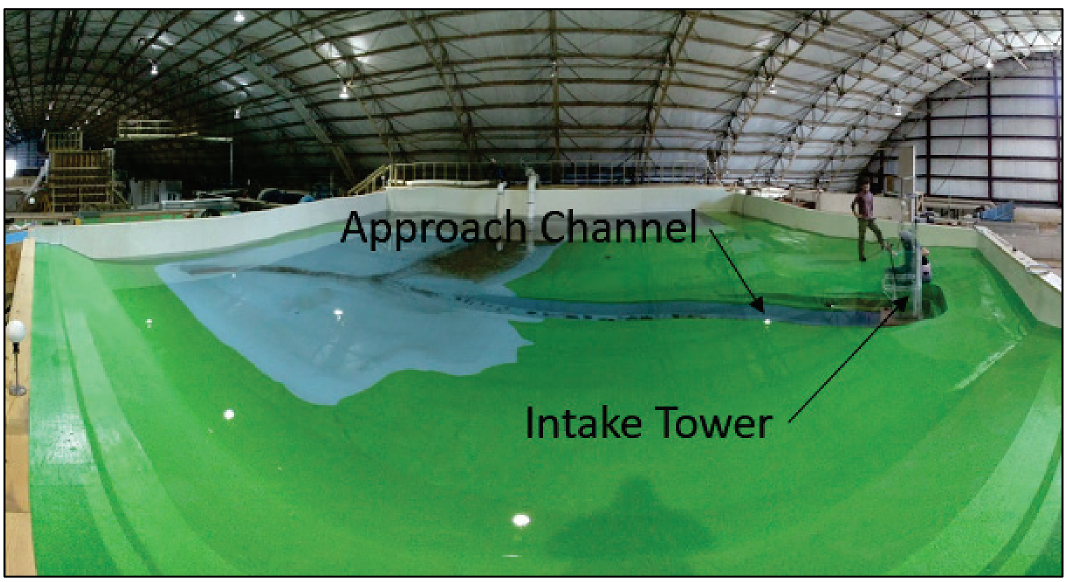


Figure 6. Upstream view of model, pool/headwater.



2.3 Model as-built

In hydraulic physical modeling, there are inherent uncertainties associated with scale, measurement, and constructability. With modern construction techniques, the error of constructability is more readily established. For the model layout of RROW, key features such as the intake tower corners, conduit, and stilling basin corners were surveyed using a 5 sec total station. Error associated with instrument shot distance was quite small since the shot distances were considered minimal. Because exact placement of surveyed points of the model structures is challenging, after construction, CHL conducted as-built surveys of the model to provide LRL confidence and possible error constraints in prototype design specifications. Achievement of these surveys applied a FARO Focus LiDAR Scanner (error of +/- 0.039 in. at a distance of 32.8 ft) of the as-built bathymetry and 5 sec total station (estimated instrument/operator error of +/- 0.15 in.) joint survey of the conduit. An estimated typical error of the as-built bathymetry was +/- 0.0116 in. (model), equivalent to +/- 0.3 in. (prototype).

The associated statistics for joint spacing of the conduit are in Table 2. The plan view of the centerline (CL) error between the design and model is shown in Figure 7. The modeled conduit CL is close to the design CL near the intake tower and beyond the PT of the curve. However, at approximately station 13+00, there is a deviation in the alignments such that the modeled conduit CL has a greater curvature radius than that of the design. The estimated modeled conduit CL curvature radius is 301.5 ft. As shown in the Table 2, the greater error occurred in the y-coordinate. In the curve, the y-error predominantly corresponds with longitudinal joint spacing.

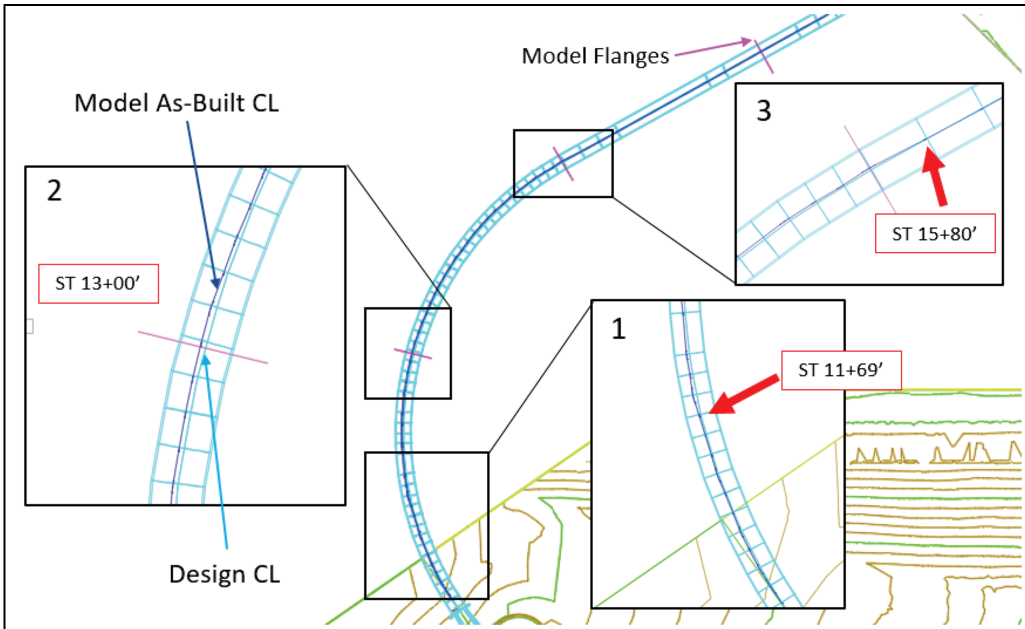
For the fabrication of the conduit, a two-part epoxy (SCIGRIP 11266 ACRYLIC 40 2-PART) glued adjacent conduit sections together. The epoxy performed well for conduit strength and water tightness; however, it caused a conduit growth in the overall length. The glue thickness was not accounted during the machining of the individual conduit sections to length. The glue thickness is equivalent to 0.025 – 0.035 in. (model or 0.65 – 0.90 in. prototype); adjustments were made to correct, but not all additional thickness was able to be removed.

Note: construction of the conduit in the model utilized connecting flanges with foam control joints (0.125 in. thickness). These flanges were the control locations for the conduit layout (Figure 8).

Table 2. Prototype vs. model as-built conduit joint locations error.

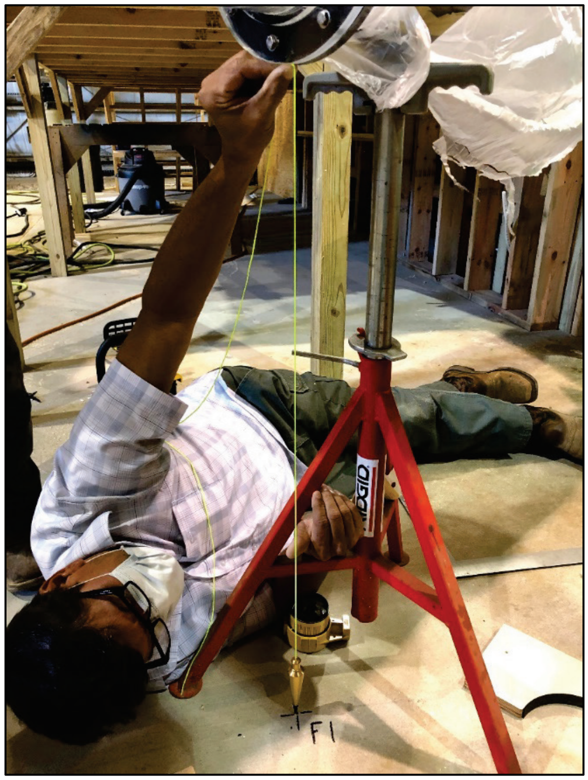
Calculation	Model, inch		Prototype, inch	
	ε x	ε y	ε x	ε y
Average	-0.130	-0.439	-3.354	-11.361
Standard Deviation	0.189	0.278	4.880	7.196
Variance	0.036	0.077	0.921	2.003
Median	-0.108	-0.539	-2.785	-13.938
Maximum	0.271	0.119	6.995	3.066
Minimum	-0.472	-0.832	-12.196	-21.499
Estimated Instrument/Operator Error (Prototype) +/- 4"				

Figure 7. Conduit design vs. model as-built error.



1. Location of centerline CL demarcation from design to model as-built, denoted by red arrow.
2. Location of greatest variation between design and model as-built.
3. Location of CL return between design and model as-built, denoted by red arrow.

Figure 8. Alignment of conduit with control points.



2.4 Data collection/instrumentation

For the discharge measurements, flow was measured using two ultrasonic flowmeters from EESIFLO International. The ultrasonic flow meter accurately measures flow within +/- 2% of reading (EESIFLO 2019).

A list of measuring locations is shown in Table 3. For water surface elevations (WSE) measurements at gauges stilling bucket (SB) SB 1 – SB 6, stilling buckets were utilized. For SB 1 – SB 3, gauge elevations were individually measured with a Leroy Type-A point gauge (error = +/- 0.001 ft) in a 5 in. × 5 in. stilling bucket. For SB 4 – SB 6, an ERDC custom point gauge, 5 ft long, was utilized in a 5 in. × 5 in. stilling bucket and has an estimated error of +/- 0.002 ft. The large range in headwater WSEs necessitated the long custom point gauges. Tailwater control utilized the reading of WSE gauge SB 6. Likewise, for the headwater control, WSE gauge SB 1 was used. Thus, these model gauges provide the head differential (ΔH) across the structure. Inside the intake tower, conduit, and stilling basin, piezometer taps were used to measure the hydraulic grade line (HGL). For pressure gauge (PG) PG 1 – PG 7, there are a right and left tap corresponding to the right and left gate passages.

PG 8 is the first tap directly downstream of the center pier in the transition section and is the location of the flow convergence from the two gates. From there downstream in the conduit, there is a tap at every station until the stilling basin.

Table 3. HGL locations along the project CL.

Location	Instrument Identification	CL Alignment Stationing		
		Model, inches		Prototype, feet
Approach Channel	SB 1	202.7		436.58
Approach Channel	SB 2	388.4		836.66
Approach Channel	SB 3	423.0		911.13
Intake Tower Face		**434.9**		**936.80**
Intake Tower	PG 1 L & R	449.6		968.49
Intake Tower	PG 2 L & R	456.1		982.54
Intake Tower	PG 3 L & R	457.3		985.01
Intake Tower	PG 4 L & R	458.9		988.55
Intake Tower	PG 5 L & R	461.0		993.05
MON 0	PG 6 L & R	463.5		998.54
MON 0	PG 7 L & R	466.6		1,005.05
MON 1	PG 8	477.5		1,028.61
Culvert	PG 9	510.6		1,100.00
Culvert	PG 10	557.1		1,200.00
Culvert	PG 11	603.5		1,300.00
Culvert	PG 12	649.9		1,400.00
Culvert	PG 13	696.3		1,500.00
Culvert	PG 14	742.7		1,600.00
Culvert	PG 15	789.2		1,700.00
Culvert	PG 16	835.6		1,800.00
Culvert	PG 17	882.0		1,900.00
Stilling Basin	PG 18	928.4		2,000.00
Stilling Basin	PG 19	942.8		2,030.90
Stilling Basin	PG 20	961.0		2,070.08
Stilling Basin	PG 21	974.1		2,098.46
Exit Channel	SB 4	991.8		2,136.59
Exit Channel	SB 5	1026.6		2,211.48
Exit Channel	SB 6	1212.3		2611.54

SB = Stilling Bucket

PG = Pressure Gauge Tap

L = Left Tunnel

R = Right Tunnel

2.5 Boundary conditions and model operation

Typical testing commenced with setting the intake towers gates to a specified opening (Figure 9 and Table 4). For gate movement, a 3/8 in. threaded rod was attached to a brass rod threaded into the acrylic gates. A brass knob threaded onto the rod allowed for user operation. Position was measured with a custom Vernier rod with estimated error of +/- 0.002 ft. The gate control provides tight tolerance for gate settings (Table 4).

Establishment of influent flow occurred through either the 8 in. or the 12 in. supply lines. Both lines have a gate valve for flow control. Often, for high pool levels, both lines where operated to fill the reservoir faster. Then the tailwater was established for the respective flow condition. The rating curve provided by LRL and shown in Figure 10 was used to set the tailwater. Testing would commence, and the pool WSE would periodically be checked at SB-1 for the establishment of an equilibrium pool. Equilibrium is defined as pool changes of <0.001 ft over a 15 min period. Once at equilibrium, the HGL through the RROW was collected, and a video of the RROW conditions was taken.

Figure 9. Intake tower gate controls.

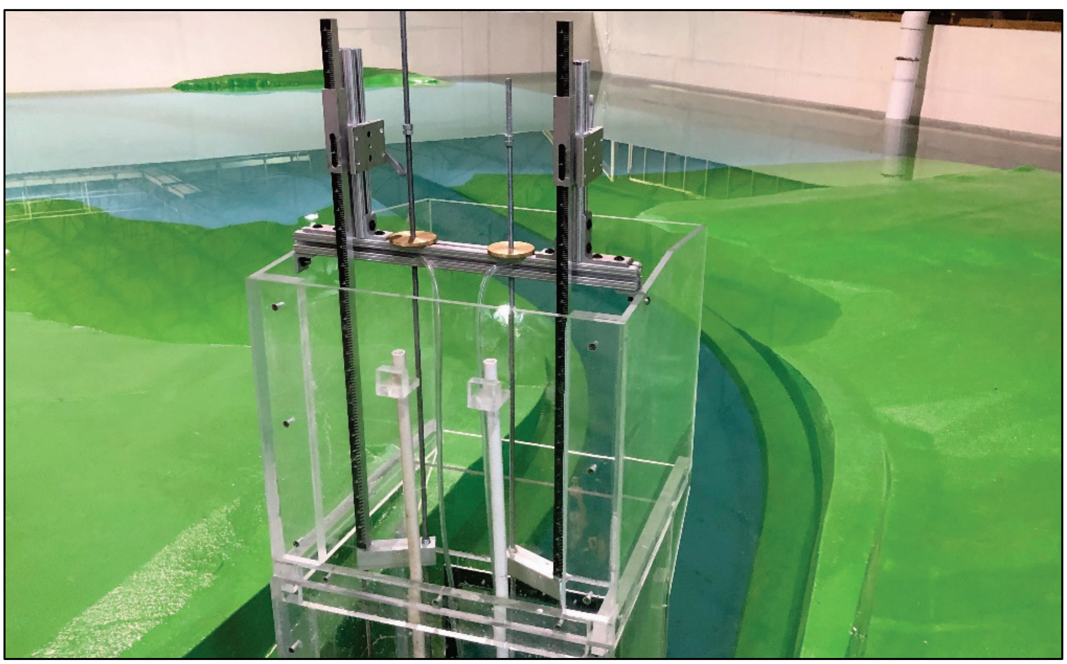
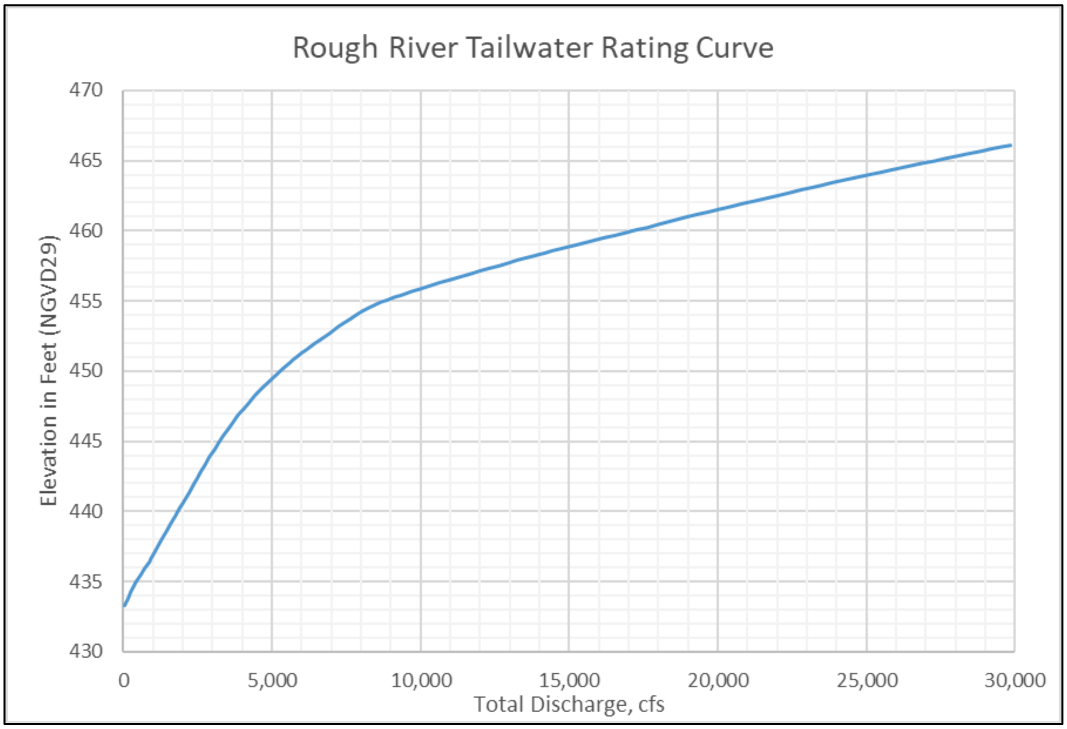


Table 4. Gate openings.

Gate Opening		
% Gate Open	Prototype, ft	Model, ft
0%	0	0.000
5%	0.7	0.027
10%	1.4	0.054
15%	2.1	0.081
20%	2.8	0.108
25%	3.5	0.135
30%	4.2	0.162
35%	4.9	0.190
40%	5.6	0.217
45%	6.3	0.244
50%	7	0.271
55%	7.7	0.298
60%	8.4	0.325
65%	9.1	0.352
70%	9.8	0.379
75%	10.5	0.406
80%	11.2	0.433
85%	11.9	0.460
90%	12.6	0.487
95%	13.3	0.515
100%	14	0.542

Figure 10. Tailwater rating curve for the RROW.



3 Design Modifications

Through the course of initial testing, several modifications where determined to be beneficial to the performance of the RROW. These modifications include retreat channel improvements, end sill variates, and transition re-design. The retreat channel modification included a zero-slope grade across the 300 ft downstream apron. Additionally, the engineered channel slope was reduced and KYTC Class III 14.5 in. Channel Lining was added to the bed. The rip-rap size was acceptable since it is 300 ft downstream of the stilling basin and will not be exposed to high velocities. The stilling basin end sill performed best with a fully dentate end sill. The LRL transition was modified based on guidance found in EM 1110-2-1602, *Hydraulic Design of Reservoir Outlet Works* (USACE 1980).

3.1 Retreat channel

As usual, a hydraulic jump formed in the stilling basin. However, during initial testing of the original retreat channel design, a second hydraulic jump formed between the downstream apron and trapezoidal channel. The second jump formed because the retreat apron's longitudinal slope was steep enough to create super-critical flow conditions immediately downstream of the stilling basin end sill. Further, downstream, the tailwater was sufficient to transition the flow back to sub-critical. Attempts to reduce or eliminate the formation of the second jump were made but were unsuccessful. Multiple baffle block configurations were tried to prevent any secondary jump: baffle blocks, chute and baffle blocks, chute and super baffle blocks, super baffle blocks, and end sill only. WSEs were measured between sta 20+00 and 23+00 to evaluate the different designs. These measurements are shown in Figure 11 and indicate minimal changes between the designs. The re-acceleration occurred due to the hydraulically steep slope on the apron and retreat channel (slope 1.1%) (Figure 12). Thus, changes that are more extensive were required to eliminate the secondary jump.

These changes include three modifications. First, the concrete apron (300 ft length downstream of the end sill) was changed to a 0% slope in the retreat channel at a 429.3 el (same as stilling basin floor elevation). Second, the trapezoidal channel slope (0.0057 ft/ft) was modified, plus adding Class III stone to the bed (14.5 in. uniformly graded stone). Finally, the end sill el was lowered, and there was an opting for a fully dentate end sill. These modifications eliminated the undular/weak jump in the retreat channel and maintained the ability to dissipate energy across the range of flow conditions tested.

Note: gradation of the Class III stone for the model is material passing the 5/8 in. screen (16.15 in. prototype) and retained on the ½ in. screen (12.93 in. prototype”). Thus, the mean size is 14.5 in.

Figure 11. Flow profile through stilling basin and retreat channel for various stilling basin configurations.

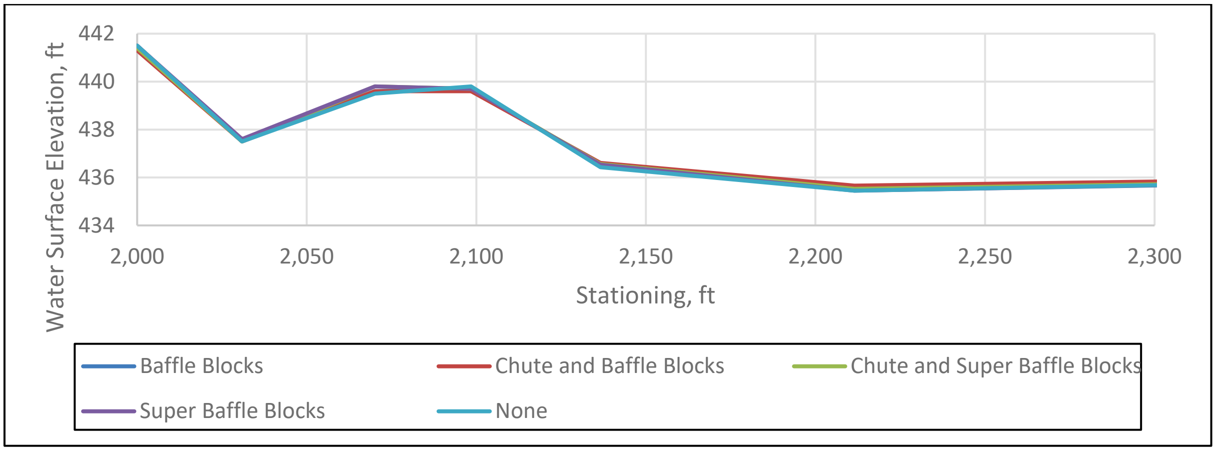
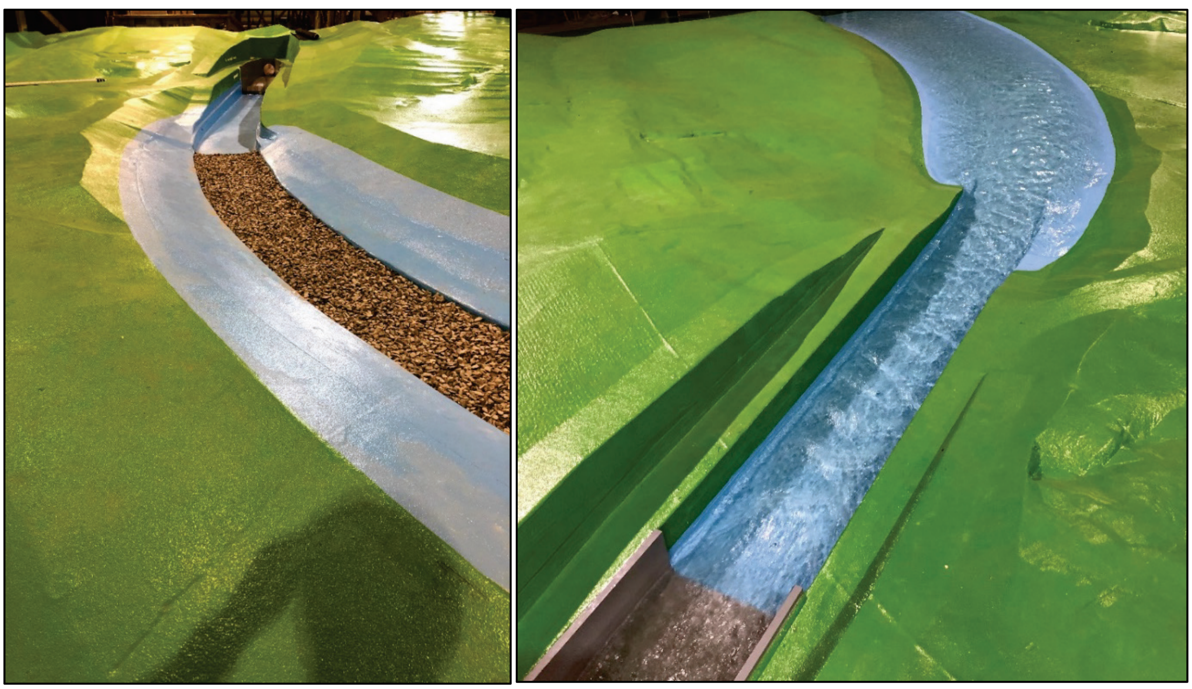


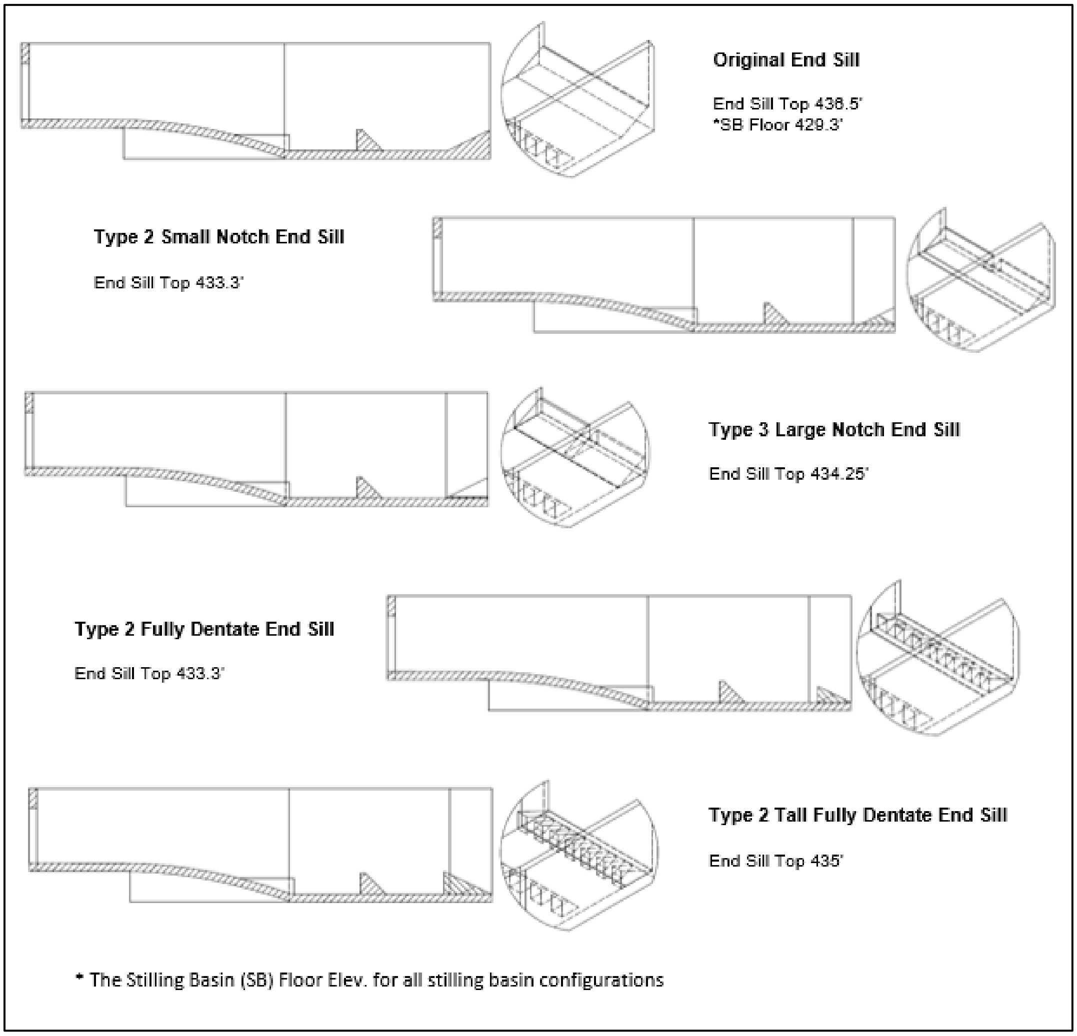
Figure 12. Completed modified retreat channel (left) and original design (right).



3.2 End sill

Performance evaluation of multiple end sills in the model determined an optimal design. An optimal design was considered one that facilitates proper energy dissipation, jump sweep out resilience, and operation/maintenance sustainability. Figure 13 shows the various end sill designs. Testing of the original end sill occurred only with the original retreat channel design and was not tested with the modified retreat channel. Then, the Type II small notch, Type III large notch, and both Type II fully dentate end sills were evaluated with the modified retreat channel. Note: chute blocks where initially reviewed but deemed unnecessary.

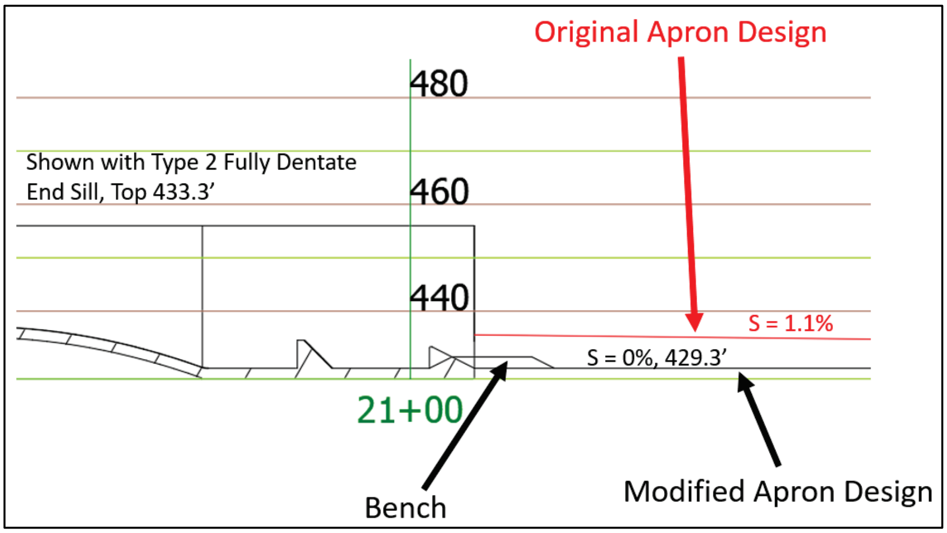
Figure 13. Various end sill configuration for the stilling basin.



3.3 End sill bench

A bench downstream (Figure 14) of the end sill facilitates the maintenance requirement for dewatering the stilling basin. It provides a raised area, which reduces the required height of a dewatering structure such as HESCO[1] baskets. The Bench is 15 ft long and traverses the entire width of the stilling basin.

Figure 14. Downstream bench detail at the end on the stilling basin.



3.4 Transition EM 1110-2-1602 (USACE 1980) vs. Louisville District (LRL) design (Singh 1969)

The PDT had questions and concerns about the Singh (1969) transition design, tested in the model (Figure 15). Note: the test data for the Singh design are in Appendix B: Singh Design Transition Test. Of primary concern was the potential for cavitation due to some of the non-tangential geometric transitions in the Singh Design Transition. Additionally, there was concern for flow separation off the downstream end of the pier, which forms a *rooster tail* that impacts the crown of the conduit. Thus, it was decided to change the design to the EM 1110-2-1602 (USACE 1980)-recommended transition design. The Singh Design Transition is shown in Figure 15, and the EM 1110-2-1602 Transition Design is shown in Figure 16, and the design under construction is shown in Figure 17. For both designs, the general specifications remained unchanged (length and conduit size). One variation from the EM 1110-2-1602 design layout is that it is slightly shorter by

[1] https://www.hesco.com/

approximately 2 ft. The shortening ensured the preservation of established location for the intake tower and conduit.

Figure 15. Singh design transition, isometric transparent view.

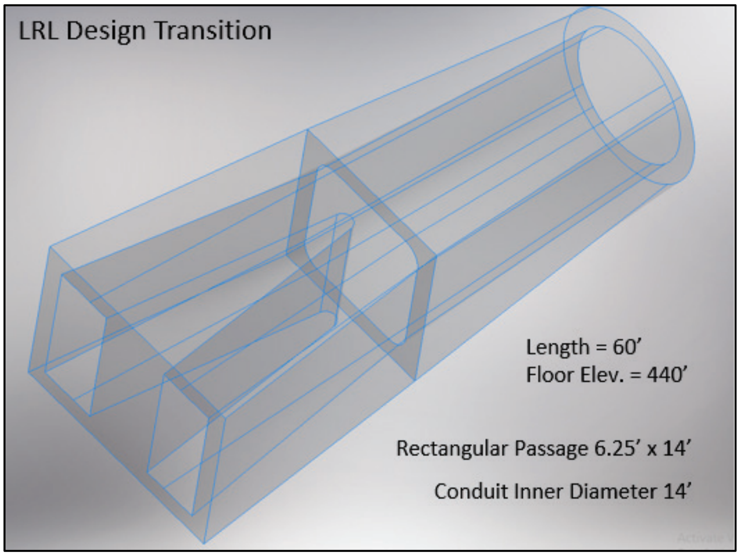


Figure 16. EM 1110-2-1602 transition.

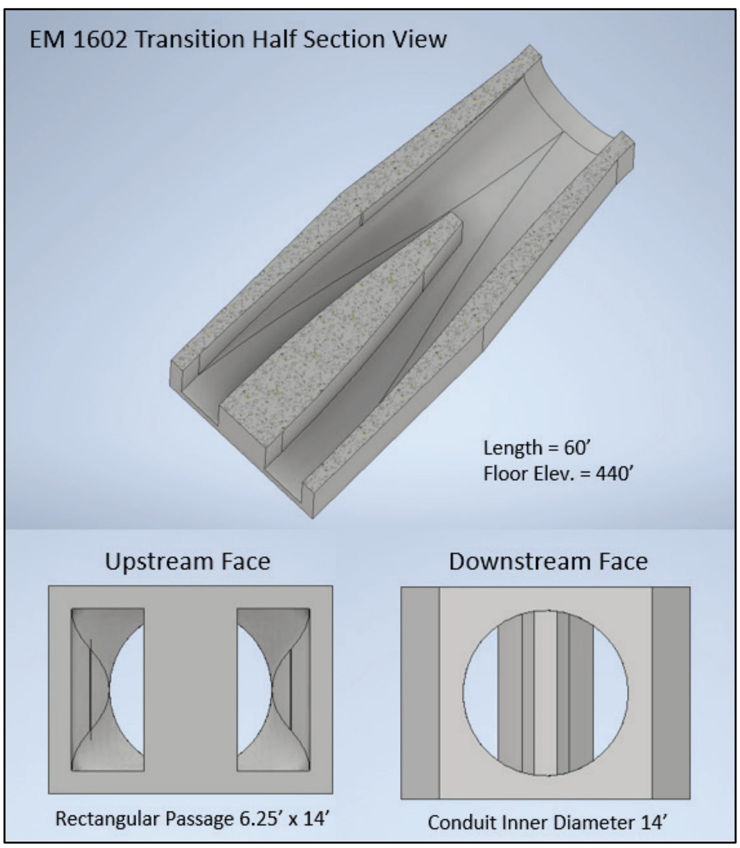
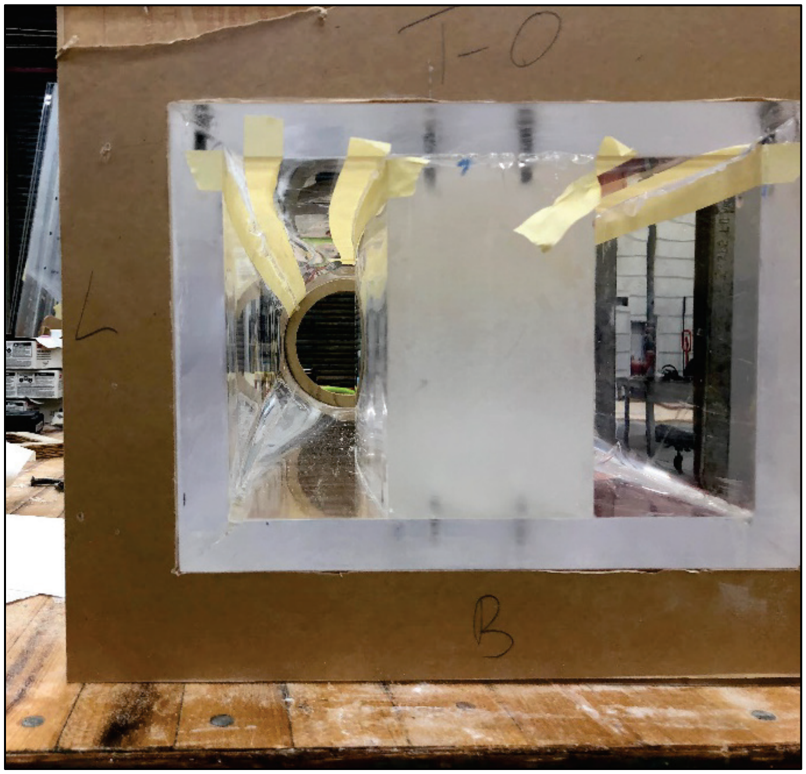


Figure 17. Fabrication of 1602 transition, looking downstream into the transition.



3.5 Test schedule for modifications

The model test schedule for evaluating the design modifications is shown below in items I-VIII.

I. Test 1 – 77 the Singh design transition was installed.
II. Test 47_1[1] – 56 retreat channel modification tests: concrete apron and end sill change. Includes all the end sills with the exception of the original end sill and the Type 2 tall fully dentate end sill.
III. Test 57 (10_2_2020) and beyond the Type 2 fully dentate end sill was installed.
IV. Test 78 (10_19_2020) and beyond the EM-1110-2-1602 (USACE 1980) transition was installed.
V. Test 92 (10_26_2020) and beyond the fillets to stilling basin were added and the distortion on the bottom of the trash rack was fixed.
VI. Test 105 (11_4_2020) and beyond the bench downstream of the stilling basin was added.

[1] Some tests had duplicate numbering, so "Test #_#" was applied in these cases.

4 Results

Data from 205 tests were collected for the 10 flows and multiple gate settings provided by LRL. Tests numbered 1 – 77 are data collected from the LRL design transition (Appendix C: Singh Design Transition Tests). Test 78 – Test 205 are data collected with the EM 1110-2-1602 (USACE 1980) transition.

4.1 Hydraulic grade line (HGL) profiles

The HGL profiles, Figure 18 – Figure 25, are the measured water elevations or piezo metric pressure readings at each of the gauge locations as laid out in Table 4. Each figure has the high and low pools for the flow along with the flow (if it occurs) at which the conduit pressurized. Additionally, Table 5 – Table 12 are provided containing the measured values for each flow at every gate opening tested and are located below the figures. Then, Table 13 has additional HGL profiles for flow cases not associated with the incremental flows. Finally, Table 14 has the single gate operation HGL profiles.

Figure 18. 500 cfs HGL.

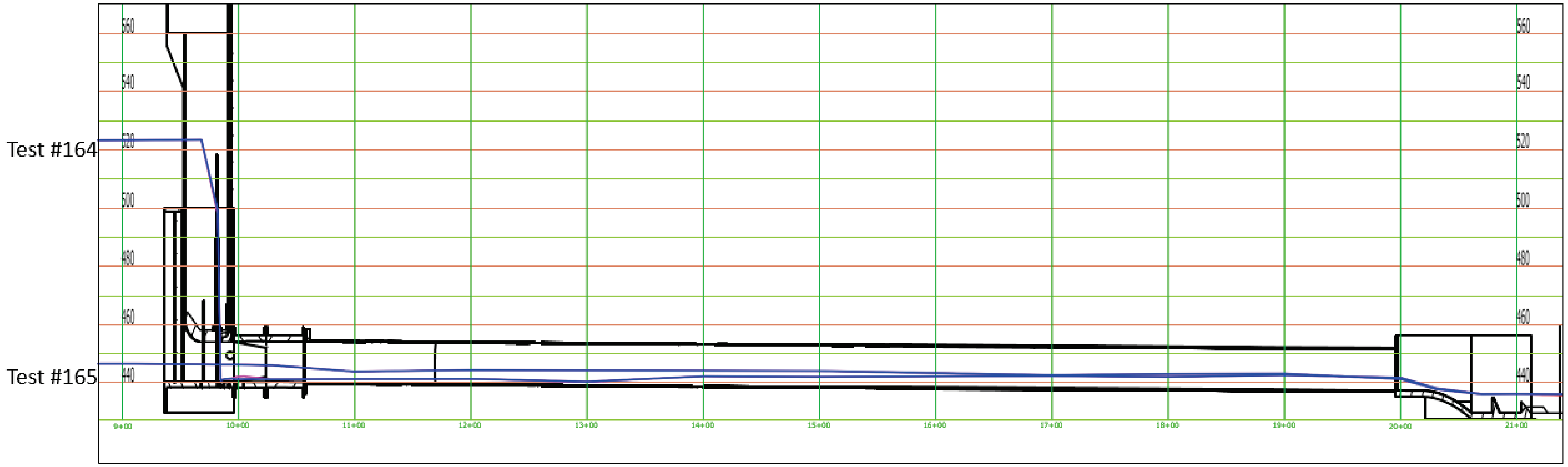


Table 5. HGLs for the 500 cfs flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Water Surface Elevation																																	
40%	105	500	447.24	447.17	447.17	447	447	446.7	447.9	446.5	446.6	446.6	446.7	446.8	446.5	446.5	446.5	446.5	446.6	446.5	444.3	445	444.9	444.5	444.3	443.8	443.4	443.5	443.5	441.4	437.8	435.9	435.9	435.55	435.53	435.45
30%	137	500	447.99	447.94	447.97	447.9	447.8	446.9	446.8	446.1	446	446	445.9	446.1	446.2	446.5	446.4	446.7	446.6	446.8	444.4	445.2	445	444.9	444.7	444	443.8	443.8	443.8	441.6	437.9	435.7	436	435.5	435.63	435.63
20%	138	500	449.57	449.52	449.54	449.7	449.7	446.8	446.6	444.3	443.9	444.2	442.8	445.1	442.7	445.9	442.9	446.1	444.9	446.9	444.4	445.2	445	444.9	444.7	444	443.8	444	443.9	441.8	437.9	435.8	436	435.66	435.66	435.5
10%	139	500	464.92	464.9	464.92	465.1	465.1	455.9	455.8	442.3	442.3	441.5	441.6	441.6	441.7	441.7	441.7	441.9	441.8	443.5	442.6	442.1	442	442.7	443.2	443	442.9	443.4	443.6	441.5	437.8	435.8	436	435.63	435.6	435.5
15%	158	500	451.79	451.79	451.82	451.8	451.8	438.8	443.3	443.3	443	442.1	442	442.1	442.1	442.1	441.9	442.2	442.2	443.9	443.5	442.9	443.9	444.8	444.5	443.4	444.2	443.4	443.5	441.5	437.8	435.6	435.9	435.6	435.6	435.47
5%	164	500	523.06	523.03	523.06	523.2	523.2	497.7	499.2	440.7	440.5	441	441	441	441.2	441.8	440.9	442	441	440.9	441	441.1	440.1	442	441.8	442	442.1	441.8	442.4	441.5	437.8	435.9	436	435.86	435.84	435.71
100%	165	500	446.31	446.26	446.29	446.1	446.1	446	446	446	446	446	446	446	446	446	446	446	445.9	445.8	443.6	444.1	444	443.9	443.8	443.1	442.4	442.8	442.9	441	437.5	435.8	435.9	435.76	435.68	435.63

Figure 19. 1000 cfs HGLs.

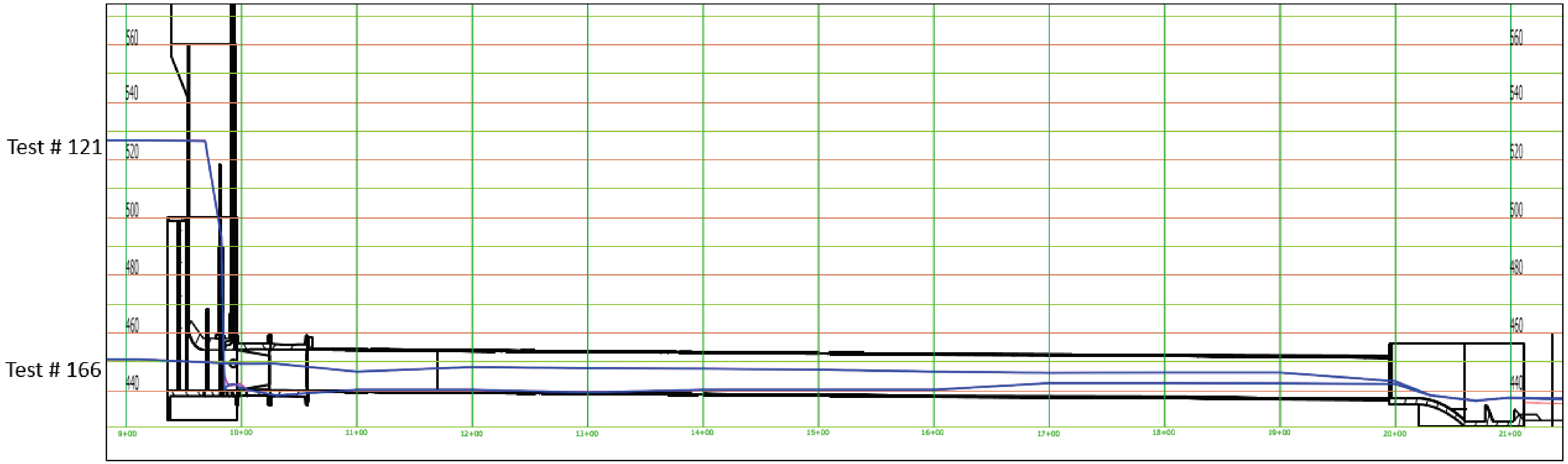


Table 6. HGLs for the 1000 cfs flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Hydraulic Grade Lines																																	
50%	106	1000	450.78	450.65	450.68	450	450	449.1	449	448.8	448.7	448.6	448.6	448.8	448.8	448.9	448.8	449	448.9	449	446.1	447.5	447.1	447	446.8	446.1	445.7	445.8	445.8	443	438.1	436.5	437.4	437.1	437.13	437
50%	112	1000	450.99	450.94	450.91	450.1	450	449.1	449	448.9	448.8	448.6	448.5	448.8	448.8	449	448.8	449	448.9	449	446.3	447.9	447.2	447.2	446.9	446.3	445.8	445.9	445.9	443	438.1	435.9	437	436.66	436.72	436.56
40%	117	1000	451.4	451.35	451.35	450.7	450.5	448.8	448.6	447.8	447.7	447.4	447.2	447.9	447.8	447.2	447.1	448.5	448.4	448.9	446.2	447.8	447.2	447.1	446.8	446.1	445.6	445.8	445.8	443	438	436.5	432.2	437.08	437.08	437
30%	118	1000	453.81	453.76	453.78	453.4	453.4	449.1	449.1	446.1	446.1	444	444.1	443.7	443.8	443.6	443.5	443.7	443.8	445.5	445	444.8	446	446.6	446.5	446	445.9	445.9	445.9	443	438	436.5	437.2	437.03	437.05	436.95
25%	119	1000	457.61	457.53	457.56	457.3	457.3	451	451	446.2	446.2	443.4	443.5	443	443.2	443.1	443	443.2	443.3	445.3	444.4	444.1	443.8	444.7	445.4	445.6	445.8	445.8	445.9	443	438.1	436.3	437.3	436.95	436.97	436.87
20%	120	1000	463.09	463.06	463.04	462.9	462.8	453.9	453.8	446	446.5	442.8	443.1	442.4	442.9	442.5	442.4	442.8	442.9	445.5	444	443.6	443	444.1	444	444.2	444.3	445.5	445.8	442.9	438	436.4	437.3	436.95	436.97	436.87
10%	121	1000	526.68	526.63	526.65	526.5	526.3	493	493	445	440.3	441.4	441.7	441.6	442	442.1	440.9	442.3	441.6	440.9	440.9	442	439.4	443.1	442.8	442	442.3	442.3	442.2	442	438	436.3	437.2	436.74	436.97	436.87
60%	140	1000	450.47	450.4	450.4	449.6	449.5	449.1	449.1	449	449	449	449	449	449	449	449	449	449	449	446.1	447.8	447.2	447.1	446.9	446.2	446	446	445.9	443	438.1	436.2	437.2	437	437	436.9
25%	141	1000	458.33	458.31	458.33	458	458	451.3	451.3	446.2	446.3	443.4	443.5	443	443.2	443	442.4	443.1	443.1	445.5	444.5	444	443.9	444.6	445.7	445.2	445.8	446	446	443	438.1	436.3	437.2	437	437.05	436.92
15%	160	1000	478.31	478.31	478.34	478	478.1	462.8	457.8	446.3	445.9	441.9	442	441.9	442.1	442.2	441.7	442.4	442.1	444.2	442	442.7	441.8	443.5	443.3	442.4	445.4	443.3	443.2	442.8	438	436.4	437.2	437	437	436.9
100%	166	1000	450.6	450.57	450.6	449.6	449.5	449.4	449.2	449.3	449.2	449.2	449.1	449.3	449.2	449.2	449	449.1	449	449.1	446.3	447.9	447.5	447.3	447	446.3	445.9	446	446	443	438.1	436.1	437.3	437.08	437.13	437

Figure 20. 2000 cfs HGLs.

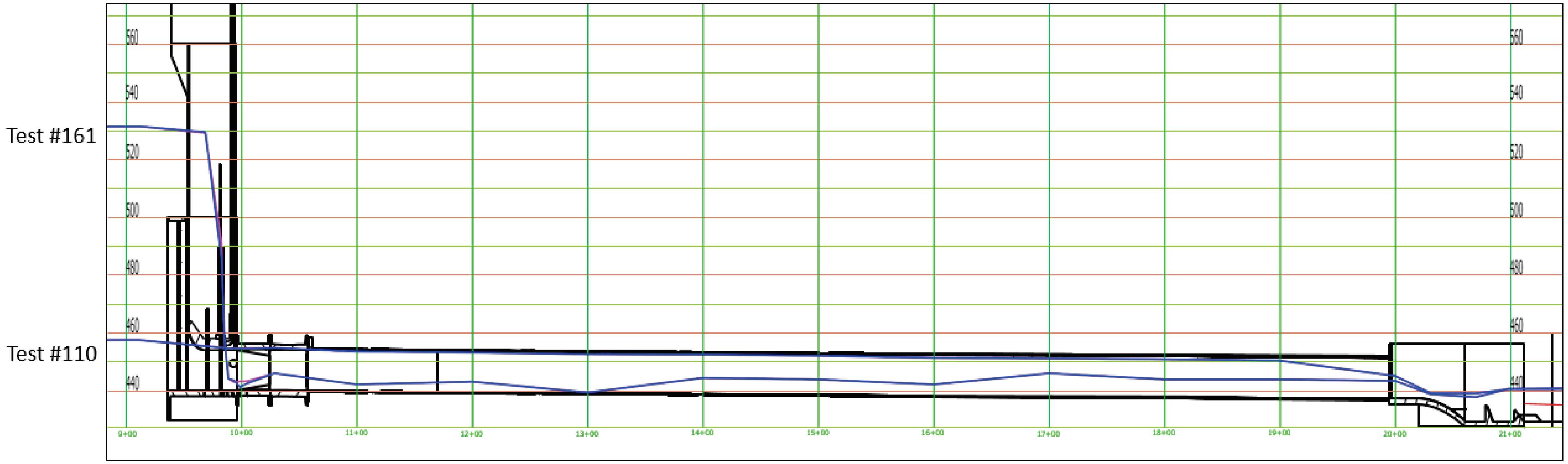


Table 7. HGLs for the 2000 cfs flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Hydraulic Grade Lines																																	
100%	91	2000	456.91	456.83	456.88	455	455	454.7	454.6	454.6	454.5	454.6	454.5	454.7	454.5	454.4	454.3	454.3	454.2	454.4	453.2	452.9	452.2	452.1	451.8	451.1	451	450.6	450.2	444.7	438.8	439.2	440.8	440.59	440.7	440.64
70%	107	2000	457.63	457.53	457.56	455.7	455.6	453.5	453.2	4522.9	452.5	452.3	452	452.3	452	452.7	452.1	453	452.9	453.9	452.7	452.4	451.9	451.5	451	450.3	449.9	449.7	449.2	445	438.9	439	440.7	440.46	440.62	440.54
90%	110	2000	457.43	457.3	457.35	455.3	455.2	454.8	454.7	454.6	454.4	454.4	454.3	454.5	454.4	454.5	454.3	454.5	454.3	454.6	453.4	453	452.4	452.3	451.9	451.2	451	450.7	450.2	444.9	438.9	438.8	440.3	440.31	440.44	440.41
50%	113	2000	461.54	461.43	461.41	459.5	459.4	453.6	453.6	450.8	450.8	448	448.2	446.5	446.8	445.9	445.6	445.7	445.8	448.2	447	446.8	447.7	451.1	451	450.2	449.9	449.6	449.2	445	438.9	439	440.6	440.54	440.64	440.62
40%	114	2000	468.47	468.41	468.41	466.5	466.5	456.5	456.5	457.4	451.4	446	446.1	445.1	445.4	444.9	444.3	444.9	444.9	447.9	446	445.5	444.9	446.3	446.2	446.6	447	449.7	449.1	444.9	438.9	439.2	440.5	440.54	440.64	440.57
30%	115	2000	486.38	486.3	486.3	484.4	484.3	466	466.1	453.9	454	445.7	445.8	443.8	444.2	443.8	442.6	443.8	443.6	447.9	444.8	444	442.3	445.2	445	444.7	445	445	445	443.9	438.6	438.8	440.5	440.54	440.64	440.59
25%	116	2000	503.44	503.36	503.42	501.5	501.4	475.4	475.4	455.7	455.9	444.9	445.1	443.3	443.9	443.2	441.8	443.4	443	447.4	443.3	443.7	440.9	445.2	444.5	443.8	444.5	444.2	444.3	443.4	438.7	438.5	440.6	440.52	440.64	440.59
80%	142	2000	457.04	456.99	456.99	455.1	455.1	454	453.9	453.6	453.4	453.3	453.2	453.3	453.3	453.7	453.5	453.8	453.8	454	452.8	452.5	451.9	451.7	451	450.3	449.9	449.8	449.1	445	439	439.1	440.7	440.57	440.67	440.64
60%	143	2000	458.28	458.25	458.25	456.3	456.2	453	452.5	451.4	450.9	450.3	449.2	450.3	448.6	450.9	448.2	451.9	449.6	453.8	452.6	452.4	451.9	451.7	451	450.3	450	449.7	449.2	445	438.8	439	440.7	440.57	440.67	440.62
35%	159	2000	474.7	474.67	474.64	472.5	472.5	460.1	454.3	452.3	446.5	446.4	444.8	440.9	444.4	443.7	444.5	444.2	448.1	444.7	445.1	444.1	446.2	445.8	445.7	444.6	445.9	446.2	446.3	444.7	438.5	438.9	440.5	440.54	440.67	440.62
20%	161	2000	531.54	531.54	531.54	529.3	529.6	491	485.5	457.8	457.4	444	443.9	442.8	443.4	443	441	443.1	442.3	445.8	441.9	442.9	439.1	444.2	443.7	441.9	445.8	443.7	443.7	443.2	438.5	437.5	440.4	440.52	440.67	440.64

Figure 21. 3000 cfs HGLs.

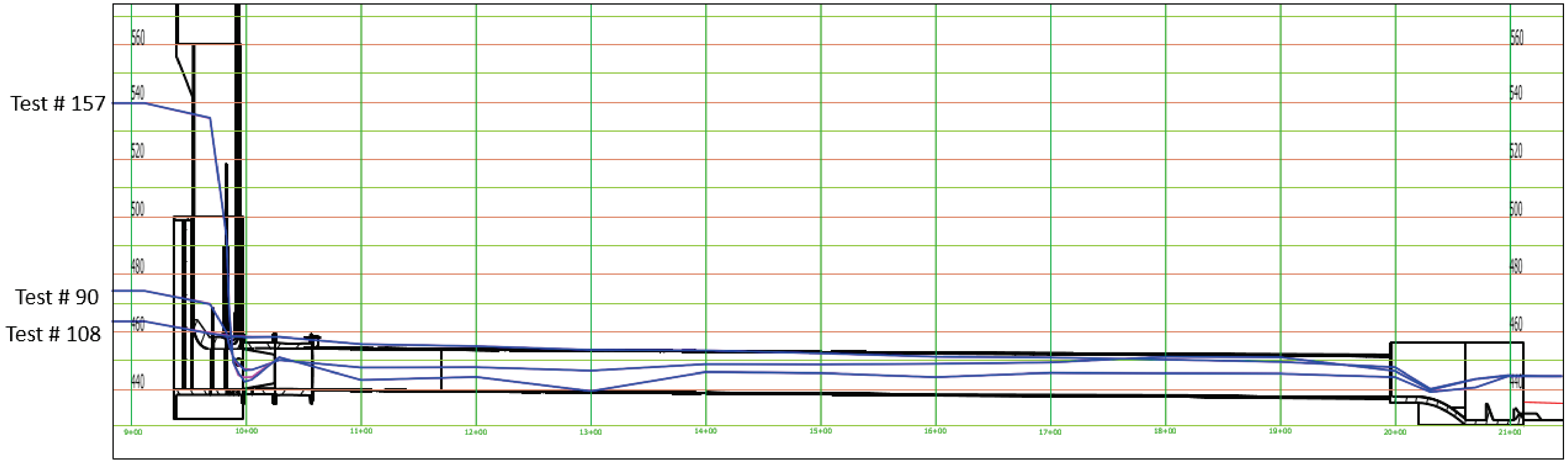


Table 8. HGLs for the 3000 cfs flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Hydraulic Grade Lines																																	
100%	78	3000	463.3	463.2	463.2	459.1	459	458.2	458	458.2	458	458.1	458	458.1	458	457.9	458	457.8	458	458	455	455	453	453	452	451	451	450	449	447	440	443	445	444.3	444.3	444.4
90%	79	3000	463.9	463.9	463.9	459.7	460	458	458	457.5	457	457.2	457	457.3	457	457.4	457	457.5	457	458	455	455	453	453	452	451	451	450	449	447	440	442	445	444.3	444.3	444.4
80%	80	3000	464.8	464.8	464.8	460.6	460	457.6	458	456.5	456	455.8	456	455.4	456	455.5	455	456.1	456	458	455	455	453	453	452	451	451	450	449	447	440	443	444	444.2	444.3	444.4
70%	81	3000	467.1	467.1	467.1	463	463	458.1	458	456.3	456	455	455	454	454	454.1	454	455.2	455	458	456	456	454	454	453	452	452	451	450	447	439	443	444	444.2	444.3	444.4
60%	82	3000	470.5	470.5	470.5	466.3	466	458.9	458	455.8	455	453	451	452	450	452.2	449	453.2	450	458	457	456	455	455	454	453	452	452	451	446	439	443	444	444.2	444.3	444.4
50%	83	3000	479.5	479.5	479.5	475	475	462.2	462	455.9	456	450.6	451	447.5	448	446	445	445.9	446	450	446	446	445	448	448	447	448	448	448	445	439	443	444	444.2	444.3	444.4
40%	84	3000	495.9	495.9	495.9	491.4	491	470.4	470	459	459	450	450	446	447	444.8	443	444.8	445	450	446	445	443	447	446	446	446	446	446	444	439	442	444	444.2	444.3	444.4
55%	90	3000	473.9	473.9	473.9	469.5	469	459.4	459	454.8	455	450.7	451	448.1	449	446.7	446	446.4	446	450	447	447	446	448	448	449	449	451	451	446	439	443	444	444.2	444.3	444.4
100%	92	3000	463.5	463.4	463.4	459.1	459	458.3	458	458.2	458	458.2	458	458.1	458	457.9	458	457.7	458	458	455	455	453	453	452	451	451	450	449	443	440	443	444	444.2	444.3	444.4
40%	93	3000	497.2	497.1	497.1	493	493	471	471	459.3	459	449.9	450	446	447	444.8	444	444.7	444	451	446	445	443	447	446	445	446	446	446	445	439	442	444	444.2	444.3	444.4
100%	108	3000	463.4	463.3	463.3	459.2	459	458.4	458	458.2	458	458.1	458	458.1	458	458	458	457.9	458	458	455	455	453	453	452	451	451	450	449	447	440	443	445	444.3	444.4	444.4
60%	109	3000	471.2	471.2	471.2	466.8	467	458.9	459	455.9	455	452.8	453	452.5	450	452.7	449	453.4	452	459	457	456	455	455	454	453	453	452	451	446	439	443	444	444.3	444.4	444.4
70%	144	3000	467.8	467.7	467.8	463.4	463	458.1	458	456.4	456	454.8	455	454	454	454.1	454	455	455	458	457	456	454	454	453	452	451	451	450	447	440	443	444	444.2	444.3	444.4
35%	156	3000	513.8	513.8	513.8	508.7	509	479.5	480	462.7	462	449.4	449	445.1	446	444.4	442	444.3	444	451	444	445	442	447	446	445	446	446	446	444	439	441	444	444.2	444.3	444.4
30%	157	3000	539.4	539.4	539.4	534	534	493	493	467	467	449	449	444.6	445	443.8	442	444	443	451	443	444	439	446	445	444	445	445	445	444	439	440	444	444.2	444.3	444.4
45%	163	3000	486.3	486.3	486.3	481.4	482	465.6	466	457.3	457	450.2	450	446.7	447	445.6	445	445.4	445	450	446	446	444	447	447	447	447	447	447	445	439	442	444	444.2	444.3	444.4
Left 76.6%, Right 0%	85	3000	501.1	501.1	501.1	501.5	483	501.3	469	439.8	463	440	458	440.6	455	440.5	450	440.5	449	441	444	446	443	447	447	446	446	446	446	444	439	442	444	444.2	444.3	444.4
Right 76.6%, Left 0%	86	3000	501.1	501	501	483.2	502	468.8	500	463	440	458.5	440	454.3	440	450.7	440	449.2	440	443	444	446	443	447	447	446	447	446	446	444	439	443	444	444.2	444.3	444.4

Figure 22. 4000 cfs HGLs.

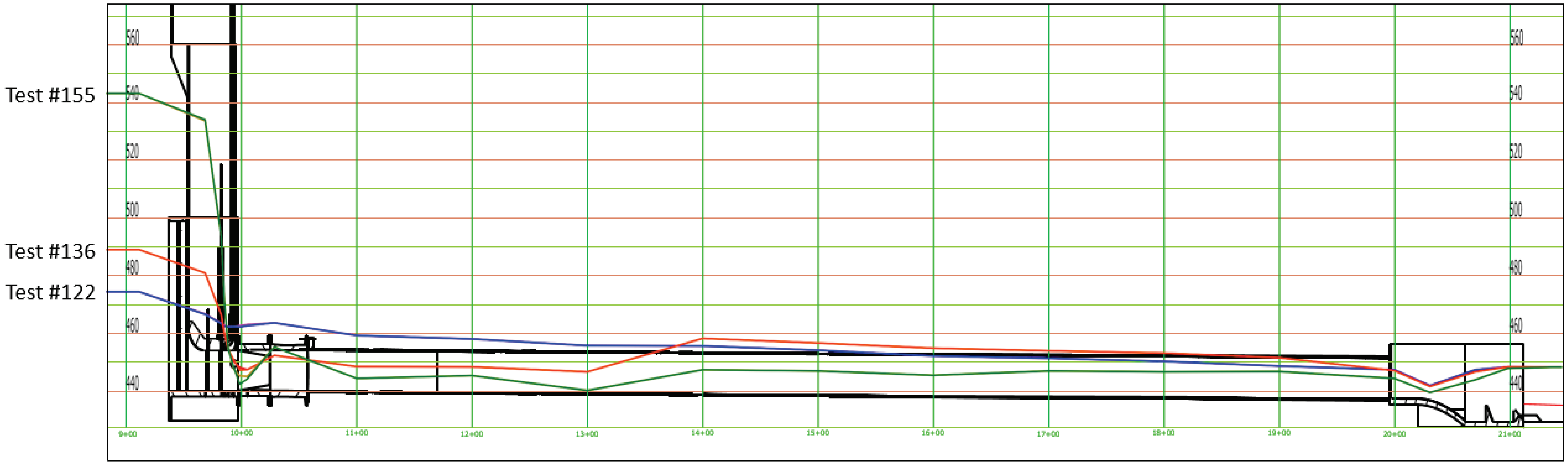


Table 9. HGLs for the 4000 cfs flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Test ID	Hydraulic Grade Lines																																	
100%	101	4000	473.48	473.48	473.48	465.9	465.8	464.2	464	464.1	463.9	464	463.9	464	463.9	463.8	463.1	463.4	463.1	463.7	459	457.9	455.7	455.5	453.9	457.9	451	449.9	448.5	446.9	440.1	445.2	446.6	446.56	446.69	446.77
90%	122	4000	474.15	474.07	474.07	466.4	466.2	463.2	463	462.4	462.1	462	461.9	462	462	462.3	461.9	462.7	462.3	463.3	458.9	457.7	455.4	455.3	453.8	451.8	451	449.9	448.3	447	441.5	447	448	447.93	448.01	448.09
80%	123	4000	476.12	476.09	476.09	468.2	468	462.8	462.6	460.8	460.5	459.1	459	458.3	458.1	458.5	457.7	459.8	459.5	463.9	458.9	457.6	455.4	455.3	453.8	451.8	451.1	449.9	448.5	447	440.2	445.8	446	447.39	447.88	448.12
70%	124	4000	480.49	480.43	480.43	472.7	472.3	464	463.8	460.5	460.4	457.7	457.5	455.8	455.7	455.4	454.5	457	456.5	463.4	460.4	459.2	456.8	456.6	455.2	454	453.5	452	450.8	447	447.9	448	449.5	449.25	449.33	449.41
60%	125	4000	488.16	488.06	488.03	479.9	479.9	465.8	465.9	459.4	459.6	453.9	454.1	45	450.4	447.8	446.8	447.1	447	451.9	447.9	447.9	454.1	457.8	456.3	454.4	453.3	452.6	451.3	446.4	443.2	448	449.2	449.25	449.33	449.41
70%	135	4000	481.86	481.73	481.73	473.8	473.2	465	464.9	460.6	460.4	457.5	457.6	456.1	456.3	455.3	454	457.7	456.8	454.7	450.7	459.8	456.5	456.4	455.4	454.4	452	451.5	450.5	447	441.5	446.6	448	447.96	448.04	448.12
60%	136	4000	488.84	488.71	488.71	480.6	480.6	466	466.1	459.8	459.9	454	454.1	450	450.6	447.8	446.9	447.1	447	452	448.1	448	446.3	457.9	456.3	454.5	453.6	452.8	451.2	446.7	441.2	446.3	448	447.96	448.04	448.14
50%	145	4000	506.78	506.72	506.67	498.1	497.9	474.7	474.8	463.6	463.8	453.9	454.3	448.5	449.4	446.1	444.7	445.8	445.3	452.5	446	446.4	443.8	448.3	447.7	446.8	447.9	447.6	447.8	445.4	440.3	445.5	447.8	447.81	447.96	448.09
45%	151	4000	521.35	521.33	521.33	509.8	509.9	481	481.1	466.7	466.8	454.2	454.2	448	449	445.6	443.8	445.1	444.9	453.2	445.2	446	442.6	448	447.1	446.3	447.5	447.2	447.2	445	439.8	444.9	447.7	447.78	447.96	448.12
40%	155	4000	542.91	542.89	542.86	533.3	533.7	493	493	471.9	471.5	454.8	454.2	447.4	448.1	444.9	442	444.7	443.8	454.9	444	445	439.8	447	446.6	445.1	446.6	446.3	446.4	444	439.1	443.5	447.5	447.91	447.75	447.91

Figure 23. 5000 cfs HGLs.

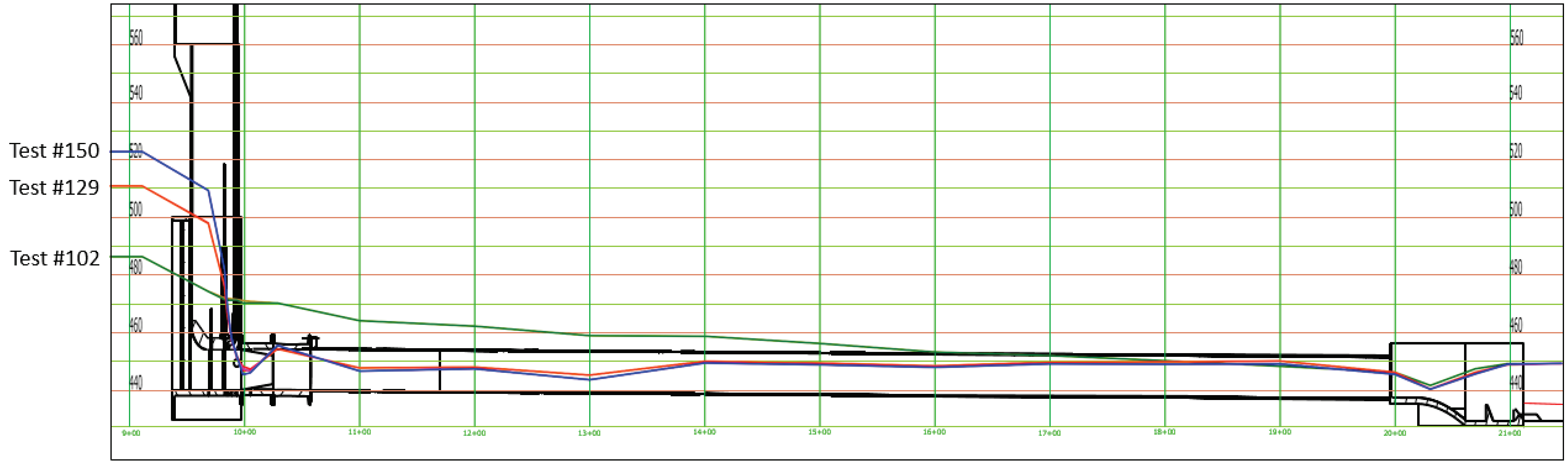


Table 10. HGLs for the 5000 cfs flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Test ID	Hydraulic Grade Lines																																	
100%	102	5000	486.2	486.12	486.12	474.1	474	471.8	471.2	471.6	471	471.5	471	471.3	471	470.9	470	470.6	470	470	463.9	462	458.7	458.5	456	453	451.8	450	448.1	446	441.4	447.2	449	449	449.19	449.3
90%	126	5000	487.78	487.67	487.67	475.5	475.1	470.6	470.2	469.2	469	468.5	468.3	468.6	468.6	469	468.3	469.5	469	470.6	463.9	462	458.6	458.5	456	453	451.8	450	448.1	446	441.3	446.8	448.9	449	449.15	449.33
80%	127	5000	490.49	490.39	490.39	4778.1	477.9	469.4	469.2	466.4	466.2	464.1	463.7	462.6	462.4	463	461.8	464.8	464.4	469.9	463.8	461.9	458.4	458.3	456	452.8	451.7	450	448	446	441.5	446.8	448.8	449	449.15	449.33
70%	128	5000	498.3	498.22	498.22	485.8	485.3	471.7	471.5	466.2	466.1	461.6	461	458.3	458.2	457.3	456	460	458	471.5	466	463.5	460.7	460.5	458	454	453.8	452	450	446.3	441	446	449.1	449	449.15	449.33
60%	129	5000	510.63	510.6	510.52	497.7	497.5	475.8	475.7	466	466.2	457.4	457.6	451.4	452.2	448	446.4	447.1	446.7	454.1	447.5	447.8	445	449.8	449.2	448.2	449.5	449.6	449.9	446	440.2	446	448.6	448.9	449.12	449.33
50%	146	5000	538.59	538.47	538.42	524.5	524.75	489.75	489.8	473	473.3	458.8	458.8	450.5	451.5	446.5	444	445.8	445	456.5	445.5	446.5	441.8	448.25	447.5	446	447.8	447.75	447.5	444.5	439.5	445	448.5	449.1	449.25	449.47
55%	150	5000	522.49	522.47	522.44	509	509	481.5	481.7	469	469.2	458	458.1	451	451.8	447.2	445.2	446.3	445.8	455.3	446.4	447.2	443.4	449.2	448.6	447.7	448.9	448.8	448.9	445.3	440.1	445.4	448.8	449.1	449.23	449.46

Figure 24. 6000 cfs HGLs.

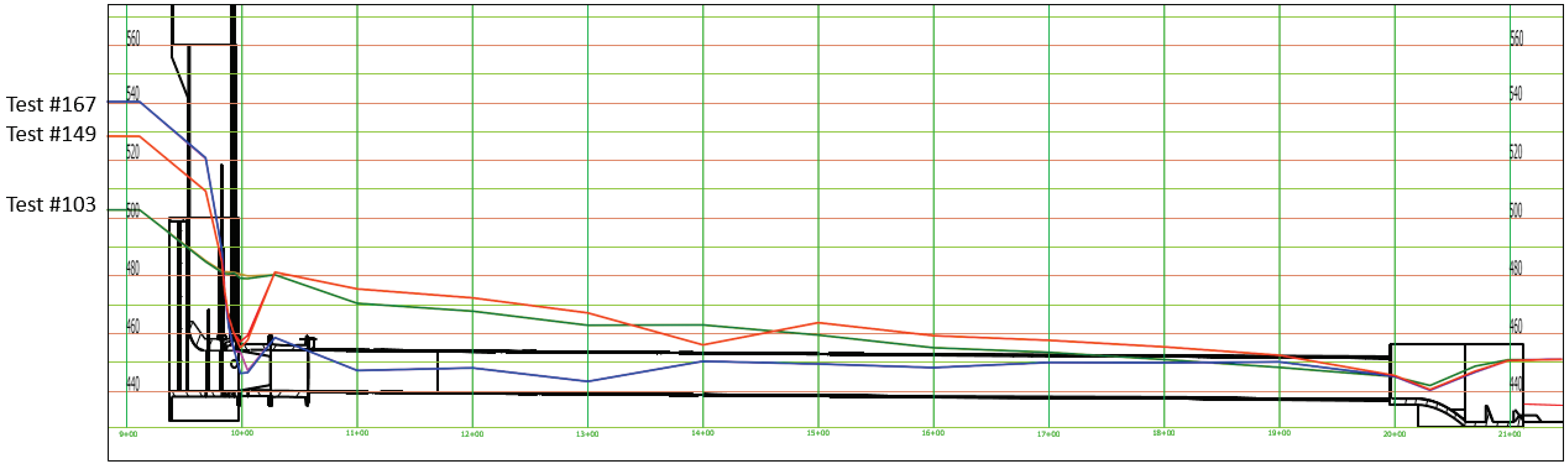


Table 11. HGLs for the 6000 cfs flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1005	1005	1029	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2031	2070	2098	2137	2211	2612
Gate	Test #	Q	Hydraulic Grade Lines																																	
100%	103	6000	502.74	502.64	502.61	485.1	484.7	481.5	481	481.3	480.6	481.2	480.5	481.1	480.5	480.4	479	479.8	478.9	480.2	470.3	467.6	462.7	462.8	459.3	454.9	453.3	450.8	448.1	444.9	441.8	448.5	450.7	450.83	451.06	451.27
90%	130	6000	505.74	505.66	505.64	487.9	487.3	480.6	480	478.7	478	477.6	477	477.8	477.4	478.1	477.1	478.9	478.2	480.7	470.6	468	463.1	463	459.7	455.1	453.4	451	448.2	445	441.8	447.9	450.4	450.83	451.06	451.29
80%	131	6000	509.15	509.08	509	491	490.8	478.5	478	474	473.6	470.7	470	468.3	468.2	468.5	467	471.1	470.7	479.1	470.2	467.8	462.9	462.8	459.3	455	453.2	451	448.2	445	442	448.1	450.3	450.83	451.04	451.29
70%	132	6000	519.08	519.08	518.98	500.4	500.3	480.6	480.4	472.5	472.7	465.8	465.3	460.7	460.5	459	456.8	461	460.8	479.5	472	469.3	464.4	464.3	461.3	456.7	455	452.5	450	445.3	441.3	447.5	450.3	450.83	451.06	451.29
60%	147	6000	534.02	533.97	533.89	515.5	515.5	485.8	486	472.8	473	461.25	461.25	453.5	454.25	448.5	446.4	447.25	446.5	457.25	447	448	443.75	450.5	449.5	448	449.8	449.8	450	445	440.25	446.5	450	450.98	451.39	451.11
65%	149	6000	528.2	528.2	528.15	509.1	509.2	484.9	484.6	474.6	474.3	465.5	465.4	459.8	459.8	457	454.9	459.2	457.6	481.1	475.3	472.2	467	455.9	463.6	459.1	457.5	455.2	452.3	445.3	440.4	446.8	450.4	450.8	451.04	451.27
60%	167	6000	540.25	540.23	540.15	520.4	520.7	488.8	488.7	474.4	474.6	462	462.2	453.6	454.3	453.4	446	447	446.3	458.4	447	447.9	443.2	450.2	449.3	448	449.8	449.7	450	445	440.2	446.5	450.4	450.93	451.19	451.42

Figure 25. PMF HGLs.

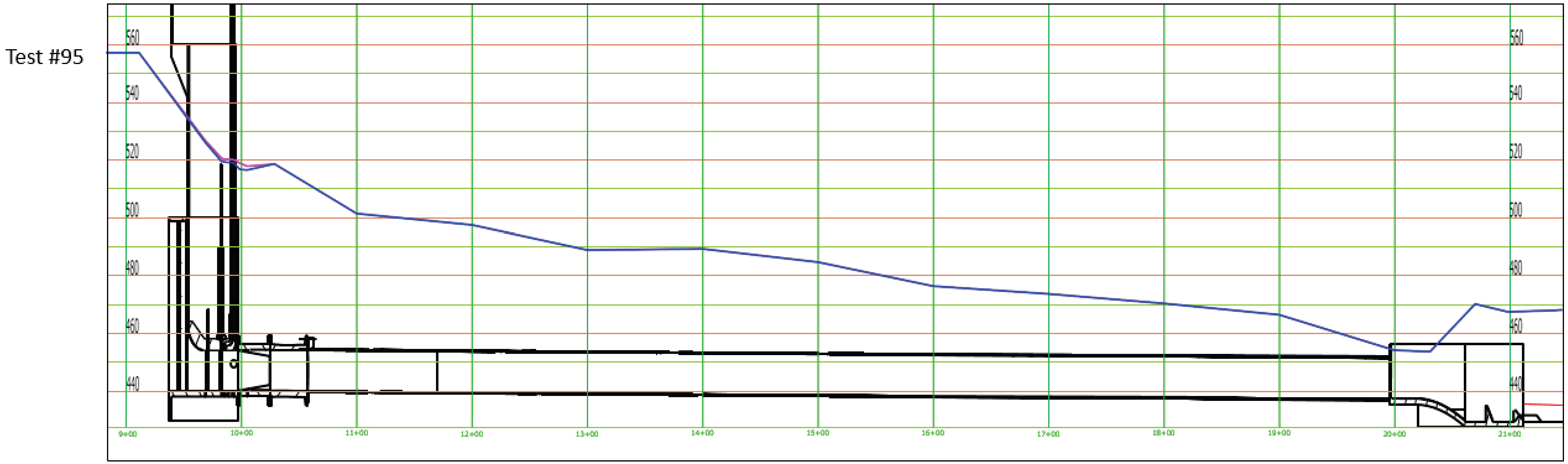


Table 12. HGLs for the PMF flow cases.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Hydraulic Grade Lines																																	
100%	89	7893	556.72	556.79	556.69	526.8	526.1	520.7	519.6	520.3	519.1	520.3	519.4	520.3	518.9	518.8	516.6	517.9	516.4	518.6	502	497.7	489.4	489.7	484.8	477.7	475.2	472	467	460.5	462.5	469.2	468.1	467.74	469.49	469.8
100%	95	7900	557.05	557.05	556.92	526.6	525.9	520.5	519.3	520	519.1	520	518.9	519.9	518.8	518.7	516.5	517.6	516.3	518.4	501.2	497.3	488.7	489.1	484.5	476.2	473.5	470.2	466.3	454	453.5	470	467.3	467.76	469.67	469.91
100%	99	7900	556.72	556.72	556.59	526.6	525.6	520.4	519.4	520	518.9	520	518.7	519.8	518.8	518.6	516.3	517.7	516.3	518.3	501.5	497.5	488.8	489.5	483.6	477	474	470.5	466	463.5	463	470	468.8	467.94	469.91	470.01

Table 13. Additional model tests and associated HGLs (both gates, unless specified).

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Hydraulic Grade Lines																																	
R 100% L 0%	87	5430	526.68	526.58	525.28	468.4	527	456.8	525.2	456	440	455.8	440.1	455.5	439.9	453.4	440.3	451.9	440.2	441.5	447.8	451.4	449.2	454.3	453.6	452.3	453.9	454	451.7	444.2	440.9	448	450.3	450.2	450.31	450.57
100%	104	7000	522.28	522.23	522.1	498.3	497.8	493	493	493	493	493	492.9	493	493	491.8	490.1	491	490	491.5	478	474.6	468	468	463.4	457.7	455.5	452.2	448.4	444	441.3	449	451.5	452	452.41	452.72
85%	162	7000	528.33	528.36	528.26	503.5	503.4	491.4	490.7	487.2	486.4	484.7	4837	483.8	483.4	485	482.9	487.4	486.2	492	479	475.3	468.8	468.7	464	458	455.8	452.3	448.8	444.1	441.2	448	451.4	452	452.48	452.72
65%	100	5938	524.04	524.04	523.99	505.8	505.7	480.9	481	470	470.2	460.9	461.1	454	454.9	449.2	447.4	447.9	447.3	456.5	448.1	449	445.4	451.6	451.2	450	451.5	452.5	452	445.2	443	450.6	452.3	452.6	452.79	453.03
70%	101	6214	523.99	523.94	523.86	504.1	504	482.5	482.3	473.8	473.5	466.2	465.8	461	461.3	459.1	457.1	461.8	461.5	481.2	473.5	470.6	466.2	465.5	462.3	457.7	456	452.5	450.2	445	441.2	448	450.5	451	451.35	451.58
100%	94_2	6400	509.77	509.75	509.62	489.9	489.2	485.8	485	485.4	484.7	485.3	484.6	485.1	484.5	484.2	483	483.8	482.8	484	472.8	470	464.1	464.6	460.6	455.5	454	451.1	448.1	444.3	442.2	449.1	451.7	451.8	452.15	452.41
100%	96	6400	508.48	508.38	508.33	488.9	488.3	484.9	484	484.5	483.8	484.5	483.7	484.3	483.7	483.5	482.1	483	482	483.4	472	469.2	463.9	464	460.2	455.4	453.8	451.1	448.1	444.5	442.5	449.5	451.3	451.9	452.2	452.4
100%	97	6500	509.72	509.67	509.59	489.7	489.1	485.6	484.9	485.2	484.6	485.2	484.4	485	484.5	484.2	482.9	483.7	482.8	484.1	472.6	459.9	454.1	454.3	460.6	455.7	453.9	451.1	448.2	444.4	442	449.5	451.4	451.9	452.2	452.48
100%	88	7107	523.99	523.97	523.84	499.3	498.7	494.3	493	493	493	493	493	493	493	493	490.8	491.8	490.7	493	478.5	475	468	468.6	464.3	458	456	452.9	449.3	442.6	441.2	449.5	451.8	452.3	452.59	452.98
100%	94	7107	523.45	523.4	523.32	498.9	497.2	493	493	493	493	493	493	493	493	493	490.4	491.5	490.3	492.9	478	474.5	467.7	468	463.5	457.4	455.4	452.1	448.5	444	441.3	449.2	451.2	452.3	452.72	453.03
100%	98	7100	523.32	523.37	523.32	498.8	498	493	493	493	493	493	493	493	493	493	490.3	491.3	490.2	493	477.9	474.4	467.7	468	463.6	457.3	455.3	452.1	448.5	444	441.2	449.5	451.5	452.4	452.79	453.13

Table 14. Model tests for left gate operations only.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Hydraulic Grade Lines																																	
15%	167	500	485.27	485.24	485.27	485.6	485	485.6	466.5	440.9	446.3	440.9	441.9	440.8	442	440.9	441.7	441	442.1	441.1	441.9	441.9	440.9	442.4	442.2	442.2	442.3	442	443.4	441.5	437.8	435.7	436	435.7	435.66	435.55
35%	169	1000	474.31	474.28	474.31	474.8	472.3	474.5	459.8	441.1	452.2	441.5	446.5	441.5	445	442	443.8	442	444.2	442.1	443.8	442.9	441.8	444	443.8	444	443.9	443.6	445	442.9	438	436.3	437.2	437	437	436.92
30%	170	1000	483.41	483.36	483.38	483.7	481.4	483.3	464.4	440.2	453.1	440.2	445.6	440.3	444.1	441	443	440.8	443.7	442	443	442.7	441.7	443.1	443.5	443.5	443.6	443.2	443	442.8	438	436.4	437.1	437	437	436.87
25%	171	1000	501.94	501.94	501.97	502.3	500	502.2	474.6	440.8	455.2	440.8	444.8	440.8	443.6	440.7	442	440.8	443	441.1	441.2	442.2	440.3	443.4	443	442.3	443	442.8	442.7	442.2	438	436.3	437.2	437	437.03	436.92
55%	172	1500	474.36	474.33	474.36	474.7	469.7	474.7	459.6	441.4	455	441	450.8	441	448.5	441	446.2	441.1	446.4	442.4	444.8	444	442.8	445.2	444.7	444.9	445.2	445	447.2	443.9	435.5	437.5	439	438.8	438.82	438.78
50%	173	1500	479.12	479.09	479.09	479.5	474.5	479.5	461.9	440.9	455.9	440.9	450.5	440.9	447.9	440.9	445.4	441	445.9	442	444.3	444.2	443.2	444.6	444.6	444.8	444.9	444.5	444.6	443.8	438.4	437.6	438.9	438.8	438.84	438.78
45%	174	1500	486.46	486.43	486.46	486.9	481.8	486.9	465.6	440.9	457.4	440.9	450.1	440.9	447.1	440.9	444.7	441	445.2	441.9	443.8	443	442	444.8	443.9	444.1	444.3	444	444	443.3	438.5	437.9	439	438.8	438.89	438.81
40%	175	1500	497.75	497.73	497.75	498	493	498.1	471.4	440.9	459.7	440.9	450	440.8	446.6	440.8	443.8	440.8	444.7	441.3	442.4	443	440.9	444.4	444	443.5	444	443.9	443.8	443	438.4	437.5	439	438.8	438.89	438.84
35%	176	1500	511.61	511.61	511.61	512	506.8	512	478.5	440.8	462	440.8	449.2	440.8	446	440.8	442.8	440.9	444	441	441.6	442.8	439.4	443.4	443	443	443.8	443.3	443.4	442.8	438.4	437.3	439	438.8	438.86	438.84
45%	177	2000	520.55	520.5	520.5	520.9	511.6	520.9	482	440.7	467.3	440.8	454.8	440.7	449	440.8	443.8	440.7	445	440.8	441.9	442.2	439.6	445	-	443.4	444.3	444	444	443.2	438.6	437.7	440.6	440.5	440.64	440.64
50%	178	2000	506.1	506.08	506.1	506.5	497.5	506.4	474.7	440.8	463.9	440.8	454.4	440.8	449.5	440.8	445	440.8	445.5	441.1	442.4	444.1	440.2	444.3	-	444	444.9	444.4	444.2	443.5	438.7	438.2	440.5	440.5	440.64	440.62
55%	179	2000	495.5	495.48	495.48	495.8	487	495.8	469.3	440.8	461.3	440.8	454.1	440.8	450.8	440.8	444.9	440.8	446.2	441.4	443.2	443.9	442.9	445.4	-	444.5	444.9	444.9	444.8	443.8	438.8	438.7	440.4	440.5	440.64	440.62
60%	180	2000	488.32	488.29	488.29	488.7	480	488.8	465.9	440.7	459.7	440.7	454	440.8	450.5	440.8	446.8	440.8	447	441.8	443.5	443.8	442.9	445.7	-	445	445.3	445.2	445	444	438.7	438.8	440.7	440.5	440.64	440.62
70%	181	2000	477.77	477.75	477.75	478	469.5	478	460.6	440.9	457	440.9	453.8	440.9	451.2	440.9	448.4	440.9	448.2	442.2	445	445.2	444	446.1	445.5	446	446.3	446	446.1	444.6	438.7	439	440.5	440.5	440.62	440.59
80%	182	2000	471.72	471.7	471.72	472	463.5	472	457.9	445.1	455.8	445.1	453.9	445.1	452.3	445.1	450.1	445.1	449.9	445	445.7	445	444.6	446	446.1	446.5	446.8	446.9	449	444.7	438.9	439	440.6	440.5	440.64	440.62
100%	183	2500	469.4	469.37	469.37	469.8	456.7	469.8	454	448.1	453.8	448.1	453.6	448.2	453.6	448.1	452.6	448	452.5	447.9	447.3	447	453.3	453.6	452.9	452	451.7	451.1	450.5	445.4	439	440.6	442.2	442.4	442.48	442.5
90%	184	2500	476.22	476.17	476.17	476.5	463.6	476.5	458.1	446	456.5	446	455	446	454	446	452	446	451.6	445.8	446.9	446	444.9	447.3	447	447.1	447.8	447.5	450.4	445.6	439	440.7	442.3	442.4	442.48	442.45
80%	185	2500	483.74	483.69	483.69	484	470.9	484	462	440.9	458.7	440.8	455.7	440.8	453.4	440.8	450.1	440.8	449.6	442	444.4	445.7	444.5	446.4	446.7	446.2	447	446.9	447	445.1	439	440.7	442.3	442.4	442.48	442.48
70%	186	2500	494.83	494.81	494.81	495.1	481.5	495.1	467.7	440.5	461.8	440.5	456.7	440.6	458	440.5	448.5	440.5	448.1	441.4	444.1	445	443.1	446.4	445.8	445.3	446.2	446	446	444.4	439	440.2	442.3	442.4	442.48	442.51
60%	187	2500	512.41	512.38	512.36	512.8	498.8	512.7	476.3	440.7	466.6	440.7	457.9	440.6	452.3	440.6	446.4	440.6	446.8	440.9	443	444.2	440.5	445.3	444.8	444.2	445.1	445.1	445.2	444	438.8	439.4	442.1	442.4	442.51	442.51
55%	188	2500	523.35	523.32	523.35	523.6	509.9	523.7	482	440.6	469.6	440.6	458.4	440.6	452	440.6	445.4	440.6	446	440.6	442.6	442.5	440.3	446	444.7	443.9	445.1	444.9	444.8	443.5	438.8	439.3	442.4	442.3	442.46	442.48
100%	189	3000	476.04	476.01	475.99	476.3	457.9	476.3	454.1	447.5	453.8	447.5	453.5	447.7	453.5	447.4	452.1	447.5	452	447.1	448.2	456.2	455.3	455.3	454.2	453.1	452.6	451.9	451	446.1	439.3	442.3	444.2	444.2	444.34	444.39
90%	190	3000	486.72	486.66	486.69	487	468.7	487	461	443	458.4	443	456.3	443	454.8	443	451.8	443	451.3	443.2	445.7	446.3	445.1	447.3	447.3	447.2	448	447.8	448.1	445.9	439.3	442.3	444.2	444.2	444.34	444.39
80%	191	3000	497.99	497.96	497.96	498.3	479.7	498.3	467.1	440.6	462.3	440.7	458.1	440.7	455	440.6	450.2	440.6	449.7	441.3	444.7	446.1	443.6	447.2	446.8	446.2	447	446.9	446.9	445	439.1	442.2	448.3	444.2	444.32	444.39
70%	192	3000	513.75	513.73	513.73	514.1	595	514.1	475.2	440.6	467.1	440.6	460	440.6	454.8	440.5	448.5	440.6	448.1	440.8	443.5	444.8	441.8	446.3	445.6	445	446	445.9	446	444.6	439.1	441.4	444.1	444.1	444.32	444.39

4.2 Operation data

The following data show the performance of the RROW with all the design modifications included. The HGL was utilized with the discharge measurements and gate openings to generate the performance curves in Figure 26 and Figure 27. For the operation manual, LRL generated contour plots for both double and single gate operations (Figure 28 and Figure 29).

Figure 26. Pool elevation vs. double gate opening for EM 1110-2-1602 transition.

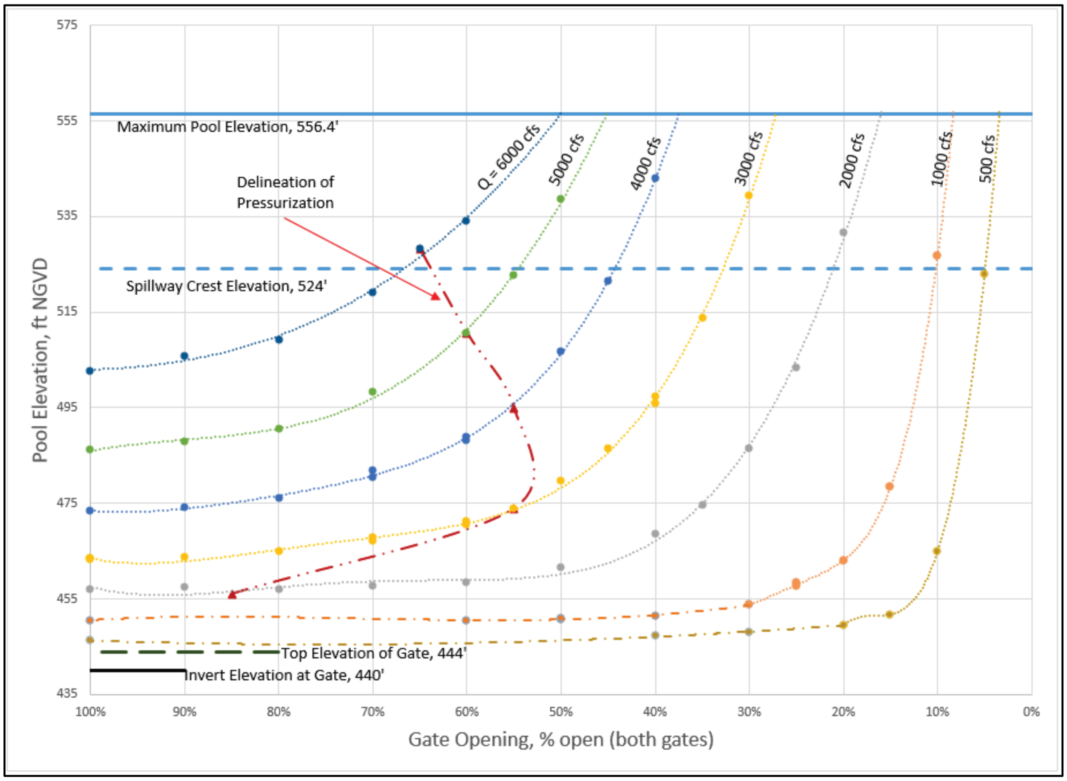


Figure 27. Pool elevation vs. discharge for EM 1110-2-1602 transition for double gate opening.

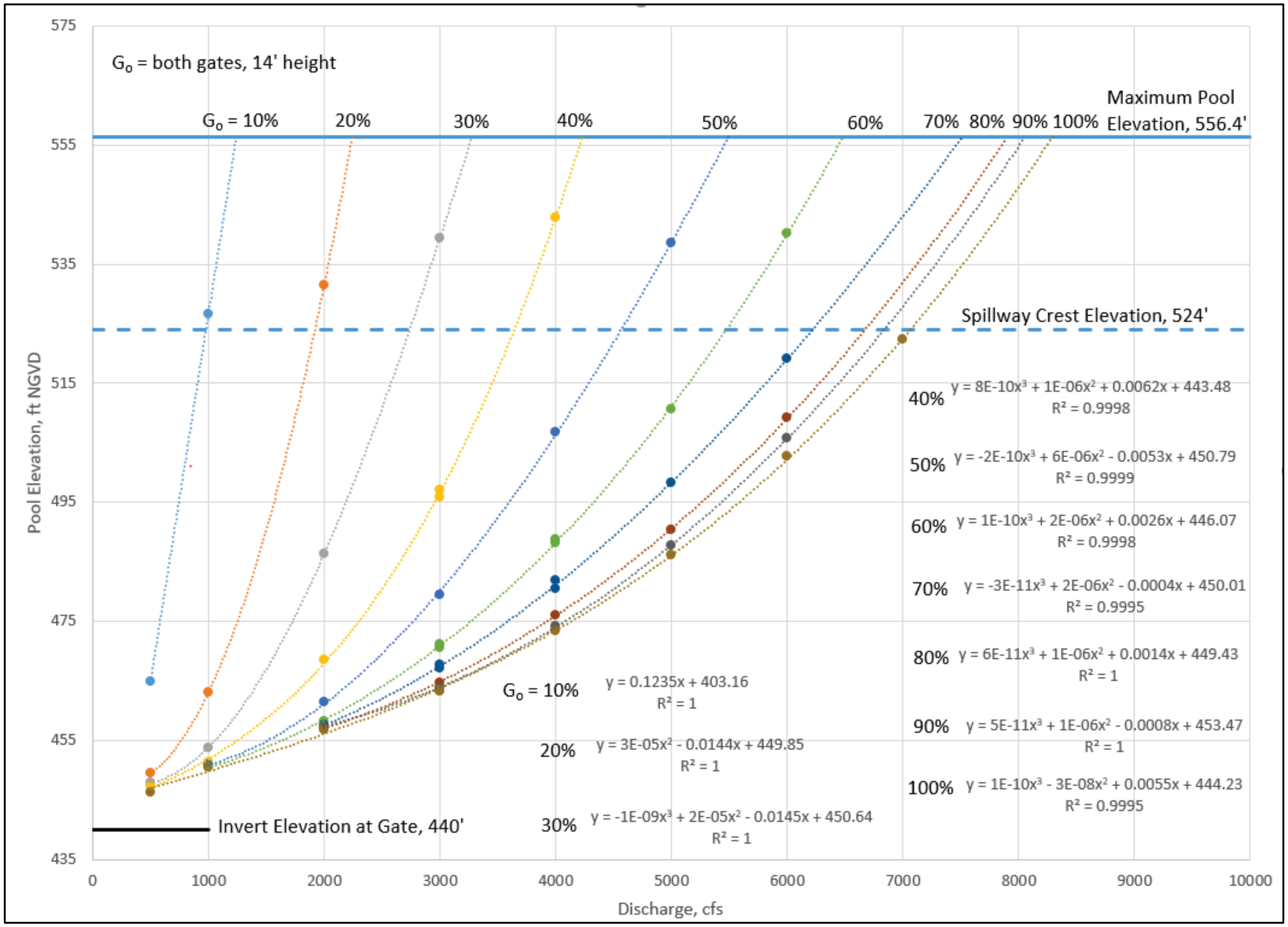


Figure 28. LRL-generated contour plot for single gate operation.

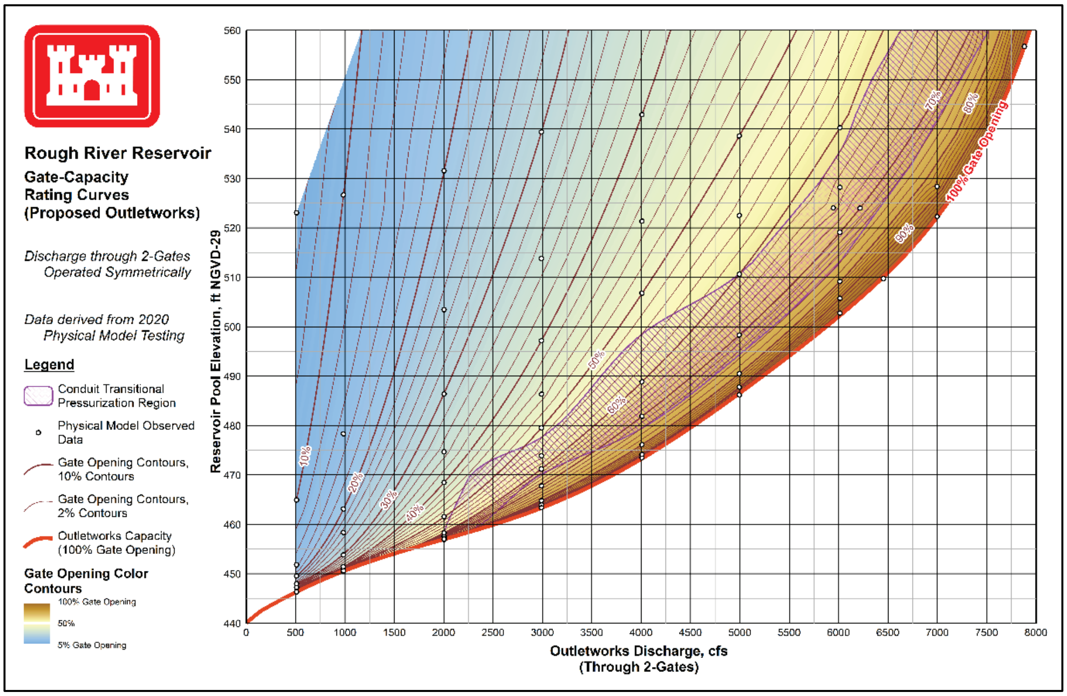
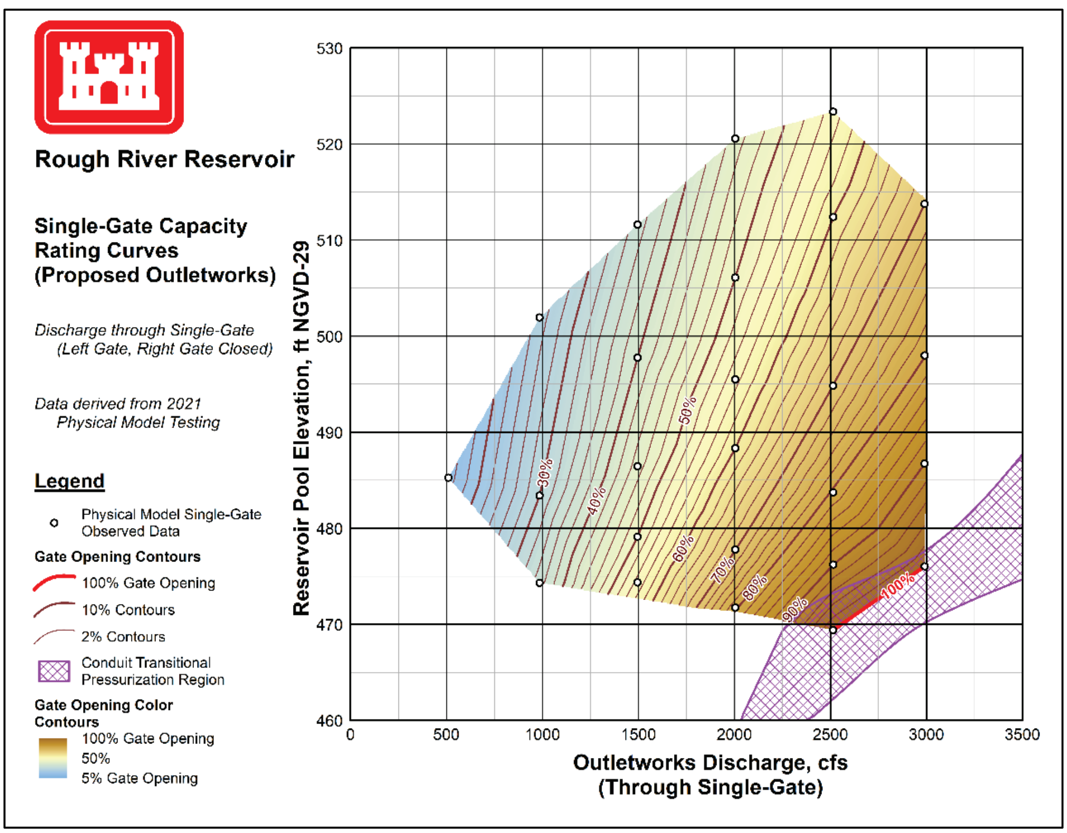


Figure 29. LRL-generated contour plot for single gate operation.



5 Discussion

5.1 EM 1110-2-1602 (USACE 1980) transition

During testing several overall performance observations were made. A primary concern was the transition. Typically, with reservoir outlet works there is concern for cavitation issues, and PDT members were concerned with this issue. Cavitation potential is assumed to be reduced by applying the USACE-recommended transition design as laid out in EM 1110-2-1602. This sentiment was echoed by hydraulic structure design experts consulted by the PDT. Three-dimensional computational fluid dynamics modeling further supported this assumption through the calculation of cavitation indices for the EM 1110-2-1602 transition. The tests demonstrated the EM 1110-2-1602 transition was only slightly less efficient than the original LRL transition design. Thus, the PDT selected cavitation reduction potential and increased compliance with published guidance over the slight loss of efficiency.

Of additional note, during partial conduit flow, as the water jets from the two passages converge into a single stream, the converging flow forms a rooster tail. For higher flows greater approximately 2,000 cfs, this rooster tail sprays upward with potential to impact the crown of the conduit. This flow action occurred in both transition designs, and there was not a noticeable change between designs. Operationally, this flow behavior is not considered a cause for concern.

5.2 Stilling basin performance and bench impacts

The various end sill configuration (Figure 13) WSE profiles are shown in Figure 30. In the original design configuration, including the original end sill and the hydraulically steep retreat channel, the flow exiting the conduit is super critical as expected. Once on the stilling basin floor, the flow transitions through a jump and is sub-critical but then again transitions back to super-critical downstream of the original end sill creating an undular or weak jump near the downstream end of the concrete apron (Figure 31). The second jump could cause damage to the channel such as undesirable erosion. Thus, changes were required to eliminate the secondary jump. For mitigation of this second jump, the PDT decided to flatten the apron to a 0% slope. The change on the apron along with a deeper backwater were the main contributing factors to preventing the secondary jump.

Due to maintenance concerns associated with dewatering the stilling basin, several end sill configurations were tested. This became a greater issue once the apron was flattened because the lower apron elevation requires a taller dewatering structure. Four end sill designs where tested. First, it was found with both the notched end sills that circulations occurred in the stilling basin. For lower flows, the notches created a jet effect on the apron which could potentially induce apron damage or other maintenance concerns. Thus, both notched end sill concepts were abandoned. The Type 2 fully dentate end sill with modified retreat channel resulted in sub-critical flow once flow passed the baffle blocks. For all flow ranges, the dentate end sill prevented hydraulic jump sweep out. The addition of the bench, downstream of the end sill, created minimum impacts to the performance of the basin. The modifications eliminated the undular/weak jump in the retreat channel and provided a self-cleaning capability with the dentate end sill. The benefits of this change are illustrated in Figure 30, where the Froude number shows the flow on the apron as sub-critical flow for stationing downstream of 21+00. These modifications maintain the ability at flows above 3000 cfs to dissipate energy and perform superior to the original design.

Testing investigated the impact of a taller dentate (435 ft) end sill for the facilitation of dewatering. Review of the Froude number, as compared to the original dentate (Figure 32 and Figure 33) for both the 500 and 3000 cfs flow cases, showed no meaningful change between the two dentate end sills.

Figure 30. WSE Profiles (Q = 1000 cfs) through the stilling basin for the various end sills.

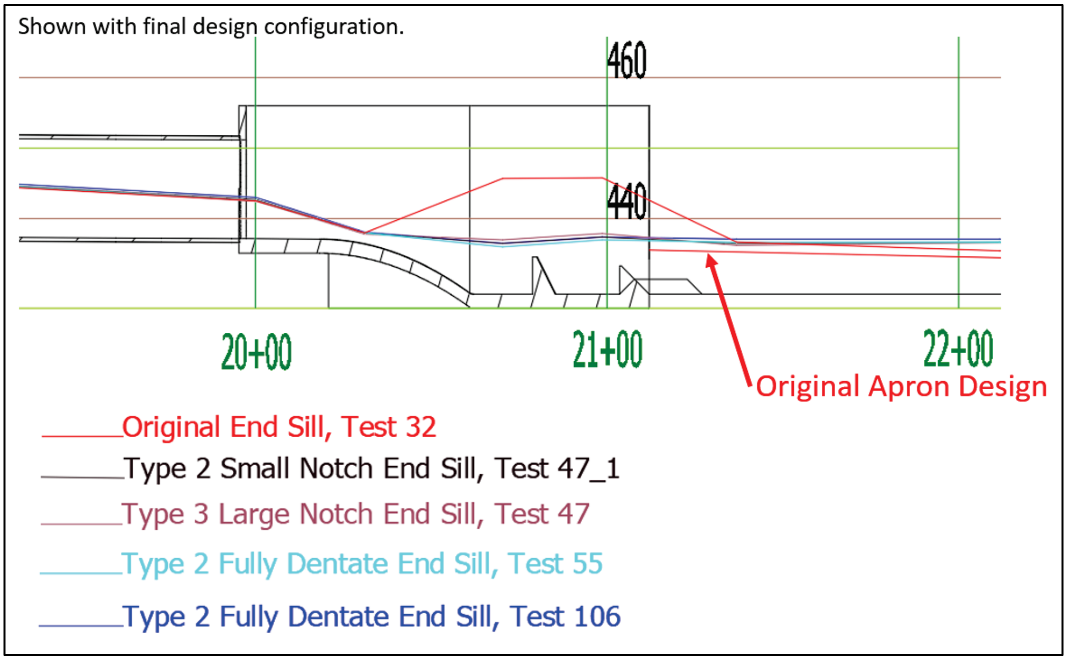


Figure 31. Original vs. modified retreat and end sill design.

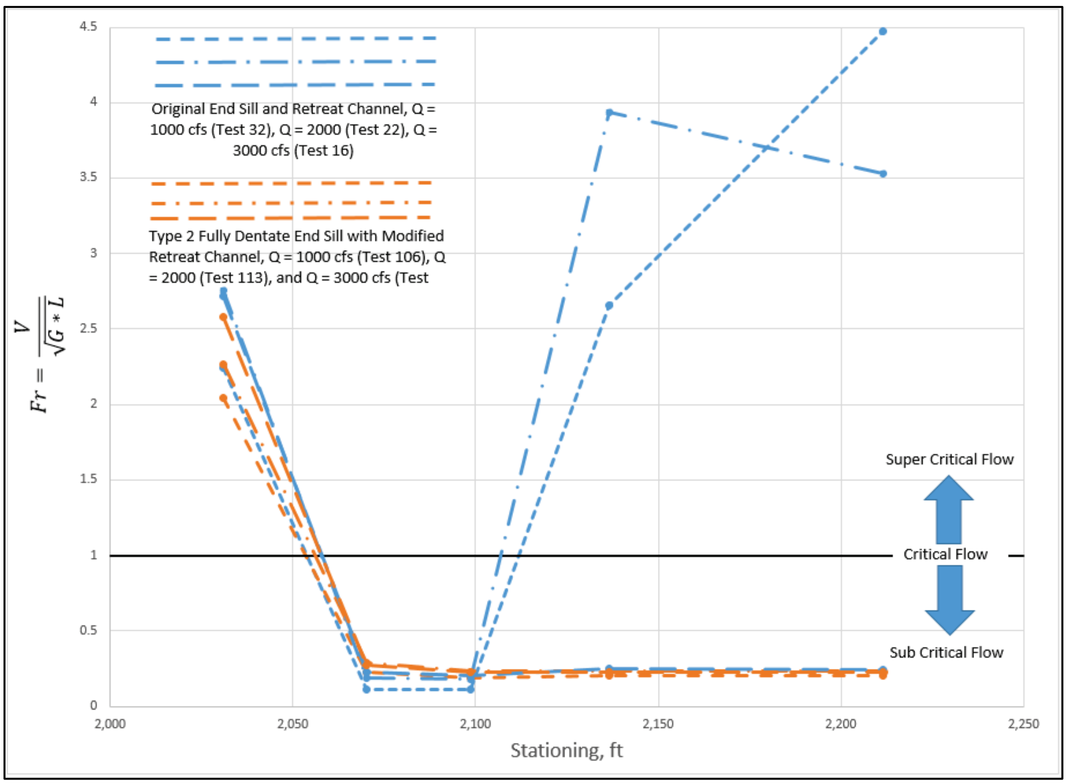


Figure 32. Original, dentate, and tall fully dentate end sill comparison for 3000 cfs flows.

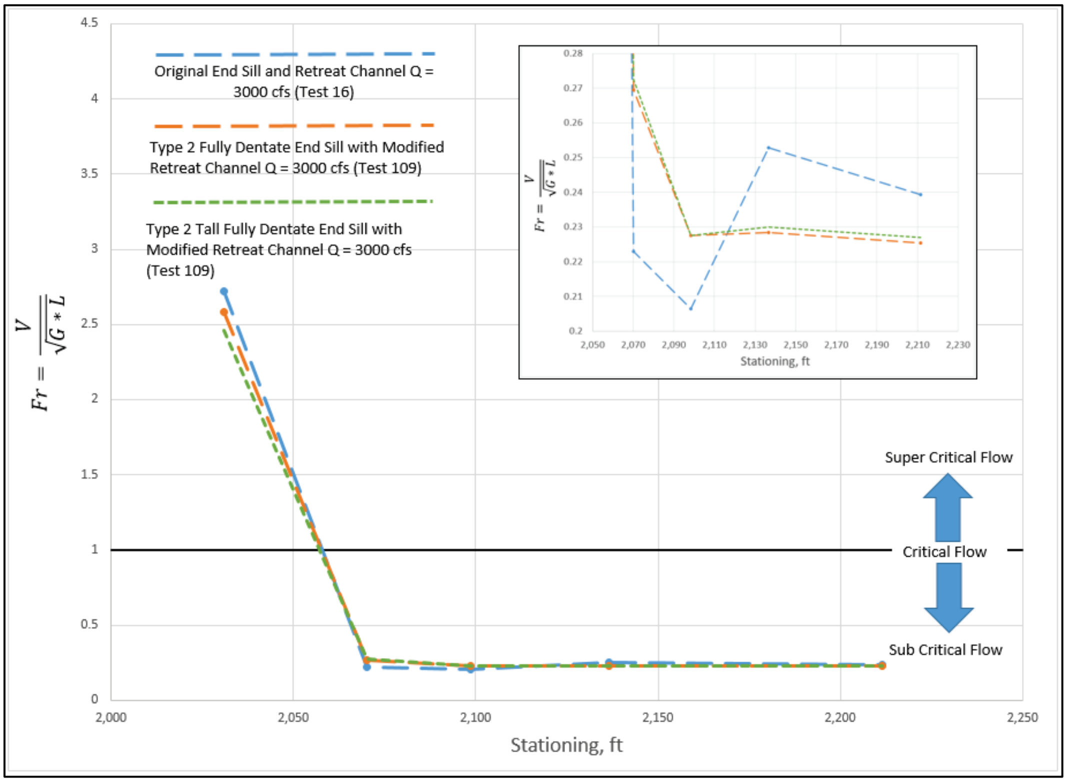
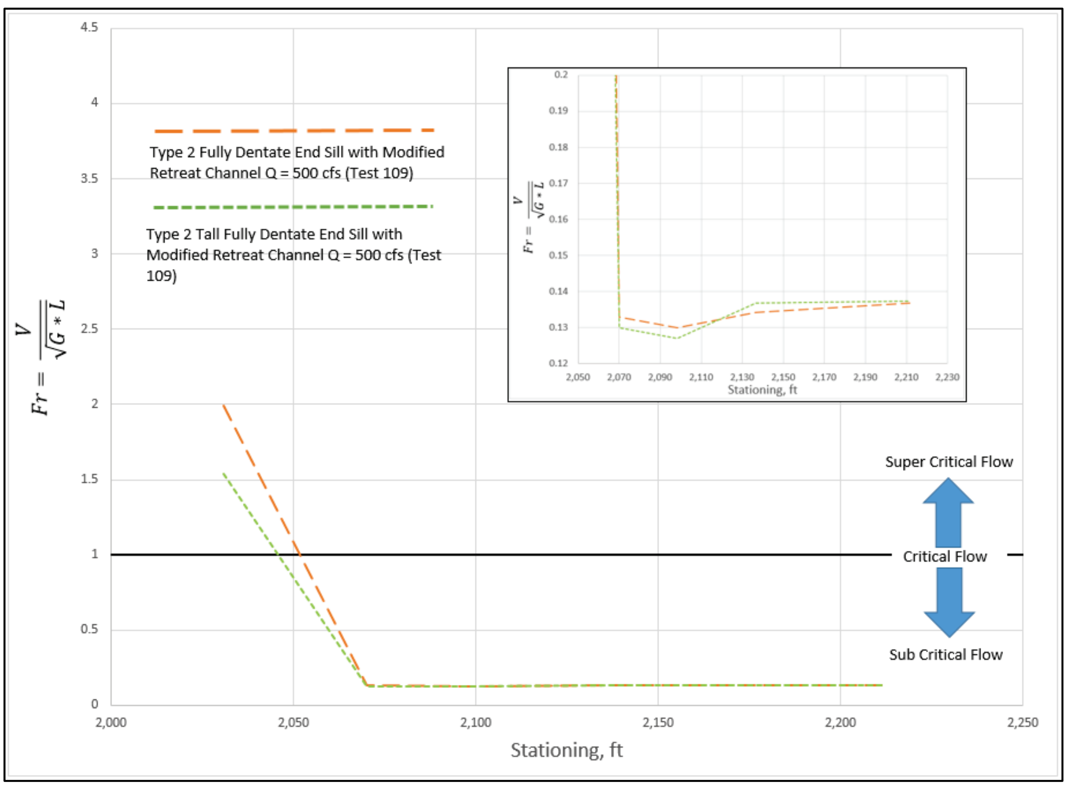


Figure 33. Dentate and tall fully dentate end sill comparison for 500 cfs flows.



5.3 Vortex formation

The curved approach channel exacerbated the vortex formation potential. Further complication occurs by the stepped geometry around the intake tower and the overbank flow direction reversal during high pool events. During lower pools (510 ft – 520 ft), vortex formation was predominantly on the right descending side of the intake tower. This is due in part to the clockwise rotation of flow around the intake tower. As the vortices periodically spin up and pass over the service deck, they break apart; however, if they drift upstream of the service deck then the vortices form up as Type 2 or 3 (Figure 34). For pool elevation of ~520 ft and above, the flow direction around the tower was counterclockwise. The flow direction reversal was due to overbank flow from the dam side of the tower. The reversal causes the vortex to set up on the center to left of the tower (Figure 35). These vortices appear to be similar in strength to those at the lower pool.

Once all the above modifications were made in the model, additional tests re-evaluated the vorticity formation at the three susceptible pool elevations. There was no observable reduction in the vortices from the modifications. These vortices did not appear to suck air or debris and were either a type 2 (surface dimple and swirl) or type 3 (dye core to intake). One attempt at reducing vortices was made by removal of the service deck from the intake tower; however, it provided no noticeable alleviation of vortices. The primary concerns for vortex formation at an intake tower are safety and debris. In this scale model, vortex strength greater than type 3 becomes a concern. Since no vortices stronger than type 3 were observed, debris should not be pulled into the intake.

Figure 34. Types of vortices as defined by the Hydraulic Institute. (Image from Knauss [1987])

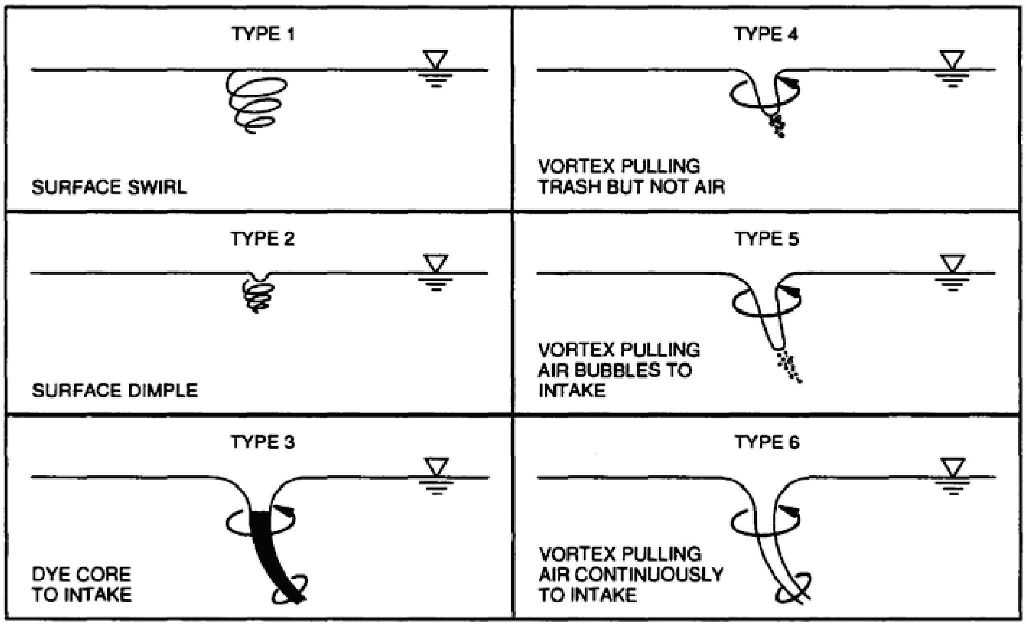
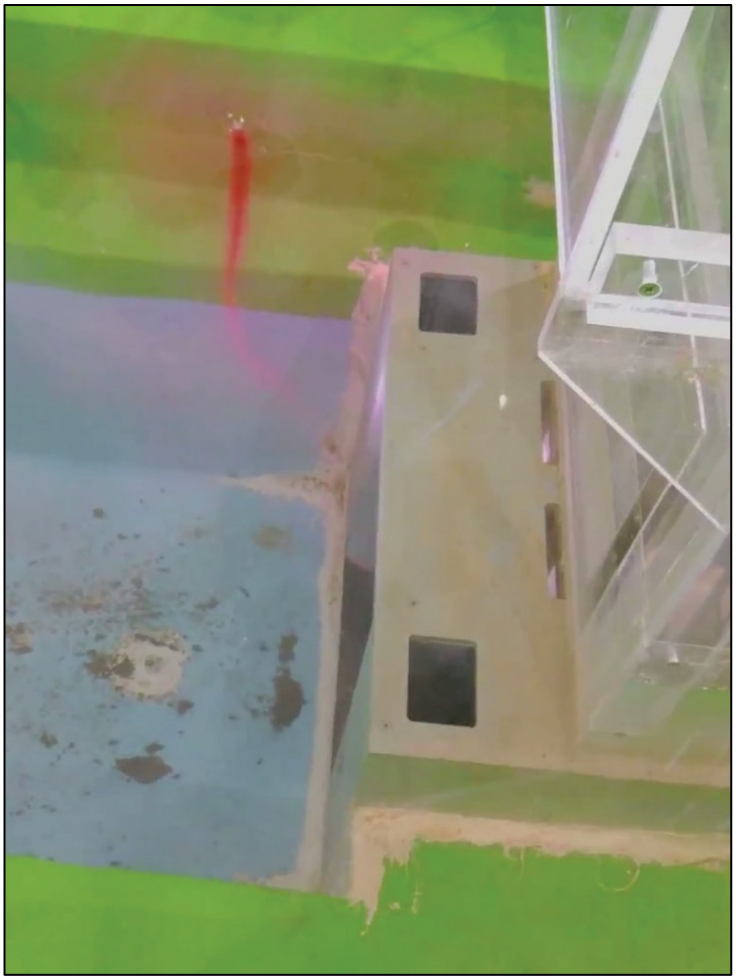


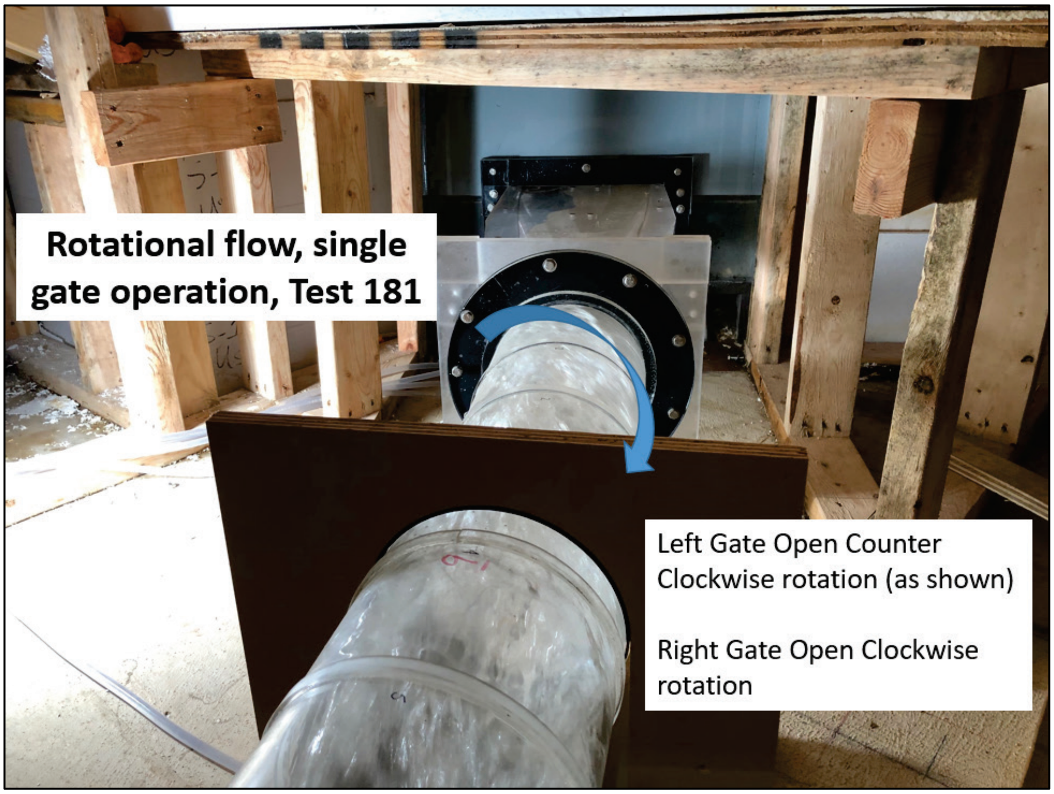
Figure 35. Test 88, typical vortex estimated type 3 (Q = 7107, Pool = 523.99 ft).



5.4 Single gate operations

While the operation of the structure should always be conducted with both gates at symmetric positions for optimal hydraulic performance, there is a recognition that gates might become stuck or damaged forcing operators to operate with a single gate. Thus, investigation into single gate operation occurred (Figure 29). Several key observations were made during the evaluation. With single gate operations, the flow exiting the gate passages causes asymmetric flow setup that is further compounded by the immediate transition into the curved conduit. From the setup, the flow will either spin counterclockwise (right gate open) or clockwise (left gate open) as dependent on the right or left gate being closed respectively (Figure 36). In some cases (flows above 1500 cfs), the rotational flow wraps all the way around conduit onto the crown. This swirling and setup on conduit wall continue downstream to the curved portion of the conduit, reflecting side to side from wall to wall. This reflection causes locations of setup on the conduit but to a lesser degree as compared to the section immediately downstream of the transition. Once the flow is in the straight portion of the conduit, the reflection is dissipated. At this point, there is no concern for conduit damage; however, debris could exacerbate the damage potential.

Figure 36. Rotation conduit flow for left gate open (Test 181).



5.5 Probable maximum flood (PMF)

During probable maximum flood (PMF*) testing, the stilling basin is submerged, and circulation of flow sets up in and around the stilling basin. Flow spills out of the basin along the sides running back upstream. This generates a circular rotation at the upstream end of the stilling basin. The effect of the rotation causes a transition from inlet-controlled, as for all other flow cases, to that of outlet-control. Furthermore, the control may switch back and forth, as some surging does occur. The significance of the circulation is dependent on the tailwater. There is some evidence of this in

* The return probability is estimated at 1/28,844, Hydrologic Hazard Curve update for Rough River Reservoir dated 01042021.

unrecorded observations during testing; the model was slightly more challenging to establish an equilibrium pool. For these PMF flow conditions, the pool is near 556 el, and the discharge is approximately 7900 cfs. Note the tailwater is set for the total flow from the dam, which includes the spillway. However, the model does not have the spillway built in, and it is unclear how the flow over the spillway, 524 el, would influence the tailwater. Of additional note is the wave action that propagates to the downstream side of the dam. However, the height of these waves does not seem to be significant enough to cause issues, and there is some question on the scalability in the model.

5.6 Vent test

The intake tower has two vents, one for each gate. During operation, the vents will fill with water as the conduit is pressurized and the pool rises. There were concerns of water level surging in the vent during operation of the gates. Thus, a series of three tests evaluated the water level vent surge potential. These tests simulated a prototype operation where the pool was held near constant at 525 el (Figure 37), and the discharge was increased from 1000 – 7100 cfs over 2.29 hr. At the PG 3 location (both left and right gates), the HGL was monitored via a camera during the test. The PG 3 location is directly under the air vents. Test results indicate there is no surge occurring in the vents (Figure 38).

Figure 37. Vent test, Test 153 (line is pool elevation).

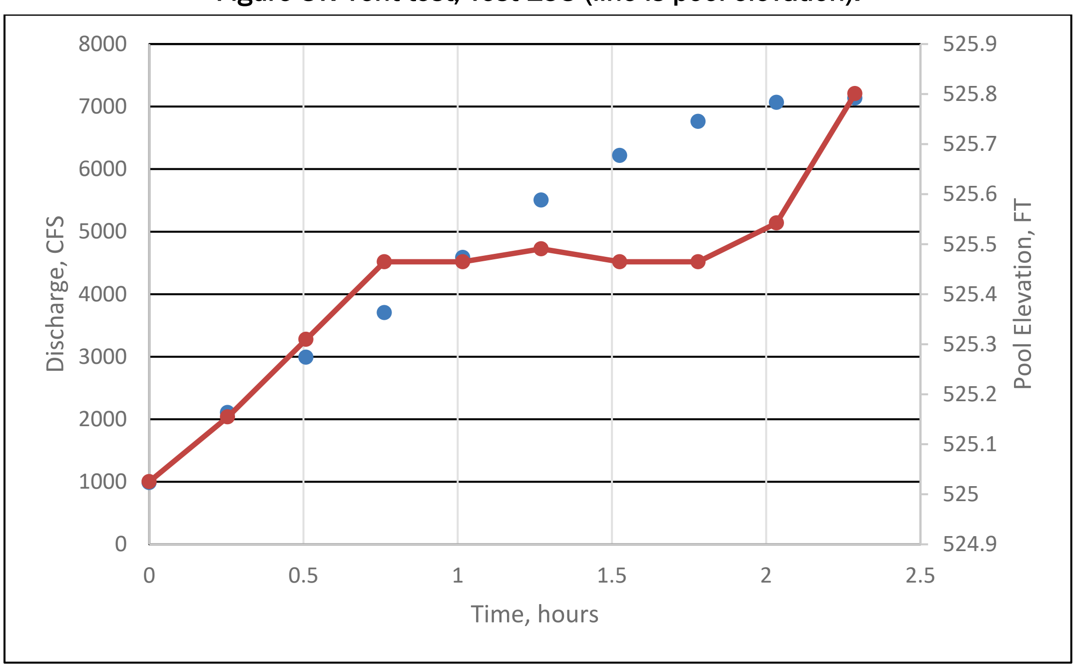
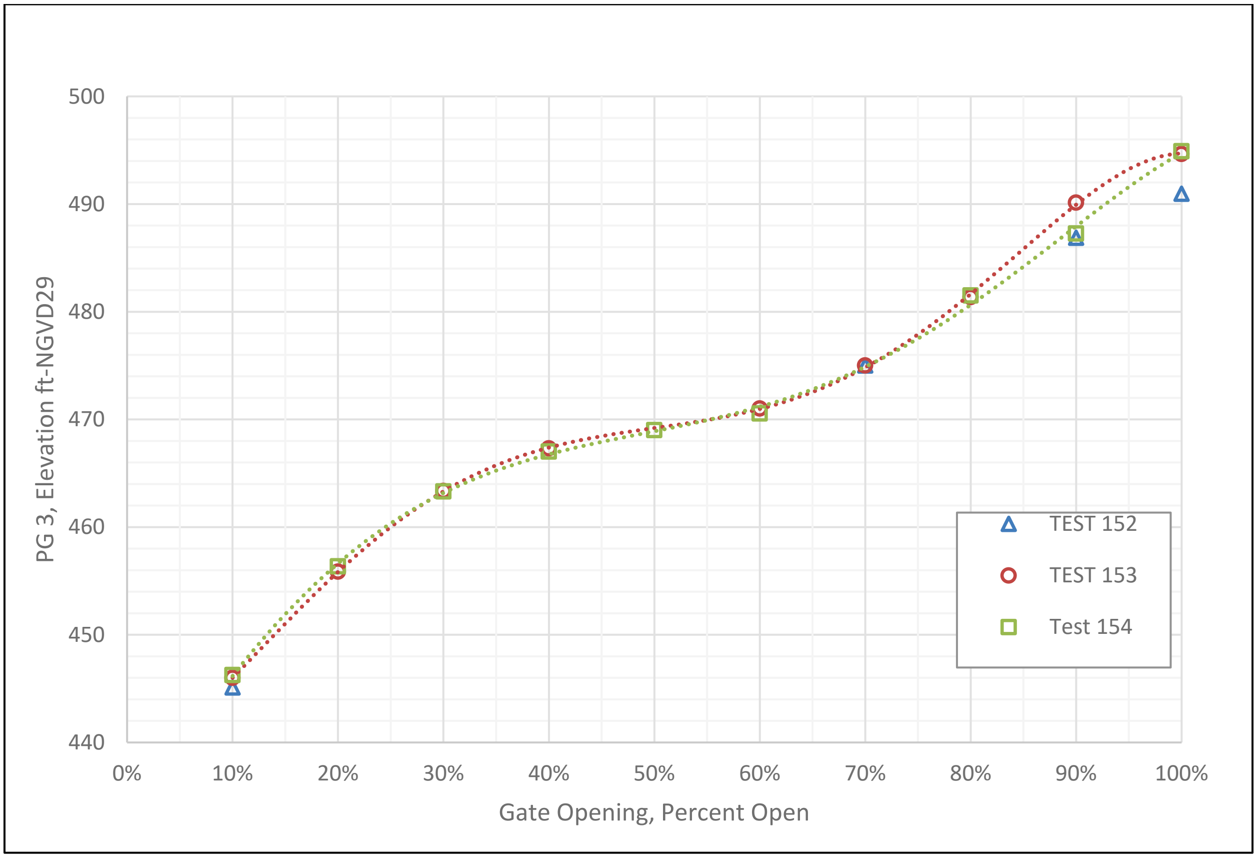


Figure 38. Vent test data.



6 Conclusions and Recommendations

The design modifications tested in this study resulted in a hydraulically superior RROW design. Over the life of the project, these modifications will significantly reduce costs associated with the operations and maintenance of the project. Inlet control predominantly regulated the performance of the structure at medium and low flows. Furthermore, the presented HGL data illustrate the right descending gate is more efficient then the left gate due to the approach channel curvature.

The following observations and recommendations are provided based on model test results.

1. The RROW would benefit from a straight approach channel, although this is not practical due to excavation cost.
2. A straighter approach channel would reduce the circulation of flow in the pool around the intake tower, which might reduce or eliminate the vortex formation.
3. For asymmetric gate operations, crown damage could occur if debris enters into the conduit. The associated risk is minimal since single gate operations are rare, and the conduit will have abrasion resistant concrete.
4. After asymmetric gate operations, the conduit should be inspected for impact damage.
5. The first 100 ft of conduit would benefit from being a straight section, alleviating the rotational flow/roller during asymmetric gate operations.
6. During reasonable flow conditions, the stilling basin with modifications did not have any sweep-out issues with the jump. This includes the incorporation of the downstream bench.
7. The flat concrete retreat channel apron performance was significantly superior to that of the original design.
8. There was no rock movement observed in the downstream trapezoidal testing. Rock sizing may be reduced.
9. The rock trap (the 5 ft step at the face of the tower) prevents the entrance of material into the conduit.
10. Any changes to the current design would necessitate additional testing to verify performance of the design changes. This would include, but not be limited to, conduit changes (mitered or curved monoliths), channel alignment, stilling basin alterations, slope changes, etc.

References

Bell, G. L., J. A. Sharp, L. M. Williams, H. E. Park, D. B. Bryant, and G. Savant. 2020. *Red River Structure Physical Model Study*. ERDC/CHL TR-20-20. Vicksburg, MS: US Army Engineer Research and Development Center.

EESIFLO. 2019. *Technical Specification SONALOK 7S, Non-Invasive Ultrasonic flowmeter*. http://eesiflo.com/TSSONALOK_7S_V2-2-3EN_Ak.pdf.

Knauss, J. 1987. *Swirling Flow Problems at Intakes*. Hydraulic Structures Design Manual, 1AA. Balkema, Rotterdam.

Singh, A. 1969. "Transition from Circular to Rectangular Section." *Journal, Hydraulic Division, American Society of Civil Engineers* 95(HY3) Proc Paper: 893–906.

USACE (US Army Corps of Engineers). 1980. *Hydraulic Design of Reservoir Outlet Works*. CECW-EH-D EM 1110-2-1602. Washington, DC: US Army Corps of Engineers.

USACE. 2014. *Engineering and Design Safety of Dams – Policy and Procedures*. CECW-CE ER 1110-2-1156. Washington, DC: US Army Corps of Engineers.

Appendix A: Center Line Alignment and Model Layout

In Figure 39, model layout from the horizontal control points shows the model layout off a control line. Then, Table 15 shows the centerline of the project in prototype units. Table 16 shows the location of joints for the conduit.

Figure 39. Model layout from the horizontal control points.

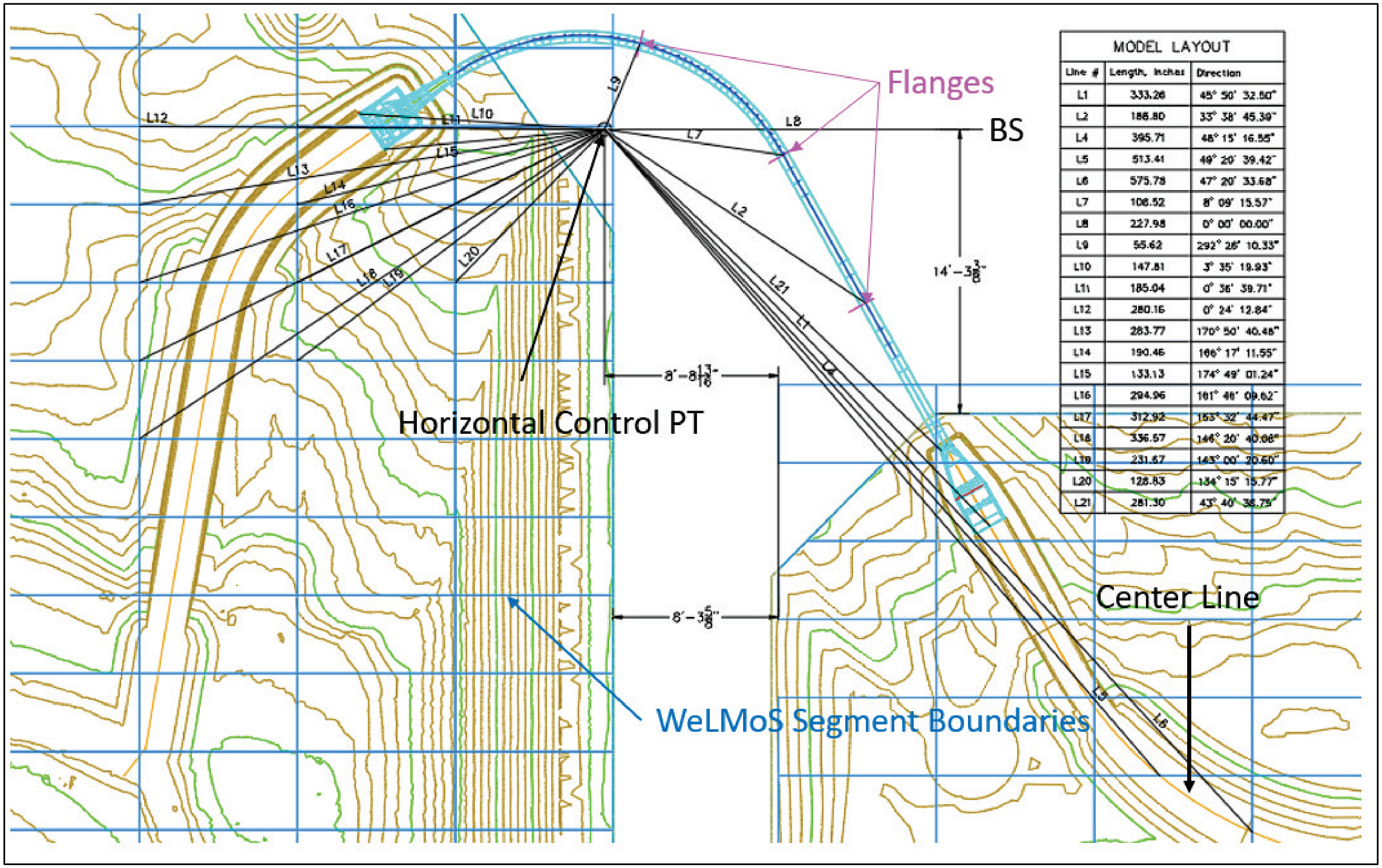


Table 15. Project center line/alignment (prototype).

No.	Length	Direction	Start Station	End Station	Start Point		End Point	
					X	Y	X	Y
1	46.125'	S79° 12' 12.44"W	0+00.00'	0+46.12'	1423438.6928'	2109326.1119'	1423393.3847'	2109317.4718'
2	0.017'	S74° 22' 36.54"W	0+46.12'	0+46.14'	1423393.3847'	2109317.4718'	1423393.3685'	2109317.4672'
3	0.017'	S64° 43' 24.75"W	0+46.14'	0+46.16'	1423393.3685'	2109317.4672'	1423393.3533'	2109317.4600'
4	0.017'	S55° 04' 12.96"W	0+46.16'	0+46.18'	1423393.3533'	2109317.4600'	1423393.3395'	2109317.4504'
5	557.393'	S50° 14' 37.06"W	0+46.18'	6+03.57'	1423393.3395'	2109317.4504'	1422964.8320'	2108960.9839'
6	26.354'	S52° 45' 39.89"W	6+03.57'	6+29.92'	1422964.8320'	2108960.9839'	1422943.8509'	2108945.0359'
7	26.354'	S57° 47' 45.54"W	6+29.92'	6+56.28'	1422943.8509'	2108945.0359'	1422921.5511'	2108930.9908'
8	26.354'	S62° 49' 51.19"W	6+56.28'	6+82.63'	1422921.5511'	2108930.9908'	1422898.1048'	2108918.9570'
9	26.354'	S67° 51' 56.84"W	6+82.63'	7+08.99'	1422898.1048'	2108918.9570'	1422873.6928'	2108909.0273'
10	26.354'	S72° 54' 02.49"W	7+08.99'	7+35.34'	1422873.6928'	2108909.0273'	1422848.5035'	2108901.2784'
11	26.354'	S77° 56' 08.15"W	7+35.34'	7+61.69'	1422848.5035'	2108901.2784'	1422822.7314'	2108895.7701'
12	26.354'	S82° 58' 13.80"W	7+61.69'	7+88.05'	1422822.7314'	2108895.7701'	1422796.5753'	2108892.5448'
13	26.354'	S88° 00' 19.45"W	7+88.05'	8+14.40'	1422796.5753'	2108892.5448'	1422770.2370'	2108891.6276'

No.	Length	Direction	Start Station	End Station	Start Point		End Point	
					X	Y	X	Y
14	26.354'	N86° 57' 34.90"W	8+14.40'	8+40.76'	1422770.2370'	2108891.6276'	1422743.9199'	2108893.0254'
15	216.072'	N84° 26' 32.07"W	8+40.76'	10+56.83'	1422743.9199'	2108893.0254'	1422528.8636'	2108913.9518'
16	27.925'	N81° 46' 28.82"W	10+56.83'	10+84.75'	1422528.8636'	2108913.9518'	1422501.2263'	2108917.9468'
17	27.925'	N76° 26' 22.33"W	10+84.75'	11+12.68'	1422501.2263'	2108917.9468'	1422474.0801'	2108924.4944'
18	27.925'	N71° 06' 15.84"W	11+12.68'	11+40.60'	1422474.0801'	2108924.4944'	1422447.6603'	2108933.5376'
19	27.925'	N65° 46' 09.35"W	11+40.60'	11+68.53'	1422447.6603'	2108933.5376'	1422422.1959'	2108944.9982'
20	27.925'	N60° 26' 02.86"W	11+68.53'	11+96.45'	1422422.1959'	2108944.9982'	1422397.9073'	2108958.7769'
21	27.925'	N55° 05' 56.36"W	11+96.45'	12+24.38'	1422397.9073'	2108958.7769'	1422375.0052'	2108974.7542'
22	27.925'	N49° 45' 49.87"W	12+24.38'	12+52.30'	1422375.0052'	2108974.7542'	1422353.6878'	2108992.7919'
23	27.925'	N44° 25' 43.38"W	12+52.30'	12+80.23'	1422353.6878'	2108992.7919'	1422334.1400'	2109012.7334'
24	27.925'	N39° 05' 36.89"W	12+80.23'	13+08.15'	1422334.1400'	2109012.7334'	1422316.5311'	2109034.4062'
25	27.925'	N33° 45' 30.39"W	13+08.15'	13+36.07'	1422316.5311'	2109034.4062'	1422301.0136'	2109057.6224'
26	27.925'	N28° 25' 23.90"W	13+36.07'	13+64.00'	1422301.0136'	2109057.6224'	1422287.7219'	2109082.1808'
27	27.925'	N23° 05' 17.41"W	13+64.00'	13+91.92'	1422287.7219'	2109082.1808'	1422276.7714'	2109107.8688'

No.	Length	Direction	Start Station	End Station	Start Point		End Point	
					X	Y	X	Y
28	27.925'	N17° 45' 10.92"W	13+91.92'	14+19.85'	1422276.7714'	2109107.8688'	1422268.2568'	2109134.4636'
29	27.925'	N12° 25' 04.42"W	14+19.85'	14+47.77'	1422268.2568'	2109134.4636'	1422262.2518'	2109161.7349'
30	27.925'	N07° 04' 57.93"W	14+47.77'	14+75.70'	1422262.2518'	2109161.7349'	1422258.8086'	2109189.4465'
31	27.925'	N01° 44' 51.44"W	14+75.70'	15+03.62'	1422258.8086'	2109189.4465'	1422257.9570'	2109217.3581'
32	27.925'	N03° 35' 15.05"E	15+03.62'	15+31.55'	1422257.9570'	2109217.3581'	1422259.7044'	2109245.2280'
33	27.925'	N08° 55' 21.54"E	15+31.55'	15+59.47'	1422259.7044'	2109245.2280'	1422264.0355'	2109272.8147'
34	759.990'	N11° 35' 24.79"E	15+59.47'	23+19.46'	1422264.0355'	2109272.8147'	1422416.7256'	2110017.3079'
35	34.250'	N09° 37' 38.88"E	23+19.46'	23+53.71'	1422416.7256'	2110017.3079'	1422422.4535'	2110051.0753'
36	34.250'	N05° 42' 07.06"E	23+53.71'	23+87.96'	1422422.4535'	2110051.0753'	1422425.8564'	2110085.1557'
37	34.250'	N01° 46' 35.25"E	23+87.96'	24+22.21'	1422425.8564'	2110085.1557'	1422426.9181'	2110119.3890'
38	34.250'	N02° 08' 56.57"W	24+22.21'	24+56.46'	1422426.9181'	2110119.3890'	1422425.6338'	2110153.6147'
39	34.250'	N06° 04' 28.39"W	24+56.46'	24+90.71'	1422425.6338'	2110153.6147'	1422422.0094'	2110187.6722'
40	34.250'	N10° 00' 00.20"W	24+90.71'	25+24.96'	1422422.0094'	2110187.6722'	1422416.0620'	2110221.4016'
41	34.250'	N13° 55' 32.02"W	25+24.96'	25+59.21'	1422416.0620'	2110221.4016'	1422407.8194'	2110254.6448'

No.	Length	Direction	Start Station	End Station	Start Point		End Point	
					X	Y	X	Y
42	34.250'	N17° 51' 03.84"W	25+59.21'	25+93.46'	1422407.8194'	2110254.6448'	1422397.3203'	2110287.2457'
43	34.250'	N21° 46' 35.66"W	25+93.46'	26+27.71'	1422397.3203'	2110287.2457'	1422384.6140'	2110319.0513'
44	34.250'	N25° 42' 07.47"W	26+27.71'	26+61.96'	1422384.6140'	2110319.0513'	1422369.7602'	2110349.9125'
45	34.250'	N29° 37' 39.29"W	26+61.96'	26+96.21'	1422369.7602'	2110349.9125'	1422352.8284'	2110379.6844'
46	34.250'	N33° 33' 11.11"W	26+96.21'	27+30.46'	1422352.8284'	2110379.6844'	1422333.8983'	2110408.2272'
47	34.250'	N37° 28' 42.92"W	27+30.46'	27+64.71'	1422333.8983'	2110408.2272'	1422313.0585'	2110435.4072'
48	34.250'	N41° 24' 14.74"W	27+64.71'	27+98.96'	1422313.0585'	2110435.4072'	1422290.4068'	2110461.0967'
49	34.250'	N45° 19' 46.56"W	27+98.96'	28+33.21'	1422290.4068'	2110461.0967'	1422266.0497'	2110485.1753'
50	34.250'	N49° 15' 18.38"W	28+33.21'	28+67.46'	1422266.0497'	2110485.1753'	1422240.1012'	2110507.5299'
51	34.250'	N53° 10' 50.19"W	28+67.46'	29+01.71'	1422240.1012'	2110507.5299'	1422212.6833'	2110528.0556'
52	167.350'	N55° 08' 36.10"W	29+01.71'	30+69.06'	1422212.6833'	2110528.0556'	1422075.3582'	2110623.7005'

Table 16. Conduit stationing on project center line and joint location.

Stationing	Point ID	Y-Coordinate	X-Coordinate	Elevation, ft
1056.90	75	2,108,914	1,422,529	440.00
1069.73	76	2,108,916	1,422,516	439.96
1079.73	77	2,108,917	1,422,506	439.93
1089.73	78	2,108,919	1,422,496	439.90
1099.73	79	2,108,921	1,422,487	439.87
1109.73	80	2,108,924	1,422,477	439.84
1119.73	81	2,108,927	1,422,467	439.81
1129.73	82	2,108,930	1,422,458	439.78
1139.73	83	2,108,933	1,422,448	439.75
1149.73	84	2,108,937	1,422,439	439.72
1159.73	85	2,108,941	1,422,430	439.69
1169.73	86	2,108,946	1,422,421	439.66
1179.73	87	2,108,951	1,422,412	439.63
1189.73	88	2,108,955	1,422,404	439.60
1199.73	89	2,108,961	1,422,395	439.57
1209.73	90	2,108,966	1,422,387	439.54
1219.73	91	2,108,972	1,422,379	439.51
1229.73	92	2,108,978	1,422,371	439.48
1239.73	93	2,108,985	1,422,363	439.45
1249.73	94	2,108,991	1,422,356	439.42
1259.73	95	2,108,998	1,422,348	439.39
1269.73	96	2,109,005	1,422,341	439.36
1279.73	97	2,109,012	1,422,334	439.33
1289.73	98	2,109,020	1,422,328	439.30
1299.73	99	2,109,028	1,422,322	439.27
1309.73	100	2,109,036	1,422,316	439.24
1319.73	101	2,109,044	1,422,310	439.21
1329.73	102	2,109,052	1,422,305	439.18
1339.73	103	2,109,061	1,422,299	439.15
1349.73	104	2,109,070	1,422,295	439.12
1359.73	105	2,109,078	1,422,290	439.09
1369.73	106	2,109,087	1,422,285	439.06

Stationing	Point ID	Y-Coordinate	X-Coordinate	Elevation, ft
1379.73	107	2,109,097	1,422,282	439.03
1389.73	108	2,109,106	1,422,278	439.00
1399.73	109	2,109,115	1,422,274	438.97
1409.73	110	2,109,125	1,422,271	438.94
1419.73	111	2,109,134	1,422,268	438.91
1429.73	112	2,109,144	1,422,266	438.88
1439.73	113	2,109,154	1,422,264	438.85
1449.73	114	2,109,164	1,422,262	438.82
1459.73	115	2,109,174	1,422,261	438.79
1469.73	116	2,109,184	1,422,260	438.76
1479.73	117	2,109,193	1,422,259	438.73
1489.73	118	2,109,203	1,422,258	438.70
1499.73	119	2,109,213	1,422,258	438.67
1509.73	120	2,109,223	1,422,258	438.64
1519.73	121	2,109,233	1,422,259	438.61
1529.73	122	2,109,243	1,422,260	438.58
1539.73	123	2,109,253	1,422,261	438.55
1549.73	124	2,109,263	1,422,263	438.52
1559.73	125	2,109,273	1,422,264	438.49
1579.73	126	2,109,293	1,422,268	438.43
1599.73	127	2,109,312	1,422,272	438.37
1619.73	128	2,109,332	1,422,276	438.31
1639.73	129	2,109,351	1,422,280	438.25
1659.73	130	2,109,371	1,422,284	438.19
1679.73	131	2,109,391	1,422,288	438.13
1699.73	132	2,109,410	1,422,292	438.07
1719.73	133	2,109,430	1,422,296	438.01
1739.73	134	2,109,449	1,422,300	437.95
1759.73	135	2,109,469	1,422,304	437.89
1779.73	136	2,109,489	1,422,308	437.83
1799.73	137	2,109,508	1,422,312	437.77
1819.73	138	2,109,528	1,422,316	437.71
1839.73	139	2,109,547	1,422,320	437.65

Stationing	Point ID	Y-Coordinate	X-Coordinate	Elevation, ft
1859.73	140	2,109,567	1,422,324	437.59
1879.73	141	2,109,587	1,422,328	437.53
1899.73	142	2,109,606	1,422,332	437.47
1919.73	143	2,109,626	1,422,336	437.41
1939.73	144	2,109,645	1,422,340	437.35
1959.73	145	2,109,665	1,422,344	437.29
1972.75	146	2,109,678	1,422,347	437.25
1992.75	147	2,109,697	1,422,351	437.19
1997.25	148	2,109,702	1,422,352	437.18

Appendix B: Singh Design Transition Tests

Figure 40 presents Singh design transition curves, and Table 17 presents LRL design transition WSE profiles.

Figure 40. LRL design transition curves.

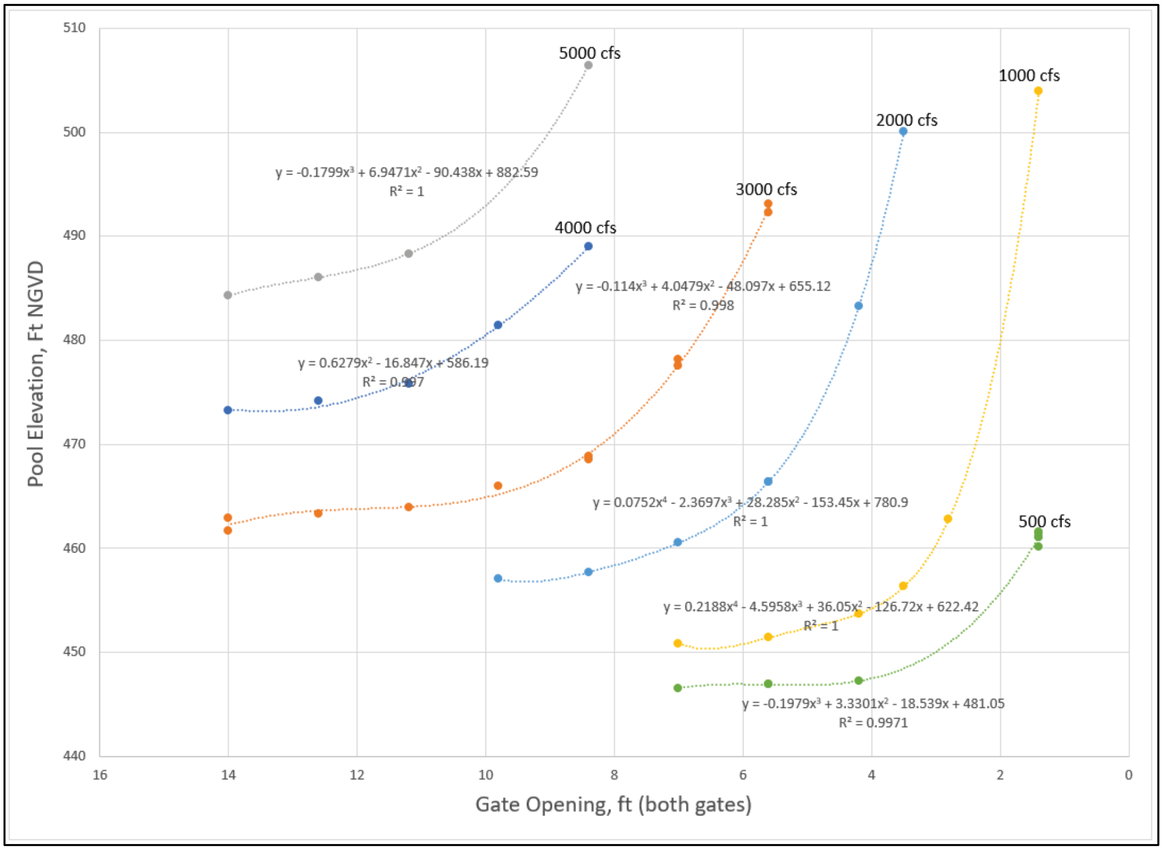


Table 17. Singh design transition HGL profiles.

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Water Surface Elevation																																	
50%	48	500	446.6	446.6	446.5	446.3	446.3	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	444.3	444.5	444.3	444.0	443.8	443.3	442.5	442.8	443.0	440.8	437.5	436.3	436.5	435.3	435.4	435.4
10%	49	500	461.6	461.6	461.6	462.0	462.0	453.9	453.8	442.3	442.3	441.4	441.4	441.5	441.5	442.0	442.1	441.7	441.6	443.2	442.5	442.4	442.0	442.6	443.1	442.8	442.7	443.0	443.3	441.0	437.4	436.5	436.7	435.3	435.5	435.4
10%	52	500	461.1	461.1	164.1	461.3	461.3	453.6	453.4	442.4	442.4	441.5	441.6	441.6	441.7	441.9	442.1	441.8	441.7	443.1	442.3	442.4	442.1	442.6	443.1	443.9	442.7	442.7	443.1	441.0	443.2	440.5	440.9	435.5	435.6	435.5
10%	54	500	461.5	461.4	461.4	461.8	461.8	453.9	453.8	442.3	442.4	441.5	441.5	441.6	442.0	442.0	442.1	441.8	441.7	443.2	442.5	442.5	442.1	442.6	443.2	442.9	442.8	442.8	443.2	441.0	437.5	435.6	435.8	435.6	435.6	435.5
10%	62	500	461.1	461.0	461.0																									441.1	437.6	435.8	435.9	435.6	435.6	435.5
10%	63	500	460.1	460.1	460.1																									441.1	437.6	434.5	434.7	433.6	433.6	433.0
40%	74	500	446.9	446.9	446.9	446.6	446.6	446.4	446.4	446.4	446.5	446.3	446.5	446.5	446.5	446.3	446.4	446.1	446.1	446.3	444.4	444.8	444.5	444.3	444.2	443.6	443.9	444.2	444.3	441.0	432.6	435.2	435.6	435.0	435.0	434.9
30%	75	500	447.3	447.2	447.3	447.1	447.0	446.4	446.5	445.9	446.0	445.7	445.9	446.0	446.2	446.1	446.2	446.2	446.3	446.4	444.5	444.9	444.7	444.3	444.2	443.6	443.2	443.3	443.4	441.1	437.7	435.6	435.9	435.6	435.5	435.4
40%	76	500	446.9	446.9	446.9	446.7	446.7	446.4	446.5	446.4	446.5	446.3	446.4	446.3	446.4	446.2	446.2	446.1	446.1	446.2	444.4	444.8	444.5	444.2	444.1	443.5	443.0	443.2	443.2	441.0	437.5	435.6	435.8	435.6	435.5	435.4
20%	77	500	448.3	448.3	448.3	448.3	448.3	446.3	446.3	444.6	444.7	444.5	444.6	445.3	445.3	445.7	445.6	445.9	445.8	446.2	444.4	444.8	444.5	444.3	444.0	443.5	442.9	443.2	443.2	441.0	437.6	435.6	435.9	435.6	435.3	435.4
20%	36	917	460.7	460.7	460.7	460.4	460.4	452.5	452.5	445.9	445.8	442.9	442.9	442.7	442.7	443.2	443.3	442.8	442.7	444.6	444.0	443.5	443.2	444.1	444.0	444.0	444.1	443.8	444.9	442.3	437.8	440.2	440.3	436.6	435.4	436.6
50%	32	1000	450.9	450.9	450.8	449.7	449.8	448.9	449.0	448.5	448.7	448.4	448.5	448.6	448.8	448.7	448.8	448.6	448.7	449.0	446.5	447.5	447.1	446.9	446.4	446.0	445.1	445.0	445.3	442.5	438.0	440.7	440.8	436.7	435.5	436.6
40%	33	1000	451.4	451.4	451.4	450.3	450.4	448.5	448.6	447.3	447.7	447.0	447.5	447.7	447.8	448.1	448.2	448.3	448.4	448.9	446.5	447.5	447.0	446.8	446.3	445.8	445.1	444.9	445.2	442.5	437.9	440.6	440.7	436.7	435.5	436.5
30%	35	1000	453.7	453.6	453.6	453.1	453.1	449.0	449.0	446.2	446.2	444.2	444.3	443.8	443.9	443.9	444.0	443.8	443.8	445.0	445.3	445.0	445.0	446.1	446.3	445.7	445.0	444.9	445.2	442.5	437.9	440.5	440.6	436.6	435.5	436.7
20%	37	1000	462.8	462.8	462.8	462.5	462.4	454.8	454.9	446.3	446.1	442.9	442.9	442.8	442.8	443.2	443.3	443.0	442.8	445.0	444.0	443.5	443.0	444.0	443.8	444.1	444.1	443.7	444.9	442.4	438.0	440.5	440.6	436.7	435.5	436.6
10%	38	1000	503.9	503.9	503.9	503.7	479.2	479.3	479.6	444.5	444.2	440.5	441.8	441.7	442.0	442.7	443.0	442.3	441.8	441.0	441.9	442.0	441.0	443.0	442.3	442.0	442.5	442.2	442.0	441.7	437.1	440.1	440.2	436.7	435.5	436.4
25%	39	1000	456.4	456.4	456.4	456.4	456.4	450.6	450.5	446.3	446.2	443.7	445.7	443.4	443.5	443.5	443.6	443.3	443.4	444.7	444.5	444.2	444.1	444.9	445.5	445.2	444.8	444.9	445.2	442.5	438.0	440.5	440.6	436.7	435.4	436.4
50%	47_1	1000	450.2	450.3	450.5	449.5	449.6	448.8	448.9	448.3	448.4	448.3	448.4	448.5	448.6	448.6	448.7	448.5	448.6	448.8	446.5	447.5	447.0	446.9	446.3	445.8	445.4	445.5	445.5	442.7	438.0	436.5	437.4	436.5	436.6	436.5
50%	47	1000	450.2	450.3	450.5	449.5	449.6	448.8	448.9	448.3	448.4	448.3	448.4	448.5	448.6	448.6	448.7	448.5	448.6	448.8	446.5	447.5	447.0	446.9	446.3	445.8	445.4	445.5	445.5	442.5	437.8	437.0	437.9	436.2	436.6	436.5
50%	53	1000	450.3	450.3	450.3	449.6	449.7	448.8	448.9	448.3	448.5	448.2	448.3	448.6	448.6	448.7	448.6	448.5	448.6	448.9	446.4	447.5	447.0	447.0	446.5	445.9	445.6	445.7	445.6	442.6	437.9	436.5	437.3	437.1	437.2	437.0
50%	55	1000	450.4	450.4	450.4	449.5	449.6	448.8	448.9	448.4	448.5	448.3	448.5	448.5	448.6	448.5	448.6	448.5	448.5	448.8	446.5	447.4	447.0	447.0	446.3	445.7	445.4	445.4	445.5	447.6	438.0	436.0	437.0	436.7	436.7	436.5
50%	59	1000	450.6	450.6	450.6																									442.7	438.0	435.2	436.3	435.8	435.8	435.5
50%	60	1000	450.6	450.6	450.6																									442.7	438.0	435.0	436.2	435.5	435.5	435.1
50%	61	1000	450.6	450.6	450.6																									442.7	438.0	434.7	435.9	433.4	434.6	434.6
30%	34	1291	461.5	461.5	461.5	460.8	460.5	453.0	453.0	448.3	448.0	444.8	444.8	443.8	444.0	444.0	444.3	443.8	443.5	445.8	445.0	444.5	444.3	445.3	445.0	445.3	445.5	445.5	446.5	443.0	438.0	441.0	441.3	436.6	436.5	436.6
40%	18	2000	466.4	466.4	466.4	464.5	464.5	455.9	455.8	451.0	451.0	447.0	447.0	445.5	445.8	445.2	445.4	444.9	444.8	447.5	445.9	445.7	445.3	446.5	446.3	446.6	446.7	446.4	447.7	444.1	438.5	442.2	442.7	437.1	436.7	440.6
30%	19	2000	483.2	483.2	483.2	481.1	481.1	464.4	464.4	453.5	453.6	446.0	446.2	444.8	444.9	444.9	445.0	443.6	443.4	446.4	443.8	444.3	443.2	445.3	445.0	444.7	445.2	445.0	444.9	443.2	438.4	442.2	442.8	437.2	436.3	440.6
25%	20	2000	500.0	499.8	499.7	497.8	497.6	473.3	473.3	455.0	455.3	445.3	445.3	443.9	444.2	444.8	445.0	443.0	442.5	445.3	444.3	443.5	442.0	445.0	444.5	443.8	444.3	444.1	444.0	442.8	438.3	442.0	442.5	437.1	436.2	440.6
50%	22	2000	460.6	460.6	460.5	458.5	458.5	453.2	453.1	450.6	450.8	448.0	448.2	446.8	447.0	446.2	446.4	445.9	445.9	447.7	447.0	446.9	446.8	450.0	450.0	449.4	448.7	448.7	448.5	444.3	438.6	442.2	442.5	437.0	436.3	440.6
70%	40	2000	457.1	457.1	457.1	454.8	454.9	452.7	452.8	451.8	452.0	451.0	451.7	451.1	451.8	451.6	452.0	452.1	452.3	453.3	452.0	451.8	451.0	450.9	450.5	449.6	449.2	448.9	448.6	444.2	438.5	441.7	442.5	438.3	437.2	440.9
60%	41	2000	457.7	457.7	457.7	455.8	455.7	452.3	452.4	450.8	450.9	449.0	449.5	448.1	448.5	447.8	448.0	448.6	448.2	452.8	452.1	451.9	451.2	451.1	450.8	450.0	449.5	449.2	448.8	444.5	438.8	441.7	442.3	437.6	437.2	440.8

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Water Surface Elevation																																	
60%	41	2000	458.0	457.9	457.9	455.8	455.9	452.3	452.3	450.7	450.7	449.0	449.1	448.0	448.2	447.5	447.6	447.5	447.6	452.4	452.1	451.9	451.2	451.0	450.5	450.0	449.5	449.1	448.9	449.5	438.7	441.8	442.5	437.7	437.3	440.9
50%	50	2000	461.2	461.2	461.2	459.4	459.3	453.6	453.5	450.8	450.8	448.0	448.2	446.8	447.0	446.2	446.3	445.8	445.9	447.8	447.0	446.9	446.8	451.0	450.6	450.1	449.8	449.2	449.1	444.5	438.7	439.7	441.0	440.4	440.7	440.6
50%	56	2000	461.5	461.4	461.4	459.6	459.5	453.8	453.9	451.0	451.0	448.2	448.3	446.8	447.0	446.3	446.5	445.9	446.0	447.9	447.1	447.0	446.9	451.0	450.0	449.9	449.8	449.5	449.2	444.8	438.7	439.5	440.9	440.6	440.7	440.6
25%	57	2000	502.1	502.1	502.1	500.3	500.2	474.8	474.7	455.5	455.7	445.0	445.2	443.6	444.1	444.7	444.9	443.5	442.8	444.9	444.1	443.4	441.9	445.1	444.5	443.8	444.4	444.2	444.3	442.8	438.3	438.7	440.7	440.6	440.7	440.6
100%	1	3000	462.9	462.8	462.8	458.3	458.5	457.3	457.5	457.3	457.5	457.3	457.5	457.0	457.3	456.8	457.0	456.5	456.8	457.5	454.8	454.0	453.0	452.8	451.8	450.5	450.0	449.5	448.5	448.8	446.5	439.5	444.5	443.5	443.7	444.4
90%	2	3000	462.8	462.8	462.8	458.5	458.8	456.8		456.5	456.5	456.8	456.3	456.3	456.4	456.3	456.3	456.0	456.3	457.3	454.8	454.0	453.0	452.8	451.8	450.5	450.8	449.5	449.0	446.3	439.3	444.3	445.0	443.5	443.8	444.4
80%	3	3000	464.4	464.4	464.3	460.3	460.4	456.5	457.0	455.8	456.0	455.1	455.3	455.0	455.0	455.3	455.3	455.5	455.5	457.5	455.1	454.3	453.0	452.0	451.0	450.8	450.0	450.0	445.5	446.0	439.3	444.5	444.8	443.5	446.8	444.4
70%	4	3000	467.5	467.4	467.4	463.0	463.5	456.8	457.5	445.8	455.5	452.0	454.3	451.5	453.5	452.5	453.5	453.5	454.5	457.8	456.0	455.3	454.3	454.0	453.3	452.3	451.8	451.3	450.5	445.8	439.8	444.3	445.0	443.5	443.8	444.4
60%	5	3000	472.6	472.6	472.5	468.3	468.5	458.3	458.3	464.3	454.0	450.5	450.0	448.3	448.0	447.3	447.0	446.5	446.5	449.8	447.3	447.3	446.8	448.0	448.0	448.0	448.8	448.5	450.3	445.5	439.3	444.5	445.0	443.5	443.8	444.5
60%	6	3000	473.9	473.9	473.9	469.3	469.5	458.8	458.8	454.5	454.3	450.5	450.3	448.3	448.3	447.3	447.0	446.5	446.3	449.8	447.3	447.3	446.5	448.3	448.0	448.0	448.8	448.5	450.3	445.3	439.3	444.5	445.0	443.5	443.8	444.4
50%	7	3000	483.0	483.0	483.0	478.5	478.8	462.5	462.5	465.3	465.0	449.5	449.0	446.8	446.8	446.0	445.8	445.3	445.0	449.3	445.5	445.8	444.5	447.0	446.5	446.8	447.0	446.8	446.8	444.3	439.0	444.5	445.3	443.5	443.8	444.4
70%	8	3000	466.0	466.0	465.9	461.5	461.8	457.3	457.8	455.5	456.0	454.0	454.3	453.0	454.0	453.8	454.3	454.8	454.8	457.8	455.8	455.0	454.3	454.0	453.0	452.0	451.5	450.5	450.0	445.5	439.3	444.5	445.0	443.5	443.8	444.4
80%	9	3000	464.0	464.0	463.9	459.8	460.0	456.8	457.0	455.8	456.0	455.3	455.5	455.0	455.3	455.3	455.3	455.5	455.8	457.3	455.0	454.3	453.3	453.0	452.0	451.0	450.5	450.0	449.3	116.3	439.0	444.5	445.0	443.5	443.8	444.4
90%	10	3000	463.3	463.3	463.3	458.8	458.8	457.0	457.0	456.5	456.8	456.3	456.5	456.3	456.5	456.3	456.5	456.3	456.3	457.3	454.5	454.0	453.0	452.5	451.8	450.8	450.3	449.5	449.0	446.5	439.5	444.8	445.3	443.4	443.8	444.4
60%	11	3000	468.5	468.5	468.5	464.5	464.5	457.3	457.3	454.0	454.0	451.0	451.0	449.3	449.5	449.0	449.5	449.5	449.8	457.3	456.0	455.5	454.5	454.3	443.9	452.3	451.8	451.3	450.5	445.0	439.0	444.3	445.0	443.5	443.9	444.4
50%	12	3000	478.2	478.3	478.3	473.5	473.5	461.5	461.5	455.8	456.0	450.5	450.5	447.8	448.3	446.8	446.8	445.8	445.8	449.8	446.8	446.5	445.5	447.8	447.3	447.3	447.8	447.5	447.5	444.8	439.3	444.5	445.0	443.5	443.8	444.4
40%	13	3000	492.3	492.3	492.3	488.5	488.3	469.0	469.0	458.3	458.5	449.8	450.0	446.3	447.3	445.8	446.3	445.0	444.0	448.8	445.0	445.5	444.0	446.8	446.0	445.5	446.3	446.0	446.0	443.8	439.0	444.5	445.3	443.5	443.8	444.4
100%	14	3000	461.7	461.7	461.5	457.5	457.8	456.8	457.0	456.5	456.8	456.5	456.8	456.5	456.8	456.3	456.5	456.0	456.3	457.0	454.3	453.5	452.8	452.5	451.5	450.5	450.0	449.5	449.0	446.3	439.5	444.5	445.0	443.6	443.6	443.4
60%	15	3000	468.9	468.9	468.9	464.8	464.5	457.3	457.3	454.0	454.3	451.3	451.3	449.8	450.0	449.5	449.3	450.5	450.5	456.8	456.0	455.0	454.3	454.0	453.3	452.0	451.5	451.0	450.5	445.0	439.0	444.3	445.0	443.5	443.9	444.4
50%	16	3000	477.6	477.6	477.6	473.3	473.1	461.4	461.4	455.7	455.9	450.7	451.0	448.0	448.4	446.8	447.0	446.0	445.8	450.0	446.9	446.6	445.8	448.0	447.5	447.5	448.0	447.9	447.7	445.0	439.3	444.5	445.3	443.3	443.8	444.5
40%	17	3000	493.1	493.0	493.0	488.5	488.3	469.1	469.0	468.5	458.6	449.8	450.2	446.5	447.3	445.8	446.3	445.0	444.0	448.9	445.2	445.5	444.1	446.9	446.2	445.7	446.5	446.1	446.0	443.7	439.1	444.4	445.2	443.6	443.9	444.4
Left Gate shut %	23	3000	499.5	499.5	499.4	495.7	482.0	498.9	468.4	440.0	463.2	440.2	458.8	440.3	455.4	440.9	451.8	440.7	448.7	442.9	444.1	445.6	444.4	447.2	446.7	445.8	446.6	446.5	446.2	443.9	439.1	443.2	444.8	443.2	443.5	444.2
Right Gate shut %	24	3000	499.1	499.1	499.0	482.0	499.4	468.3	499.0	462.9	440.4	458.5	440.4	454.9	440.3	451.5	441.0	449.0	440.7	442.6	442.8	445.5	444.5	446.7	446.2	446.0	446.8	446.3	446.3	443.8	439.2	443.5	444.8	443.2	442.8	444.2
55%	64	3000	474.1	474.0	474.0	469.6	469.5	459.6	459.6	455.0	455.1	451.0	451.1	448.5	448.8	447.3	447.3	446.3	446.4	450.1	447.3	447.2	446.7	452.7	453.8	452.8	452.3	451.7	451.0	445.5	439.2	442.7	444.1	444.2	444.3	444.3
55%	65	3000	474.1	474.0	474.0																									445.6	439.3	441.7	443.5	443.4	443.5	443.5
55%	66	3000	474.1	474.0	474.0																									445.6	439.2	441.0	443.1	443.0	443.2	443.2
55%	67	3000	474.3	474.2	474.3																									445.6	439.3	439.6	442.1	442.0	442.2	442.3
55%	68	3000	474.5	474.5	474.5	470.0	469.9	459.8	459.8	455.2	455.3	451.0	451.1	448.4	448.7	447.3	447.4	446.3	446.3	450.3	447.3	447.2	446.7	450.0	453.8	452.8	452.3	451.8	451.0	445.6	439.2	438.8	441.6	441.5	441.7	441.8
55%	69	3000	474.5	474.5	474.5																									445.6	439.3	437.1	440.7	440.4	440.7	440.7
50%	17_2	3363	485.6	485.6	485.4	479.8	479.5	465.0	465.0	457.8	458.0	451.8	452.0	448.3	449.0	446.8	447.3	445.8	445.3	450.3	446.0	446.5	445.3	447.8	447.5	447.0	447.8	447.5	447.8	444.5	439.3	444.3	445.3	443.3	443.6	445.8
80%	42	4000	475.8	475.8	475.7	467.7	468.0	462.1	462.5	460.2	460.5	458.8	459.2	458.2	458.7	458.2	458.5	459.3	459.6	463.2	458.8	457.5	455.6	455.2	453.8	451.9	451.0	450.0	448.7	445.9	442.0	448.0	448.5	447.5	447.6	448.1

Location			Approach Channel (HW)			Intake Tower										Transition					Culvert									Stilling Basin				Exit Channel		
Instrument ID			SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station			437	837	911	968	968	983	983	985	985	989	989	993	993	999	999	1,005	1,005	1,029	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,031	2,070	2,098	2,137	2,211	2,612
Gate	Test #	Q	Water Surface Elevation																																	
70%	43	4000	481.4	481.4	481.3	473.0	473.0	463.8	463.5	461.0	460.8	456.5	457.0	456.0	456.5	455.3	455.8	457.0	457.0	464.3	460.5	459.5	457.5	457.3	455.3	453.3	453.5	451.0	451.3	445.3	441.5	447.5	448.3	447.4	447.6	448.9
100%	71	4000	473.2	473.2	473.1	465.4	465.8	463.7	464.1	463.6	463.9	463.5	463.9	463.4	463.9	463.0	463.3	462.4	462.7	464.2	459.0	457.8	455.9	455.6	454.0	452.0	451.2	450.0	448.8	445.9	441.5	447.0	447.8	447.9	448.0	448.0
60%	72	4000	489.0	488.9	489.0	480.7	480.6	466.3	466.2	459.9	460.0	454.3	454.4	450.4	450.9	448.4	448.6	446.9	446.9	452.2	447.6	447.9	446.8	449.5	449.3	448.9	449.8	449.8	450.8	445.5	440.7	446.5	447.8	447.8	448.0	448.0
90%	73	4000	474.2	474.1	474.1	466.2	466.5	463.0	463.5	462.1	462.7	461.8	462.2	461.7	462.4	461.9	462.4	461.9	461.1	464.0	459.0	457.8	456.0	455.6	454.0	452.0	451.1	450.0	448.8	445.9	441.5	447.1	448.0	448.0	448.1	448.2
60%	25	5000	506.5	506.4	506.3	494.1	494.0	473.8	473.8	464.8	464.9	456.9	457.0	451.8	452.2	448.5	448.6	446.9	446.2	453.1	448.0	448.1	446.0	449.9	449.2	448.1	449.6	449.5	449.6	444.2	441.3	447.7	449.5	449.5	448.9	448.8
100%	26	5000	484.3	484.3	484.3	472.3	472.9	469.9	470.4	469.6	470.2	469.6	470.1	469.4	470.0	468.8	469.3	468.0	468.3	470.7	462.9	461.2	458.3	458.0	455.9	453.0	451.9	450.1	448.4	444.6	442.1	448.5	449.6	448.7	448.9	449.5
90%	30	5000	486.1	486.0	485.9	473.8	474.2	469.1	469.7	467.8	468.5	467.1	468.0	467.2	468.1	467.2	468.0	467.3	467.8	470.7	463.0	461.2	458.5	458.0	455.9	453.0	452.0	450.3	448.5	444.7	442.5	449.1	449.8	448.9	449.0	449.5
80%	31	5000	488.3	488.1	488.1	476.0	476.4	467.8	468.5	464.7	465.6	462.7	463.6	461.4	462.6	461.8	462.9	463.3	464.1	469.5	462.8	461.1	458.2	457.9	455.7	452.9	451.8	450.1	448.5	444.7	442.7	448.5	449.7	448.8	449.0	449.5
Descending right gate 0%, left 100%	28	5600	524.4	524.4	524.4	524.7	456.0	523.3	453.6	440.0	452.8	440.1	452.2	440.2	451.9	440.5	448.5	440.8	443.6	442.2	444.8	465.2	461.6	462.0	459.5	455.7	454.8	453.0	451.0	443.7	441.2	448.2	450.2	449.9	449.9	450.5
Descending right gate 100%, left 0%	29	5600	525.6	525.6	525.5	465.0	525.8	453.0	525.6	551.0	440.0	451.5	440.0	450.8	440.8	447.3	441.5	443.8	441.0	442.5	442.0	465.5	462.3	461.3	459.5	456.3	455.0	453.0	450.5	443.5	441.0	443.5	450.0	449.6	449.9	450.6
100%	27	7300	523.6	523.4	523.3	497.5	498.7	493.0	493.0	491.8	493.0	491.6	493.0	491.4	493.0	490.0	491.2	488.5	489.2	494.4	477.8	474.4	468.6	468.0	463.8	457.6	455.8	452.6	449.0	442.4	449.5	450.0	451.9	452.7	452.0	451.6
100%	51	7300	523.5	523.5	523.4	497.9	499.2	493.0	493.0	493.0	493.0	493.0	493.0	493.0	493.0	490.6	491.8	489.0	490.0	494.9	478.3	475.0	469.2	468.7	464.1	458.0	456.1	452.9	449.3	442.5	440.5	446.0	450.1	450.7	451.2	451.6
100%	45	8050	556.5	556.5	556.4	525.2	526.5	518.7	520.5	518.3	519.8	518.0	519.3	518.0	519.5	515.8	517.4	514.5	515.5	521.7	501.7	497.5	490.8	490.0	485.0	478.0	475.0	471.0	467.0	460.2	463.0	469.5	470.0	466.4	468.9	469.9
100%	70	8494	553.3	553.3	553.1	516.3	518.9	510.0	511.7	509.5	511.1	509.4	510.9	509.9	510.7	507.1	508.7	504.9	506.1	513.4	490.2	485.7	477.7	476.9	470.9	462.5	459.9	455.8	450.8	441.7	439.8	451.0	452.8	453.6	454.3	456.7
100%	46	8700	557.2	557.2	557.2	521.1	519.5	511.7	513.4	511.2	513.0	511.1	512.8	510.7	512.6	508.6	510.4	506.5	507.7	515.6	490.9	486.6	478.2	477.6	471.4	462.7	460.1	455.7	450.8	441.3	439.1	451.0	451.5	452.9	453.5	454.2
50%	21	~2000	459.2	459.1	459.1	467.3	467.3	450.3	450.5	450.3	450.0	447.8	448.0	446.5	446.8	446.3	446.5	445.8	445.8	447.3	447.0	446.8	447.3	450.3	449.8	449.0	448.3	448.0	448.3	444.0	438.3	441.8	442.3	437.2	438.4	440.6

Appendix C: LRL Physical Model Notes

US Army
Corps
of Engineers
Louisville District

Rough River Reservoir
Outletworks

Louisville District Physical Modeling Observations and Summary of Design Modifications

February 2021

Table of Contents

1. Model Overview

Discussion and details of physical model construction are included in the ERDC Technical Report (ERDC/CHL TR-21-5). To avoid duplication of information, they will not be discussed in detail here. Broadly speaking, the physical model is a 1:25.85 scale model of the proposed Rough River Outletworks. This model includes roughly 42 acres of the reservoir body, referred to as the head bay; the entire excavated approach channel leading to the intake tower; the intake tower itself which includes trash racks, entrance curves, slots for the bulkheads and auxiliary gates, operational service gates, air vents, and transition geometry. Downstream of the intake tower, the 14-ft diameter curved conduit is modeled of clear acrylic pipe and the curve itself is constructed of straight segments of pipe mitered at an angle to form the 300-ft radius of curvature. The conduit exits through a headwall leading to a parabolic drop down to the stilling basin. The stilling basin includes magnetically attached baffle blocks, can accommodate chute blocks, and is bookended on the downstream side by an end sill. Downstream of the end sill is a concrete lined retreat channel apron which transitions to rock-lined channel near station 24+00. In total the downstream portion of the physical model includes approximately 16-acres of tailwater area with over 600 linear feet of retreat channel. Figure 1 displays an overhead photo of the physical model taken from the left (southwest) dam abutment. Figure 2 displays an aerial image of the project location with proposed outletworks features of physical mode domain included. Additional details on model construction are included in the ERDC/CHL TR-21-5.

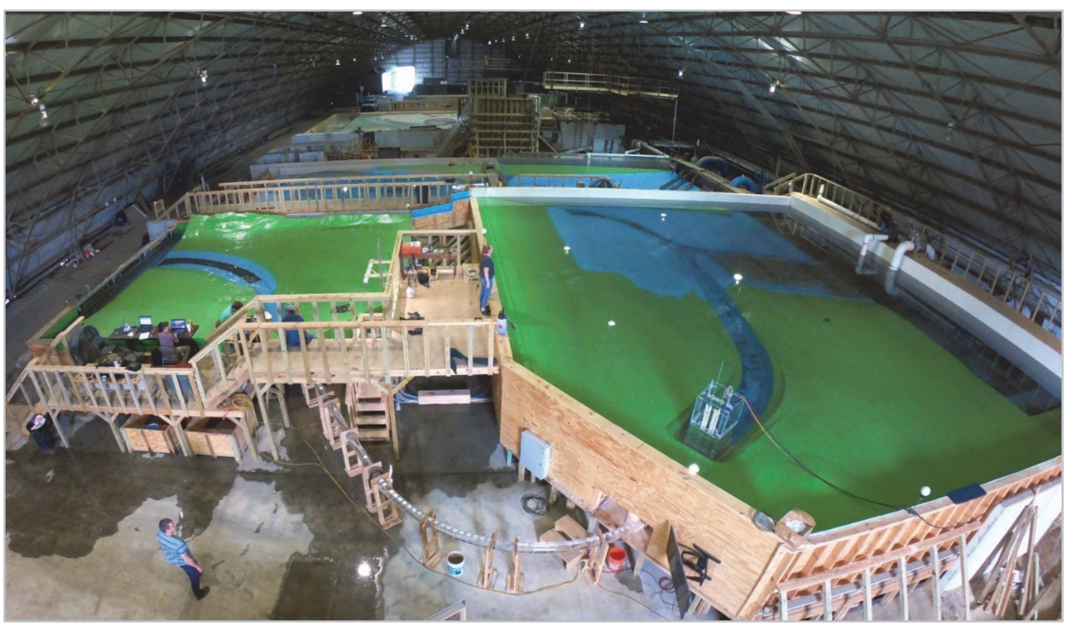


Figure 1. Overhead Photo of Rough River Outletworks Physical Model

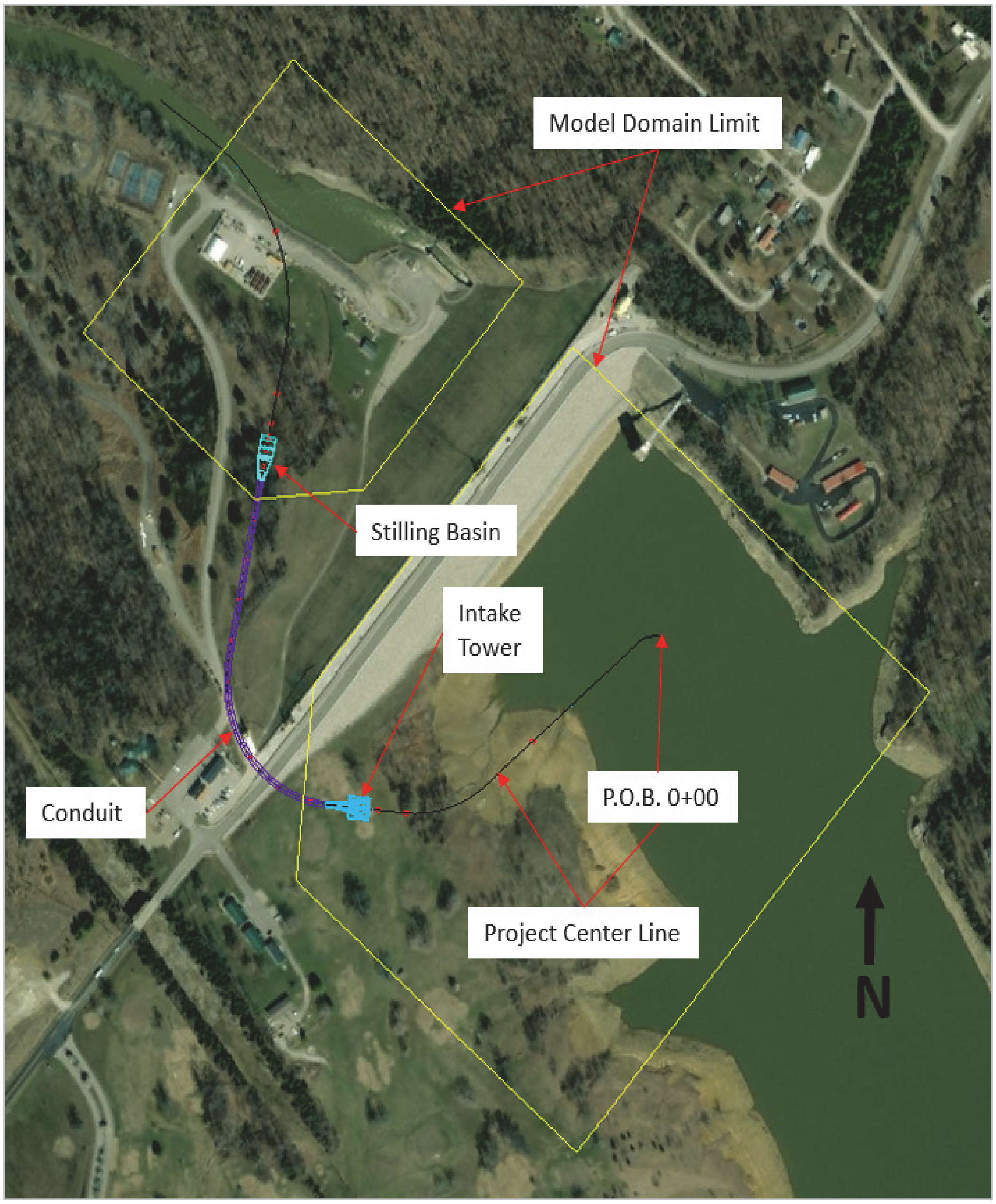


Figure 2. Aerial Image of Rough River Dam including Physical Model Domain

2. CFD Validation

Throughout the design process, a computational fluid dynamics (CFD) model was developed to help inform design. As part of the CFD model validation process, results from the numerical model have been compared to results obtained from physical model testing as well as analytical calculations. Numerical model parameters have been updated accordingly. Additional discussion regarding CFD modeling and comparisons with physical modeling are included in the Rough River Dam Outlet Works CFD Model Report, included as an appendix to the project Design Documentation Report (DDR).

3. Approach Channel Performance

There are several hydraulic concerns associated with the curved approach channel leading to the intake tower. These concerns primarily revolve around flow behavior and the potential for detrimental vortices formation in front of the control tower.

3.1. Vortex Behavior

The first elevation where vortices were noted was near spillway crest (524-ft), although some occurrences were observed as low as elevation 510-ft with less frequency. Generally these vortices were unstable; intermittently forming and dissolving as they migrated in front of the intake tower. Vortices appeared to occur when the pool elevation was near two distinct pool elevations and rotational behavior differed slightly at each of these elevations. Figure 3 displays the various types of vortices as described by Knauss (1987). Vortices are not generally considered to be an operational problem unless they are of Type 5 or 6. Vortices observed in the Rough River physical model very rarely exceeded Type 3, and a questionable Type 4 vortex was only observed once.

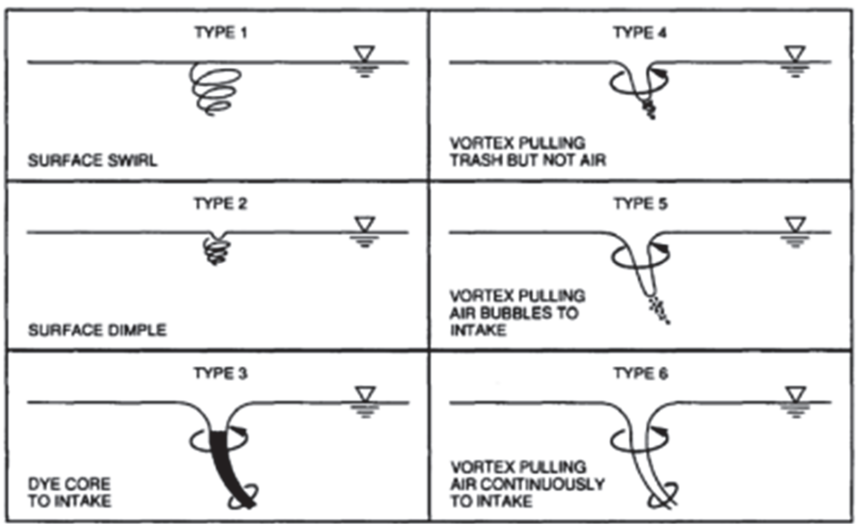


Figure 3. Vortex Types (Image from Knauss, 1987)

For lower pool vortices with the pool between approximately 510 and 530 ft-NGVD29, vortex rotation was in a clockwise direction if viewed from above. This is due to the approach channel's clockwise curvature as it approaches the intake tower. Vortex intensity in this region was generally Type 1 or 2, with an unstable Type 3 forming occasionally. A small piece of floating debris was once observed to be sucked from the water surface down to the gates, however the scaling of such objects (in this case a large insect) and their buoyancy is questionable. Small pieces of floating wood were unable to be sucked down from the surface. With the pool above elevation 524 ft-NGVD, vortices formed when gates were opened fully. For lower pools such as between 510 and 524 ft, vortices were noted with discharges of 3,000 cfs, but were less frequent and more unstable.

It should be noted here that the emergency spillway (crest elevation 524 ft-NGVD29) was not included in the physical model due to a number of modeling limitations. This does not impact testing for reservoir elevations less than spillway crest, however for higher pools, flow patterns within the reservoir will not match prototype flow patterns exactly. This anticipated difference is due to the significant amount of flow that would be diverted through the spillway. The lack of a modeled spillway likely has a negligible impact on flow behavior at all locations downstream of the intake tower, even at high pools, as tailwater elevation was controlled at the downstream boundary to simulate the effect spillway flows would have on the tailwater. However, the lack of a modeled spillway could have implications on vortex formation and behavior at high pools, where spillway flow would be substantial. For example, during a PMF event, greater than 80% of total project outflow is through the emergency spillway. For this reason, vortex behavior with the pool above spillway crest has greater uncertainty than the behavior at lower pools.

At higher pools, beginning around elevation 530-ft and continuing up to the top of dam, vortex rotation transitions to a counter-clockwise direction when viewed from above. This is likely due to the ability for more flow to approach from the overbanks at higher pool elevations than at lower elevations. Vortices appeared to have a stronger rotation at these higher pools, but were equally unstable and not persistent. Their intensity typically peaked as Type 3 or lower.

Usually the vortex formation occurred between 10- and 30-ft in front of the intake tower. Vortices forming at higher pools, such as near PMF elevation, tended to form nearer the intake tower, often occurring directly over the service deck. The lower pool vortices tended to favor the right-descending side of the intake tower, whereas they favored the left side at higher pools.

It was thought that perforation of the service deck would allow flow to enter the tower from above and therefore eliminate the stagnation zone above the deck, perhaps alleviating vortices. This was evaluated in the physical model by removing the service deck, however it had no noticeable effect on vortex formation or persistence. Another alternative which may reduce vortices is the implementation of a floating anti-vortex mattress that would be anchored in front of the tower. This possibility has not yet been evaluated in the physical model. Operating the gates asymmetrically, specifically with flow only released through the right-descending gate, appeared to exacerbate and strengthen vortex formation.

Figure 4 displays two photos of typical vortices. The left photo was taken from underwater and shows a Type 3 vortex and dye core/tendril entering the right-descending gate. This screenshot was taken from a video with the reservoir near PMF conditions. Note that light is being cast from the left side of the tower and creates a projection or shadow of the vortex tendril on the intake tower face. The right photo was taken from the right side of the dam looking downwards with the pool near spillway crest and intake tower gates opened fully.

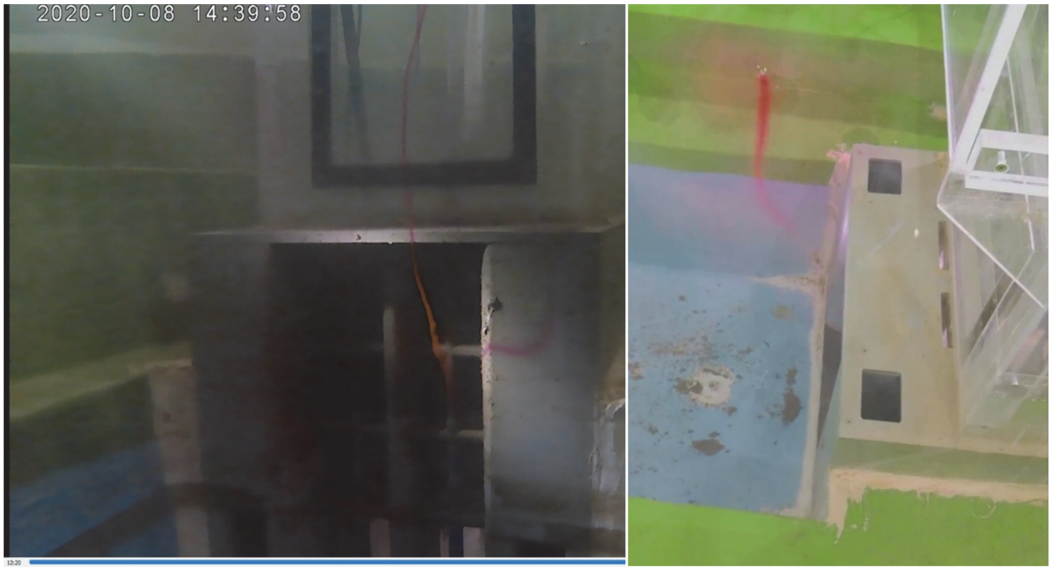


Figure 4. Typical Vortices Photos. Left is underwater photo.

3.2. Flow and Debris Behavior

3.2.1. Flow Behavior

Flow behavior through the approach channel is fairly dynamic and can vary significantly with pool elevation and discharge through the intake tower. When viewed at a large scale, the flow is fairly one-dimensional, but this is not the case when observed at more local and smaller scales where currents exhibit highly 2- and 3-dimentional patterns. For example, the approach channel is constructed with successive benches at various elevations. As the pool rises, and water begins to effectively flow over these benches, swirling horizontal and vertically oriented rollers can be observed if dye is injected into the water column. These currents roll over the benches and into the approach channel before taking on a more streamlined approach as they near the intake tower.

Because of the dynamic nature of these small-scale vortices, boats and other vessels should exercise caution when nearing the approach channel while the intake tower is operating. Unauthorized vessels should not be allowed within the approach channel. Even though the average flow velocity through the channel is relatively low (less than 2 ft/s), the currents appear unpredictable and caution is prudent. This is further emphasized due to the vortex potential discussed in section 3.1.

3.2.2. Rock Trap

The invert elevation of the approach channel in front of the intake tower is at elevation 435-ft NGVD29, whereas the intake tower passage invert is 5-ft higher at elevation 440-ft. This 5-ft step creates a rock and debris trap in front of the tower to prevent sunken objects from entering the control tower. Brief evaluation of the rock trap's effectiveness was performed using rock and negatively buoyant wood. This material was placed immediately in front of the intake tower within the rock trap at elevation 435-ft. No movement of the material was noted and the rock trap was effective at preventing debris from entering the tower.

Throughout model testing, it was also noted that a thin layer of silt and other fine sediment tended to accumulate on the approach channel floor. While rigorous investigation was not performed, this supports the assumption that approach channel velocities are low enough that scour and coarse particle transport will not take place within the approach channel. It is possible that fine sediments could aggrade over time in the approach channel, but if the silts were to accumulate to any significant degree, they would likely be swept downstream during high-flow project releases. Historic sediment load at the dam site is thought to be very low.

3.2.3. Trash Boom

Because of the vortex potential discussed in section 3.1, installation of a trash boom spanning the approach channel appears to be prudent. Preventing floating objects and woody debris from entering the approach channel is an appropriate safeguard against the potential maintenance concerns that this debris may pose if it reaches the intake tower. While vortex intensity did not appear high enough to transport debris from the reservoir surface to the intake tower gates, neutrally buoyant objects are capable of entering the tower. While the approach channel is relatively narrow at lower pools, it becomes wider and wider as the pool rises. Once the pool rises to near spillway crest, flow can approach the tower from nearly 180-degrees, potentially making trash boom implementation more difficult at these high pools. The trash boom should be functional between elevations 470 and 530 ft-NGVD29 at a minimum. Discussions with the boom manufacturer will occur to determine if this level of protection can practically be increased. It should be noted that the historic debris load near the dam site is considered to be very low.

3.2.4. Rotation Around Tower

As the reservoir pool approaches elevation 500 ft-NGVD29, a circulation current develops that flows around the control tower in a clockwise direction if viewed from above. Point velocity measurements indicate that flow velocity was nearly 0.1 ft/s in the model, which scales to approximately 0.5 ft/s in the prototype. This current likely lacks the erosive force required to scour material off of the excavation walls, however it does have the potential to transport silt and other neutrally buoyant debris behind the tower. A trash boom spanning the approach channel would reduce debris load that reaches the intake tower.

As the pool elevation rises approaching elevation 530 ft-NGVD29, the direction of the rotation reverses from clockwise to counter-clockwise. This rotation is likely due to the nature of the curved approach channel which induces asymmetry into the flow behavior. As the reservoir pool rises such that it is above the approach channel excavation, more flow can approach the intake tower from above the left-descending overbank. This overbank flow above the approach excavation limits is likely responsible for the changing rotation direction. Rotation direction of intake tower vortices also appears to be related to the approach conditions and circulation around the control tower.

4. Tower and Conduit Performance

4.1. Transition Monolith Design and Behavior

The intent of the transition monoliths is to smoothly transition flow from two rectangular gate passages (6.25-ft wide x 14-ft tall) to a single 14-ft diameter circular conduit. The transition should be as streamlined as is practical to minimize head losses through the transition, this is generally done through a gradual change in cross-sectional flow area. An initial transition monolith design was adapted from Singh's 1969 publication *Transition from Circular to Rectangular Section* (referenced as item 114 in EM 1110-2-1602). The objective of the Singh transition is to create a transition section that has a linear variation of cross-sectional area, thus minimizing flow disturbances.

This Singh transition design was evaluated in the physical model and produced acceptable results with a few specific caveats, notably some highly turbulent flow conditions when service gates are operated asymmetrically. Specifically, this turbulent flow through the transition occurred when all flow was discharged through a single gate, with the opposing gate fully closed. Partial asymmetric releases – where both gates were operational but one open more than the other – also showed turbulent behavior, but to a lesser degree. When these asymmetric flows are released, a swirling effect is imparted on the flow by the transition monolith. Releasing only through the right-descending gate results in a clockwise swirl when observed looking downstream. Conversely, releasing

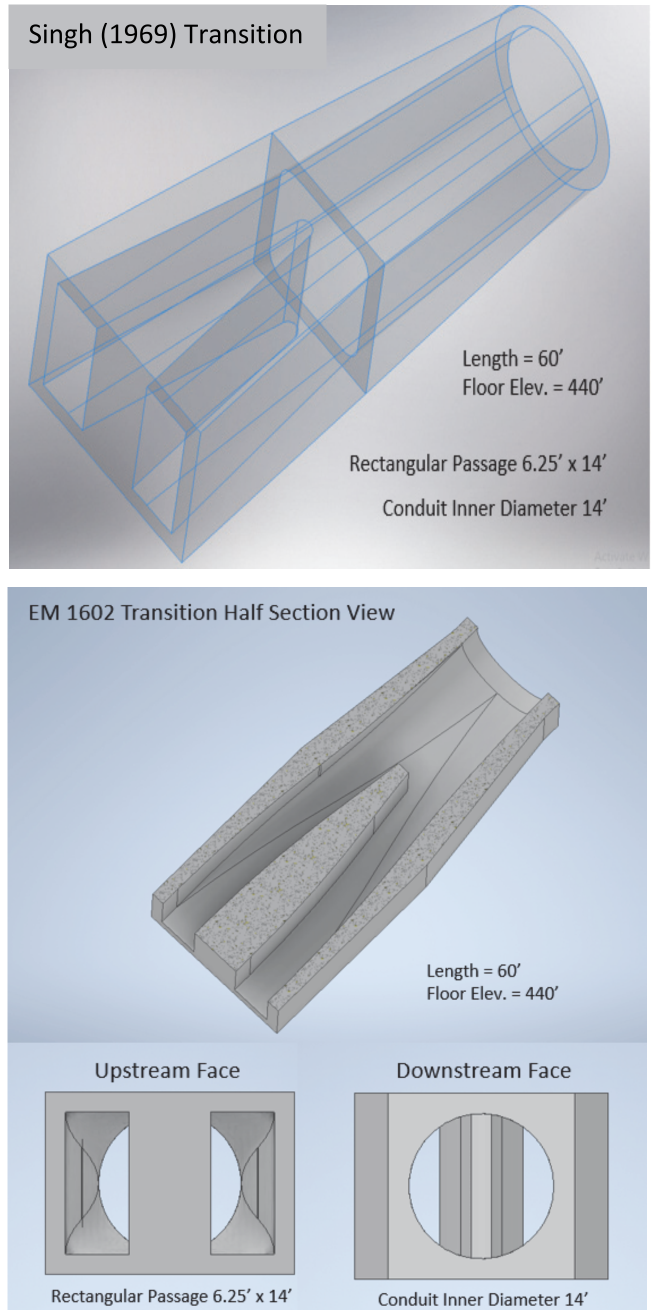


Figure 5. Comparison of Transition Monolith Designs

through the left-descending gate results in a counter-clockwise swirl. For flows exceeding approximately 1,500 cfs, the swirl or rotation is significant enough to reach the crown of the conduit. The rotation’s impact on the flow propagates downstream to some extent, creating regions of setup where flow rides slightly up on the sides of the conduit wall. The setup appears to reflect off the walls and alternates sides as it continues downstream. Once the flow has passed through the curved portion of the conduit, the setup on the side walls has generally been dissipated and there is no noticeable impact from the asymmetric releases in the stilling basin.

It was also noted for symmetric flows (through both gates), as flow from the two passages converges to a single passage, the converging flow forms a “rooster tail” that sprays upwards towards the conduit crown. For higher flows exceeding approximately 2,000 cfs, the “rooster tail” has the potential to impact the conduit crown and increases turbulence immediately downstream of the conduit monolith. While this performance is not ideal, it is considered acceptable given the spatial constraints of the project, and the turbulent flow behavior is not expected to result in adverse operating conditions. A potential option to alleviate this transition turbulence would be to lengthen the transition section and significantly increase the length of straight conduit upstream of the curved section. This option is not feasible because it would significantly increase the required underground tunnel excavation and length – shifting the location of the stilling basin and retreat channel substantially – and ultimately would only improve flow behavior that is already generally acceptable. Additional discussion regarding these rotational and turbulent flows is included in the ERDC TR.

In an effort to improve hydraulic performance and reduce turbulence within the conduit, a new transition section was designed in accordance with guidance given in EM 1110-2-1602 Appendix E. Both transitions maintain the same 60-ft overall length, however the two differ slightly in how they allocate this length. Generally speaking, the Singh transition splits its overall length evenly into 2 halves, with the upstream half dedicated to transitioning 2 passages into 1, and the downstream half is concerned with transition the cross-sectional shape from square to circular. The Appendix E transition dedicates approximately ⅔ of its length to transitioning 2 passages into 1, and the remaining ⅓ transitioning from a rectangular to circular section. The appendix E transition also utilizes horizontal curves on the inner and outer passage walls, whereas the Singh transition’s walls are straight. Additional details on this transition can be found in the Section 6 of the Design Documentation Report (DDR) and **Error! Reference source not found.** displays both transition schematics.

The resulting new EM 1110-2-1602 Appendix E transition was evaluated with the physical model and it was found that there was little change in hydraulic performance regarding flow turbulence downstream of the gates compared with the Singh design. It is not anticipated that these turbulent conditions pose a concern, as their presence is generally limited upstream of the curved portion of the conduit and does not result in premature conduit pressurization or prevention of air flow through the conduit.

It was noted that the transition as described in EM 1110-2-1602 Appendix E did appear to be slightly less efficient, with increased head losses over the Singh transition. Generally the Appendix E transition had 1-ft to 4-ft additional feet of head loss which varied with gate opening and discharge. As flow velocity increased, so did the head loss difference, with the greatest increase in losses observed at smaller gate openings and large discharges. Figure 6 below displays a comparison of gate rating curves for selected discharges. Solid lines are the Appendix E transition, whereas dashed lines are the Singh transition. Note that for all the 1,000-, 2000-, 3000-, and 5000-cfs runs shown, a higher reservoir elevation was required to pass the same discharge through an identical gate opening.

Aside from the increased losses associated with the EM 1110-2-1602 Appendix E transition, no significant negative flow behavior was noted over the Singh transition. The Appendix E transition also incorporates more streamlined wall curves which reduces the likelihood of cavitation damage occurring. Monolith joint placement is also thought to be more favorable with the Appendix E transition. Therefore, in an effort to conform more closely with published USACE guidance, and in addition to the other considerations noted here, the transition section as described in EM 1110-2-1602 Appendix E was selected as a basis of design and carried forward.

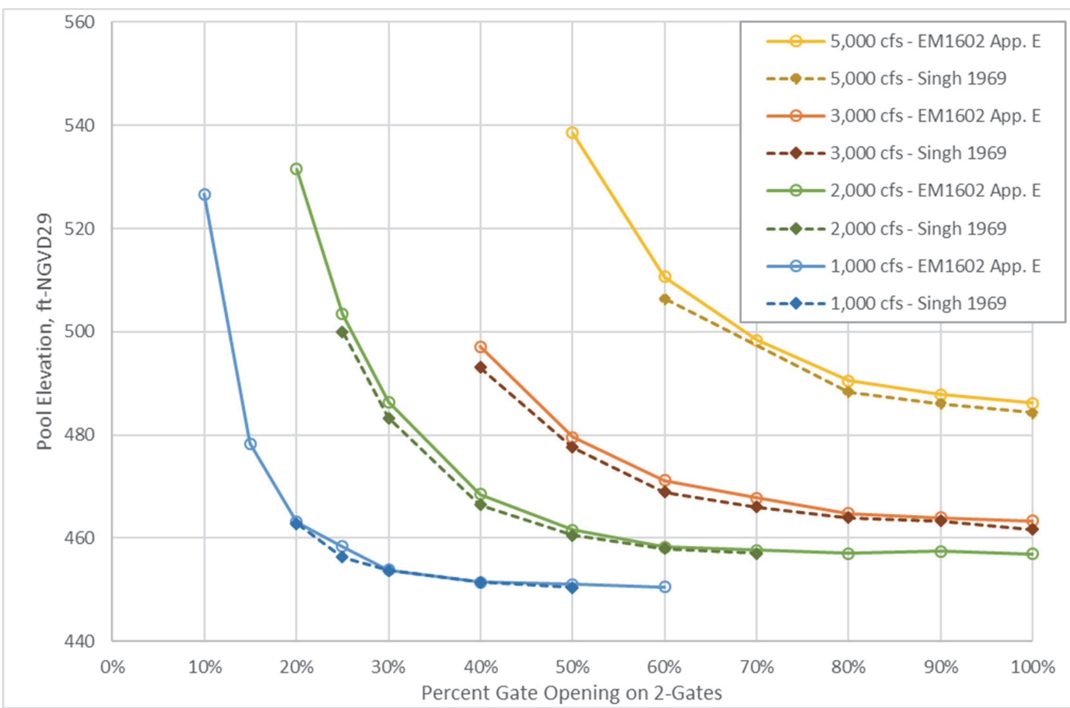


Figure 6. Comparison of Gate Rating Curves for both Transition Monolith Designs

4.2. Conduit Flow Behavior

4.2.1. General Conduit Behavior

Flow behavior through the conduit primarily varies based upon gate opening and discharge. Specific behavior, such as the transition from open-channel to pressurized flow, is discussed in sections below.

4.2.2. Conduit Curve Behavior

It was noted that the joints connecting mitered sections of conduit through the curved portion can create some minor disturbance in flow. These joints cause small standing waves which cross the conduit diagonally in a downstream direction. These waves are stable and do not adversely impact the conduit's performance. It is thought that these joints and associated standing waves are a construction limitation of the physical model, and while the waves will likely be present in the prototype, they are expected to be less pronounced than in the physical model.

There is also notable superelevation of the water surface through the conduit's curve favoring the outside of the bend, this is most notable with small gate openings where depths are relatively low and velocities are high. This superelevation is to be expected and does not pose operational concerns for the outletworks. Flow was never observed to roll over the conduit and form trapped air pockets as it banks around the curve, and therefore the 300-ft radius of curvature selected does appear to be appropriate. The superelevation, possibly in conjunction with the standing waves described in the previous paragraph, creates alternating regions of setup on the conduit walls. Water rides up higher on the walls in these areas of setup. Downstream of the curved portion of the conduit, in the straight region before the stilling basin, flow quickly stabilizes and the superelevation is no longer evident by the time the flow reaches the conduit exit and stilling basin entrance.

4.2.3. Normal Maximum Release (3,000 cfs) Behavior

Of particular interest to the project is the discharge rate of 3,000 cfs which represents the project's normal maximum release. For this release, flow conditions through the conduit are favorable. There is some turbulence induced by the transition monolith on the upstream end of the conduit, but flow becomes notably more streamlined mid-way through the conduit's curve. With the exception of the regions of alternating setup and superelevation, flow is relatively streamlined at this discharge for the majority of anticipated gate operations. The conduit flows open-channel at 3,000 cfs for gate settings less than 50% open. The conduit undergoes a transition from open-channel to full-pipe pressurized flow at 3,000 cfs when gates are between 50% and 65% open. When gates are opened wider than 65% at this flowrate, the conduit flows fully. The transition region of 50-65% gate opening at 3,000 cfs corresponds to a pool elevation between 478-ft and 470-ft NGVD29, respectively. Additional discussion on this transitional behavior is in Section 4.2.5.

4.2.4. Asymmetric Release Behavior

It is preferable to release flow symmetrically through both gates when possible, however flow may be released asymmetrically when required. Discussion of this flow behavior as it relates to the transition section of the outletworks is discussed in Section 4.1. The asymmetric release tends to create regions of flow setup on the conduit walls. This setup, which is similar to water surface superelevation, alternates from side-to-side as flow travels down the conduit. When 3,000 cfs is released through a single gate, the nodes of superelevation setup riding up the walls are spaced between 40- and 50-ft longitudinally down the length of the conduit. The greatest magnitude of setup occurs near the upstream end of the conduit and the magnitude is fully diminished once flow is mid-way through the straight portion of the conduit, approximately near station 17+00.

Small asymmetric differences between gate openings, such as less than 2-ft, show little difference in transition section and conduit flow behavior when compared with symmetric releases. Generally the most turbulent conditions occur when gates are operated fully asymmetrically with one gate open and the opposing gate closed. It was noted that with one gate opened to 77% (single-gate discharge of 3,000 cfs with pool near 501-ft), flow behavior was notably improved when the opposing gate was opened 10% versus when it was closed (0%). This improvement in flow conditions diminished completely when the opposing gate was increased from 10% open to 20%. Operations should generally strive to minimize differential gate openings when possible, small gate opening differences have been found to be broadly acceptable.

A series of approximately 25 tests were conducted to evaluate outlet works operation through a single gate as opposed to both gates. Data collected from these tests, as well as single-gate stage-discharge rating curves, are included in sections 8.1 and 8.2 below.

4.2.5. Open-Channel to Pressurized Flow Behavior

During most normal operating conditions, the Rough River outletworks is designed to operate as an open-channel system through the length of the conduit. The exception to this is when the reservoir pool rises above elevation 524-ft NGVD29 and the emergency spillway is activated. At this occurrence, control tower gates are opened fully and the outletworks will transition from open-channel to pressurized flow.

As the gates are opened wider, velocity under the gates and through the conduit decreases. This allows for the formation of a hydraulic jump within the conduit, initially forming at the downstream end of the conduit. As gates are continually opened, the jump will contact the roof of conduit creating a condition where open-channel flow exists in the upstream portion of the conduit and pressurized flow occurs downstream. Immediately downstream of the hydraulic jump, the turbulent flow appears to entrap air bubbles into the water column where they move quickly downstream. If the jump is occurring in the conduit, but away from the outlet, these bubbles suspended in the flow tend to coalesce together into large pockets and continue flowing downstream.

As gates are opened further, the location of the jump moves upstream. During this occurrence, air is pushed upstream and through the air vents until the jump location reaches the intake tower and the conduit is fully pressurized throughout its extent.

It is expected that the greatest air demand, and therefore air flow velocity through the air vents, will occur just before and during conduit pressurization. Generally speaking, as the conduit transitions from open-channel to pressurized flow, air will flow upstream out of the conduit and up through the air vents (although some air pockets that mix with water will be carried downstream). In reverse, as the conduit transitions from pressure-flow to open-channel flow, air will be demanded by the conduit and air flow will be downwards from the vents into the conduit.

Through physical model testing, it was determined that the transitional hydraulic jump within the conduit is very stable given constant gate settings, discharge, and tailwater elevation. It is possible to create a stable condition where the hydraulic jump is trapped within conduit. The hydraulic jump can be moved upstream or downstream by respectively opening or closing the gates. It was initially thought that this transitional condition of imminent pressurization would induce violent surging of water or air through the conduit. However, through testing of these conditions, no significant surging was noted in the conduit, stilling basin, or within the air vents. It was noted that as the conduit undergoes the transition to pressurized flow, a brief spike in piezometric pressure of approximately 20% over static pressure occurred. The conduit liner will be structurally designed to withstand this pressure spike, which is substantially less than pressures exerted under full reservoir head. The pressurization-transition occurred predictably during testing, and this transition region is displayed as a hatched area on the outlet rating curves in Figure 15 on page 29.

It is not anticipated that the outletworks will be operated frequently in the region where flow transitions from open-channel to pressure flow. While no violent surging was noted during testing, it is still recommended to avoid prolonged operation within this transitional region. When conditions require the outletworks be operated in a pressurized state, the period of time spent in the transitional zone should be minimized by passing through gate operations as quickly as possible. Based on examination of historic project operation from 1983 to 2020, it is rare that the outlet works will be required to operate within this transitional range. Continuous gate operation, following constraints given in the published Water Control Manual, minimizes potential for adverse flow behavior. Once the conduit has achieved a fully pressurized state, flow is stable and pressure spikes will not occur.

The prime scenario when such a transitional operation would be required is when the reservoir pool exceeds spillway crest elevation and the Water Control Manual mandates conduit gates be opened fully. In this scenario, both gates would be opened to 100%. With the pool near elevation 524-ft NGVD29, the transitional flow regime will likely occur when gates are between 60% and 75% open.

Another region of operation where unstable flow conditions may exist is when outflow is at normal maximum release of 3,000 cfs and pools are relatively low, such as less than 480-ft NGVD29. At 3,000 cfs, the conduit's pressurization region is expected to occur with gate openings between 50% and 65% (these gate openings correspond to pool elevations of 478-ft and 470-ft NGVD29, respectively). Special care should be taken when operations are near this region and it may be prudent to reduce gate opening and therefore outflow. Analysis of historical operation of the existing outletworks shows that this low-pool transitional flow regime is a relatively rare occurrence. Conditions which are likely to create an unstable regime of open-channel / pressure-flow transition occurred twice in 1985 (with event durations of 4- and 12-days), and once in 2016 (with an 18-hour duration). In future instances, this flow condition can be avoided if water management personnel are aware of the operational limitation.

When flow is released through only a single gate as opposed to both gates, the conduit flows within the open-channel regime for nearly all gate-settings and pool elevations. The exception is when a single gate is fully opened to near 100%, at this point, discharge is sufficiently high through the conduit to transition from open-channel to pressure flow. This transitional range of operation is approximated by the purple hatched region in Figure 16.

5. Stilling Basin Performance

5.1. End sill configurations

Figure 9 displays all end sills which were evaluated in the physical model with the exception of the enlarged dentated end sill, see section 5.1.4 for more details.

5.1.1. Ramp End Sill

The initial design for the end sill was a simple downstream facing ramp as recommended by the USBR Type III basin in USBR's EM25 *Hydraulic Design of Stilling Basins and Energy Dissipators*. This stilling basin configuration is shown in Figure 7. This end sill generally performed acceptably, however when the retreat channel apron was lowered (see Section 6.2), the end sill was elevated above the downstream channel and a cascading waterfall occurred during low flow conditions. Additionally, once the retreat channel was lowered, a vertical roller developed immediately downstream of the end sill, which has the potential to trap rock and other debris causing a potential long-term O&M issue.

To improve performance and eliminate the waterfall, various additional end sill configurations were tested and are discussed below.

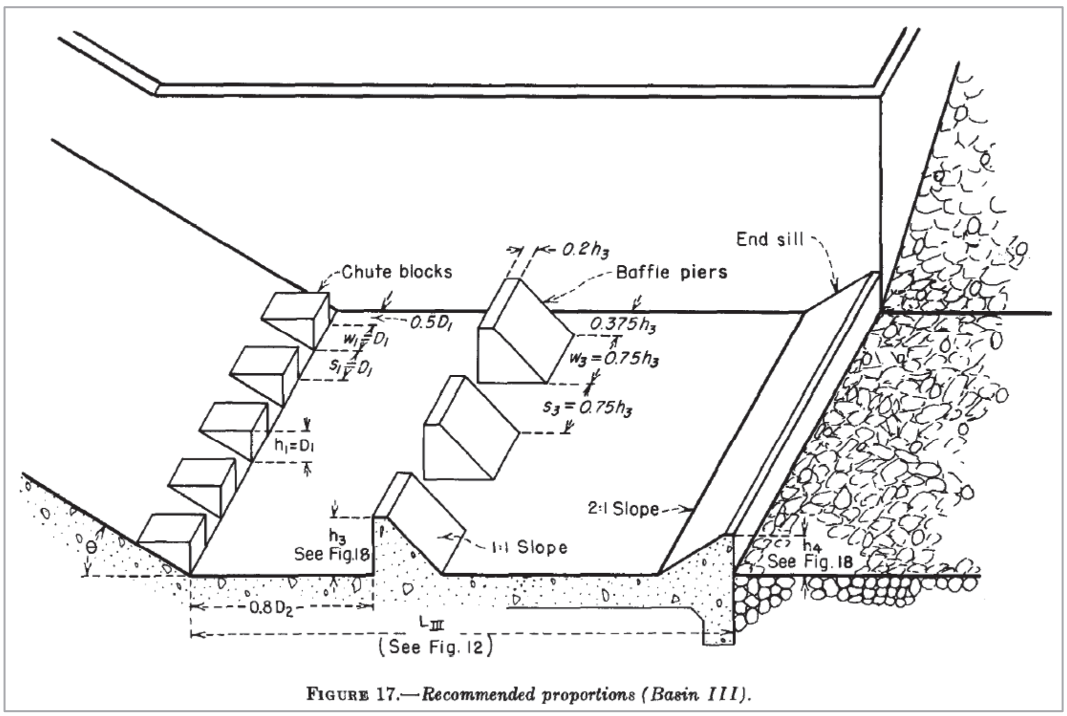


Figure 7. USBR Type III Stilling Basin

5.1.2. Notched End Sill

To reduce the magnitude of water falling over the ramped end sill, a small notch was included in the center of the end sill and sized to pass approximately 50 cfs, which is the project's specified minimum release. This notched end sill was evaluated in the physical model and it was found that a relatively high velocity flow jet developed in the notch. While this jet is not inherently a problem, it was also noted that a recirculation current had developed in the stilling basin upstream of the baffle blocks. This recirculation current, or eddy, located on the right descending side of the basin has the potential to trap debris and rock that can damage the stilling basin floor and baffle structures. This sort of debris induced abrasion is a leading cause of stilling basin damage that requires maintenance and repair. Immediately downstream of the end sill, it was also noted that the flow over the end sill was asymmetrical and favored the right descending side. Lastly it was noted that the vertical roller current present with the simple ramp end sill was also present with the notched end sill.

A second notched configuration was also evaluated using a smaller notch and produced similar results to the larger notched end sill. The smaller notch configuration was adapted from the USBR Type II stilling basin end sill design, and is similar to the dentated end sill configuration, however it contained only a single notch as opposed to many notches spread across the length of the sill.

5.1.3. Dentated End Sill

Because of the adverse flow conditions associated with the notched end sill discussed above, a dentated-style end sill configuration was also evaluated in the physical model. This end sill is typically associated with the USBR Type II stilling basin and consists of an inverted ramp that has multiple notches cut partially through the sill. **Error! Reference source not found.** displays this end sill configuration. Upon physical model testing, the dentated end sill was able to distribute flow out of the basin evenly across the entire span of the sill, including for low flows. This even distribution eliminated the recirculation current noted

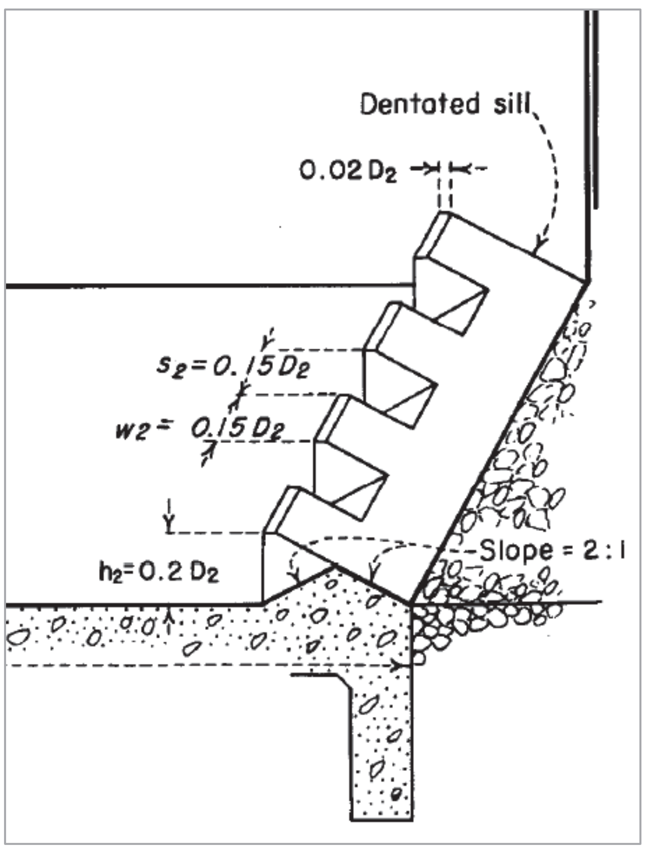


Figure 8. USBR Type II Dentated End Sill

with the notched design, as well as the high velocity jet and roller currents. The dentated end sill was evaluated across the full range of flow conditions and proved to be a very effective energy dissipation device. The front facing 'teeth' of the dentated end sill appeared to act as a secondary row of baffle blocks, which further improved energy dissipation and basin performance. Additional discussion is included in sections 5.2 and 5.3.

5.1.4. Enlarged Dentated End Sill

A variation on the dentated end sill that was also evaluated in the physical model is an enlarged version of the USBR Type II dentated end sill. By enlarging and increasing the height of the dentated teeth on the end sill, the sill structure becomes more suitable to act as a dewatering structure. The concept is that a bulkhead system could be placed over or within the enlarged dentates, effectively creating a cofferdam with a crest at elevation 435-ft NGVD29. The configuration being testing includes dentates that are 5.7-ft tall, as opposed to the 4.0-ft tall dentates recommended in the standard USBR Type II design. The lower notch elevation, 431.3 ft-NGVD29, is unchanged between the enlarged and standard dentated end sill to preserve low-flow performance of the end sill. No notable difference in hydraulic performance was noted between the standard and enlarged dentated end sill.

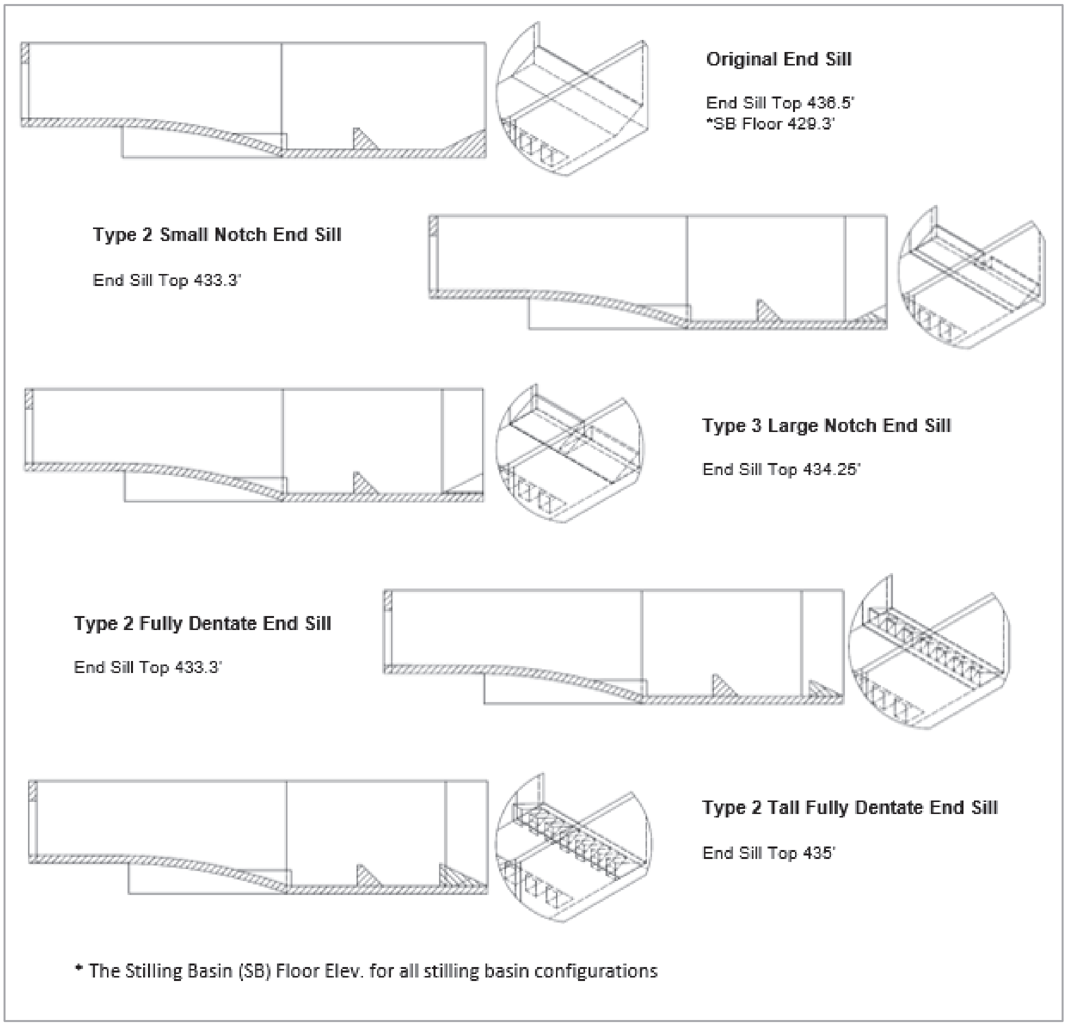


Figure 9. All Stilling Basin Configurations Evaluated in Physical Model Study

5.2. Tailwater elevation sensitivity

A series of tests were conducted to evaluate stilling basin vulnerability to low tailwater conditions. These conditions are of particular interest considering the presence of the Falls-of-Rough low-head dam located approximately 6.5-miles downstream of Rough River Reservoir Dam. If this low-head dam were to be removed or fail to hold its pool at some point in the future, it is expected to induce a reduction in tailwater elevation at the Rough River dam site, particularly at low discharges.

Figure 10 displays the various tailwater sensitivity tests which were conducted with the dentated end sill installed. The red dashed line represents the tailwater rating curve as published in the Water Control Manual. The green line represents a tailwater rating curve under a future condition where the downstream dam is removed, this curve was derived from HEC-RAS modeling using conservative assumptions and is assumed to be a lower bound threshold for tailwater given low-head dam removal. The purple points represent low-tailwater sensitivity tests performed in the physical model with the dentated end sill installed.

Under all conditions, even with unrealistically low tailwater elevations, the hydraulic jump was contained fully within the stilling basin and did not sweep out. The only adverse flow behavior noted with these low tailwaters was that wave action increased slightly on the concrete apron and a slight drawdown was noted over the end sill. These adverse flow behaviors are not expected to cause issues and are very acceptable considering the very small amount of tailwater that was provided. The dentated end sill's performance under very low tailwater conditions verifies the design's resiliency to potential future conditions. With this consideration in mind, as well as the numerous other improvements noted regarding the dentated end sill, this end sill was selected as the basis of design and carried forward.

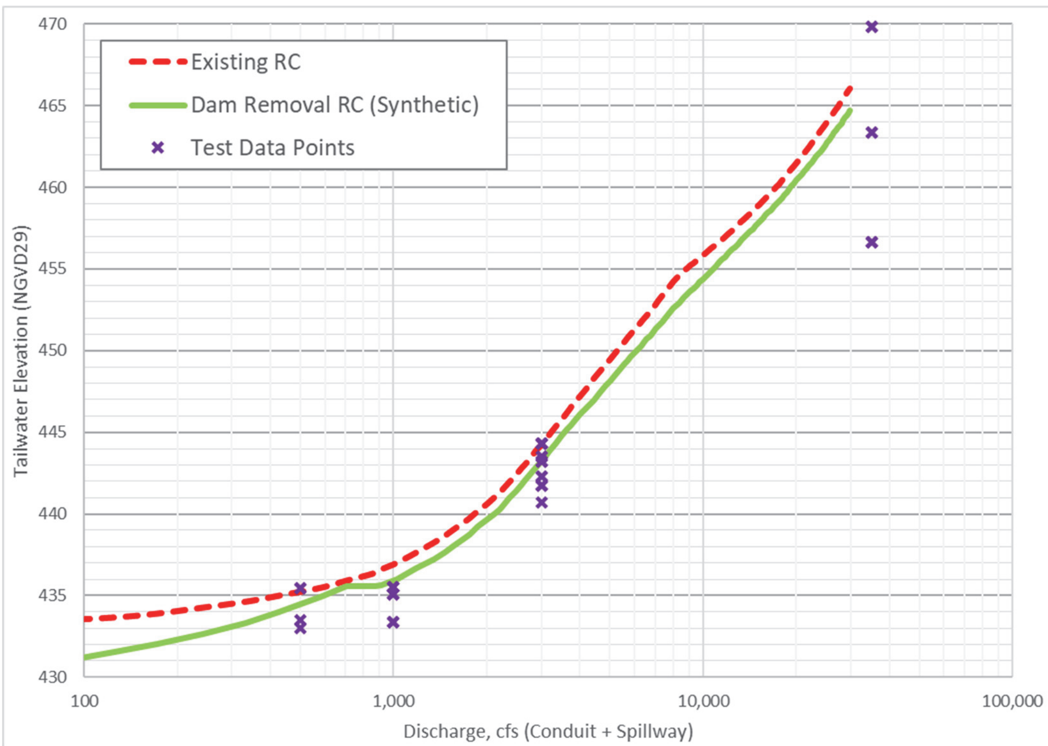


Figure 10. End Sill Tailwater Elevation Resilience Testing

5.3. Stilling Basin Rock Entrapment and Cleanout

An additional benefit of the dentated end sill which was not noted for other end sill configurations is the ability for the basin to sweep debris, such as large stones, out of the basin. This debris cleaning ability was tested in the physical model with rock that scales to between 12- and 16-inches in diameter. Under flow conditions of 3,000 cfs, all rock was quickly swept up the dentated end sill, through the low notches, and out of the basin. This rock then tended to temporarily deposit on the concrete apron, but all was eventually transported further downstream where it does not pose a potential O&M problem. This is significant because if rock becomes trapped in the stilling basin for prolonged periods of time, it can abrade concrete surfaces and damage features such as baffle blocks. This rock abrasion is one of the leading causes of stilling basin damage that requires repair. The ability of the dentated end sill stilling basin to remove rock out of the basin before damage can occur is a unique advantage and further supports the decision to carry the dentated end sill configuration into the final design over other designs.

5.4. Stilling Basin Dewatering

The dentated end sill does have a special consideration regarding dewatering for inspections and maintenance. Because the dentated end sill's crest elevation is significantly lower than the ramp end sill's, utilizing the end sill as a pseudo-cofferdam during dewatering is made more difficult. Additionally, because the dentated notches are distributed across the width of the end sill, sandbagging these notches is not a feasible option to create a dewatering barrier. Therefore, a commercial temporary water dam is needed to create the dewatering barrier for inspections.

To facilitate the use of a commercial dewatering barrier, a 2-ft tall bench was attached to the downstream side of the end sill and evaluated within the physical model. This bench creates a platform at elevation 431.3 ft-NGVD29 upon which a dewatering system can be placed, thus reducing the water depth that the dam will have to be placed from around 4-ft to around 2-ft. This dewatering bench is shown in profile view in Figure 11. The red line represents the bench itself which is 2-ft tall and 15-ft long. The yellow cloud in the figure represents the commercial dewatering system, of which there are many varieties.

The bench's impact on hydraulic performance was evaluated in the physical model and found to not cause undue adverse impacts. Some additional wave action was noted in the water surface above the bench itself, but this is not anticipated to cause any issues of concern.

An additional modification to facilitate dewatering is a version of dentated end sill that includes enlarged dentates which can be used as an effective dewatering cofferdam. See section 5.1.4.

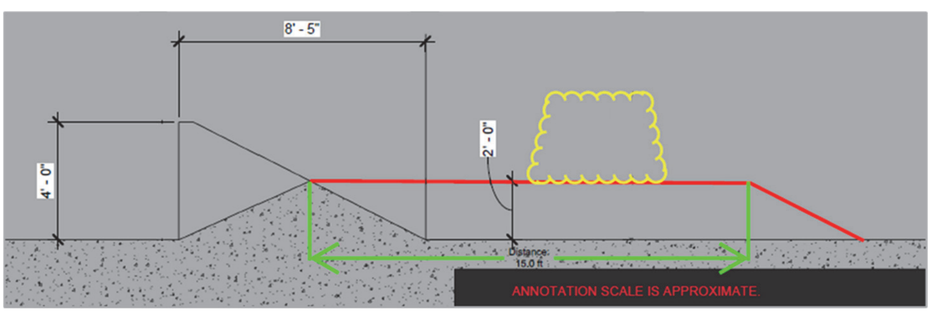


Figure 11. End Sill Dewatering Bench (Bench shown as red line)

5.5. Extreme High Flow Performance

The stilling basin design was evaluated across the full range of anticipated flow conditions, one of which is the probable maximum flood (PMF). This event corresponds to a reservoir pool elevation of just under 557-ft NGVD29, and under these conditions, the intake tower's gates would be opened fully. Under a PMF scenario, tailwater elevation is expected to be very high due to the substantial discharge through the emergency spillway which creates a backwater effect at the location of the stilling basin.

Under these conditions, the stilling basin exhibited unique behavior not present at lower discharges and tailwater elevations. Tailwater elevation is near elevation 470-ft NGVD29 during the PMF event, which completely inundates the stilling basin structure, training walls, and conduit exit portal. A photo showing the model stilling basin under these conditions is included as Figure 12. A significant clockwise swirl (when looking downward, shown as gold arrow in photo) is present over the stilling basin training walls.

The high tailwater elevation associated with this event creates an increased back pressure on the conduit and there is notable surging visible at the outlet. This flow condition is very chaotic and turbulent in nature; however, the stilling basin was able to provide adequate energy dissipation even when tailwater elevation was reduced substantially below where it is expected to be for an event of this magnitude. Considering the extreme probability of such an event, the performance shown in the model is very acceptable, although the basin should be inspected for damage and erosion following such an event. Some wave action lapping at the dam toe near the right abutment was also noted, with a wave amplitude varying between 0.25- and 0.5-ft in height.

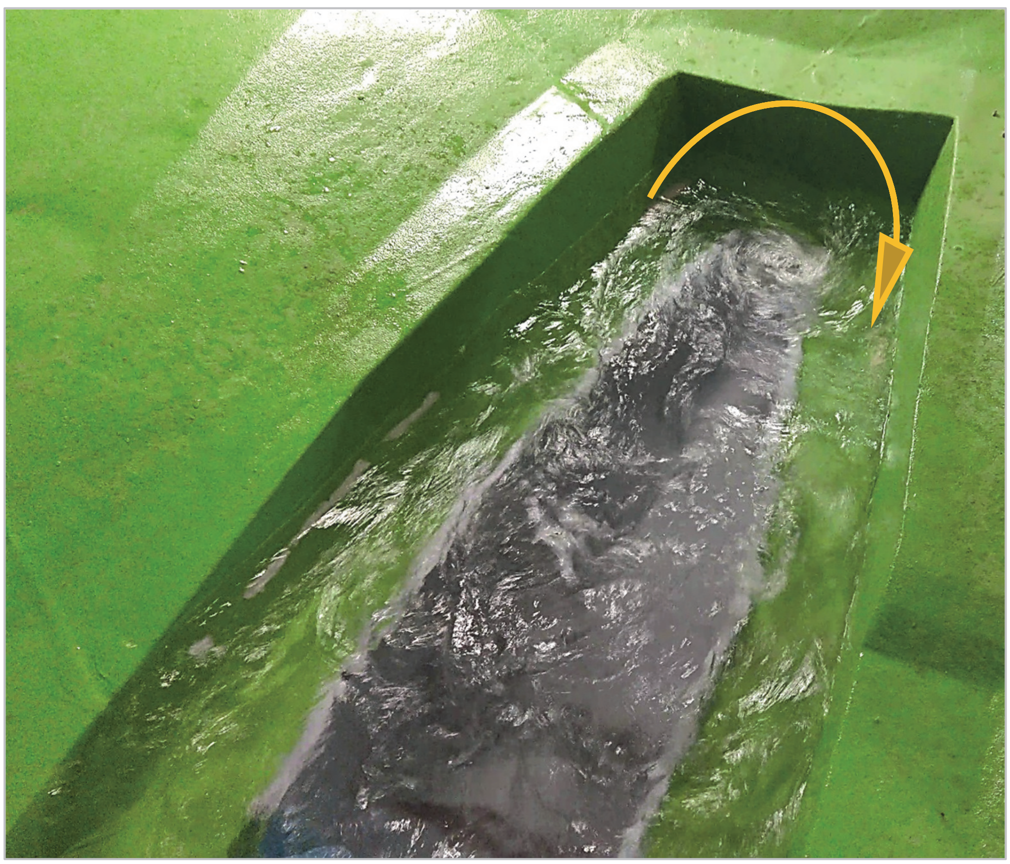


Figure 12. PMF Event at Stilling Basin (TW Elevation near 470 ft-NGVD29)

6. Retreat Channel Performance

6.1. Initial Performance

Upon initial physical model testing it was noted that a weak hydraulic jump was forming on the concrete apron portion of the retreat channel. This jump causes increased turbulence, wave action, and is not desirable from an operational perspective. This hydraulic jump was noted at 2,000 and 3,000 cfs modeled flows and was not present at higher flows where tailwater elevation was correspondingly higher. Lower discharges were not tested, but it can be assumed that the jump would be present at these lower flows as well.

It was determined that the hydraulic jump was resulting from an overly steep longitudinal slope on the concrete apron, this slope of approximately 1.15% induced supercritical flow under specific flow conditions. Because of this root cause, alterations to stilling basin, such as baffle block placement, shape, and sizing, would have little impact on the retreat channel performance.

6.2. Modification to Slope

To eliminate this jump, the profile of the retreat channel was altered to reduce the channel slope. This was done by extending the concrete apron horizontally at elevation 429.3 ft-NGVD29 from the stilling basin downstream to near station 24+00. The 429.3-ft elevation corresponds to the stilling basin floor elevation. The slope downstream of station 24+00 was reduced from 1.15% to 0.5%. Figure 13 displays a comparison of the longitudinal retreat channel profiles before and after the slope was reduced.

Other alternatives to eliminate this secondary hydraulic jump were considered, but ultimate screened out from consideration. One such alternative was to raise the downstream end of the apron, as opposed to lowering the upstream end, to reduce the overall apron slope. This was screened out as it would require a drop structure and secondary energy dissipation device to tie the apron in with the existing retreat channel elevation. Another alternative considered was to modify the current stilling basin configuration to dissipate enough energy such that flows could not achieve supercritical status. This alternative would not have had any impact on the root cause of the secondary hydraulic jump, which was induced by a supercritical slope on the overly steep apron.

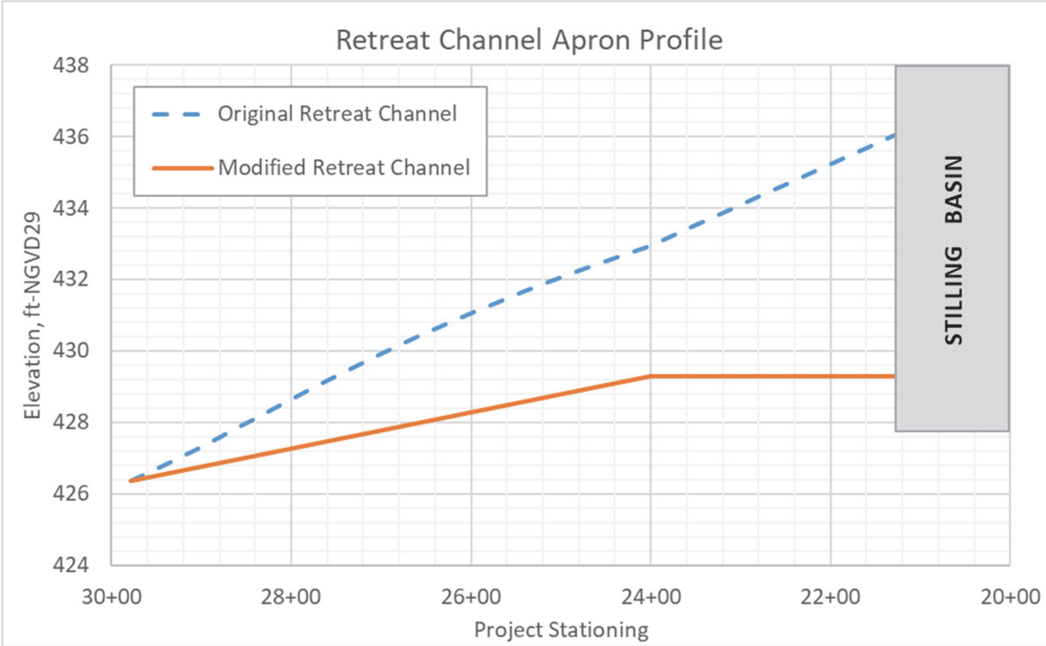


Figure 13. Retreat Channel Profile before and after slope modification

This modification was evaluated with the physical model by removing a portion of the retreat channel bathymetry and replacing it with a mobile stone bed. The stone bed allows for easy alterations of the channel shape if desired and can also be used to assess channel protection stability and upstream energy dissipation. Figure 14 displays this modification in schematic view on the left and a photo of the physical model on the right.

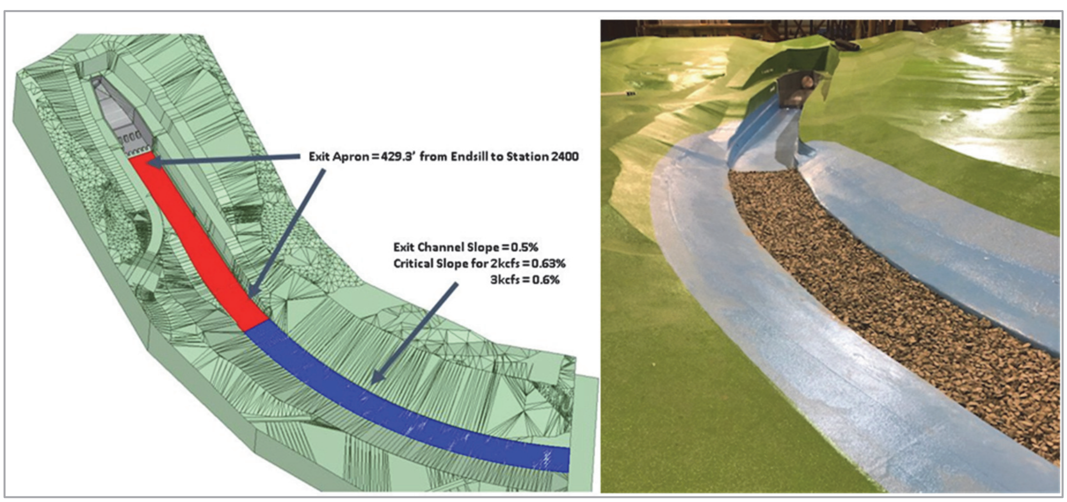


Figure 14. Schematic and Photo of Retreat Channel Modification

6.3. Performance of Modified Slope Design

Upon testing of the reduced retreat channel slope, it was found that the hydraulic jump on the apron was eliminated through the full range of operations and flow conditions. After the modification was installed, retreat channel performance was found to be excellent with acceptably low velocities and smooth flowlines downstream. This modification was maintained throughout the remainder of testing.

The sloped portion of the retreat channel downstream of station 24+00 was modeled as a mobile bed of scaled angular stones to simulate the rip-rap armor which will be included in the prototype retreat channel. The stone used simulates Class III rip-rap composed of 14.5-inch uniformly graded stone. Additional details on the stone gradation used are included in the ERDC/CHL TR-21-5. The mobile bed allowed for evaluation of particle transport and stability of the stone lining. Throughout all testing following the rock armor’s installation, no appreciable bed movement was noted. This is a strong indicator that the upstream stilling basin is providing adequate energy dissipation and that the retreat channel slope and dimensions are appropriate to ensure that the retreat channel streambed will be stable and should not experience undue scour.

7. Summary of Design Changes Stemming from Physical Modeling

The primary design changes that resulted from physical model testing include:

i. Modification of transition monolith design. (Section 4.1)
ii. Modification and refinement of stilling basin end sill. (Section 5.1)
iii. Modification of end sill design to facilitate dewatering. (Section 5.4)
iv. Modification to retreat channel slope and concrete apron. (Section 6)

Table 1 displays the modifications that were made to the physical model and how these modifications relate to test number and date. Note that 'EoT' stands for 'End of Testing,' indicating that these modifications were retained through the remainder of tests performed.

Table 1.Test Schedule and Physical Model Modifications

Test Number	Start Date	End Date	Notes on Testing
1 – 7	08/19/2020	08/19/2020	Testing starts. Gates installed backwards
8 +	08/20/2020	EoT	Gates installed correctly
1 – 77	08/19/2020	10/18/2020	Singh (1969) Transition Installed
1 – 46	08/19/2020	09/14/2020	Original retreat channel apron with 1.15% slope installed
47 – 56	09/28/2020	10/01/2020	Evaluation of various end sill configurations
47 +	09/28/2020	EoT	Modified retreat channel apron with 0% slope installed
57 – 192	10/02/2020	02/03/2021	Fully Dentated End Sill Installed
78 +	10/19/2020	EoT	EM 1110-2-1602 Transition Installed
105 +	11/04/2020	EoT	End Sill Bench Installed
167 – 192	01/13/2021	02/03/2021	Single Gate Tests
193 – 206	02/04/2021	02/09/2021	Enlarged End Sill Testing

8. Physical Model Data Summary

8.1. Tabular Data

Tabular data of all tests collected with the final transition design (EM 1110-2-1602 Appendix E) are included in Table 2 on page 28 for 2-gates operating symmetrically. Table 3 on page 30 displays similar data for the single-gate tests; these tests were conducted with all flow released through the left-descending gate with the right gate closed. Additional data collected is included in the ERDC/CHL TR-21-5.

8.2. Graphical Stage-Discharge Rating Curves

Discharge-stage rating curves for multiple gate openings are included in Figure 15 on page 29. Note the purple hatched area describes the region where conduit flow transitions from open-channel to pressurized-pipe flow. Colored contouring and contour lines correspond to gate opening percent. The discharge values are total flowrate through both gates operated symmetrically. Data points observed in the physical model are also plotted in the figure. The transitional pressurization region shown in Figure 15 was determined by plotting the position of test data where the conduit was nearly pressurized and fully pressurized. This bounded the hatched area shown on the rating curves and the points were connected by smoothed lines.

Figure 16 on page 31 displays discharge-stage rating curves for single gate operations. For these tests, all flow was released through the left-descending gate with the right gate closed. Only two tests, both with gates opened fully to 100%, displayed pressurized conduit conditions. All other tests with gate openings less than 100% had open-channel flow throughout the length of the conduit.

8.3. Hydraulic Grade Lines

Hydraulic grade lines (HGL), collected from piezometric measurements in the physical model, are included in Figure 17 through Figure 24. Each figure displays various gate openings for the same discharge. Discharges were released symmetrically through both gates and range from 500 cfs to 7,900 cfs. The solid black line represents the outletworks invert elevation (for the approach channel, conduit, stilling basin, and retreat channel). The dashed grey line represents the intake tower face, tower intake curves, and conduit crown. Locations where the grey dashed line is vertical represent the end of the transition monolith and the conduit portal where flow opens to the stilling basin. Test numbers for individual profile lines are included in the legend and correspond to the test numbers provided in the 4th column of Table 2. Additional discussion of these profile lines is included in the ERDC/CHL TR-21-5.

8.4. Prototype Validation

Upon construction of the prototype outletworks being completed, it is recommended the data collected from the physical model be validated to the real world as-built conditions. This would include discharge and stage measurements being collected as flow is released through the project at various gate settings and pool elevations, as is practical.

Table 2. Physical Model Test Data with EM 1110-2-1602 Appendix E Transition Installed

Gate (ft)	Gate (%)	Date	Test #	Proto Q (Nominal)		Instrument ID:	SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
						Station Number:	04+36.6	08+36.7	09+11.1	09+68.5	09+68.5	09+82.5	09+82.5	09+85.0	09+85.0	09+88.5	09+88.5	09+93.0	09+93.0	09+98.5	09+98.5	10+05.0	10+05.0	10+28.6	11+00.0	12+00.0	13+00.0	14+00.0	15+00.0	16+00.0	17+00.0	18+00.0	19+00.0	20+00.0	20+30.9	20+70.1	20+98.5	21+36.6	22+11.5	26+11.5
					Proto Q (Computed)	Model Q	Approach Channel (HW)	Approach Channel	Approach Channel 2	Intake Tower	Intake Tower 3	Intake Tower 4	Intake Tower 5	Intake Tower 6	Intake Tower 7	Intake Tower 8	Intake Tower 9	Intake Tower 10	Intake Tower 11	MON 0	MON 012	MON 013	MON 014	MON 1	Culvert	Culvert 15	Culvert 16	Culvert 17	Culvert 18	Culvert 19	Culvert 20	Culvert 21	Culvert 22	Stilling Basin	Stilling Basin 23	Stilling Basin 24	Stilling Basin 25	Exit Channel	Exit Channel 26	Exit Channel (TW)
12.6	90%	10/19/20	**79**	3,000	2,990	0.88	463.92	463.92	463.92	459.7	459.5	458.0	457.9	457.5	457.4	457.2	457.2	457.3	457.2	457.4	457.0	457.5	457.4	457.8	455.4	454.6	453.4	453.3	452.2	451.0	450.6	450.0	449.0	446.8	439.7	442.3	444.5	444.26	444.34	444.42
11.2	80%	10/20/20	**80**	3,000	2,990	0.88	464.79	464.77	464.77	460.6	460.4	457.6	457.5	456.5	456.3	455.8	455.8	455.4	455.6	455.5	455.3	456.1	456.1	457.8	455.2	454.7	453.3	453.2	452.2	451.1	450.7	450.1	449.2	446.8	439.5	443.2	444.4	444.24	444.34	444.40
7.0	50%	10/20/20	**83**	3,000	2,990	0.88	479.53	479.50	479.49	475.0	474.9	462.2	462.2	455.9	456.1	450.6	450.8	447.5	448.0	446.0	445.3	445.9	445.8	449.9	446.3	446.4	445.1	447.8	447.5	447.3	447.9	447.8	448.1	445.3	439.3	442.9	444.4	444.24	444.34	444.40
7.7	55%	10/23/20	**90**	3,000	2,990	0.88	473.89	473.89	473.92	469.5	469.3	459.4	459.4	454.8	454.9	450.7	450.9	448.1	448.6	446.7	446.2	446.4	446.4	449.8	447.2	447.3	446.1	448.4	448.3	448.5	449.0	451.0	450.8	446.0	439.4	443.2	444.4	444.24	444.34	444.39
14.0	100%	10/23/20	**91**	2,000	2,004	0.59	456.91	456.83	456.88	455.0	455.0	454.7	454.6	454.6	454.5	454.6	454.5	454.7	454.5	454.4	454.3	454.3	454.2	454.4	453.2	452.9	452.2	452.1	451.8	451.1	451.0	450.6	450.2	444.7	438.8	439.2	440.8	440.59	440.70	440.64
5.6	40%	10/26/20	**93**	3,000	2,990	0.88	497.16	497.13	497.13	493.0	493.0	471.0	470.9	459.3	459.4	449.9	450.1	446.0	446.7	444.8	443.5	444.7	444.4	450.5	445.7	445.1	442.8	446.8	446.2	445.4	446.3	446.1	446.2	444.7	439.0	442.0	444.2	444.16	444.34	444.39
14.0	100%	10/28/20	**97**	6,500	6,455	1.90	509.72	509.67	509.59	489.7	489.1	485.6	484.9	485.2	484.6	485.2	484.4	485.0	484.5	484.2	482.9	483.7	482.8	484.1	472.6	459.9	454.1	454.3	460.6	455.7	453.9	451.1	448.2	444.4	442.0	449.5	451.4	451.92	452.20	452.48
14.0	100%	10/28/20	**99**	7,900	7,882	2.32	556.72	556.72	556.59	526.6	525.6	520.4	519.4	520.0	518.9	520.0	518.7	519.8	518.8	518.6	516.3	517.7	516.3	518.3	501.5	497.5	488.8	489.5	483.6	477.0	474.0	470.5	466.0	463.5	463.0	470.0	468.8	467.94	469.91	470.01
9.1	65%	10/29/20	**100**	5,938	5,946	1.75	524.04	524.04	523.99	505.8	505.7	480.9	481.0	470.0	470.2	460.9	461.1	454.0	454.9	449.2	447.4	447.9	447.3	456.5	448.1	449.0	445.4	451.6	451.2	450.0	451.5	452.5	452.0	445.2	443.0	450.6	452.3	452.61	452.79	453.03
9.8	70%	10/29/20	**101**	6,214	6,217	1.83	523.99	523.94	523.86	504.1	504.0	482.5	482.3	473.8	473.5	466.2	465.8	461.0	461.3	459.1	457.1	461.8	461.5	481.2	473.5	470.6	466.2	465.5	462.3	457.7	456.0	452.5	450.2	445.0	441.2	448.0	450.5	451.04	451.35	451.58
14.0	100%	10/30/20	**101**	4,000	4,009	1.18	473.48	473.48	473.48	465.9	465.8	464.2	464.0	464.1	463.9	464.0	463.9	464.0	463.9	463.8	463.1	463.4	463.1	463.7	459.0	457.9	455.7	455.5	453.9	457.9	451.0	449.9	448.5	446.9	440.1	445.2	446.6	446.56	446.69	446.77
14.0	100%	10/30/20	**102**	5,000	4,994	1.47	486.20	486.12	486.12	474.1	474.0	471.8	471.2	471.6	471.0	471.5	471.0	471.3	471.0	470.9	470.0	470.6	470.0	470.0	463.9	462.0	458.7	458.5	456.0	453.0	451.8	450.0	448.1	446.0	441.4	447.2	449.0	448.99	449.19	449.30
14.0	100%	11/2/20	**103**	6,000	6,013	1.77	502.74	502.64	502.61	485.1	484.7	481.5	481.0	481.3	480.6	481.2	480.5	481.1	480.5	480.4	479.0	479.8	478.9	480.2	470.3	467.6	462.7	462.8	459.3	454.9	453.3	450.8	448.1	444.9	441.8	448.5	450.7	450.83	451.06	451.27
14.0	100%	11/2/20	**104**	7,000	6,999	2.06	522.28	522.23	522.10	498.3	497.8	493.0	493.0	493.0	493.0	493.0	492.9	493.0	493.0	491.8	490.1	491.0	490.0	491.5	478.0	474.6	468.0	468.0	463.4	457.7	455.5	452.2	448.4	444.0	441.3	449.0	451.5	452.04	452.41	452.72
5.6	40%	11/4/20	**105**	500	510	0.15	447.24	447.17	447.17	447.0	447.0	446.7	447.9	446.5	446.6	446.6	446.7	446.8	446.5	446.5	446.5	446.5	446.6	446.5	444.3	445.0	444.9	444.5	444.3	443.8	443.4	443.5	443.5	441.4	437.8	435.9	435.9	435.55	435.53	435.45
9.8	70%	11/4/20	**107**	2,000	2,004	0.59	457.63	457.53	457.56	455.7	455.6	453.5	453.2	4522.9	452.5	452.3	452.0	452.3	452.0	452.7	452.1	453.0	452.9	453.9	452.7	452.4	451.9	451.5	451.0	450.3	449.9	449.7	449.2	445.0	438.9	439.0	440.7	440.46	440.62	440.54
14.0	100%	11/4/20	**108**	3,000	2,990	0.88	463.35	463.27	463.30	459.2	459.0	458.4	458.1	458.2	458.0	458.1	458.0	458.1	458.0	458.0	457.8	457.9	457.8	457.9	455.4	454.7	453.4	453.2	452.2	451.0	450.7	450.0	449.2	447.3	439.8	443.3	444.6	444.29	444.37	444.44
8.4	60%	11/4/20	**109**	3,000	2,990	0.88	471.21	471.15	471.15	466.8	466.7	458.9	458.8	455.9	454.7	452.8	452.9	452.5	449.5	452.7	448.7	453.4	451.5	458.7	457.1	456.4	455.1	455.0	454.1	452.9	452.5	451.8	451.2	446.1	439.4	442.7	444.3	444.26	444.39	444.44
12.6	90%	11/5/20	**110**	2,000	2,004	0.59	457.43	457.30	457.35	455.3	455.2	454.8	454.7	454.6	454.4	454.4	454.3	454.5	454.4	454.5	454.3	454.5	454.3	454.6	453.4	453.0	452.4	452.3	451.9	451.2	451.0	450.7	450.2	444.9	438.9	438.8	440.3	440.31	440.44	440.41
7.0	50%	11/5/20	**112**	1,000	985	0.29	450.99	450.94	450.91	450.1	450.0	449.1	449.0	448.9	448.8	448.6	448.5	448.8	448.8	449.0	448.8	449.0	448.9	449.0	446.3	447.9	447.2	447.2	446.9	446.3	445.8	445.9	445.9	443.0	438.1	435.9	437.0	436.66	436.72	436.56
7.0	50%	11/5/20	**113**	2,000	2,004	0.59	461.54	461.43	461.41	459.5	459.4	453.6	453.6	450.8	450.8	448.0	448.2	446.5	446.8	445.9	445.6	445.7	445.8	448.2	447.0	446.8	447.7	451.1	451.0	450.2	449.9	449.6	449.2	445.0	438.9	439.0	440.6	440.54	440.64	440.62
5.6	40%	11/6/20	**114**	2,000	2,004	0.59	468.47	468.41	468.41	466.5	466.5	456.5	456.5	457.4	451.4	446.0	446.1	445.1	445.4	444.9	444.3	444.9	444.9	447.9	446.0	445.5	444.9	446.3	446.2	446.6	447.0	449.7	449.1	444.9	438.9	439.2	440.5	440.54	440.64	440.57
4.2	30%	11/6/20	**115**	2,000	2,004	0.59	486.38	486.30	486.30	484.4	484.3	466.0	466.1	453.9	454.0	445.7	445.8	443.8	444.2	443.8	442.6	443.8	443.6	447.9	444.8	444.0	442.3	445.2	445.0	444.7	445.0	445.0	445.0	443.9	438.6	438.8	440.5	440.54	440.64	440.59
3.5	25%	11/6/20	**116**	2,000	2,004	0.59	503.44	503.36	503.42	501.5	501.4	475.4	475.4	455.7	455.9	444.9	445.1	443.3	443.9	443.2	441.8	443.4	443.0	447.4	443.3	443.7	440.9	445.2	444.5	443.8	444.5	444.2	444.3	443.4	438.7	438.5	440.6	440.52	440.64	440.59
5.6	40%	11/9/20	**117**	1,000	985	0.29	451.40	451.35	451.35	450.7	450.5	448.8	448.6	447.8	447.7	447.4	447.2	447.9	447.8	447.2	447.1	448.5	448.4	448.9	446.2	447.8	447.2	447.1	446.8	446.1	445.6	445.8	445.8	443.0	438.0	436.5	432.2	437.08	437.08	437.00
4.2	30%	11/9/20	**118**	1,000	985	0.29	453.81	453.76	453.78	453.4	453.4	449.1	449.1	446.1	446.1	444.0	444.1	443.7	443.8	443.6	443.5	443.7	443.8	445.5	445.0	444.8	446.0	446.6	446.5	446.0	445.9	445.9	445.9	443.0	438.0	436.5	437.2	437.03	437.05	436.95
2.8	20%	11/9/20	**120**	1,000	985	0.29	463.09	463.06	463.04	462.9	462.8	453.9	453.8	446.0	446.5	442.8	443.1	442.4	442.9	442.5	442.4	442.8	442.9	445.5	444.0	443.6	443.0	444.1	444.0	444.2	444.3	445.5	445.8	442.9	438.0	436.4	437.3	436.95	436.97	436.87
1.4	10%	11/16/20	**121**	1,000	985	0.29	526.68	526.63	526.65	526.5	526.3	493.0	493.0	445.0	440.3	441.4	441.7	441.6	442.0	442.1	440.9	442.3	441.6	440.9	440.9	442.0	439.4	443.1	442.8	442.0	442.3	442.3	442.2	442.0	438.0	436.3	437.2	436.74	436.97	436.87
12.6	90%	11/12/20	**122**	4,000	4,009	1.18	474.15	474.07	474.07	466.4	466.2	463.2	463.0	462.4	462.1	462.0	461.9	462.0	462.0	462.3	461.9	462.7	462.3	463.3	458.9	457.7	455.4	455.3	453.8	451.8	451.0	449.9	448.3	447.0	441.5	447.0	448.0	447.93	448.01	448.09
11.2	80%	11/12/20	**123**	4,000	4,009	1.18	476.12	476.09	476.09	468.2	468.0	462.8	462.6	460.8	460.5	459.1	459.0	458.3	458.1	458.5	457.7	459.8	459.5	463.9	458.9	457.6	455.4	455.3	453.8	451.8	451.1	449.9	448.5	447.0	440.2	445.8	446.0	447.39	447.88	448.12
12.6	90%	11/13/20	**126**	5,000	4,994	1.47	487.78	487.67	487.67	475.5	475.1	470.6	470.2	469.2	469.0	468.5	468.3	468.6	468.6	469.0	468.3	469.5	469.0	470.6	463.9	462.0	458.6	458.5	456.0	453.0	451.8	450.0	448.1	446.0	441.3	446.8	448.9	448.99	449.15	449.33
11.2	80%	11/13/20	**127**	5,000	4,994	1.47	490.49	490.39	490.39	4778.1	477.9	469.4	469.2	466.4	466.2	464.1	463.7	462.6	462.4	463.0	461.8	464.8	464.4	469.9	463.8	461.9	458.4	458.3	456.0	452.8	451.7	450.0	448.0	446.0	441.5	446.8	448.8	449.02	449.15	449.33
9.8	70%	11/16/20	**128**	5,000	4,994	1.47	498.30	498.22	498.22	485.8	485.3	471.7	471.5	466.2	466.1	461.6	461.0	458.3	458.2	457.3	456.0	460.0	458.0	471.5	466.0	463.5	460.7	460.5	458.0	454.0	453.8	452.0	450.0	446.3	441.0	446.0	449.1	448.99	449.15	449.33
8.4	60%	11/17/20	**129**	5,000	4,994	1.47	510.63	510.60	510.52	497.7	497.5	475.8	475.7	466.0	466.2	457.4	457.6	451.4	452.2	448.0	446.4	447.1	446.7	454.1	447.5	447.8	445.0	449.8	449.2	448.2	449.5	449.6	449.9	446.0	440.2	446.0	448.6	448.94	449.12	449.33
12.6	90%	11/17/20	**130**	6,000	6,013	1.77	505.74	505.66	505.64	487.9	487.3	480.6	480.0	478.7	478.0	477.6	477.0	477.8	477.4	478.1	477.1	478.9	478.2	480.7	470.6	468.0	463.1	463.0	459.7	455.1	453.4	451.0	448.2	445.0	441.8	447.9	450.4	450.83	451.06	451.29
11.2	80%	11/17/20	**131**	6,000	6,013	1.77	509.15	509.08	509.00	491.0	490.8	478.5	478.0	474.0	473.6	470.7	470.0	468.3	468.2	468.5	467.0	471.1	470.7	479.1	470.2	467.8	462.9	462.8	459.3	455.0	453.2	451.0	448.2	445.0	442.0	448.1	450.3	450.83	451.04	451.29
9.8	70%	11/17/20	**132**	6,000	6,013	1.77	519.08	519.08	518.98	500.4	500.3	480.6	480.4	472.5	472.7	465.8	465.3	460.7	460.5	459.0	456.8	461.0	460.8	479.5	472.0	469.3	464.4	464.3	461.3	456.7	455.0	452.5	450.0	445.3	441.3	447.5	450.3	450.83	451.06	451.29
9.8	70%	11/18/20	**135**	4,000	4,009	1.18	481.86	481.73	481.73	473.8	473.2	465.0	464.9	460.6	460.4	457.5	457.6	456.1	456.3	455.3	454.0	457.7	456.8	454.7	450.7	459.8	456.5	456.4	455.4	454.4	452.0	451.5	450.5	447.0	441.5	446.6	448.0	447.96	448.04	448.12
8.4	60%	11/19/20	**136**	4,000	4,009	1.18	488.84	488.71	488.71	480.6	480.6	466.0	466.1	459.8	459.9	454.0	454.1	450.0	450.6	447.8	446.9	447.1	447.0	452.0	448.1	448.0	446.3	457.9	456.3	454.5	453.6	452.8	451.2	446.7	441.2	446.3	448.0	447.96	448.04	448.14
4.2	30%	11/19/20	**137**	500	510	0.15	447.99	447.94	447.97	447.9	447.8	446.9	446.8	446.1	446.0	446.0	445.9	446.1	446.2	446.5	446.4	446.7	446.6	446.8	444.4	445.2	445.0	444.9	444.7	444.0	443.8	443.8	443.8	441.6	437.9	435.7	436.0	435.50	435.63	435.63
2.8	20%	11/19/20	**138**	500	510	0.15	449.57	449.52	449.54	449.7	449.7	446.8	446.6	444.3	443.9	444.2	442.8	445.1	442.7	445.9	442.9	446.1	444.9	446.9	444.4	445.2	445.0	444.9	444.7	444.0	443.8	444.0	443.9	441.8	437.9	435.8	436.0	435.66	435.66	435.50
1.4	10%	11/19/20	**139**	500	510	0.15	464.92	464.90	464.92	465.1	465.1	455.9	455.8	442.3	442.3	441.5	441.6	441.6	441.7	441.7	441.7	441.9	441.8	443.5	442.6	442.1	442.0	442.7	443.2	443.0	442.9	443.4	443.6	441.5	437.8	435.8	436.0	435.63	435.60	435.50
8.4	60%	11/20/20	**140**	1,000	985	0.29	450.47	450.40	450.40	449.6	449.5	449.1	449.1	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	446.1	447.8	447.2	447.1	446.9	446.2	446.0	446.0	445.9	443.0	438.1	436.2	437.2	437.00	437.00	436.90
3.5	25%	11/20/20	**141**	1,000	985	0.29	458.33	458.31	458.33	458.0	458.0	451.3	451.3	446.2	446.3	443.4	443.5	443.0	443.2	443.0	442.4	443.1	443.1	445.5	444.5	444.0	443.9	444.6	445.7	445.2	445.8	446.0	446.0	443.0	438.1	436.3	437.2	437.00	437.05	436.92
11.2	80%	11/20/20	**142**	2,000	2,004	0.59	457.04	456.99	456.99	455.1	455.1	454.0	453.9	453.6	453.4	453.3	453.2	453.3	453.3	453.7	453.5	453.8	453.8	454.0	452.8	452.5	451.9	451.7	451.0	450.3	449.9	449.8	449.1	445.0	439.0	439.1	440.7	440.57	440.67	440.64
8.4	60%	11/20/20	**143**	2,000	2,004	0.59	458.28	458.25	458.25	456.3	456.2	453.0	452.5	451.4	450.9	450.3	449.2	450.3	448.6	450.9	448.2	451.9	449.6	453.8	452.6	452.4	451.9	451.7	451.0	450.3	450.0	449.7	449.2	445.0	438.8	439.0	440.7	440.57	440.67	440.62
9.8	70%	11/23/20	**144**	3,000	2,990	0.88	467.79	467.74	467.77	463.4	463.2	458.1	457.9	456.4	456.4	454.8	454.5	454.0	454.3	454.1	453.7	455.0	454.9	458.2	456.5	455.6	454.4	453.9	453.1	452.0	451.4	450.6	450.3	446.9	439.5	442.8	444.3	444.24	444.32	444.42
7.0	50%	11/24/20	**145**	4,000	4,009	1.18	506.78	506.72	506.67	498.1	497.9	474.7	474.8	463.6	463.8	453.9	454.3	448.5	449.4	446.1	444.7	445.8	445.3	452.5	446.0	446.4	443.8	448.3	447.7	446.8	447.9	447.6	447.8	445.4	440.3	445.5	447.8	447.81	447.96	448.09
7.0	50%	12/9/20	**146**	5,000	4,994	1.47	538.59	538.47	538.42	524.5	524.8	489.8	489.8	473.0	473.3	458.8	458.8	450.5	451.5	446.5	444.0	445.8	445.0	456.5	445.5	446.5	441.8	448.3	447.5	446.0	447.8	447.8	447.5	444.5	439.5	445.0	448.5	449.12	449.25	449.47
9.1	65%	12/14/20	**149**	6,000	6,013	1.77	528.20	528.20	528.15	509.1	509.2	484.9	484.6	474.6	474.3	465.5	465.4	459.8	459.8	457.0	454.9	459.2	457.6	481.1	475.3	472.2	467.0	455.9	463.6	459.1	457.5	455.2	452.3	445.3	440.4	446.8	450.4	450.80	451.04	451.27
7.7	55%	12/15/20	**150**	5,000	4,994	1.47	522.49	522.47	522.44	509.0	509.0	481.5	481.7	469.0	469.2	458.0	458.1	451.0	451.8	447.2	445.2	446.3	445.8	455.3	446.4	447.2	443.4	449.2	448.6	447.7	448.9	448.8	448.9	445.3	440.1	445.4	448.8	449.05	449.23	449.46
6.3	45%	12/16/20	**151**	4,000	4,009	1.18	521.35	521.33	521.33	509.8	509.9	481.0	481.1	466.7	466.8	454.2	454.2	448.0	449.0	445.6	443.8	445.1	444.9	453.2	445.2	446.0	442.6	448.0	447.1	446.3	447.5	447.2	447.2	445.0	439.8	444.9	447.7	447.78	447.96	448.12
5.6	40%	12/17/20	**155**	4,000	4,009	1.18	542.91	542.89	542.86	533.3	533.7	493.0	493.0	471.9	471.5	454.8	454.2	447.4	448.1	444.9	442.0	444.7	443.8	454.9	444.0	445.0	439.8	447.0	446.6	445.1	446.6	446.3	446.4	444.0	439.1	443.5	447.5	447.91	447.75	447.91
4.9	35%	12/18/20	**156**	3,000	2,990	0.88	513.78	513.75	513.75	508.7	508.9	479.5	479.7	462.7	462.3	449.4	449.1	445.1	445.8	444.4	442.3	444.3	443.8	450.5	444.1	445.0	441.9	446.7	446.0	445.1	446.0	445.9	445.8	444.1	439.0	441.0	444.1	444.20	444.34	444.42
4.2	30%	12/18/20	**157**	3,000	2,990	0.88	539.40	539.37	539.35	534.0	534.2	493.0	493.0	467.0	466.5	449.0	448.9	444.6	445.4	443.8	442.3	444.0	443.1	450.8	442.9	444.0	439.0	445.7	445.3	443.9	445.4	445.2	445.1	443.9	438.7	440.3	444.2	444.19	444.32	444.42
2.1	15%	12/28/20	**158**	500	510	0.15	451.79	451.79	451.82	451.8	451.8	438.8	443.3	443.3	443.0	442.1	442.0	442.1	442.1	442.1	441.9	442.2	442.2	443.9	443.5	442.9	443.9	444.8	444.5	443.4	444.2	443.4	443.5	441.5	437.8	435.6	435.9	435.60	435.60	435.47
4.9	35%	12/28/20	**159**	2,000	2,004	0.59	474.70	474.67	474.64	472.5	472.5	460.1	454.3	452.3	446.5	446.4	444.8	440.9	444.4	443.7	444.5	444.2	448.1	444.7	445.1	444.1	446.2	445.8	445.7	444.6	445.9	446.2	446.3	444.7	438.5	438.9	440.5	440.54	440.67	440.62
2.1	15%	12/31/20	**160**	1,000	985	0.29	478.31	478.31	478.34	478.0	478.1	462.8	457.8	446.3	445.9	441.9	442.0	441.9	442.1	442.2	441.7	442.4	442.1	444.2	442.0	442.7	441.8	443.5	443.3	442.4	445.4	443.3	443.2	442.8	438.0	436.4	437.2	437.00	437.00	436.90
2.8	20%	12/31/20	**161**	2,000	2,004	0.59	531.54	531.54	531.54	529.3	529.6	491.0	485.5	457.8	457.4	444.0	443.9	442.8	443.4	443.0	441.0	443.1	442.3	445.8	441.9	442.9	439.1	444.2	443.7	441.9	445.8	443.7	443.7	443.2	438.5	437.5	440.4	440.52	440.67	440.64
11.9	85%	1/6/21	**162**	7,000	6,999	2.06	528.33	528.36	528.26	503.5	503.4	491.4	490.7	487.2	486.4	484.7	4837.0	483.8	483.4	485.0	482.9	487.4	486.2	492.0	479.0	475.3	468.8	468.7	464.0	458.0	455.8	452.3	448.8	444.1	441.2	448.0	451.4	452.04	452.48	452.72
6.3	45%	1/7/21	**163**	3,000	2,990	0.88	486.33	486.33	486.30	481.4	481.5	465.6	465.5	457.3	457.1	450.2	450.1	446.7	447.0	445.6	444.5	445.4	445.1	450.0	446.1	446.0	444.2	447.3	447.0	446.8	447.4	447.1	447.2	445.2	439.2	442.0	444.0	444.19	444.32	444.39
0.7	5%	1/7/21	**164**	500	510	0.15	523.06	523.03	523.06	523.2	523.2	497.7	499.2	440.7	440.5	441.0	441.0	441.0	441.2	441.8	440.9	442.0	441.0	440.9	441.0	441.1	440.1	442.0	441.8	442.0	442.1	441.8	442.4	441.5	437.8	435.9	436.0	435.86	435.84	435.71
14.0	100%	1/8/21	**165**	500	510	0.15	446.31	446.26	446.29	446.1	446.1	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	446.0	445.9	445.8	443.6	444.1	444.0	443.9	443.8	443.1	442.4	442.8	442.9	441.0	437.5	435.8	435.9	435.76	435.68	435.63
14.0	100%	1/12/21	**166**	1,000	985	0.29	450.60	450.57	450.60	449.6	449.5	449.4	449.2	449.3	449.2	449.2	449.1	449.3	449.2	449.2	449.0	449.1	449.0	449.1	446.3	447.9	447.5	447.3	447.0	446.3	445.9	446.0	446.0	443.0	438.1	436.1	437.3	437.08	437.13	437.00
8.4	60%	1/12/21	**167**	6,000	6,013	1.77	540.25	540.23	540.15	520.4	520.7	488.8	488.7	474.4	474.6	462.0	462.2	453.6	454.3	453.4	446.0	447.0	446.3	458.4	447.0	447.9	443.2	450.2	449.3	448.0	449.8	449.7	450.0	445.0	440.2	446.5	450.4	450.93	451.19	451.42

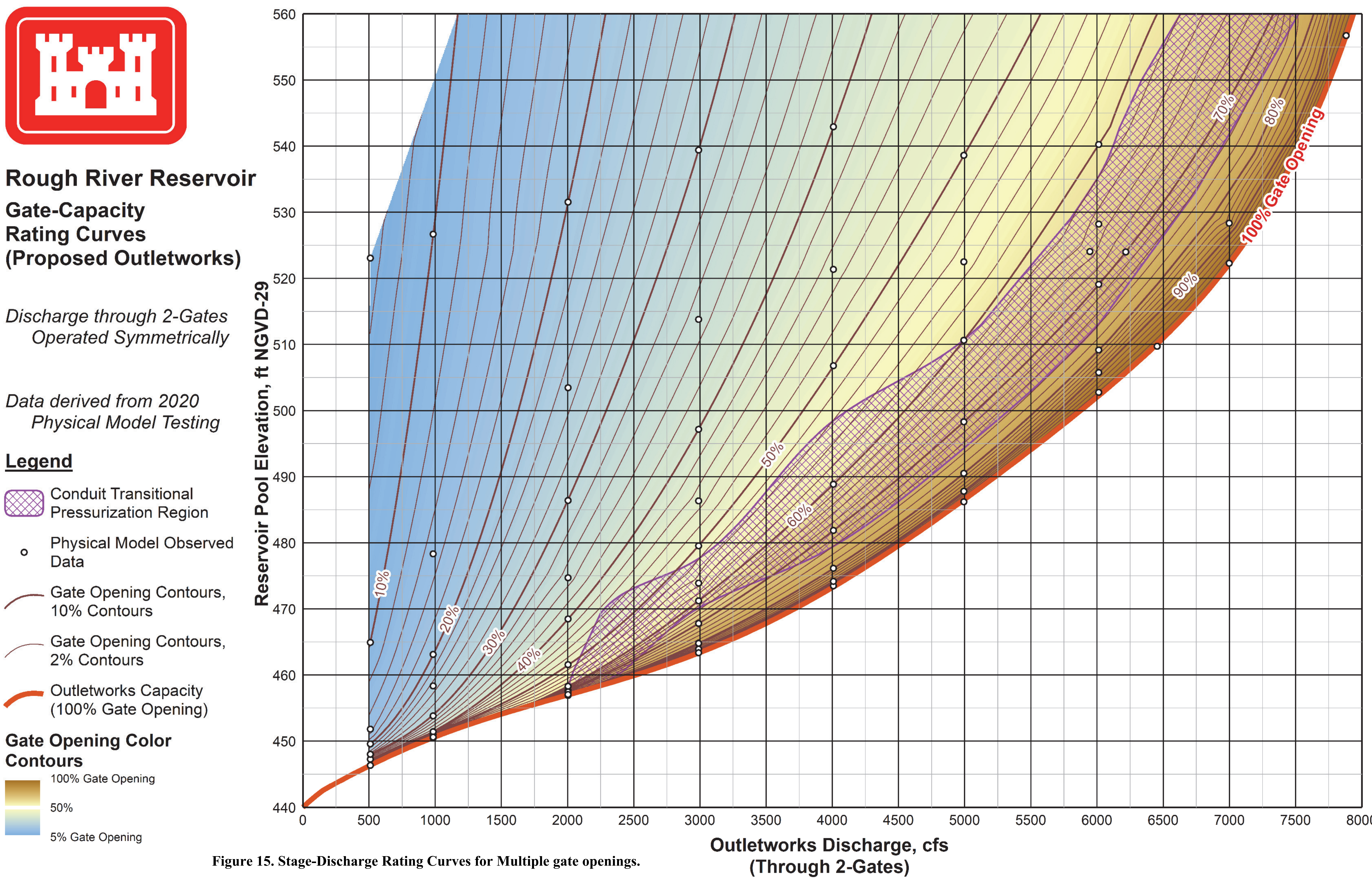


Figure 15. Stage-Discharge Rating Curves for Multiple gate openings.

Table 3. Physical Model Test Data for Single-Gate Operation. Operated through left-gate.

Gate (ft)	Gate (%)	Date	Test #	Proto Q (Nom-inal)	Instrument ID:		SB 1	SB 2	SB 3	PG 1 R	PG 1	PG 2 R	PG 2	PG 3 R	PG 3	PG 4 R	PG 4	PG 5 R	PG 5	PG 6 R
					Station Number:		04+36.6	08+36.7	09+11.1	09+68.5	09+68.5	09+82.5	09+82.5	09+85.0	09+85.0	09+88.5	09+88.5	09+93.0	09+93.0	09+98.5
					Proto Q (Computed)	Model Q	Approach Channel (HW)	Approach Channel	Approach Channel2	Intake Tower	Intake Tower 3	Intake Tower 4	Intake Tower 5	Intake Tower 6	Intake Tower 7	Intake Tower 8	Intake Tower 9	Intake Tower 10	Intake Tower 11	MON 0
2.1	15%	1/13/21	167	500	510	0.15	485.27	485.24	485.27	485.6	485.0	485.6	466.5	440.9	446.3	440.9	441.9	440.8	442.0	440.9
3.5	25%	1/14/21	171	1,000	985	0.29	501.94	501.94	501.97	502.3	500.0	502.2	474.6	440.8	455.2	440.8	444.8	440.8	443.6	440.7
4.2	30%	1/14/21	170	1,000	985	0.29	483.41	483.36	483.38	483.7	481.4	483.3	464.4	440.2	453.1	440.2	445.6	440.3	444.1	441.0
4.9	35%	1/13/21	169	1,000	985	0.29	474.31	474.28	474.31	474.8	472.3	474.5	459.8	441.1	452.2	441.5	446.5	441.5	445.0	442.0
4.9	35%	1/21/21	176	1,500	1,495	0.44	511.61	511.61	511.61	512.0	506.8	512.0	478.5	440.8	462.0	440.8	449.2	440.8	446.0	440.8
5.6	40%	1/20/21	175	1,500	1,495	0.44	497.75	497.73	497.75	498.0	493.0	498.1	471.4	440.9	459.7	440.9	450.0	440.8	446.6	440.8
6.3	45%	1/19/21	174	1,500	1,495	0.44	486.46	486.43	486.46	486.9	481.8	486.9	465.6	440.9	457.4	440.9	450.1	440.9	447.1	440.9
6.3	45%	1/21/21	177	2,000	2,004	0.59	520.55	520.50	520.50	520.9	511.6	520.9	482.0	440.7	467.3	440.8	454.8	440.7	449.0	440.8
7.0	50%	1/15/21	173	1,500	1,495	0.44	479.12	479.09	479.09	479.5	474.5	479.5	461.9	440.9	455.9	440.9	450.5	440.9	447.9	440.9
7.0	50%	1/22/21	178	2,000	2,004	0.59	506.10	506.08	506.10	506.5	497.5	506.4	474.7	440.8	463.9	440.8	454.4	440.8	449.5	440.8
7.7	55%	1/15/21	172	1,500	1,495	0.44	474.36	474.33	474.36	474.7	469.7	474.7	459.6	441.4	455.0	441.0	450.8	441.0	448.5	441.0
7.7	55%	1/22/21	179	2,000	2,004	0.59	495.50	495.48	495.48	495.8	487.0	495.8	469.3	440.8	461.3	440.8	454.1	440.8	450.8	440.8
7.7	55%	1/29/21	188	2,500	2,514	0.74	523.35	523.32	523.35	523.6	509.9	523.7	482.0	440.6	469.6	440.6	458.4	440.6	452.0	440.6
8.4	60%	1/22/21	180	2,000	2,004	0.59	488.32	488.29	488.29	488.7	480.0	488.8	465.9	440.7	459.7	440.7	454.0	440.8	450.5	440.8
8.4	60%	1/29/21	187	2,500	2,514	0.74	512.41	512.38	512.36	512.8	498.8	512.7	476.3	440.7	466.6	440.7	457.9	440.6	452.3	440.6
9.8	70%	1/26/21	181	2,000	2,004	0.59	477.77	477.75	477.75	478.0	469.5	478.0	460.6	440.9	457.0	440.9	453.8	440.9	451.2	440.9
9.8	70%	1/28/21	186	2,500	2,514	0.74	494.83	494.81	494.81	495.1	481.5	495.1	467.7	440.5	461.8	440.5	456.7	440.6	458.0	440.5
9.8	70%	2/3/21	192	3,000	2,990	0.88	513.75	513.73	513.73	514.1	595.0	514.1	475.2	440.6	467.1	440.6	460.0	440.6	454.8	440.5
11.2	80%	1/26/21	182	2,000	2,004	0.59	471.72	471.70	471.72	472.0	463.5	472.0	457.9	445.1	455.8	445.1	453.9	445.1	452.3	445.1
11.2	80%	1/27/21	185	2,500	2,514	0.74	483.74	483.69	483.69	484.0	470.9	484.0	462.0	440.9	458.7	440.8	455.7	440.8	453.4	440.8
11.2	80%	2/2/21	191	3,000	2,990	0.88	497.99	497.96	497.96	498.3	479.7	498.3	467.1	440.6	462.3	440.7	458.1	440.7	455.0	440.6
12.6	90%	1/27/21	184	2,500	2,514	0.74	476.22	476.17	476.17	476.5	463.6	476.5	458.1	446.0	456.5	446.0	455.0	446.0	454.0	446.0
12.6	90%	2/2/21	190	3,000	2,990	0.88	486.72	486.66	486.69	487.0	468.7	487.0	461.0	443.0	458.4	443.0	456.3	443.0	454.8	443.0
14.0	100%	1/26/21	183	2,500	2,514	0.74	469.40	469.37	469.37	469.8	456.7	469.8	454.0	448.1	453.8	448.1	453.6	448.2	453.6	448.1
14.0	100%	2/1/21	189	3,000	2,990	0.88	476.04	476.01	475.99	476.3	457.9	476.3	454.1	447.5	453.8	447.5	453.5	447.7	453.5	447.4

Instrument ID:	PG 6	PG 7 R	PG 7	PG 8	PG 9	PG 10	PG 11	PG 12	PG 13	PG 14	PG 15	PG 16	PG 17	PG 18	PG 19	PG 20	PG 21	SB 4	SB 5	SB 6
Station Number:	09+98.5	10+05.0	10+05.0	10+28.6	11+00.0	12+00.0	13+00.0	14+00.0	15+00.0	16+00.0	17+00.0	18+00.0	19+00.0	20+00.0	20+30.9	20+70.1	20+98.5	21+36.6	22+11.5	26+11.5
Test #	MON 012	MON 013	MON 014	MON 1	Culvert	Culvert 15	Culvert 16	Culvert 17	Culvert 18	Culvert 19	Culvert 20	Culvert 21	Culvert 22	Stilling Basin	Stilling Basin 23	Stilling Basin 24	Stilling Basin 25	Exit Channel	Exit Channel 26	Exit Channel (TW)
167	441.7	441.0	442.1	441.1	441.9	441.9	440.9	442.4	442.2	442.2	442.3	442.0	443.4	441.5	437.8	435.7	436.0	435.68	435.66	435.55
171	442.0	440.8	443.0	441.1	441.2	442.2	440.3	443.4	443.0	442.3	443.0	442.8	442.7	442.2	438.0	436.3	437.2	436.97	437.03	436.92
170	443.0	440.8	443.7	442.0	443.0	442.7	441.7	443.1	443.5	443.5	443.6	443.2	443.0	442.8	438.0	436.4	437.1	437.00	437.00	436.87
169	443.8	442.0	444.2	442.1	443.8	442.9	441.8	444.0	443.8	444.0	443.9	443.6	445.0	442.9	438.0	436.3	437.2	436.97	437.00	436.92
176	442.8	440.9	444.0	441.0	441.6	442.8	439.4	443.4	443.0	443.0	443.8	443.3	443.4	442.8	438.4	437.3	439.0	438.81	438.86	438.84
175	443.8	440.8	444.7	441.3	442.4	443.0	440.9	444.4	444.0	443.5	444.0	443.9	443.8	443.0	438.4	437.5	439.0	438.81	438.89	438.84
174	444.7	441.0	445.2	441.9	443.8	443.0	442.0	444.8	443.9	444.1	444.3	444.0	444.0	443.3	438.5	437.9	439.0	438.84	438.89	438.81
177	443.8	440.7	445.0	440.8	441.9	442.2	439.6	445.0	-	443.4	444.3	444.0	444.0	443.2	438.6	437.7	440.6	440.52	440.64	440.64
173	445.4	441.0	445.9	442.0	444.3	444.2	443.2	444.6	444.6	444.8	444.9	444.5	444.6	443.8	438.4	437.6	438.9	438.76	438.84	438.78
178	445.0	440.8	445.5	441.1	442.4	444.1	440.2	444.3	-	444.0	444.9	444.4	444.2	443.5	438.7	438.2	440.5	440.49	440.64	440.62
172	446.2	441.1	446.4	442.4	444.8	444.0	442.8	445.2	444.7	444.9	445.2	445.0	447.2	443.9	435.5	437.5	439.0	438.78	438.82	438.78
179	444.9	440.8	446.2	441.4	443.2	443.9	442.9	445.4	-	444.5	444.9	444.9	444.8	443.8	438.8	438.7	440.4	440.54	440.64	440.62
188	445.4	440.6	446.0	440.6	442.6	442.5	440.3	446.0	444.7	443.9	445.1	444.9	444.8	443.5	438.8	439.3	442.4	442.31	442.46	442.48
180	446.8	440.8	447.0	441.8	443.5	443.8	442.9	445.7	-	445.0	445.3	445.2	445.0	444.0	438.7	438.8	440.7	440.54	440.64	440.62
187	446.4	440.6	446.8	440.9	443.0	444.2	440.5	445.3	444.8	444.2	445.1	445.1	445.2	444.0	438.8	439.4	442.1	442.35	442.51	442.51
181	448.4	440.9	448.2	442.2	445.0	445.2	444.0	446.1	445.5	446.0	446.3	446.0	446.1	444.6	438.7	439.0	440.5	440.52	440.62	440.59
186	448.5	440.5	448.1	441.4	444.1	445.0	443.1	446.4	445.8	445.3	446.2	446.0	446.0	444.4	439.0	440.2	442.3	442.35	442.48	442.51
192	448.5	440.6	448.1	440.8	443.5	444.8	441.8	446.3	445.6	445.0	446.0	445.9	446.0	444.6	439.1	441.4	444.1	444.13	444.32	444.39
182	450.1	445.1	449.9	445.0	445.7	445.0	444.6	446.0	446.1	446.5	446.8	446.9	449.0	444.7	438.9	439.0	440.6	440.54	440.64	440.62
185	450.1	440.8	449.6	442.0	444.4	445.7	444.5	446.4	446.7	446.2	447.0	446.9	447.0	445.1	439.0	440.7	442.3	442.35	442.48	442.48
191	450.2	440.6	449.7	441.3	444.7	446.1	443.6	447.2	446.8	446.2	447.0	446.9	446.9	445.0	439.1	442.2	448.3	444.19	444.32	444.39
184	452.0	446.0	451.6	445.8	446.9	446.0	444.9	447.3	447.0	447.1	447.8	447.5	450.4	445.6	439.0	440.7	442.3	442.35	442.48	442.45
190	451.8	443.0	451.3	443.2	445.7	446.3	445.1	447.3	447.3	447.2	448.0	447.8	448.1	445.9	439.3	442.3	444.2	444.24	444.34	444.39
183	452.6	448.0	452.5	447.9	447.3	447.0	453.3	453.6	452.9	452.0	451.7	451.1	450.5	445.4	439.0	440.6	442.2	442.35	442.48	442.50
189	452.1	447.5	452.0	447.1	448.2	456.2	455.3	455.3	454.2	453.1	452.6	451.9	451.0	446.1	439.3	442.3	444.2	444.21	444.34	444.39

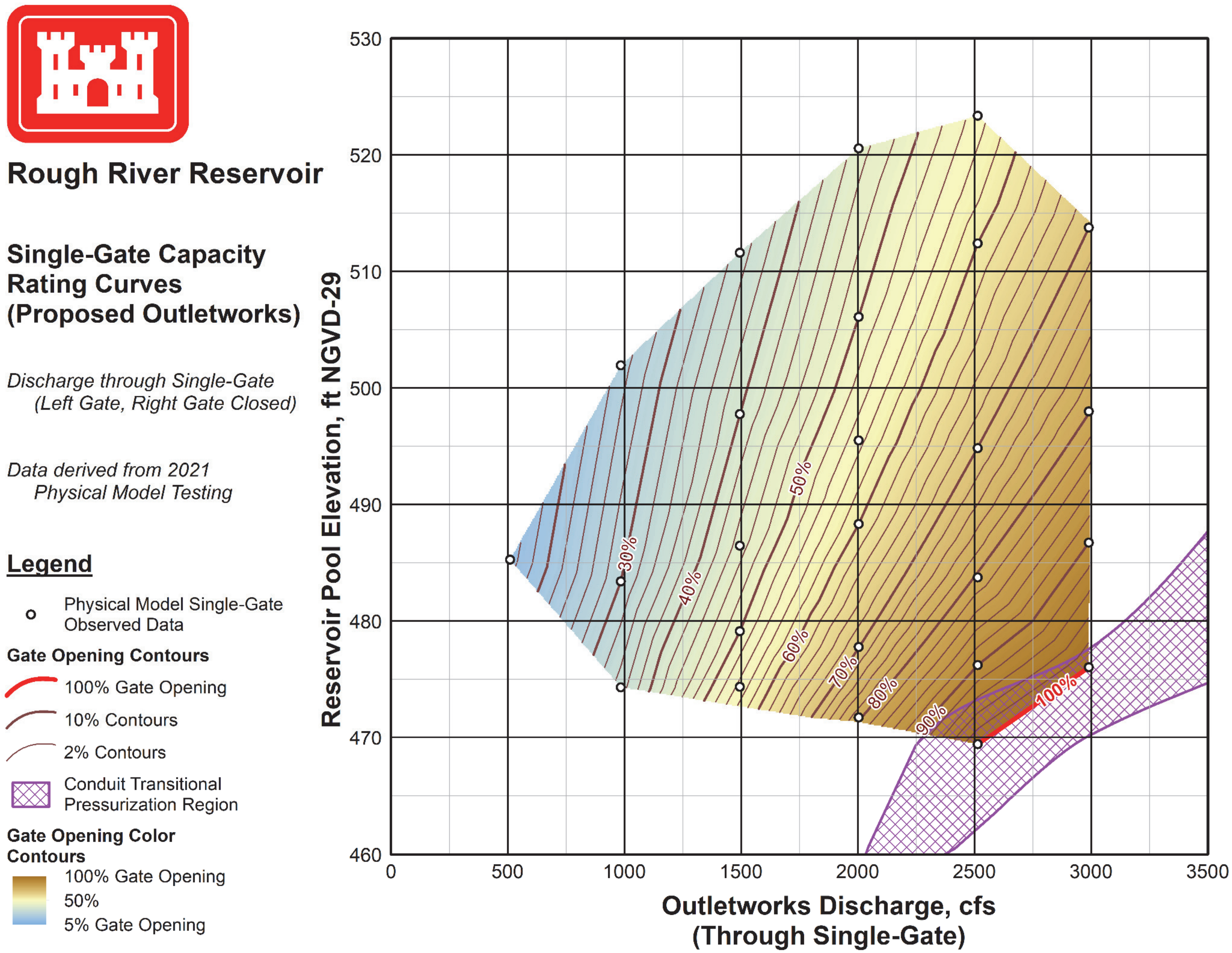


Figure 16. Stage-Discharge Rating Curves for Single-Gate opening.

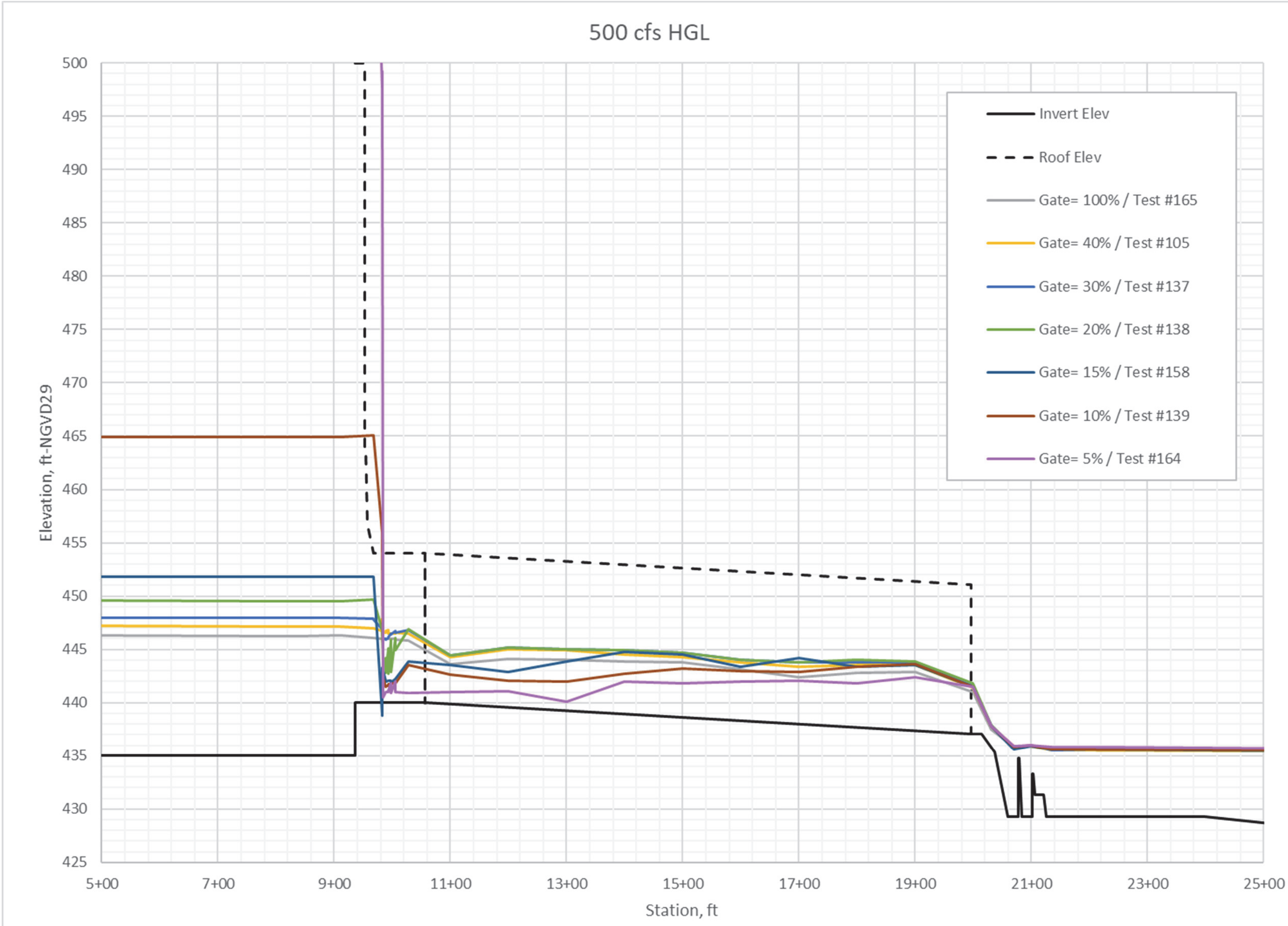


Figure 17. Hydraulic Grade Lines: 500 cfs for Various Gate Openings

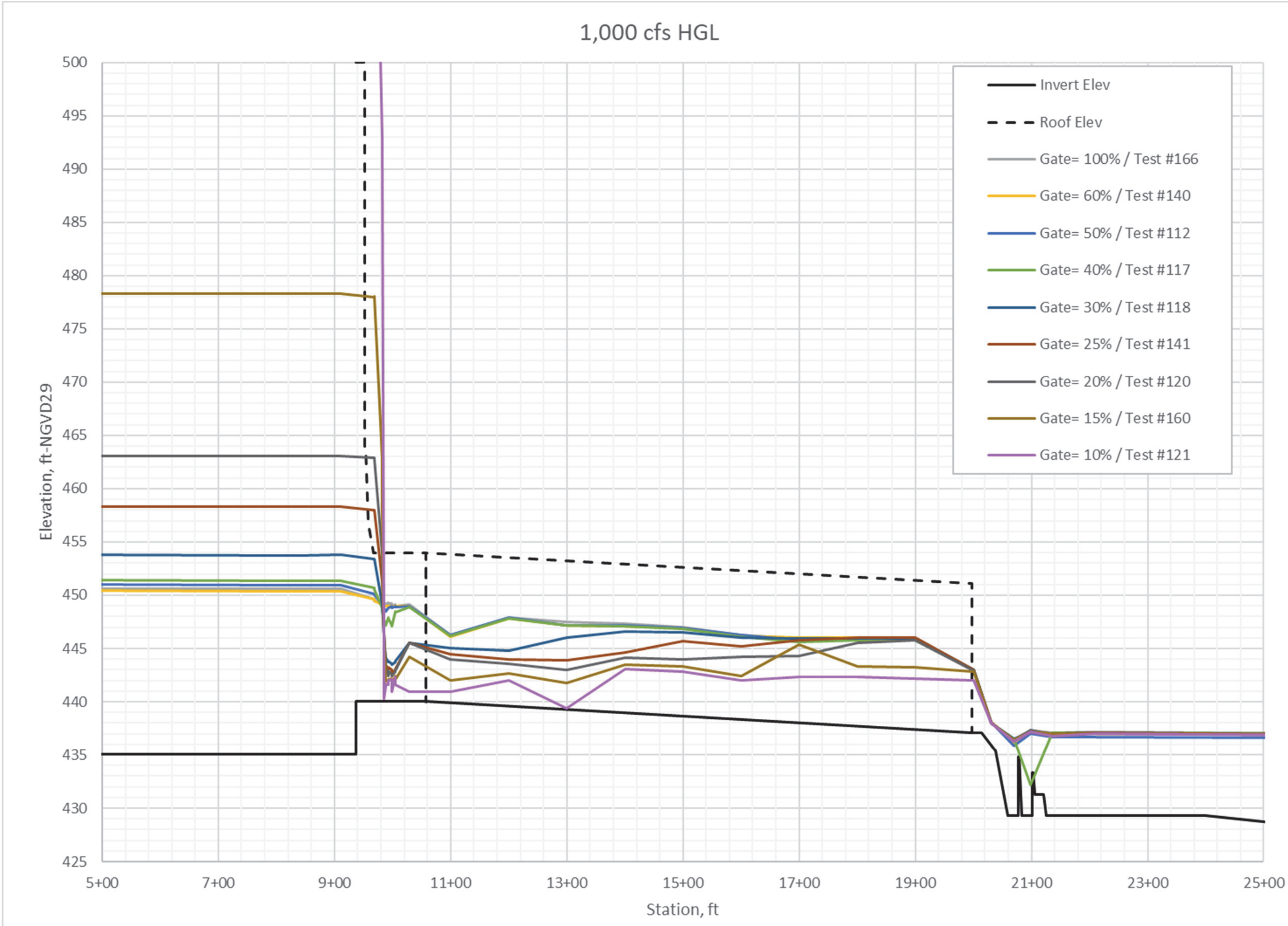


Figure 18. Hydraulic Grade Lines: 1,000 cfs for Various Gate Openings

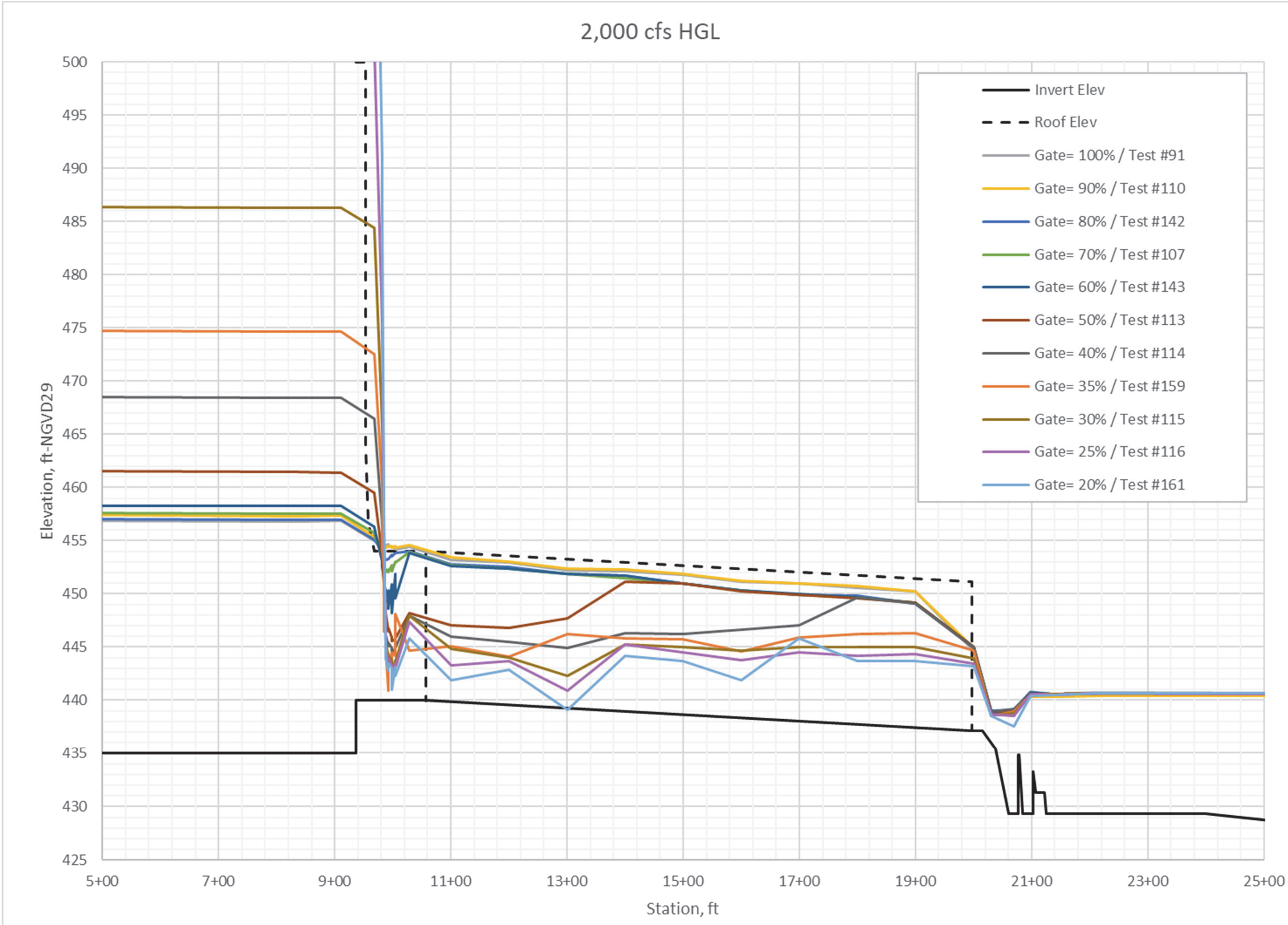


Figure 19. Hydraulic Grade Lines: 2,000 cfs for Various Gate Openings

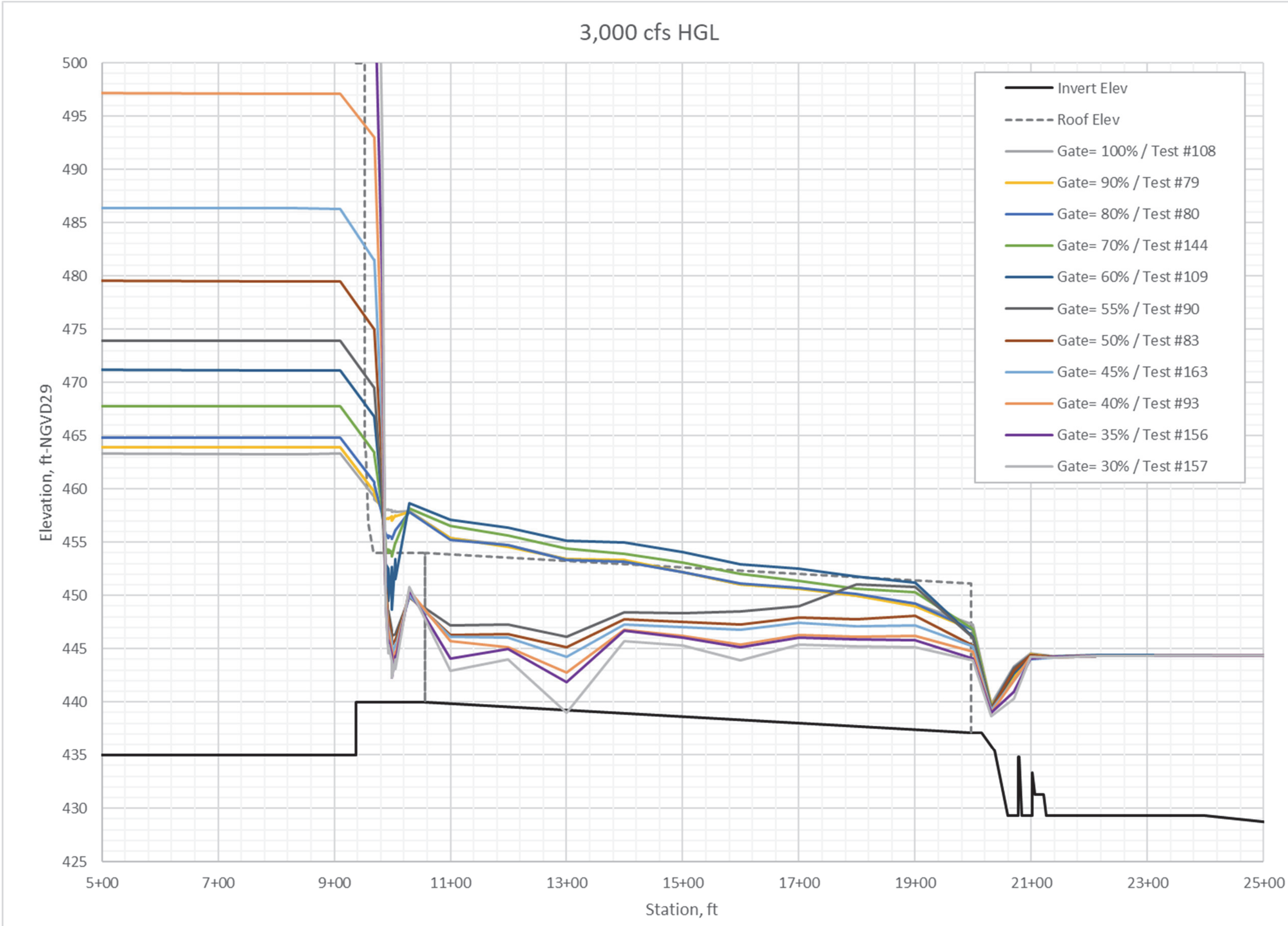


Figure 20. Hydraulic Grade Lines: 3,000 cfs for Various Gate Openings

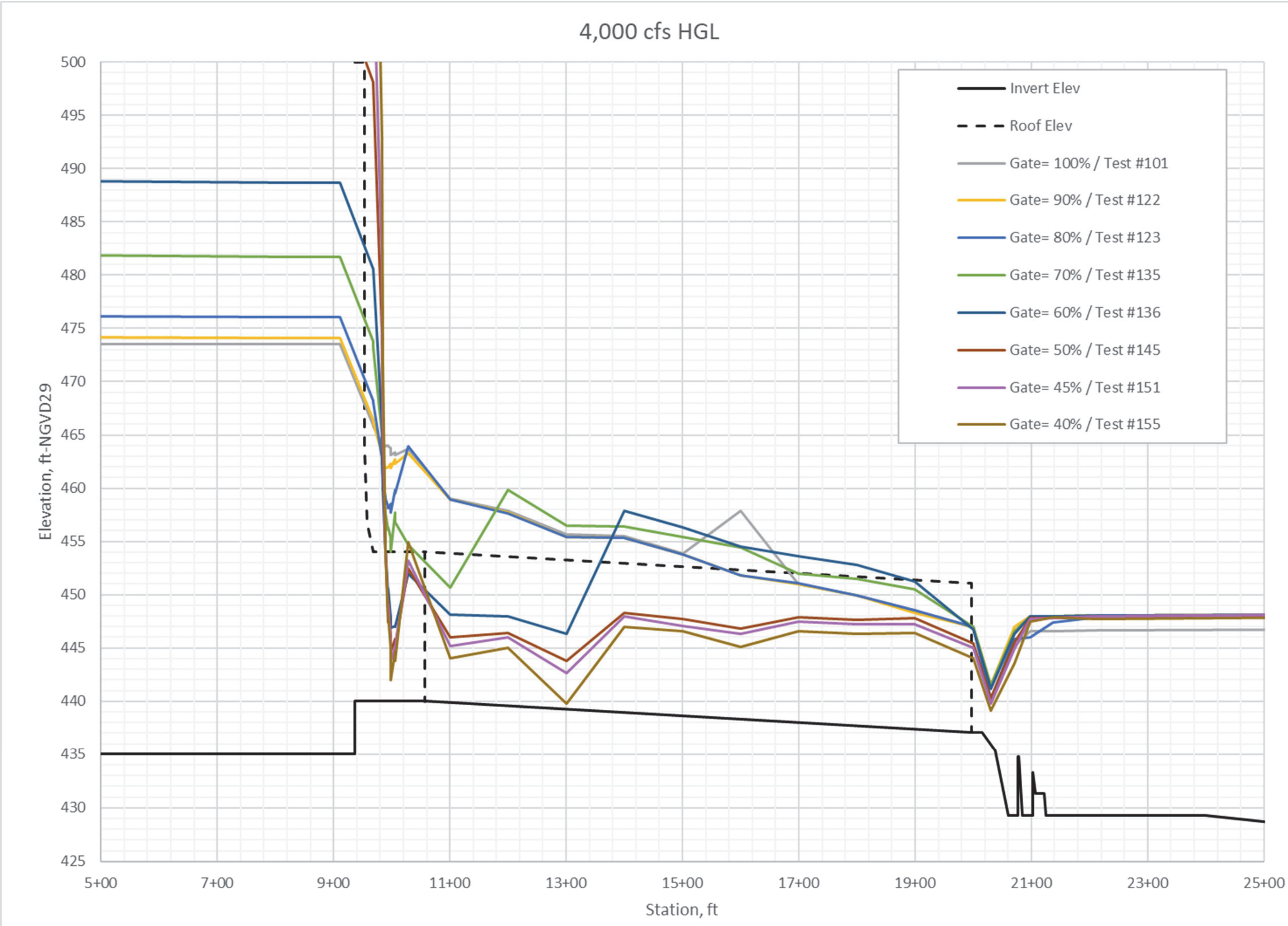


Figure 21. Hydraulic Grade Lines: 4,000 cfs for Various Gate Openings

Figure 22. Hydraulic Grade Lines: 5,000 cfs for Various Gate Openings

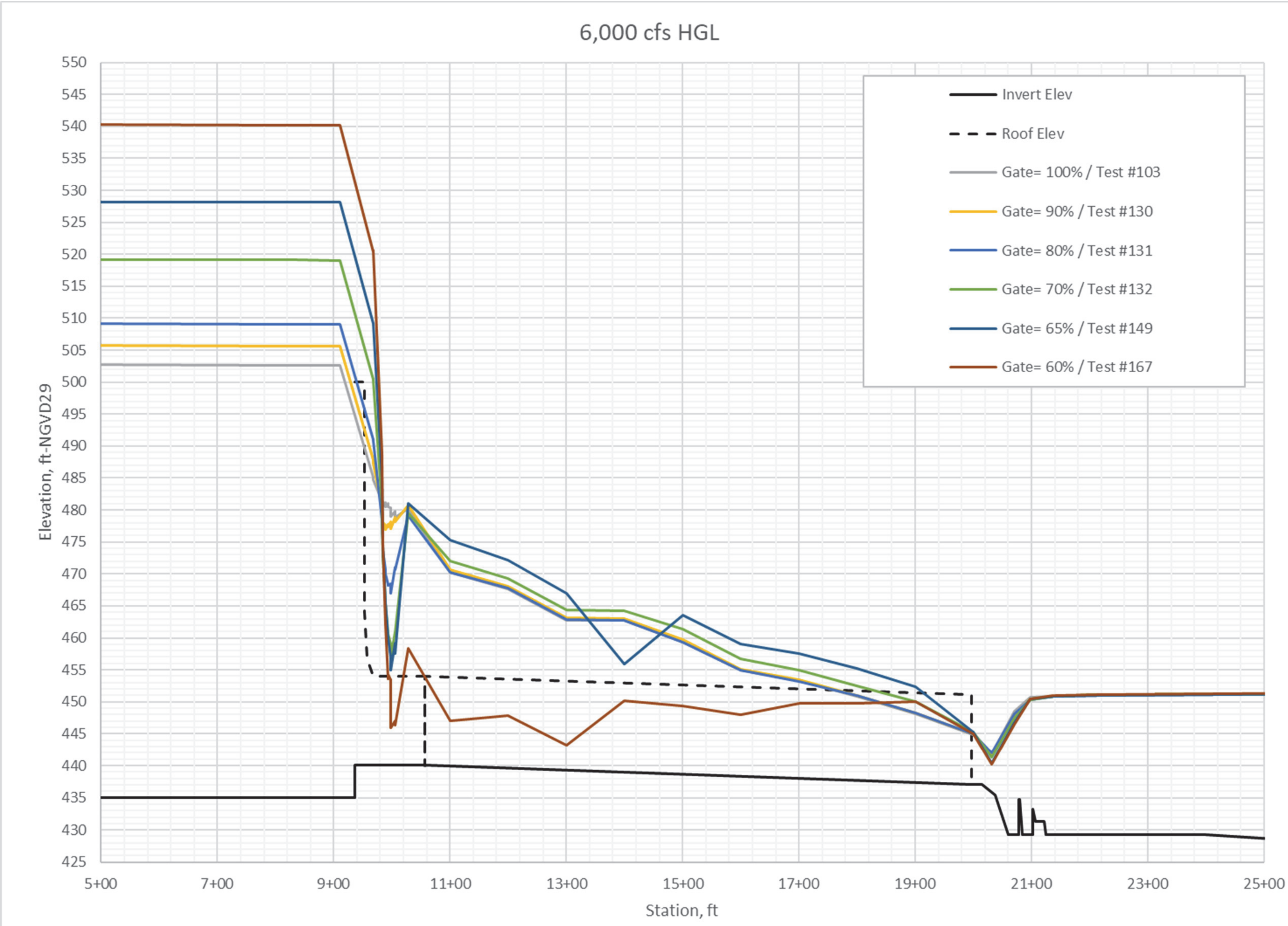


Figure 23. Hydraulic Grade Lines: 6,000 cfs for Various Gate Openings

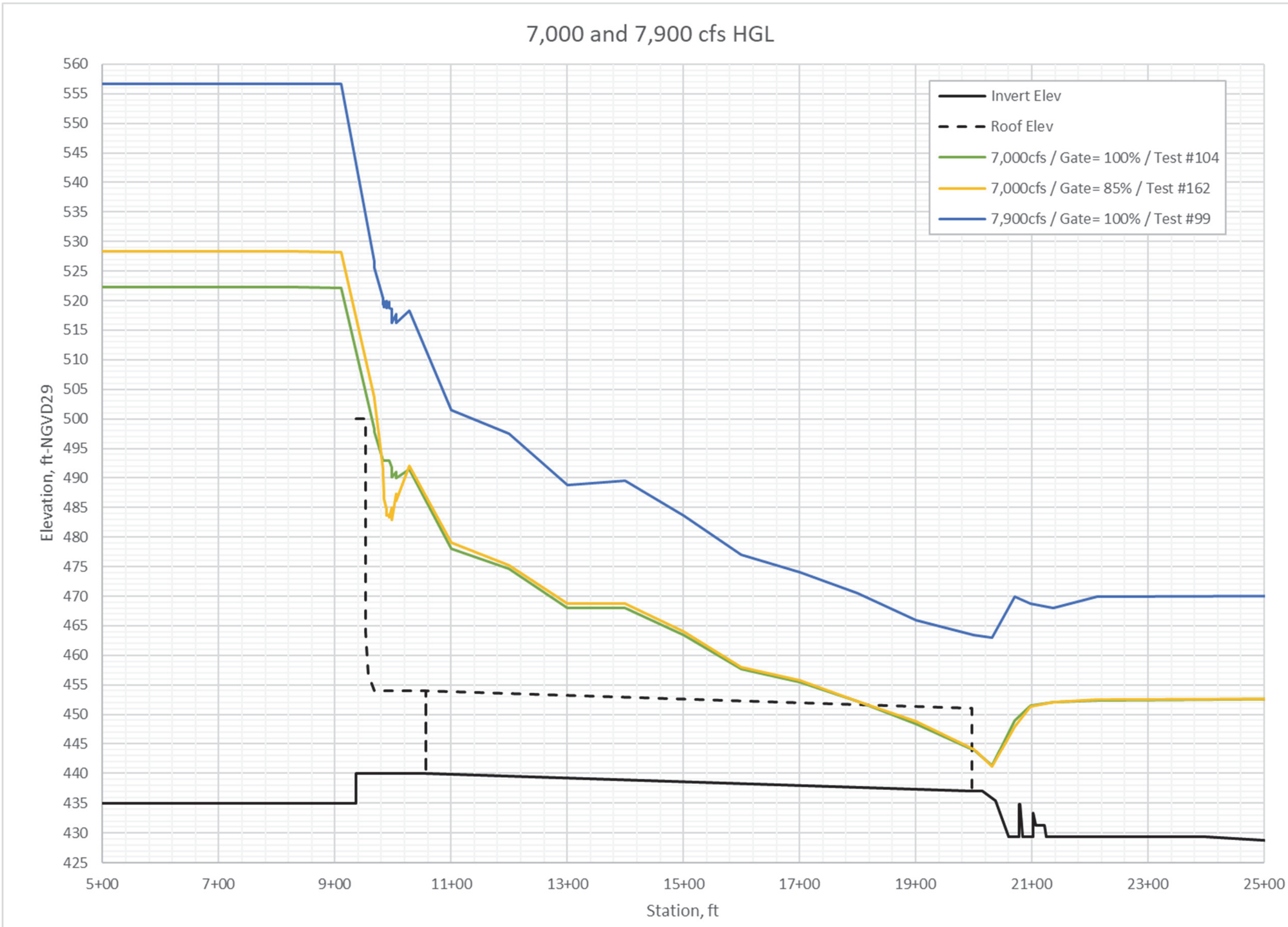


Figure 24. Hydraulic Grade Lines: 7,000 cfs and 7,900 cfs for Various Gate Openings

Acronyms and Abbreviations

CHL	Coastal and Hydraulics Laboratory
CL	centerline
DSAC	Dam Safety Action Classification
DSMR	Dam Safety Modification Report
DSOG	Dam Safety Senior Oversight Group
el	elevation
ERDC	US Army Research and Development Center
HGL	hydraulic grade line
ID	inside diameter
LRL	Louisville District
PDT	Project Delivery Team
PFMA	Potential Failure Mode Analysis
PG	pressure gage
PMF	probable maximum flood
PT	point of tangency
RROW	Rough River Outlet Works
SQRA	Semi-Quantitative Risk Assessment
SB	stilling bucket
USACE	US Army Corps of Engineers
WeLMos	Waterways Lightweight Modeling System
WSE	water surface elevations

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14. ABSTRACT
The US Army Corps of Engineers, Louisville District, requested the support and assistance of the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL), in the evaluation of the hydraulic performance of the replacement Outlet Works for Rough River Dam. To support the design effort, CHL constructed a 1:25.85 scale physical model. The proposed features of the model in the domain are the curved approach channel, intake structure, transition, curved conduit, stilling basin, concrete apron, and retreat channel. Tests performed to evaluate the hydraulic performance illuminated a few design concerns. To address these issues, several key design changes were made. These included the retreat channel slope, end sill design, and transition design.

15. SUBJECT TERMS
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