COMPARISON OF INTAKE PRESSURES IN PHYSICAL AND NUMERICAL MODELS OF THE CABINET GORGE DAM TUNNEL

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ABSTRACT

Dissolved gas at supersaturated concentrations has been identified as a water quality issue affecting aquatic organisms. The principal source of supersaturation at dams is gas transfer in the highly aerated flood discharges from spillways. Avista Utilities has determined that when operating, the spillway of the Cabinet Gorge Dam produces high concentrations of dissolved gas in the downstream river. Avista is therefore looking to reconstruct the original river bypass tunnels to reduce the use of the spillway when the hydraulic capacity of the powerhouse is exceeded. The bypass tunnel design is intended to reduce downstream dissolved gas concentration by avoiding use of the spillway and air entrainment in the tunnel discharge.

Avista chose to use physical and numerical modeling efforts to address the risks and issues associated with this highly complex project. ENSR constructed a 1:50 scale physical model to define the hydraulic performance of an initial tunnel design concept, support design development of the tunnels, and to confirm the hydraulic performance of the final concept. Hatch Energy used Flow-3D, a commercially available computational fluid dynamics (CFD) computer program, to evaluate design alternatives prior to testing final concepts in the physical model.

In this paper, a comparison of intake pressures measured in the physical model and computed in the CFD model is presented. The location and magnitude of low pressures in the intake are of particular importance to avoid cavitation and to verify the actual discharge capacity of the tunnel. The CFD model was used to identify low pressure areas in the intake. Piezometric taps were installed in the physical model at the corresponding locations and connected to calibrated pressure transducers. The physical model and CFD model results showed good agreement of minimum pressure locations and reasonably good agreement of average pressure magnitudes, but not the dynamic fluctuations of pressure. Determination of the tunnel discharge capacity required careful interpretation of both sets of model results due to the potential for cavitation to occur in the tunnel intakes.

1 Introduction

Avista Corporation owns and operates the Cabinet Gorge Hydroelectric development on the Clark Fork River 5 miles east of the community of Clark Fork, Idaho. The reservoir lies largely across the state line in Montana. The project facilities, shown in **Figure 1.1**, include 4 generating units with a total generating capacity of 263 MW, a 100-foot high concrete arch dam, and an eight-bay spillway above the arch section. During the construction of the dam, the river flows were diverted through two diversion tunnels, approximately 1,000 feet long, through the rock on the right bank. The tunnels have a 29-foot diameter modified cross section and are unlined over most of their length. A concrete intake structure, with gate slots, is located at the upstream end of the tunnels. Once the dam construction was complete, steel bulkheads were placed in the slots and concrete plugs constructed downstream from the bulkheads. At the downstream end, the tunnel outlets have remained open and, as a result, have been partially filled with water from the tailrace.

Figure 1.1: Cabinet Gorge Hydroelectric Development

Dissolved gas at supersaturated concentrations has been identified as a water quality issue affecting aquatic organisms, with a principal source of supersaturation in the tailraces of dams being flood releases from spillways. Most spillway discharges are highly aerated and the turbulence and energy dissipation in the project tailrace results in entrained air being carried to depth where gas dissolves at high concentrations in the flow. This is the case at Cabinet Gorge, where total dissolved gas (TDG) levels as high as 153 percent of saturation have been recorded in the tailrace during spill events (DES 2002). The Idaho water quality criterion for TDG is 110% saturation. Avista has a regulatory obligation to develop mitigation measures to address the issue of elevated levels of TDG during periods of high flows and spill. . The ten-year, seven-day average flood event (7Q10) was agreed to as the design flow. The calculated 7Q10 flood was determined to be about 118,400 cubic feet per second (cfs).

In order to address the TDG issue, Avista has proposed reconstructing the existing diversion tunnels into new low level outlets for flood releases above powerhouse capacity up to the 7Q10 flow of 118,400 cfs with little or no net increase in TDG. Given the powerhouse capacity of 38,400 cfs, with planned turbine upgrades, the design discharge for the modified tunnels will be 40,000 cfs each at a head differential of 100 feet. A combination of a 1:50 scale physical hydraulic model and a three-dimensional computational fluid dynamics (CFD) model of the project facilities and the planned tunnel modifications was used to analyze the tunnel concept design. The main objectives were to assess whether the tunnels could safely pass the design flows and whether resulting conditions in the tunnel tailrace would meet the goal of minimizing air entrainment that could lead to TDG uptake. Initial studies, described by this paper, focused on the tunnel capacity objective.

The plan for the tunnel modifications included increasing the cross sectional area and lining the tunnels downstream from the closure plugs, construction of appropriate outlet structures, installing control/closure gates in the tunnels, installing bulkheads over the existing tunnel intakes, mining out the plugs, and then removing the bulkheads. The existing tunnel intakes, originally intended for passage of diversion flows during project construction under lower heads and flows, were to be used without modification, because modification would require either expensive cofferdams or construction by divers in the depths of 100 feet or more. The existing intakes proved to be the limiting element in the tunnel conceptual design due to cavitation potential defined through the application of both modeling tools.

2 Physical Model Studies

2.1 Model Description and Instrumentation

The tunnels were part of a general model of the project, which included the powerhouse, spillway, and about 3,000 feet of forebay and 2,000 feet of tailrace. The general model scale of 1:50 was selected based on Reynolds number turbulence criteria in the tunnel and tailrace.

Figure 2.1 shows the overall model layout and **Figure 2.2** shows an overview of the finished model in the ENSR laboratory. The overall length and width of the model, including a headbox and a tailbox, were 93 feet and 45 feet, respectively. The model wall height was approximately 7 feet in the forebay and 5 feet in the tailrace. The structural details such as the powerhouse and spillway components were made of clear acrylic plastic. The two bypass tunnels (North Tunnel and South Tunnel), shown in the foreground of **Figure 2.2**, were also constructed of clear acrylic plastic to facilitate viewing of internal flow phenomena such as flow separation and to maintain more precise construction tolerances (±0.06 model inches).

The overall flow supply was provided by two pumps with a combined capacity of 160,000 prototype cfs (9 model cfs at scale of 1:50). The flow was varied by an adjustable valve and measured using orifice flow meters constructed and installed according to ASME standards.

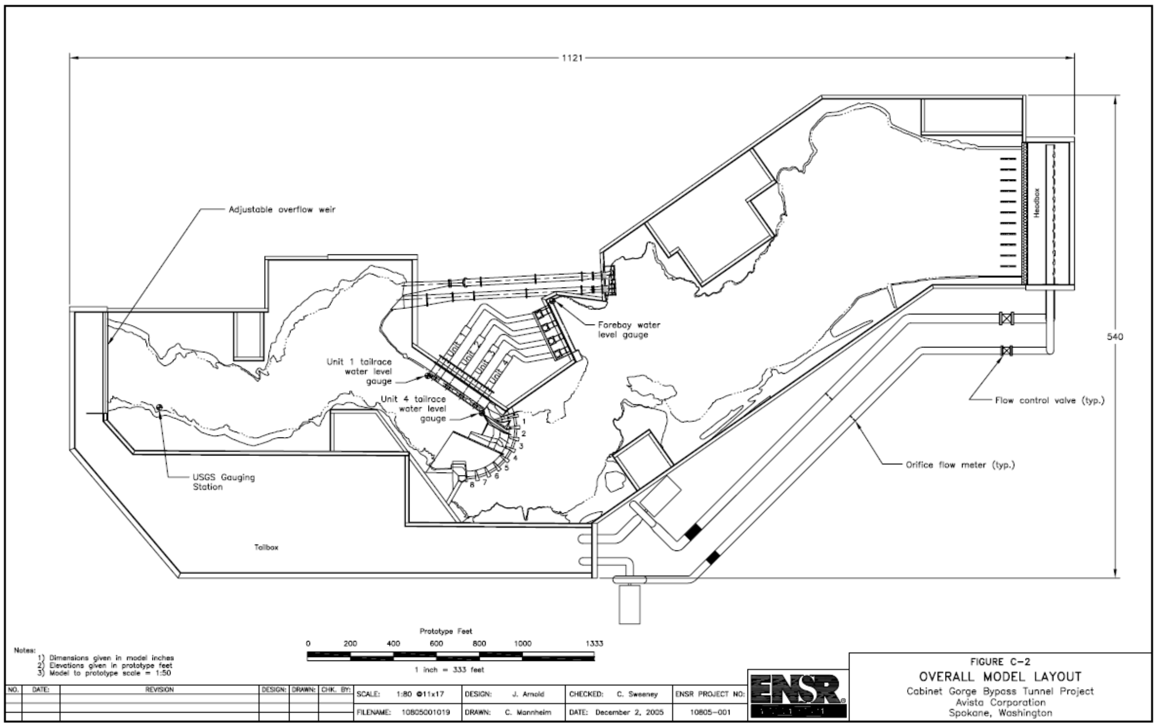

Figure 2.1: Overall layout of Cabinet Gorge physical model

Figure 2.3 shows a profile view of the two tunnels and **Figure 2.4** shows a frontal elevation view of the tunnel entrances.

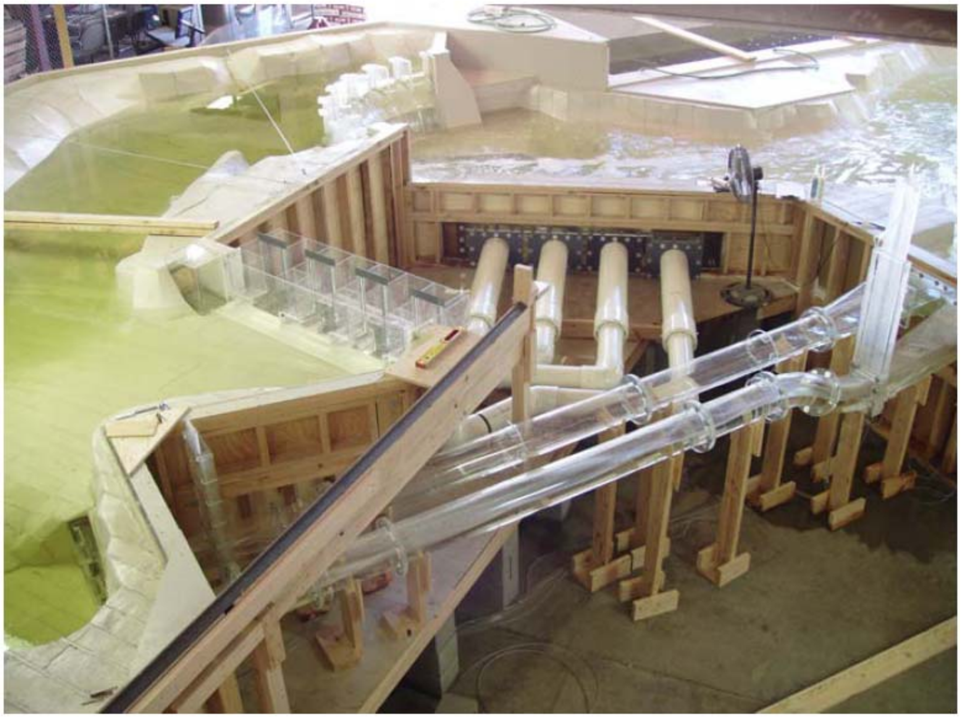

Figure 2.2: Physical model overview with bypass tunnels in foreground

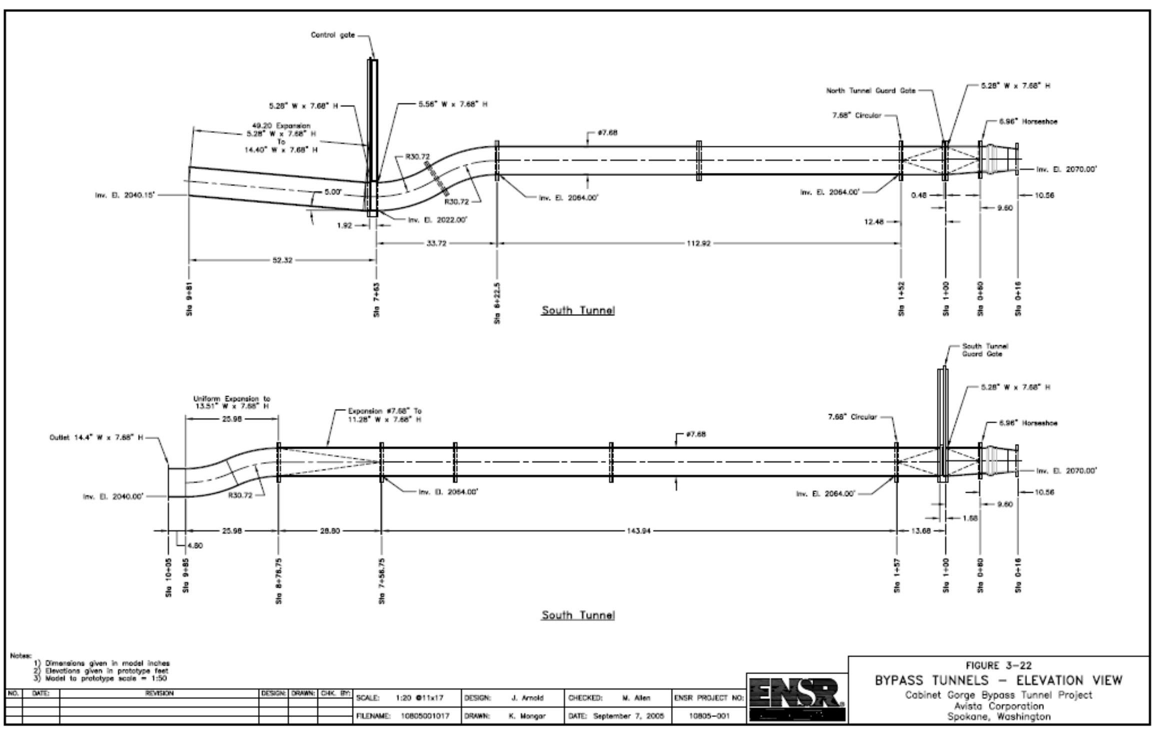

Figure 2.3: Elevation view of the tunnels

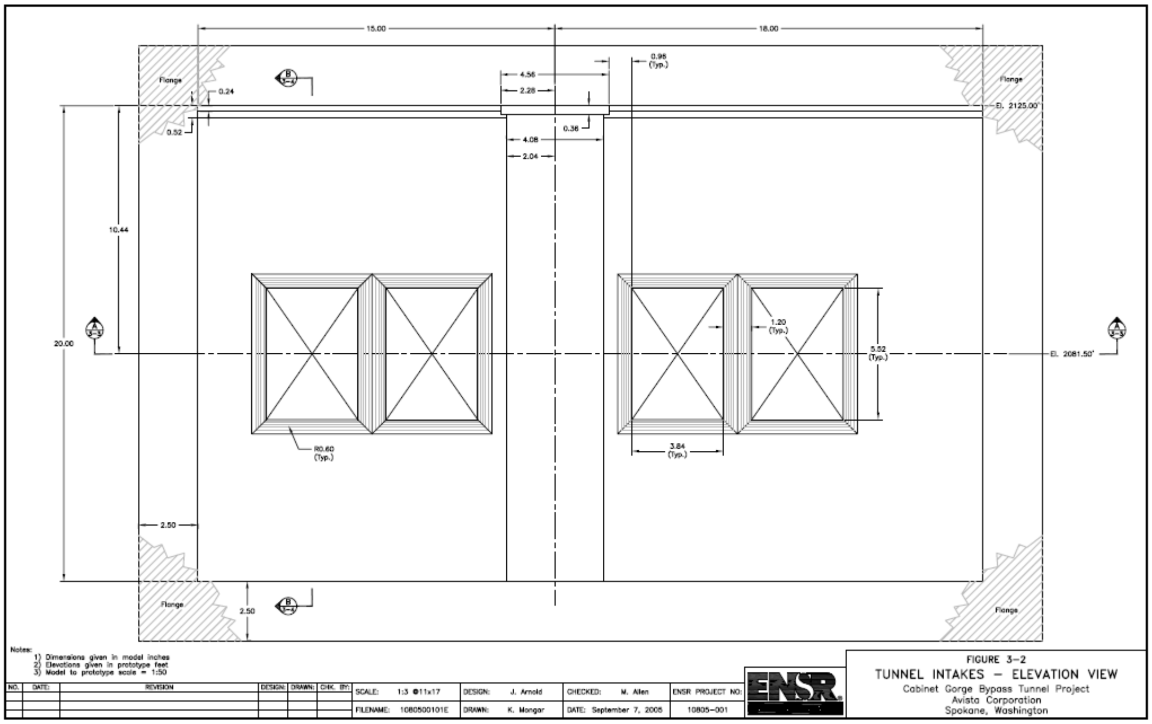

Figure 2.4: Frontal elevation view of tunnel entrances

Piezometric pressure taps were installed along the length of each tunnel to monitor the hydraulic grade line. Additional taps were installed to monitor pressures in specific areas of interest. Forebay and tailrace water levels were measured in stilling wells connected to piezometric taps in the model boundary next to Powerhouse Unit 1 intake for the forebay water level and the corners of the tailrace powerhouse structure for tailrace water level measurements.

2.2 Model Tests

The U.S. Army Corp of Engineer's Hydraulic Design Criteria (USACE 1987), indicates the minimum pressure in an entrance flared in all four directions should occur along the top radius or the top corner. Preliminary results from Hatch Energy's CFD model confirmed that the lowest entrance pressures develop in the top right corner of the North Tunnel entrance.

The U.S. Army Corps of Engineers (USACE, 1980) recommends that the minimum average pressure at an inlet where boundary changes are abrupt or the local flow is highly turbulent, such as gate slots, offsets, and baffle piers of standard design, should not be lower than -10 feet of water relative to atmospheric pressure at sea level required to prevent cavitation. This pressure recommendation is meant to accommodate local instantaneous pressure fluctuations of ±10 feet of water. Adjusted for elevation, the recommended presssure corresponds to a minimum allowable average pressure at Cabinet Gorge Dam (El. 2100 feet) of -6 feet of water. The objective of the tests presented herein was to use the 1:50 scale physical model of the tunnels to measure average pressures and pressure fluctuations at the critical entrance locations for a range of flows. Therefore, piezometer taps were installed in several locations near the North Tunnel entrance as shown in **Figure 2.5.** The tap locations are numbered 1 through 10. The pressures were measured using a manometer board connected to the taps with flexible tubing.

The average piezometric pressures were measured for 5 tunnel discharges ranging from approximately 15,000 cfs to 50,000 cfs at the locations shown in **Figure 2.5**. The pressure fluctuations were then measured at the two locations of minimum average pressure using a 2.5-psi pressure transducer. The overall accuracy of the pressure transducer was 0.1% of the full range (2.5 psi), which corresponds to 0.3 feet water prototype. The accuracy of the discharge measurements was approximately 1,500 cfs at 38,000 cfs.

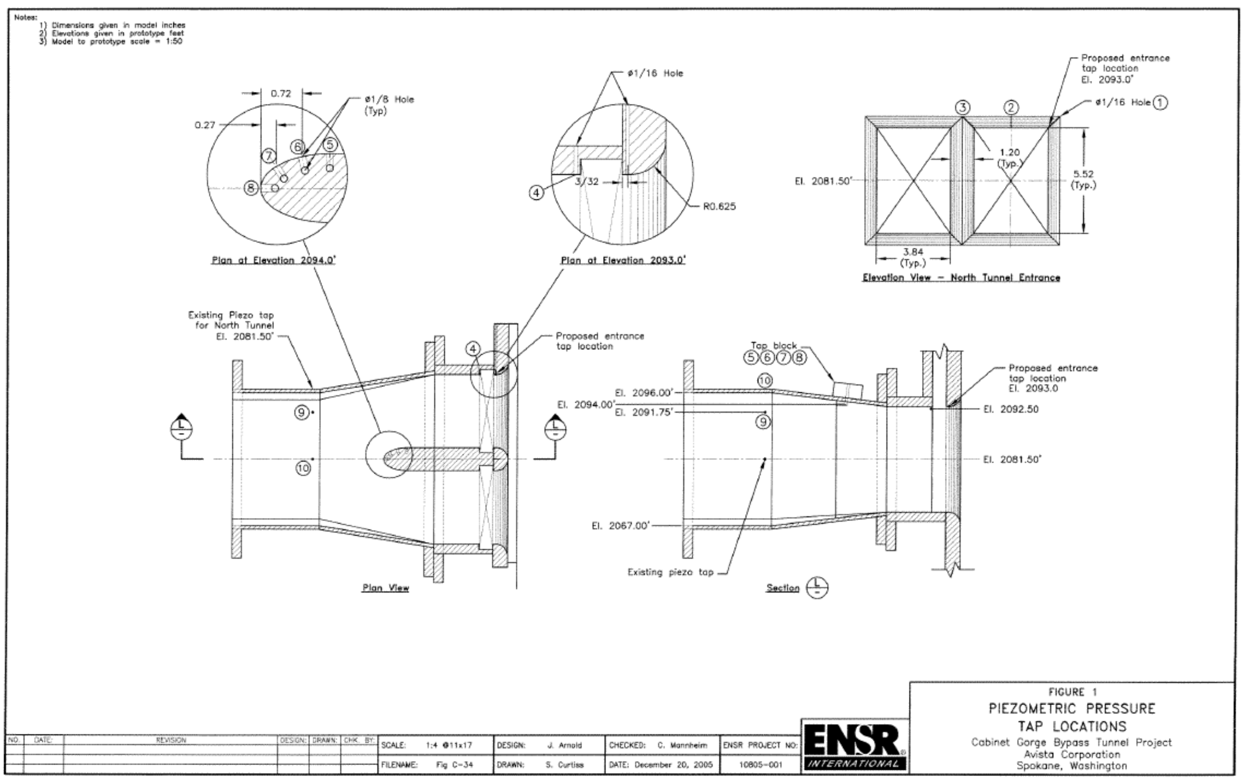

Figure 2.5. Pressure tap locations in North Tunnel inlet

2.3 Model Results

The minimum average pressures occurred at taps 2 and 3. Pressure transducers were used to record time histories of pressure at these tap locations. The average, standard deviation, and the 99th percentile pressures were calculated from the time series. These results are presented in Table 1. The 99th percentile pressure fluctuations at taps 2 and 3 were equal to ±5.0 and ±11.2 feet of water, respectively, for a discharge of 39,900 cfs.

Figure 2.6 presents the results of the pressure measurements as a function of the tunnel discharge squared. **Figure 2.7** presents the results of the dynamic pressure measurements using the transducer at tap 3, which recorded the lowest pressures of all of the taps. The error bars in **Figures 2.7** represent the 99th percentile of the pressure fluctuations for that particular discharge.

Table 1. Summary of pressure measurements

Tap No.	**2**				**3**			
Tunnel Discharge (cfs)	**Piezometric Pressure (feet of water)**							
	Avg*	**Avg**	**Std. Dev.**	**99th Percentile**	**Avg***	**Avg**	**Std. Dev.**	**99th Percentile**
15,040	**69.5**	**70.2**	**0.1**	**0.4**	**69.6**	**70.0**	**0.2**	**0.6**
25,070	**49.2**	**46.2**	**0.5**	**1.2**	**46.2**	**46.0**	**1.4**	**3.5**
30,050	**31.4**	**31.0**	**0.9**	**2.2**	**30.7**	**29.6**	**2.3**	**5.9**
39,920	**-10.8**	**-11.5**	**2.0**	**5.0**	**-11.1**	**-12.1**	**4.4**	**11.2**
50,070	**-64.0**	**-64.7**	**2.5**	**6.3**	**-63.7**	**-68.0**	**7.5**	**19.3**

Based on pressure measurements using manometer

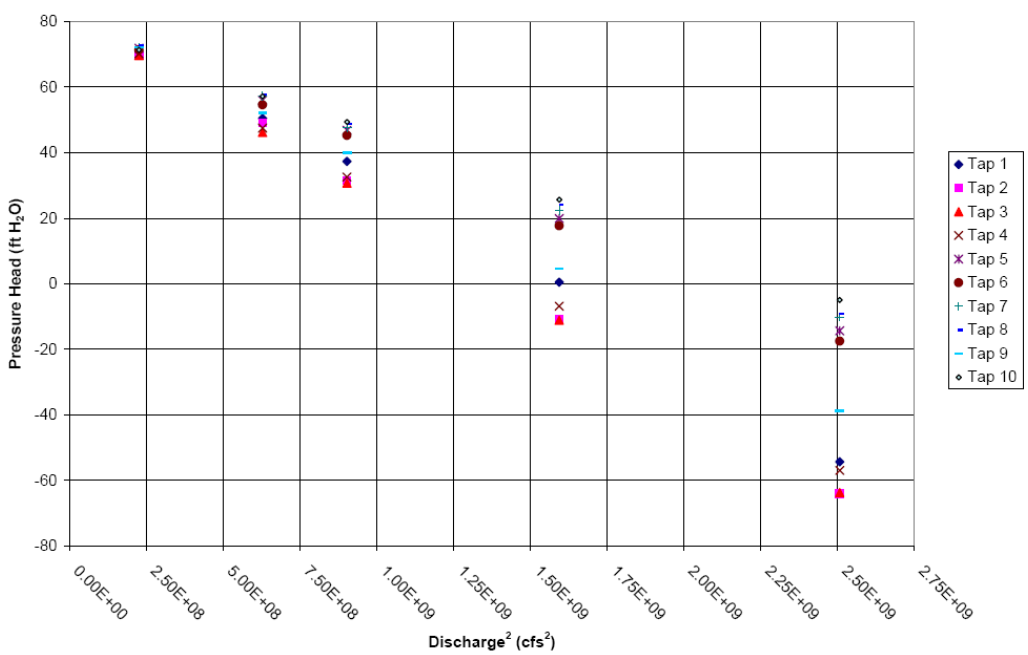

Figure 2.6. Average piezometric pressures versus tunnel discharge

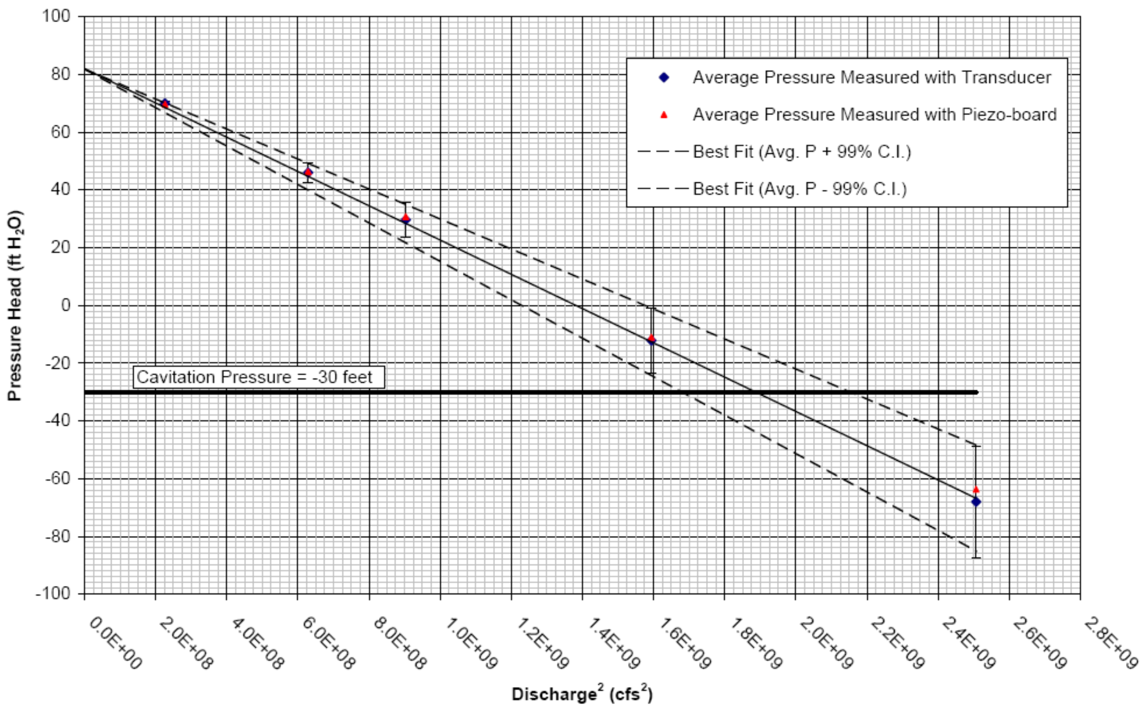

Figure 2.7. Dynamic pressure measurements at Tap no. 3

3 Numerical Model Studies

With the advancements in computing power made since the 1980's, CFD analysis has emerged as a powerful alternative design tool. CFD analysis involves the solution of the governing equations for fluid flow at thousands of discrete points on a computational grid, giving the analyst a full three-dimensional representation of the fluid flow domain. For the Cabinet Gorge tunnel studies, the commercially developed model “FLOW 3D” was utilized to provide this advanced design support.

3.1 Modeling Tool – FLOW-3D

FLOW-3D is a well-tested, reliable CFD computer program developed and supported by Flow Science, Inc. of Los Alamos, New Mexico, USA. The program is designed to assist in investigation of the dynamic behavior of liquids and gases in a very broad range of applications. FLOW-3D has been designed for the treatment of time-dependent (transient) problems in one, two and three dimensions, and is based on a finite difference solution of the complete Navier-Stokes equations. Because the program is based on the fundamental laws of mass, momentum, and energy conservation, it can be applied to almost any type of flow process. For this reason, FLOW-3D is often referred to as a “general purpose” CFD solver.

One of the major strengths of FLOW-3D for hydraulic analysis is its ability to accurately model a flow interface between a gas and a liquid, which is referred to as free surface flow. In FLOW-3D, free surfaces are modeled using the Volume of Fluid (VOF) technique. The VOF method consists of three components: a scheme to locate the surface, an algorithm to track the surface as a sharp interface moving through a computational grid, and a means of applying boundary conditions at the surface. It is robust, handling transitions between sub-critical and super-critical flow within a single model set up. These capabilities make the model well-suited for simulating the varied and complex flow conditions that will occur at the intakes during operation of the tunnel(s).

FLOW-3D also requires the specification of various fluid properties, such as density, viscosity, surface tension, etc. For the model runs described below, all fluid properties were based on the physical properties of water at 50^{o}F.

3.2 Model Set Up

The numerical model domain for this analysis included the approach channel, the powerhouse intakes, and the North and South Tunnels. Like the physical model, the numerical model was developed based on available drawings and bathymetric survey information. All available information was imported into a GIS database, and used to create a geo-referenced digital elevation model (DEM) of the bathymetric channels and over-land topography. The DEM was then exported to a stereolithographic STL file for import into FLOW-3D. Separate modules were then created for all water retaining structures within AutoCAD, and these were subsequently imported into FLOW-3D as STL objects. **Figure 3.1** illustrates a computer generated rendering of the final model setup of the tunnel intakes.

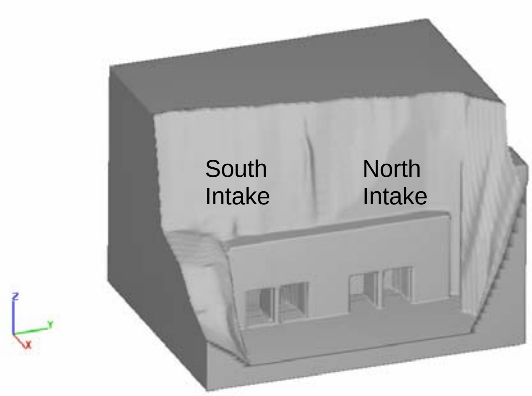

Figure 3.1: Rendering of final model setup of the intakes

To minimize the computational time associated with each model run, the numerical domain only included the upper 600 feet of each diversion tunnel. This allowed a more refined mesh to be adopted at the tunnel entrance – the focus of this series of runs. Boundary conditions for the model simply consisted of a user specified reservoir level upstream of the project (2175 feet), and a user specified discharge rate at the downstream end of the tunnel. The downstream boundary was formed through the careful placement of a mass sink within the tunnel. This "sink" consisted of a flat surface, which was oriented perpendicular to the tunnel centerline, and was set to draw the specified flow out of the mesh at a uniform rate across this surface. The sink provided perfect control on the amount of flow being drawn through the intake, and allowed a smaller areal extent to be simulated.

3.3 Model Results

The numerical model was then run to simulate hydraulic conditions within the intake for a series of three discharges: 35,000 cfs, 38,000 cfs, and 42,000 cfs. The results of these runs were initially used to assist in guiding the placement of pressure taps for the physical model intake tests, and subsequently to run additional flow scenarios that were not included in the physical model test program.

Figures 3.2 and 3.3 illustrate sample results of these simulations for a case in which the north tunnel is discharging 38,000 cfs. In these figures, pressures and velocities are shown along a horizontal plane cut very near to the crown elevation of the tunnel.

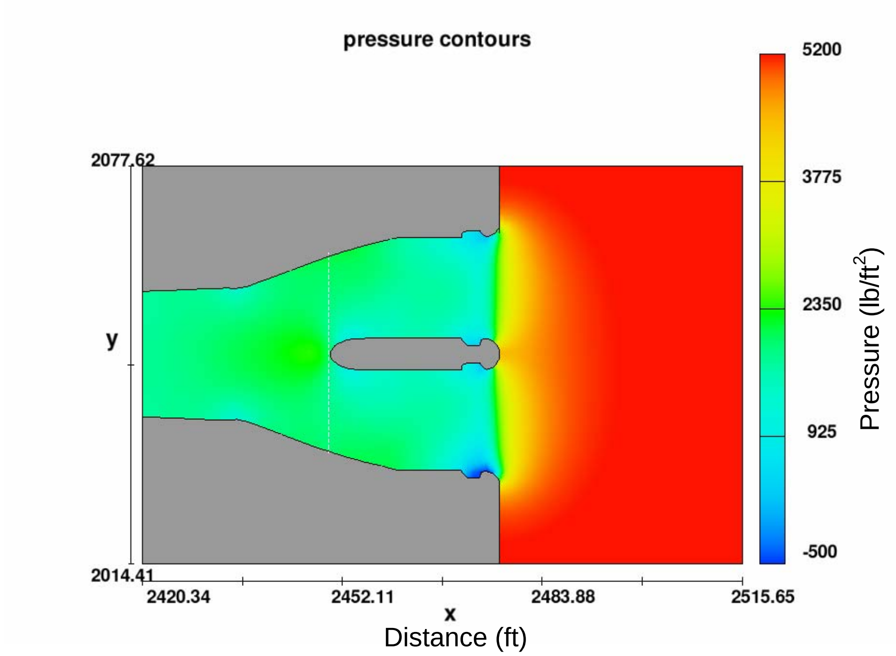

Figure 3.2: Pressure distribution for tunnel discharge of 38,000 cfs

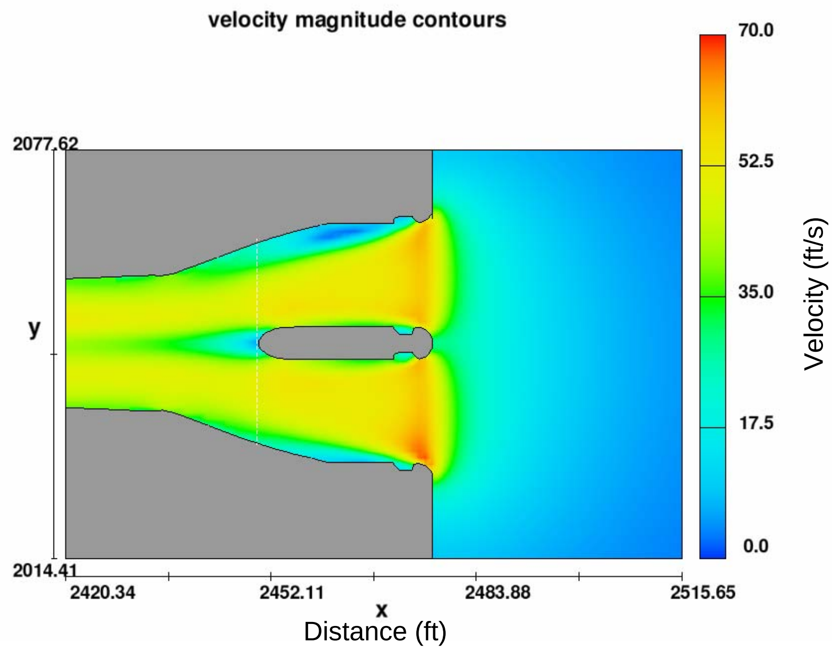

Figure 3.3: Velocity distribution for tunnel discharge of 38,000 cfs

For all cases, pressures were seen to reach a minimum in the upper corners of each water passage, at or immediately downstream of the gate slot. Additional low pressure zones occur along the downstream end of the pier, and also just downstream of the relatively abrupt corner in which the intake transitions into the tunnel proper. Initial runs, based on a full flow of 42,000 cfs within the bypass tunnels, showed significant potential for cavitation within the existing intake. The small radius of curvature associated with the existing intake causes significant separation to occur as flows are drawn into the water passage. The minimum average pressure recorded was approximately -24 feet for this flow rate, in the upper left corner of the water passage.

The minimum pressures associated with operation at 38,000 cfs were considerably greater, and measured -6 ft in upper left corner of the water passage. The pressures associated with operation at 35,000 cfs were once again improved, with a minimum recorded pressure of +4 ft.

4 Comparison of Model Results

As described in the previous sections, various runs were undertaken with both the physical and numerical models. Although the models were used in complementary roles, their results were compared to determine how well they matched in terms of pressure distribution and magnitude. The comparison revealed:

The models showed a good match in predicted pressure patterns, and their identification of the minimum pressure location within the intake. Both models show that lowest pressure will likely occur in the upper corners of the intake section, where flow accelerations and velocities are largest.

The models also showed a good match in predicting the magnitude of average pressures within the tunnel entrance. As an example, **Figure 4.1** provides a comparison of the average pressure magnitude as recorded at the minimum pressure location - the crown of the intake near each corner. As shown, both the physical and numerical models predict an unacceptably low pressure magnitude of -24 feet for a tunnel discharge of 42,000 cfs. The match shown for all tunnel discharges is reasonable, providing confidence in the numerical model's ability to replicate real world processes.

The pressure at any point in the tunnel intake will not be constant – rather it will oscillate about a mean value due to flow turbulence. Pressure transducers installed in the physical model recorded pressure fluctuations at locations of minimum average pressure within the intake to be up to +/- 11 feet. FLOW3D is also a transient model, but the model predicted less variation – fluctuations were limited to approximately +/- 3 feet. Given the dynamic process involved and the small length and time scales associated with these turbulent fluctuations, the physical model measurements are believed to be more representative, and were adopted as representing the dynamic variation to be expected.

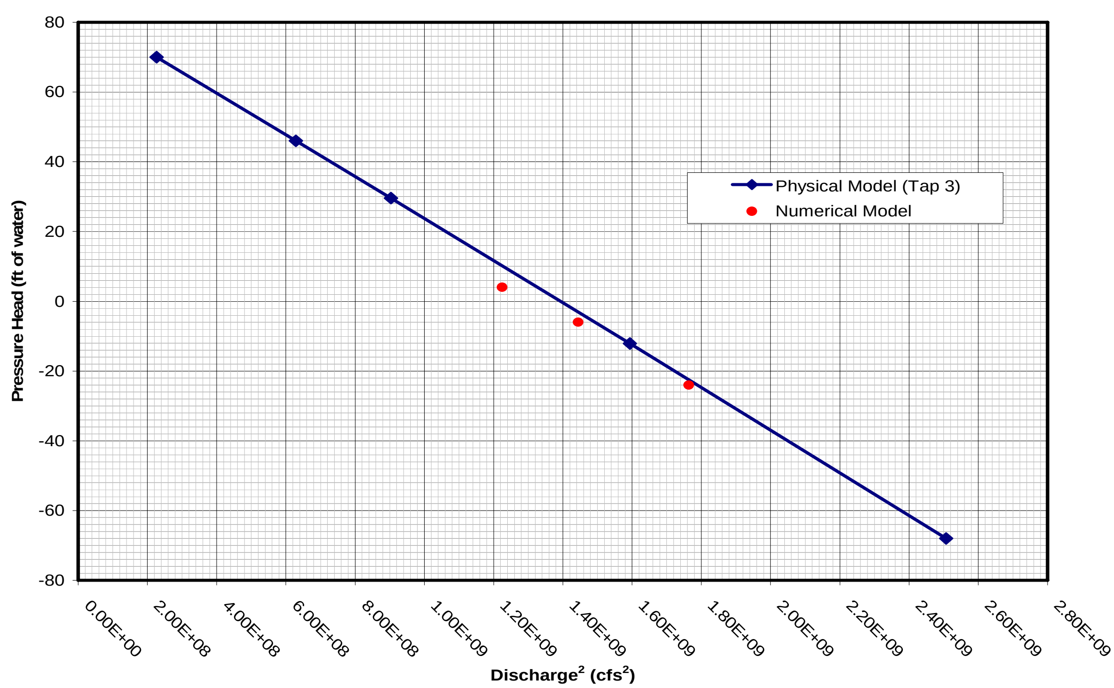

Figure 4.1: Comparison of Average Pressure

5 Summary and Conclusions

Physical and numerical model studies were performed to analyze the complex hydraulic conditions associated with operation of the proposed Cabinet Gorge bypass tunnels. The models were successfully used in complementary roles: the numerical model was first used to assist in planning the location of pressure taps for the physical model then later to run additional flow scenarios that were not included within the physical model test program. The physical model was used to provide more refined estimates of the pressure magnitude and fluctuation anticipated at critical locations within the intake structure. Interpretation of results from both models required understanding of the physics of cavitation and application of design standards for cavitation suppression as neither model simulates the cavitation phenomenon.

Overall, the match in average pressure predicted with the two models was very good, and it was of value to have input from both models in planning and executing these design studies.

6 Acknowledgments

The authors would like to acknowledge and thank Avista Corporation for their support and willingness to allow the results of these studies to be published.

7 References

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