RECLAMATION
Managing Water in the West

Hydraulic Laboratory Technical Memorandum PAP-1088

Feasibility Investigation of Alternatives to Improve Flow Conditions at the Homestake Tunnel Parshall Flume

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

July 2014

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BUREAU OF RECLAMATION

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Hydraulic Laboratory and PAP Reports

The Hydraulic Laboratory Report and PAP series is produced by the Bureau of Reclamation's Hydraulic Investigations and Laboratory Services Group (Mail Code 85-846000), PO Box 25007, Denver, Colorado 80225-0007. At the time of publication, this report was also made available online at **http://www.usbr.gov/pmts/hydraulics_lab/pubs/**.

Disclaimer

Funding for this project was provided by The Homestake Project

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Background

The Homestake Project (Homestake) provides water supply to the cities of Aurora and Colorado Springs, Colorado, utilizing Homestake Dam on the western slope and the Homestake Tunnel which delivers water through the Continental Divide into the Bureau of Reclamation's Turquoise Lake near Leadville, Colorado.

A 12-ft Parshall flume located just downstream from the exit of the Homestake Tunnel measures the flow before it reaches Turquoise Lake. Current-meter measurements are regularly made by the Colorado Dept. of Water Resources (DWR) to verify the flume rating. Discharge measurements are available on the DWR web site under station name HOMTUNCO.

Homestake contacted the Bureau of Reclamation (Reclamation) in July 2013 to request assistance in resolving a chronic condition of excessive waves in the approach channel leading to the flume. The flow condition creates uncertainty in the accuracy of both the flume rating and the current-meter discharge measurements. DWR has expressed repeated concerns about the accuracy of the current-meter measurements and associated flow depth measurements due to the excessive waves. Homestake contacted Reclamation because of our expertise related to several features of the site (e.g., fixed-cone valve, stilling basin, Parshall flume, current metering). To investigate the issues, Bob Einhellig and Tony Wahl from the Hydraulics Laboratory visited the site on July 17, 2013.

The main components of the facility shown in Figure 1 are a 54-inch Howell-Bunger (fixed-cone) valve regulating releases through the tunnel from Homestake Reservoir, an energy-dissipation vault downstream from the valve, a 12.75-ft simple vertical drop stilling basin with a 2.5-ft-high end sill located 10-ft downstream from the drop, a 210-ft-long and 20-ft-wide rectangular concrete approach channel, and a 12-ft Parshall flume. The flume is constructed to standard dimensions for such flumes, with a flared entrance that extends the converging section sidewalls upstream until they intersect the 20-ft-wide approach channel. The structure has always suffered from large waves in the approach channel leading up to and through the flume. The problems begin with high levels of turbulent energy and non-uniform flow distribution exiting the valve energy dissipation vault. One might expect the stilling basin to dissipate much of this energy and produce a uniform flow. However, the jet produced by the free overfall lands downstream from the stilling basin end sill at typical operational flow rates, rendering the stilling basin completely ineffective for dissipating the jet's energy. For unknown reasons the basin was not sized appropriately for the normal operating conditions. Wave amplitudes up to 1 ft (±6 inches) have been reported just upstream and through the Parshall flume entrance.

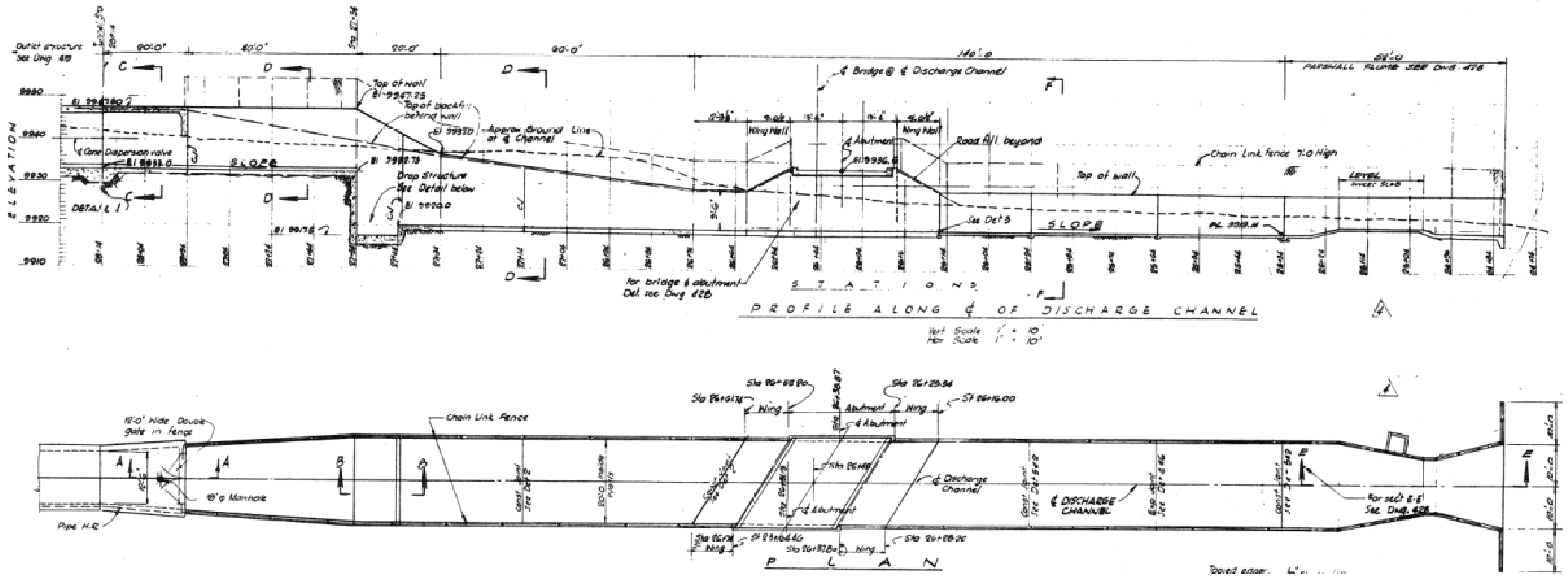

Figure 1. — Homestake Tunnel outlet structure and flow measuring flume. The Howell-Bunger valve is located just to the left of this drawing.

Initial Investigations

On the day of the site visit, a stoplog-style baffle had been installed into the channel beneath the roadway bridge crossing. The baffle had been previously tested at a 2-ft height and was being tested during the site visit at a height of 3 ft. The stoplog baffle seemed to significantly reduce wave amplitudes. Reclamation observed wave heights of about ±0.2 ft at a flow of about 260 ft^3/sec.

Following the site visit, Reclamation reviewed the field stage and discharge measurement records for the flume, using data available from the Colorado DWR web site from 1999 to present (42 measurements). The flume rating has been relatively stable during the previous 14 years, but differs from the standard rating equation for a 12-ft Parshall flume, as shown in Figure 2. Measurements consistently indicate flows higher than the standard rating equation for this size flume (Reclamation, 2001), but the variability is low. With the exception of two measurements made in April 2012 at extremely low discharges (and with a different current meter), most measurements have been in the range of 3 to 9 percent higher than the standard Parshall flume equation, with an average deviation of about +6%. Preliminary analysis did not reveal significant trends in the rating as a function of season, passage of time, or changes in hydrographic personnel. During the site visit the flume structure was observed to be in generally good condition. Project personnel familiar with the site reported that key dimensions had been checked and verified to be consistent with standard dimensions for this size flume. Concrete surfaces in the flume were noted to be relatively rough due to long-term freeze-thaw deterioration of the concrete surfaces that had removed surface mortar and left the rounded aggregate of the concrete material exposed. This is not unusual for a flume of this age in this type of environment.

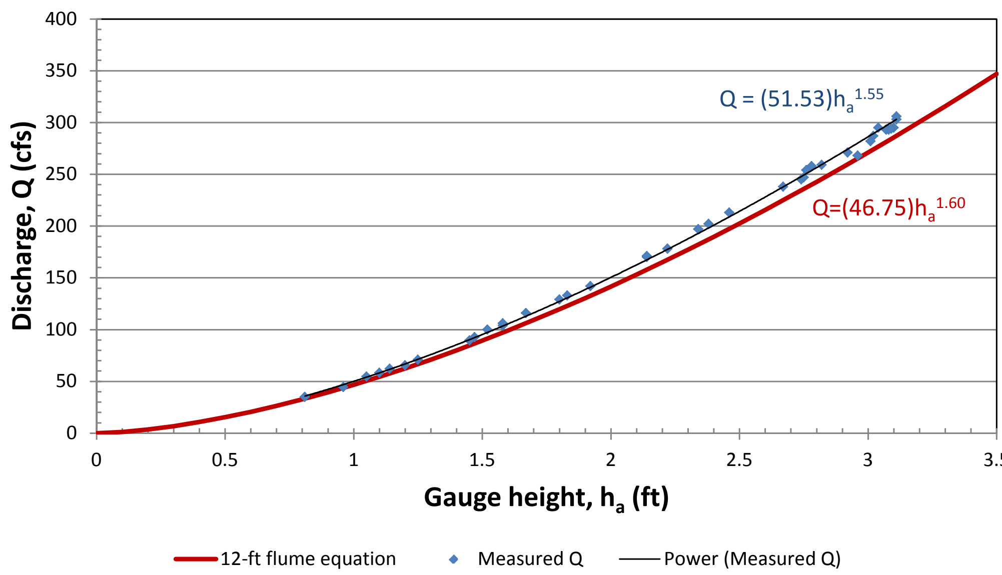

Figure 2. — Discharge measurements since 1999 compared to standard free-flow rating equation for a 12-ft Parshall flume.

These results are encouraging and suggest that despite the history of large waves in the approach channel, flume performance and current-meter measurements have been relatively consistent for at least the past 14 years. This is likely due to the fact that the flume is equipped with a good stilling well that effectively dampens wave oscillations so that measuring head (h_a) can be accurately determined. The standard deviation of the percentage differences between the current-meter measurements and the best-fit line in Figure 2 is about 2.3%, which puts them between the standard USGS stream flow measurement quality ratings of excellent (2% error) and good (5% error). The systematic deviation of the measured flows from the standard 12-ft Parshall flume equation is not surprising, as there is not true standardization of the entrance details for this size flume, so the "standard" equation probably represents an average of the performance of many large field-calibrated Parshall flumes, each with slightly unique geometric details. In practice, large Parshall flumes are often empirically calibrated against independent field measurements of discharge (Parshall 1953).

Over the past 6 years, flows from the Homestake Tunnel have ranged from 0 to 325 ft^3/sec (Figure 3). A simple frequency analysis was performed on the data to determine the most common ranges of operation. Zero flow (not included in the histogram) occurs over 73% of the time. Figure 4 shows that the most common operations are in the ranges of 1 to 50 ft^3/sec, and from 201 to 300 ft^3/sec. Conversations with the Homestake Project staff indicated that their target release is typically 300 ft^3/sec, and flows above this level are avoided because they cause erosion damage in the channel leading from the Parshall flume to Turquoise Lake. The flow distribution during this 6-year period has been affected to some degree by non-typical operations of the Homestake Tunnel during rehabilitation work on the dam (releasing small flows to keep the reservoir as low as possible).

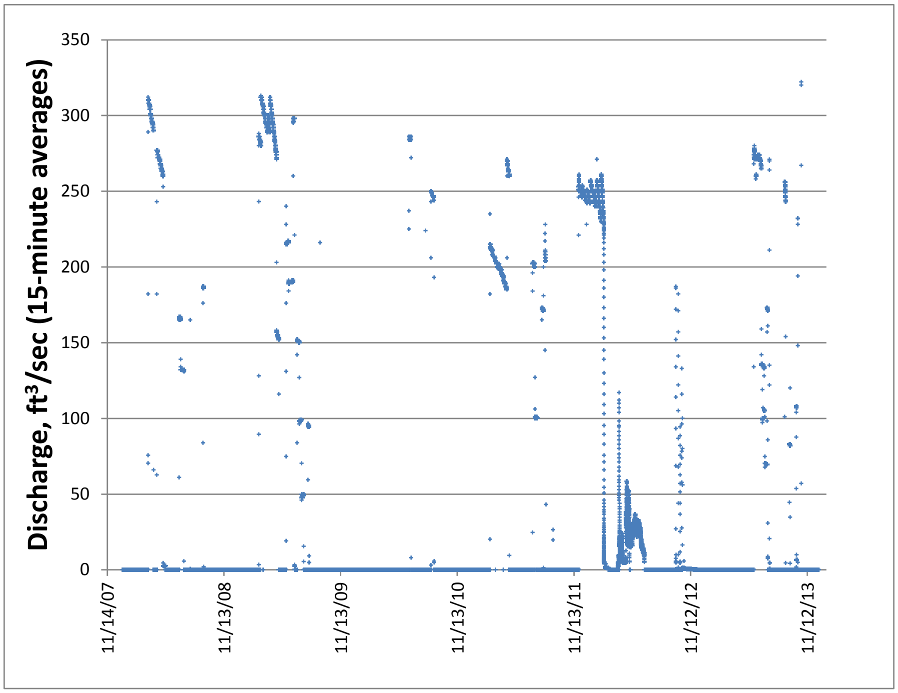

Figure 3. — 15-minute average flows from the Homestake Tunnel over the past 6 years.

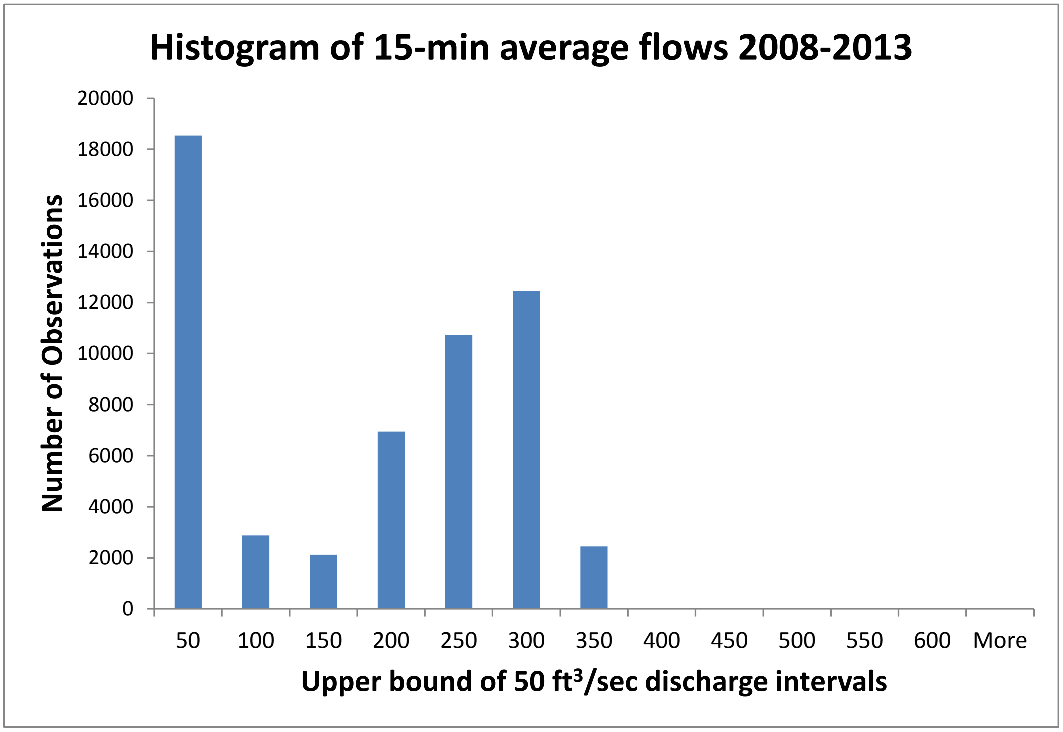

Figure 4. — Frequency histogram of the flows from the Homestake Tunnel over the past 6 years. Bars show the number of flows observed in intervals of 1-50 ft^3/sec, 51-100 ft^3/sec, etc. Conditions of exactly zero flow (approx. 153,000 observations) are not included.

STUDY APPROACH

In response to the request from Homestake, Reclamation proposed an initial phase of investigation using a computational fluid dynamics (CFD) model of the structure. The agreement between Homestake and Reclamation allowed for an optional second phase of modeling, which would require additional funding and include construction and testing of a physical model, if needed.

The initial study's objectives were to identify potential modifications to the existing facility that might reduce waves at the Parshall flume entrance, and to study the relative effectiveness of the different alternatives using the CFD model. Based on relative performance and estimated costs, this report provides recommendations for those modifications that are likely to be most beneficial and cost effective. CFD modeling was chosen for this initial phase because of the relatively low cost to set up and run a basic model, and the ability to easily evaluate the proposed wave suppression alternatives

Reclamation believes that the modifications recommended will reduce wave height and improve the quality of future discharge measurements at the flume. Long-term confidence in the flume rating will also improve if modifications are implemented. This improvement may be in the form of reduced measurement variability (i.e., better repeatability) and/or improved accuracy. Following implementation of improvements, it is possible that long-term monitoring of the structure will show that the rating curve for the flume has changed due to wave reduction and should be adjusted. It is also possible that the flume rating will not change and reduction in wave amplitude may have no other effect than to decrease the variability of future discharge measurements made by DWR upstream from the Parshall flume.

Computational Fluid Dynamics (CFD) Modeling

FLOW-3D, a commercially available CFD software package developed by Flow Science Inc. was used for all CFD simulations, and was chosen because of its ability to accurately model free-surface flows. FLOW-3D utilizes the Reynolds-averaged Navier-Stokes (RANS) equations to solve for fluid flow. Modifications to the standard RANS equations include algorithms to accurately track the water surface and flow around geometric objects (Hirt and Nichols, 1981; Flow Science, 2012; Hirt and Sicilian, 1985; Hirt, 1992).

The CFD model was configured using prototype dimensions to avoid any scale effects and to simplify comparison with any physical data that might be collected in the future. The three-dimensional model was configured to contain the entire outlet channel structure from the 54-inch Howell-Bunger (fixed cone) valve to the end of the 12-ft Parshall flume. The Howell-Bunger valve geometry was simplified as an open discharging jet. The model was configured to test the following alternatives proposed by the client and Reclamation:

- Existing condition (baseline for comparison)
- Underpass-type wave suppressor
- Modified (lengthened) stilling basin
- Stoplog baffle at two different locations (similar to the baffle being tested in the field during July 2013 site visit)

One additional alternative, the slotted-grating dissipator (Bureau of Reclamation, 1987), was not included in the initial study because it was not expected to perform well in the typical Froude number range of the drop structure and was also expected to be difficult to accurately model with CFD.

Details of the tested model configurations are given below:

- Existing condition with as-built stilling basin and no wave suppression features (baseline test) (Figure 5)

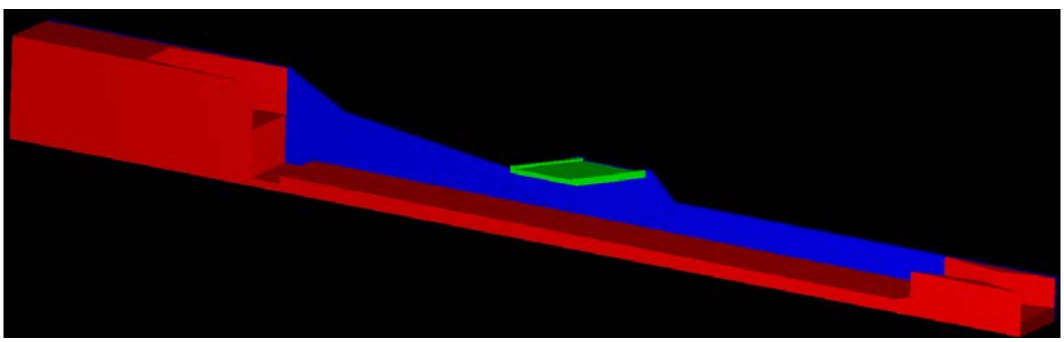

Figure 5. — As-built configuration. The near wall of the flume approach channel is not shown in order to make approach channel details visible.

- Underpass-type wave suppressor as described in Engineering Monograph 25 by Peterka (1978) (Figure 6). The dimensions of the wave suppressor were sized for a flow of 300 ft^3/sec and are described in Figure 7. Simplified solid box geometry was used in the CFD model to represent the wave suppressor. The box had a bottom length of 17 ft, spanned the entire 20-ft channel, and was located directly under the road bridge crossing.

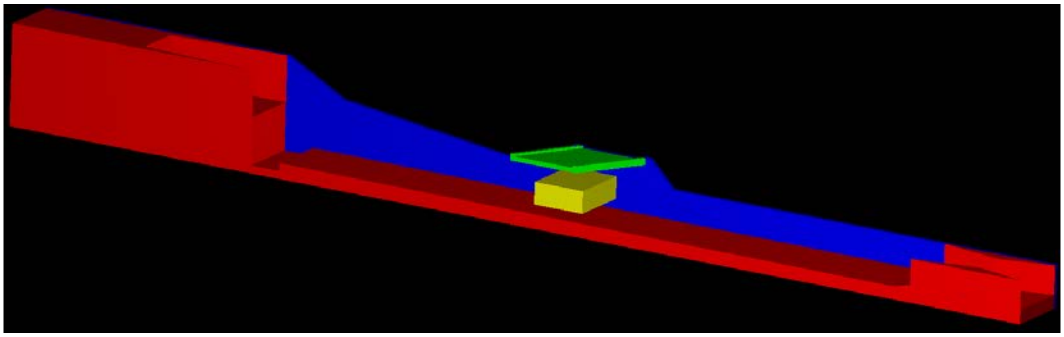

Figure 6. — Wave suppressor configuration. Near wall of approach channel is not shown.

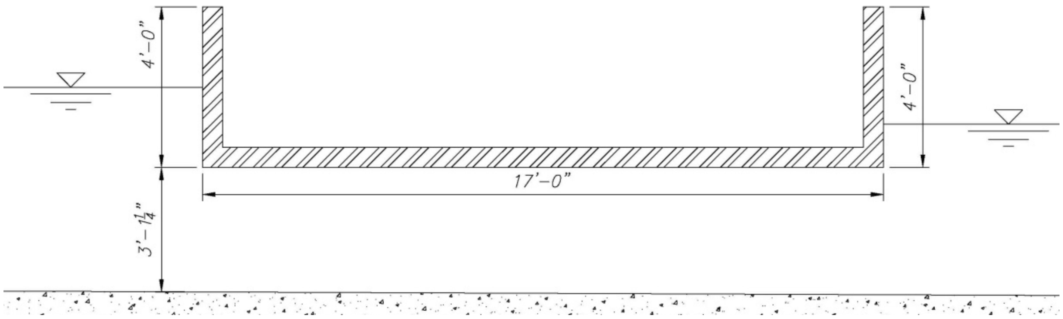

Figure 7. — Dimensions of an underpass wave suppressor designed for the Homestake channel with a discharge of 300 ft^3/sec.

- Modified stilling basin by changing length and depth to contain hydraulic jump in basin (Figure 8). The basin end sill (step) was moved 30 ft downstream, and the basin floor was extended at the existing basin floor elevation of 9917.5 ft. This modification would require the removal of approximately 900 ft^3 of concrete (Figure 9).

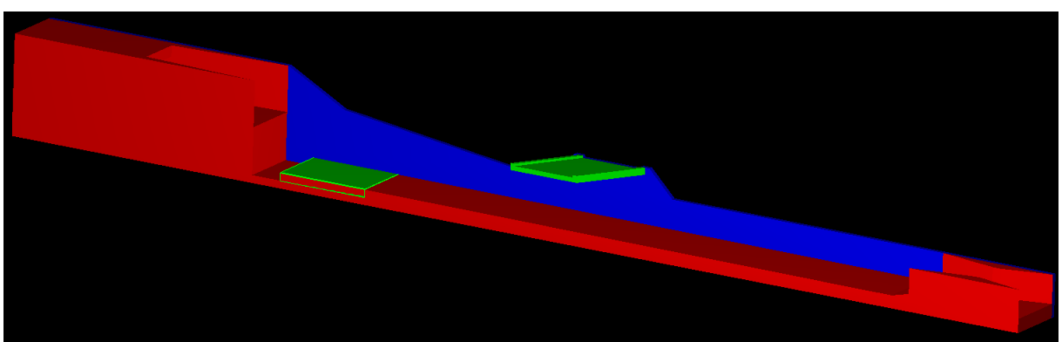

Figure 8. — Modified stilling basin configuration (green box highlights existing concrete that would be removed). The near wall of the channel is not shown.

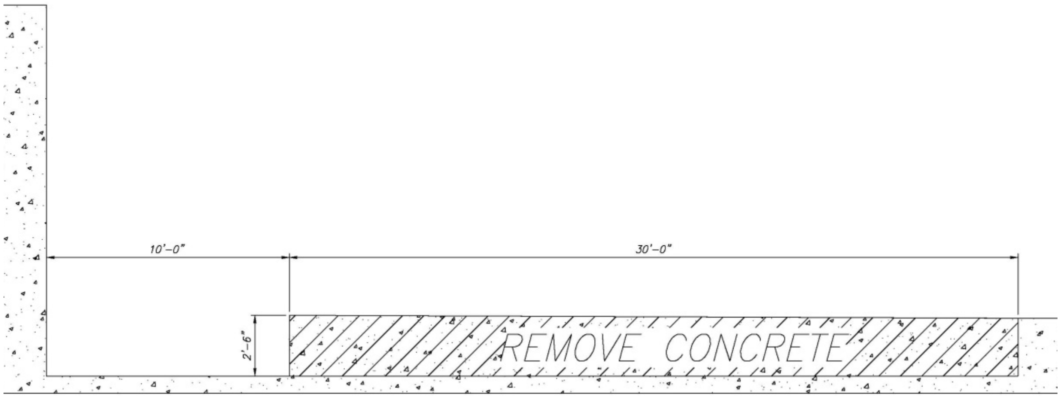

Figure 9. — Modified stilling basin dimensions.

- 3-ft-high stoplog baffle located 30 ft downstream from the vertical drop (Figure 10). The stoplog baffle would extend fully across the channel and be constructed of common lumber products with structural steel supports anchored into the approach channel concrete. (Other locations were also tested and this position was found to be most effective across a wide range of flow conditions).

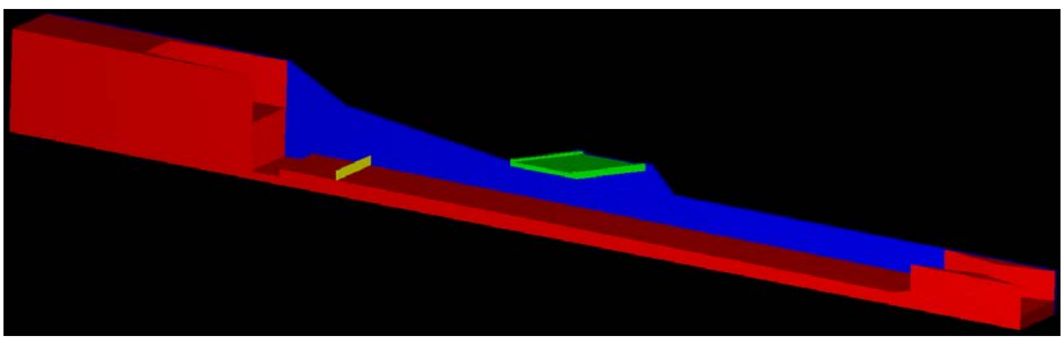

Figure 10. — 3-ft-high stoplog baffle located 30 ft downstream from vertical drop. The near wall of the approach channel is not shown.

- 3-ft-high stoplog baffle located beneath the road bridge crossing. This is a similar location to the concept tested in the field during 2013 (Figure 11). The stoplog baffle would extend fully across the channel and be constructed of common lumber products with downstream structural steel supports.

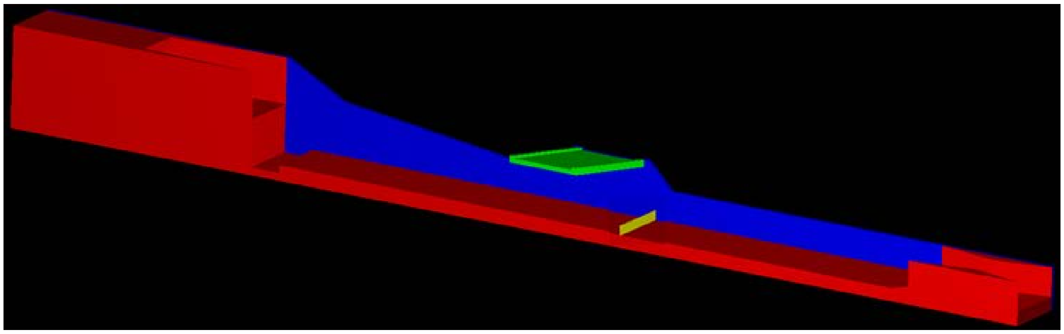

Figure 11. — Stoplog baffle located beneath road bridge, as tested in 2013. The near wall of the approach channel is not shown.

Three dimensional geometry files of each scenario were developed using AutoCAD (Figures 5, 6, 8, 10, 11) and imported into FLOW-3D as stereolithography files. The geometry was overlaid with a computational grid having 0.25-ft cubic cells in the x (streamwise) y & z (vertical) direction. To reduce the number of cells required and decrease the simulation time, a symmetry boundary was used down the midline of the channel allowing for only half of the channel to be simulated but to accurately reproduce the hydraulic characteristics of the system.

The inflow boundary (minimum x) of the model was set to match the normal operating condition of 300 ft^3/sec. A symmetry boundary condition was applied along the centerline of the channel (maximum y). The floor (minimum z) and wall (minimum y) were set as no-slip wall boundaries, which do not allow any discharge to pass the boundary. The top (maximum z) boundary was set as a pressure boundary with gauge pressure equal to zero. The fluid exited the simulation through the maximum x boundary which was set as an outflow boundary. All solid objects were given roughness values representative of aged concrete.

Turbulence was modeled using the Renormalized Group theory (RNG) modeling option because it more accurately describes low intensity turbulent flows and flows with strong shear regions using fewer computations than other methods (Flow Science, 2012).

Each test simulation was initialized and allowed to run until it reached quasi-steady state. After reaching quasi-steady state the models were run an additional 25 seconds while water surface elevations (waves) were recorded at the same location in the flume and entrance channel for each configuration. The wave data from each tested configuration were compared to the baseline as-built condition.

RESULTS

Water surface elevations were collected at two locations: upstream from the Parshall flume in the center of the channel (similar to where DWR performs current metering) and in the center of the channel where the Parshall flume staff gauge and stilling well are located, commonly referred to as the (2/3)A location. Water surface elevations were sampled at 0.25 second intervals over 25 seconds of quasi-steady state run. Table 1 summarizes the water surface data collected upstream from the Parshall flume and includes the maximum, minimum and average observed water surface elevation with the standard deviation and maximum difference (maximum – minimum) for each scenario. Figure 12 through Figure 15 plots the entire 25 seconds of data for each scenario compared to the as-built baseline scenario.

Table 1. — Summary of water surface data recorded upstream from the Parshall flume for each scenario.

Water Surface Elevation Upstream from Parshall Flume					
	As Built	Wave Suppressor	Modified Basin	Baffle at 30 ft	Baffle at Bridge
Max	9924.44	9924.38	9924.40	9924.40	9924.37
Min	9924.19	9924.24	9924.24	9924.24	9924.12
Avg	9924.30	9924.31	9924.32	9924.31	9924.30
StDev	0.056	0.036	0.030	0.038	0.046
Max Diff	0.25	0.15	0.16	0.16	0.25

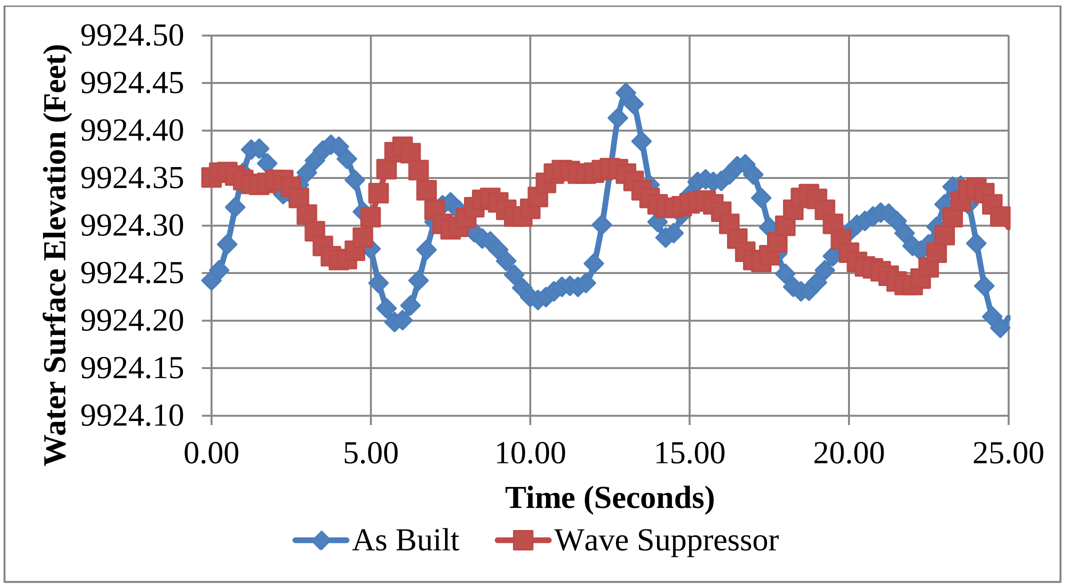

Figure 12. — Simulated waves upstream from Parshall flume, comparing wave suppressor to as-built condition.

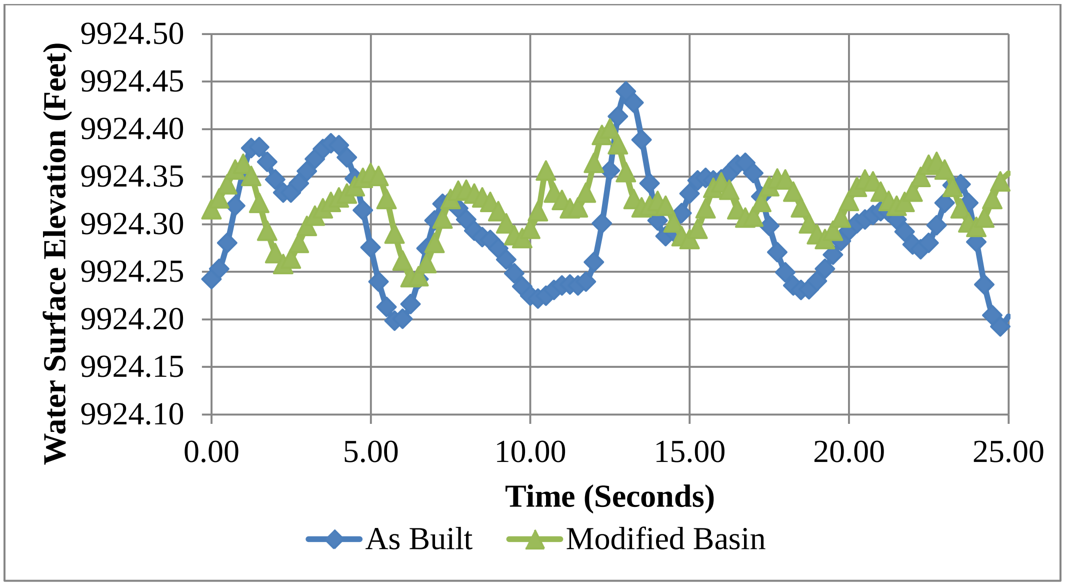

Figure 13. — Simulated waves upstream from Parshall flume, comparing modified stilling basing to as-built condition.

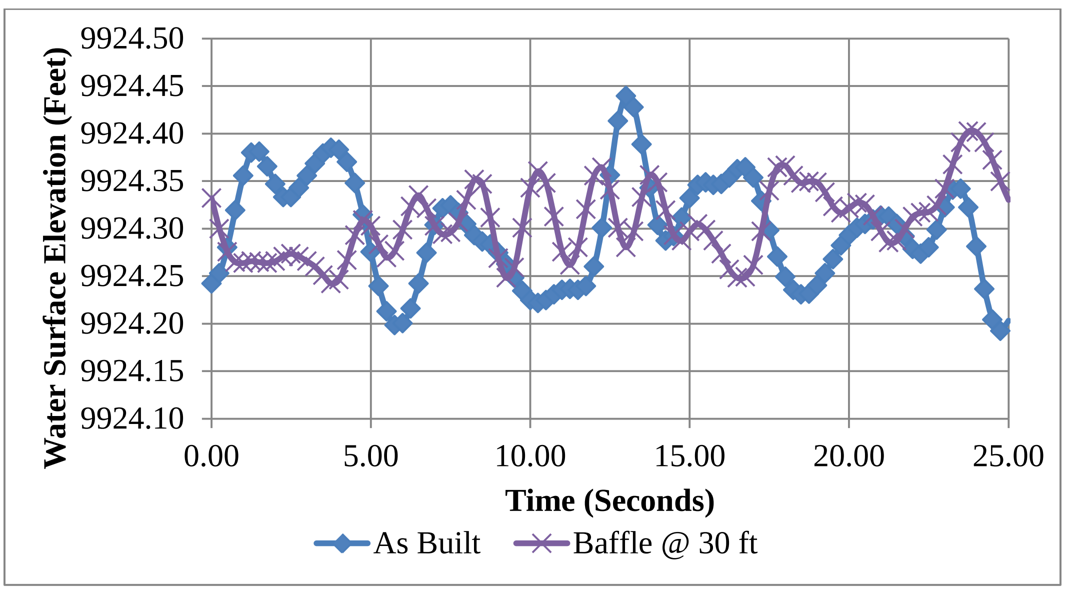

Figure 14. — Simulated waves upstream from Parshall flume, comparing baffle at 30 ft to as-built condition.

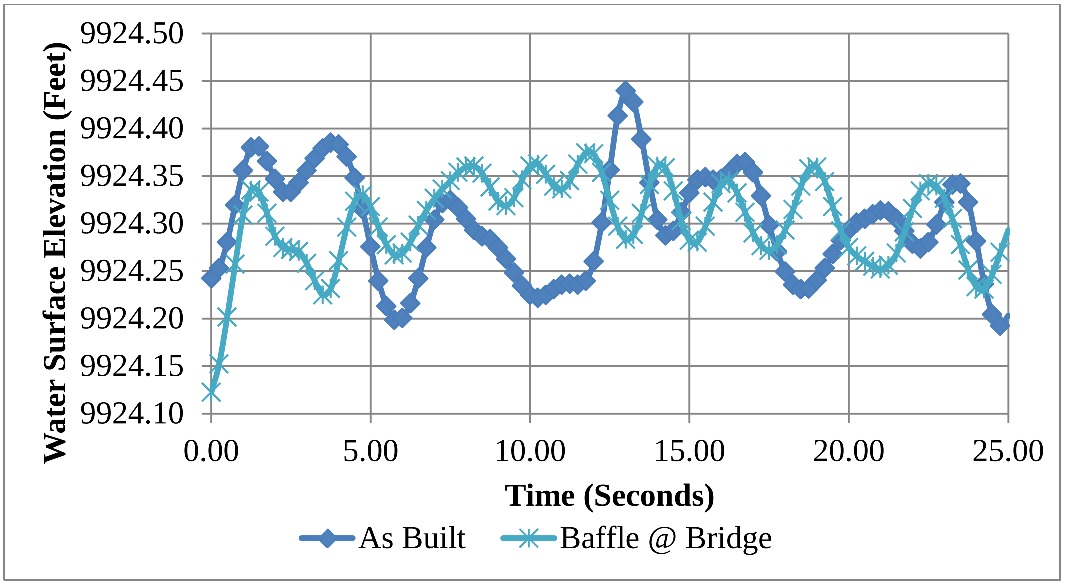

Figure 15. — Simulated waves upstream from Parshall flume, comparing baffle at bridge to as-built condition.

Table 2 summarizes the water surface data collected in the center of the channel at the (2/3)A location where the Parshall flume stilling well and staff gauge are located. The table includes the maximum, minimum and average observed water surface elevation with the standard deviation and maximum difference (maximum – minimum) for each scenario. Figure 16 through Figure 19 plots the entire 25 seconds of data for each scenario compared to the as-built baseline scenario.

Table 2. — Summary of water surface data at the location where the Parshall Flume stilling well and staff gauge are located [(2/3)A location] for each scenario.

Water Surface Elevation Statistics at Parshall Flume (2/3)A Location					
	As Built	Wave Suppressor	Modified Basin	Baffle at 30 ft	Baffle at Bridge
Max	9923.92	9923.85	9923.88	9923.86	9923.83
Min	9923.66	9923.71	9923.72	9923.72	9923.59
Avg	9923.78	9923.78	9923.80	9923.78	9923.77
Std Dev	0.060	0.035	0.030	0.035	0.051
Max Diff	0.25	0.14	0.16	0.14	0.25

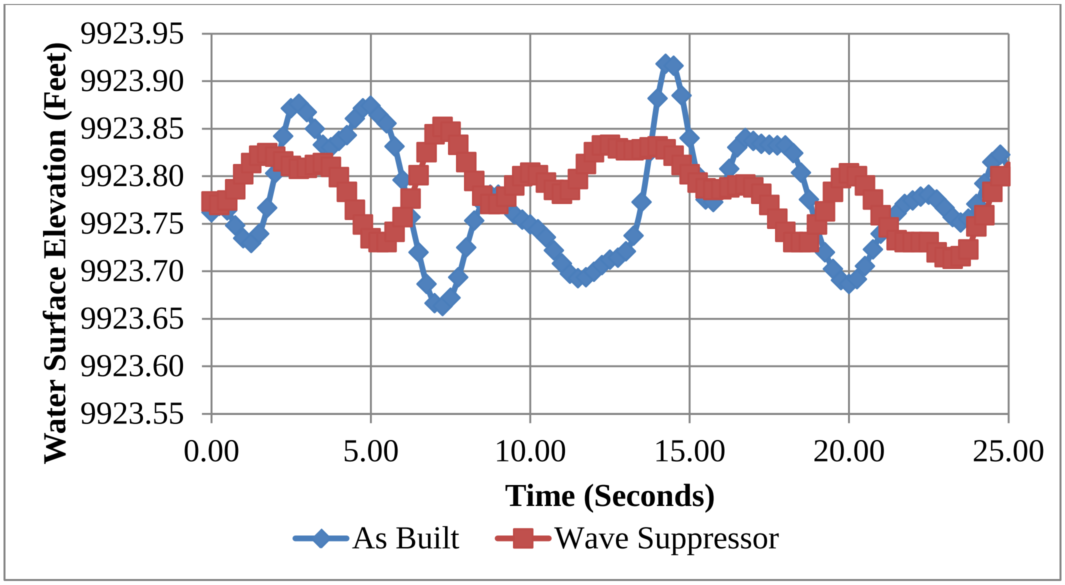

Figure 16. — Simulated waves at (2/3)A location in Parshall flume, comparing wave suppressor to as-built condition.

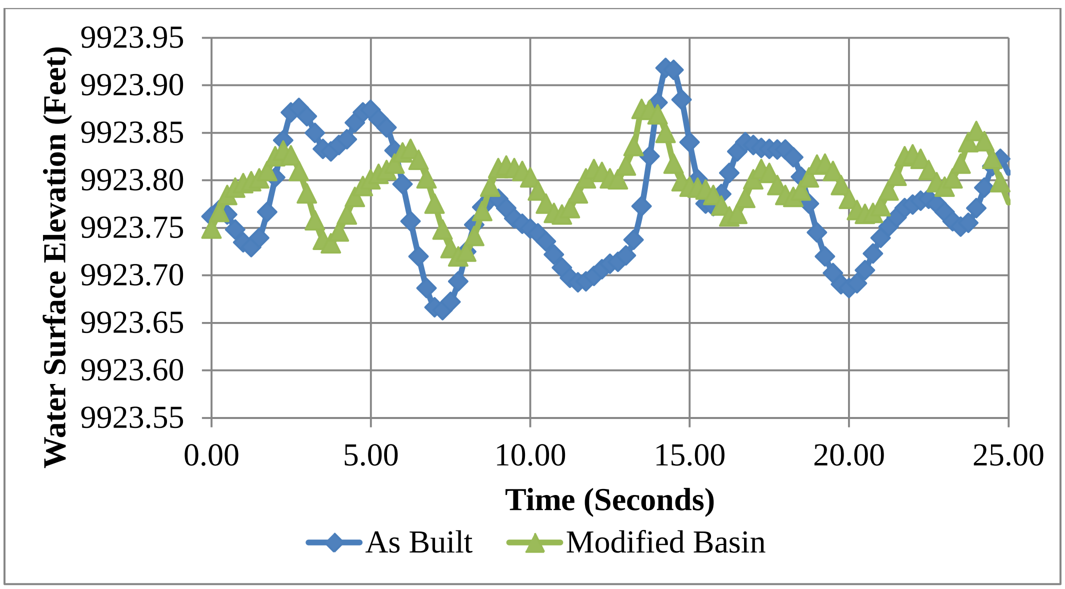

Figure 17. — Simulated waves at (2/3)A location in Parshall flume, comparing modified stilling basin to as-built condition.

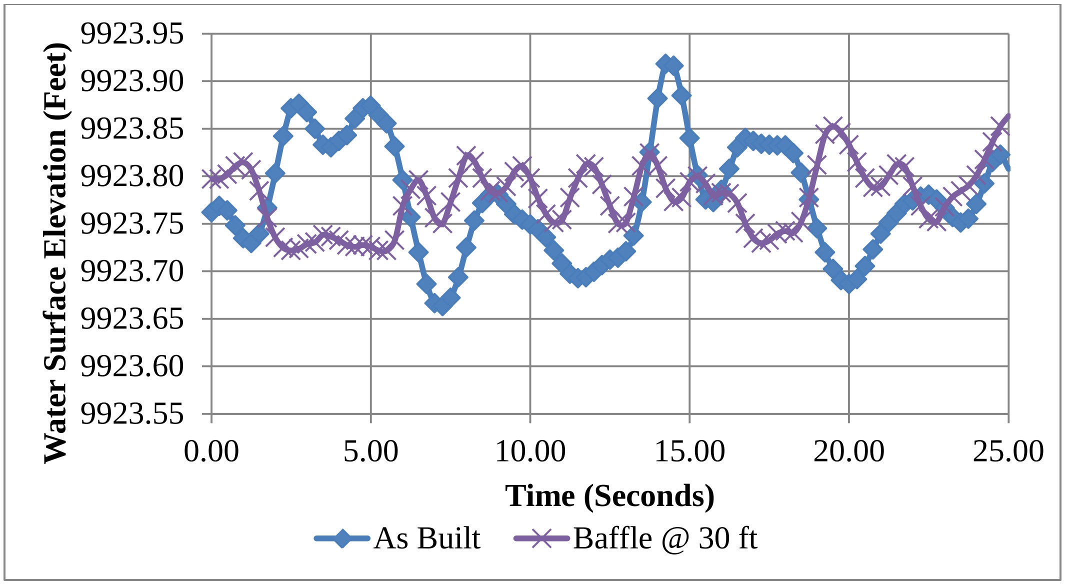

Figure 18. — Simulated waves at (2/3)A location in Parshall flume, comparing baffle at 30 ft to as-built condition.

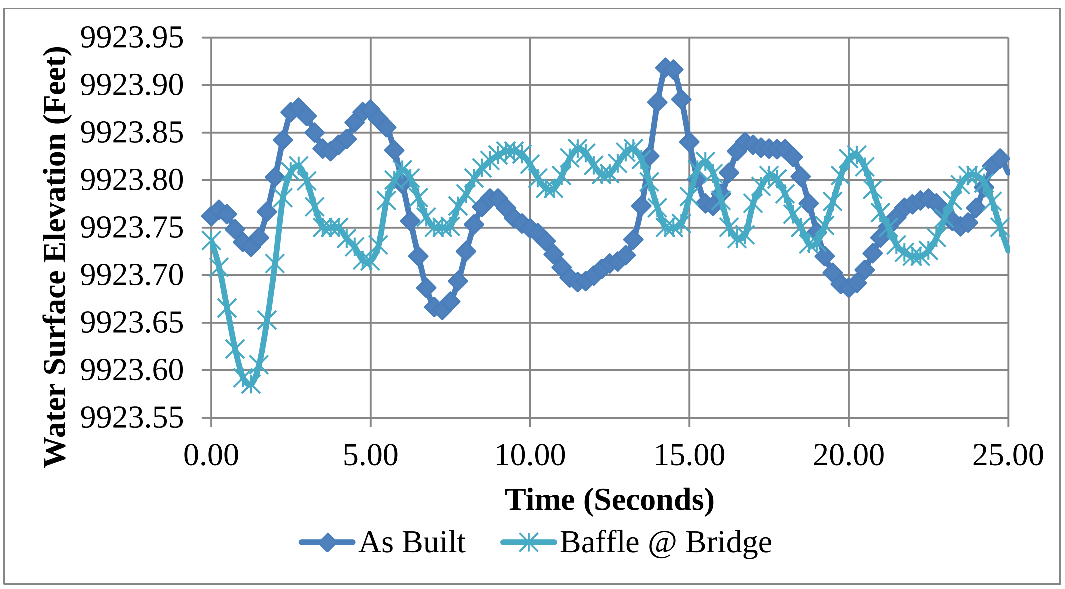

Figure 19. — Simulated waves at (2/3)A location in Parshall flume, comparing baffle at bridge to as-built condition.

ANALYSIS

The as-built scenario produced wave heights on the order of 0.25 ft (±0.125 ft) both upstream from the flume and at the (2/3)A staff gauge location in the

Parshall flume. This wave height range is smaller than the ±0.5 ft that has been observed in the field. This is an expected result that is primarily due to the size of the cells used in the CFD model. Smaller cell size would likely improve the modeling of turbulence and generate larger instantaneous waves but would take significantly longer to run each model. This study utilizes a comparative approach in its analysis with the performance of wave reduction alternatives compared only to the modeled baseline condition. Exact matching of the wave heights observed in the field was not intended and the lack of an exact match does not affect the findings and recommendations.

Comparison of each wave reduction method to the baseline case shows that all methods reduce the maximum difference and standard deviation of the waves. The underpass wave suppressor, modified stilling basin, and 3-ft-high baffle at 30 ft all performed similarly and reduced the maximum difference of water surface elevation by an average of 0.10 ft and improved the standard deviation to an average of 0.034 ft both upstream from the flume and at the (2/3)A measurement location. Any of these options appear to reduce the waves by about half of the current levels.

The 3-ft-high baffle located under the bridge crossing did not improve the maximum difference but improved the standard deviation to 0.046 ft upstream from the Parshall flume and to 0.051 ft at the (2/3)A location. When this configuration was tested in the field it appeared to significantly reduce the waves when operating at lower discharges (100 to 260 ft^3/sec). At 300 ft^3/sec the CFD model showed an undulating jump downstream from the drop. These jumps are very unstable and can develop from very small changes in flow rates and produce large waves. This type of jump was not noticed in the field during the 260 ft^3/sec discharge, which would explain why waves were reduced significantly in the field trial but less so in the CFD model with the baffle at this location. Although the exact nature of the hydraulic jump may not be perfectly simulated in the CFD model, the modeling did show that the performance of the baffle was more consistent across a broad range of flow conditions when it was located 30 ft downstream from the drop, rather than at the bridge. This appeared to be mostly caused by increased tailwater at the jet impingement point (moving the baffle upstream also increases its elevation due to the slope of the channel) and a better, more stable form of hydraulic jump. There may also be some benefit due to an increased distance between the baffle and the flume entrance, which allows more time and space for natural dissipation of wave energy to take place downstream from the baffle.

Based on the results of the CFD simulations, the wave suppressor, modified stilling basin, and baffle at 30 ft were judged to be approximately equivalent from a performance standpoint. The baffle option was believed to be the easiest to construct and most economical to implement, and would also offer the greatest operational flexibility since it can be readily removed if necessary to allow access to the upstream end of the channel for cleaning or other maintenance. The baffle at the location 30 ft downstream from the drop performed more consistently than the baffle at the bridge location, and thus, the baffle option at the 30 ft position was considered to be the best alternative.

After initial results were compiled and analyzed, additional runs were made to test whether the height of the baffle or location could be improved. Multiple locations from 20 ft to 40 ft downstream from the vertical drop were simulated. Baffle heights ranging from 2 ft to 4 ft were also simulated. Results of the simulations showed that when the baffle was too close to the vertical drop excessive splashing occurred because the plunging jet would impact the baffle directly. Testing also showed that baffle heights below 2.25 ft were inadequate to submerge the impinging jet downstream from the drop and thus did not reduce the wave action at the flume. Baffle heights greater than 3 ft did not produce any significant change in performance. From the additional simulations Reclamation determined that the 3-ft baffle height located at 30-ft downstream from the vertical drop would provide optimal energy dissipation and reduction of channel waves over a wide range of discharges.

Reclamation ran one simulation with the preferred 3-ft-high baffle at 30 ft downstream from the vertical drop with the tunnel releasing 600 ft^3/sec - double the normal amount. This operation may be required at some point if Homestake reservoir needs to be evacuated quickly. Results of the 600 ft^3/sec simulation showed that splashing would occur if the baffle were left in place, but flows would remain within the confines of the channel walls. As a result, there would be no need to remove the baffle prior to releasing 600 ft^3/sec.

RECOMMENDATIONS

Results from each simulation of the CFD model were evaluated using several factors including ability to reduce waves in the channel, ease of construction, cost of construction and ability to access the upstream stilling basin which periodically needs to be cleared of debris deposits. All of these factors were used to determine which option would be best suited for implementation in the Homestake Tunnel channel.

Reclamation recommends moving the trial 3-ft-high baffle to a location about 30 ft downstream from the vertical drop. The CFD model showed that this location and height would reduce the wave action by approximately half and would perform well over a wide range of discharges. Installing the baffle at this location will allow more energy dissipation in the channel upstream from the Parshall flume. The baffle is simple to construct and can easily be removed and replaced when the upstream stilling basin needs to be maintained. To help reduce any buildup of sand and cobbles upstream from the baffle it is recommended that the baffle be installed approximately 2-3 inches off the bottom of the channel. Raising the baffle by this amount was not modeled in the CFD model but should not reduce the ability to suppress channel waves.

Reclamation recommends improving the accuracy of the 12-ft Parshall flume by creating a custom rating equation to replace the standard rating equation that is currently in use. Historic current-meter measurements performed by DWR have shown that the Parshall flume does not currently provide an accurate flow measurement, if the standard 12-ft flume equation is used. Currently, DWR applies a shift to the Parshall flume rating that varies with head and is adjusted slightly on a periodic basis to maintain agreement with current-meter measurements. The variation of the shift with head effectively creates a custom rating for the flume, but does so in a relatively complicated manner. Changes in the shift table over time are more likely caused by variability of current-meter measurements than systematic changes in the Parshall flume rating. Despite the effects of the waves that have reduced confidence in DWR's current-meter measurements, the stilling well on the flume does a good job of damping waves in the approach channel so that an accurate, consistent, average measurement head (h_a) has been used to compute flume flows. This has led to a high-quality historical data record that would support the development of a custom rating for this flume (as shown in Figure 2).

Reclamation expects that implementing the baffle option to reduce the waves upstream from the flume will not change the existing head-discharge rating or accuracy of the Parshall flume. The flume rating should continue to follow the unique rating curve that is defined by the historic data record. Wave reduction should increase the confidence in future current-meter measurements made by DWR. If this is the case, future measurements can be combined with the existing historical record to develop a custom rating. Those measurements could be obtained during a short calibration period when the tunnel releases can be adjusted at will. If the head-discharge rating is found to change as a result of wave suppression, then a new rating can still be developed using only the new calibration data collected after the implementation of wave suppression. Reclamation recommends creating a new rating with data that includes flow rates from near zero to around 400 ft^3/sec, which is 100 ft^3/sec above the current target operating condition.

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