IT'S A BIRD, IT'S A PLANE, IT'S A SUPER-CAVITATING BAFFLE BLOCK – CHARACTERISTICS OF ENERGY DISSIPATION

Nathan C. Cox, P.E., Hydraulic Engineer, US Army Corps of Engineers, Sacramento District.
Harold C. Huff, P.E., Hydraulic Engineer, US Army Corps of Engineers, Sacramento District.
Robert F. Einhellig, P.E., Group Manager, Bureau of Reclamation, Hydraulic Investigations and Laboratory Services Group.
Connie D. Svoboda, P.E., Hydraulic Engineer, Bureau of Reclamation, Hydraulic Investigations and Laboratory Services Group.
K. Warren Frizell, Research Hydraulic Engineer, Bureau of Reclamation, Hydraulic Investigations and Laboratory Services Group.

Abstract

The proposed Folsom Dam auxiliary spillway will be built near the left abutment of Folsom Dam. Folsom Dam is on the American River about 20 miles northeast of Sacramento, California. The dam was designed and built by the Corps of Engineers (Corps) and transferred to the Bureau of Reclamation (Reclamation) for operation and maintenance in 1956. The dam is a 340 foot high concrete gravity structure and impounds a reservoir of a little more than one million acre-ft. The current flood release capacity of the main spillway is approximately 518,000 ft^3/s. The proposed auxiliary spillway control structure houses six 23 feet wide by 34 feet high submerged tainter gates with an additional release capacity of 312,000 ft^3/s. The control structure discharges into a 2,100-foot-long chute, which conveys flows to a stepped chute, stilling basin, and exit channel.

Velocities entering the stilling basin are about 83 feet per second (fps) and 109 fps, for the design and maximum flow respectively. These are very high velocities for a stilling basin with baffle blocks and cavitation problems would normally be expected if a traditional shaped baffle block were installed. As part of Corps' overall modeling for the Folsom Dam Joint Federal Project (JFP), several baffle block shapes combined with different schemes for ramps were analyzed in Reclamations Low Ambient Pressure Chamber (LAPC) to come up with acceptable super-cavitating baffle block and ramp combinations. The optimum baffle block shape and ramp combination was then tested in a 1:48 scale Froude scale model of the stilling basin and American River/Auxiliary Spillway confluence area. The 1:48 scale physical model showed that there was a difference in the energy dissipation characteristics of a traditional shaped baffle block and a super-cavitating baffle block and ramp combination. Different ramp shapes for the super-cavitating baffle blocks were also evaluated. The paper will summarize and compare the findings from the physical model with regard to energy dissipation characteristics between a traditionally shaped baffle block and a super-cavitating baffle block and ramp design.

Introduction

Folsom Dam is on the American River about 20 miles northeast of Sacramento, California. The dam was designed and built by the Corps of Engineers (Corps) and transferred to the Bureau of Reclamation (Reclamation) for operation and maintenance in 1956. The dam is a 340 foot high concrete gravity structure and impounds a reservoir of a little more than one million acre-ft. Prior to the adoption of the Joint Federal Project (JFP), the Corps and Reclamation were pursuing their respective authorizations/missions. The dam safety issue was Reclamation's primary focus while optimal flood damage reduction was the Corps' primary focus. The proposed Corps' Folsom Dam Modifications Project included significantly increasing the size of the existing outlets in the main dam and adding two new large outlets, thus increasing flood protection for the city of Sacramento. Reclamation's proposed project included a fuse plug spillway located near the left abutment of the main dam embankment to prevent overtopping of the main dam structure. The Corps' proposal was abandoned when construction bids came in significantly higher than the government estimate. After coordination between the Corps, Reclamation, Corps sponsors, and Congress, it was determined that the needs of both agencies could be met with one project; the JFP was born. The JFP was designed to address both flood reduction goals and dam safety issues.

The current flood release capacity of the main spillway is approximately 518,000 ft^3/s. The proposed auxiliary spillway is designed to release an additional 312,000 ft^3/s to safely pass the Probable Maximum Flood (PMF) without encroaching into dam freeboard. The auxiliary spillway will also enhance flood reduction capabilities of the dam, making it possible to release 160,000 ft^3/s (downstream levee capacity) sooner to better utilize the flood control storage during passage of a flood event that would occur on the average of once in 200 years.

Physical Cavitation Model

Knowing that the entrance velocities that would occur in the stilling basin would be well above the recommended limits of 50-60 ft/s for stilling basins with baffle blocks (Peterka, 1984), it was decided to perform a cavitation study to design a new baffle block that would promote cavitation in a controlled manner without damaging the concrete surfaces of the stilling basin. The cavitation study was evaluated at Reclamation's Hydraulics Laboratory in the Low Ambient Pressure Chamber (LAPC). A detailed description of the LAPC facility and the test set-up can be found in the laboratory report *Cavitation Potential of the Folsom Auxiliary Spillway Stilling Basin Baffle Blocks* (Frizell, 2009).

The Froude number entering the auxiliary spillway stilling basin for the design discharge of 135,000 ft^3/s is about 4.4 and about 4.5 for the PMF peak release of about 312,000 ft^3/s. Average velocities entering the stilling basin are about 83 fps and 109 fps, respectively. These are very high velocities for a stilling basin with baffle blocks (especially blocks located relatively near the upstream end of a stilling basin) and cavitation problems would normally be expected if traditionally shaped baffles blocks were to be installed. The original baffle block design was tested in the LAPC, as shown in Figure 1, to provide a baseline condition for comparison to the super-cavitating baffle blocks. Results from the LAPC tests confirmed that the original baffle block design produced the potential for cavitation damage on both sides of the baffle blocks and on the floor of the stilling basin.

Several different baffle block / ramp shapes were tested in the LAPC. Each baffle block tested had the same frontal area as the original blocks (16-feet tall by 12-feet wide). The most effective block shape for limiting cavitation damage consisted of 4-ft-wide tapered tail with a 1:2 slope on the back face of the blocks. The LAPC cavitation testing showed that the inclusion of a ramp on the basin floor either immediately upstream of the baffles as shown in Figure 2 or between the baffles as shown on Figure 3, was necessary to cause cavitation to occur within the flow instead of on concrete surfaces. The ramp selected for both conditions was 4 feet tall and 12 feet long with a 1:3 slope. The ramp location immediately upstream of the baffles resulted in slightly better cavitation results in terms of floor protection than the baffles located between the baffles.

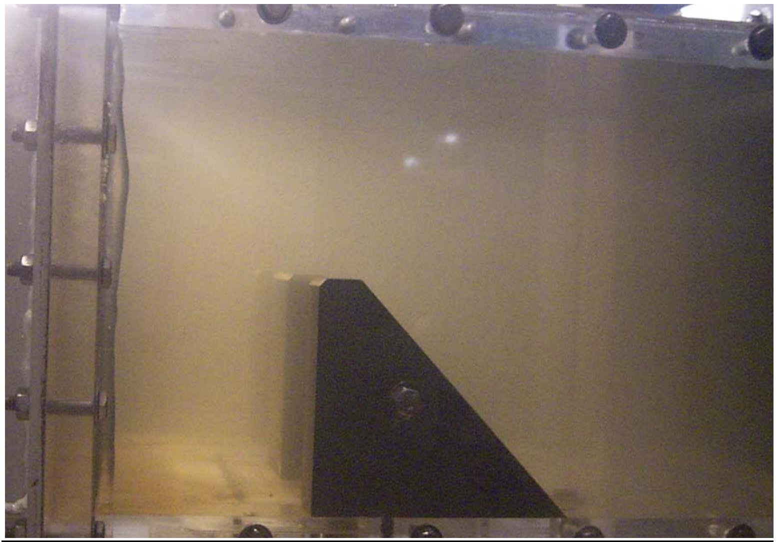

Figure 1. Original Baffle Block tested in LAPC.

Figure 2. Super-Cavitating Baffle Blocks with Ramp in Front of Block.

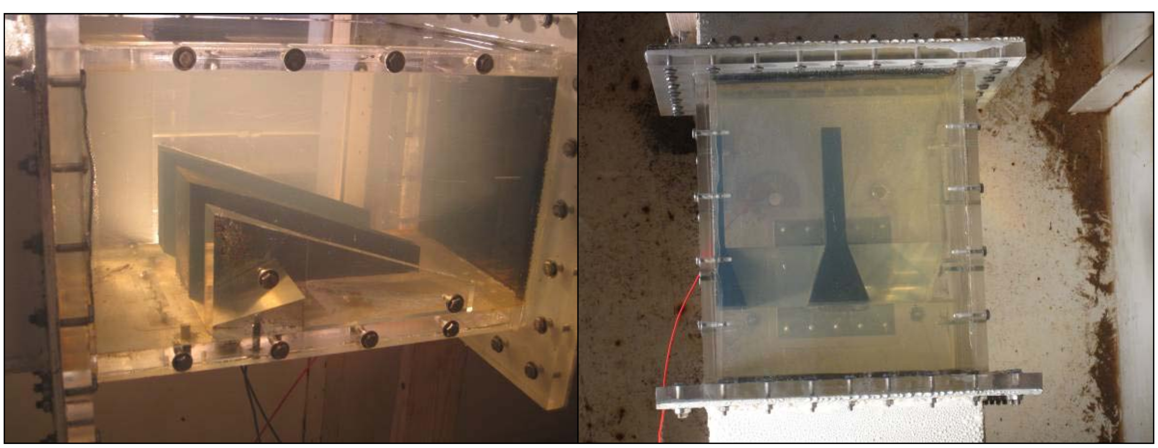

Figure 3. Super-Cavitating Baffle Blocks with Ramp in between Blocks.

Physical Confluence Model

A 1:48 scale Froude scale physical model of the confluence of the discharges from the main dam and the auxiliary spillway was modeled by Reclamation's Hydraulics Laboratory in Denver, Colorado (Svoboda et al., 2009). This is an overall model of the JFP that includes the main dam, the auxiliary spillway stepped chute and a portion of the spillway chute, the new auxiliary spillway stilling basin and exit channel, and the American River from the main dam to about 500 feet downstream of the new Folsom Lake Crossing bridge (Figure 4 and 5).

The primary purpose of the 1:48 scale Folsom confluence model study was to evaluate the three-dimensional flow characteristics at the confluence of the auxiliary spillway stilling basin and exit channel with the American River. Energy dissipation and the interaction between flows from the main dam and the auxiliary spillway were of particular interest. The items documented and observed in the model were: the overall flow conditions in the American River, water surface elevations, velocities along the American River and auxiliary spillway exit channel, evaluation for potential erosion areas, hydraulic loadings on the auxiliary spillway stilling basin walls, the hydraulic influence of the cofferdam along the haul road, the sensitivity of the auxiliary spillway basin performance to tailwater elevations, a comparison of the performance between the stepped spillway chute and a smooth spillway chute, measurement of energy dissipation along the stepped spillway, and testing of the redesigned super-cavitating baffle blocks in the stilling basin.

Figure 4. 1:48 Scale Model of the Confluence of the American River and the New Auxiliary Spillway.

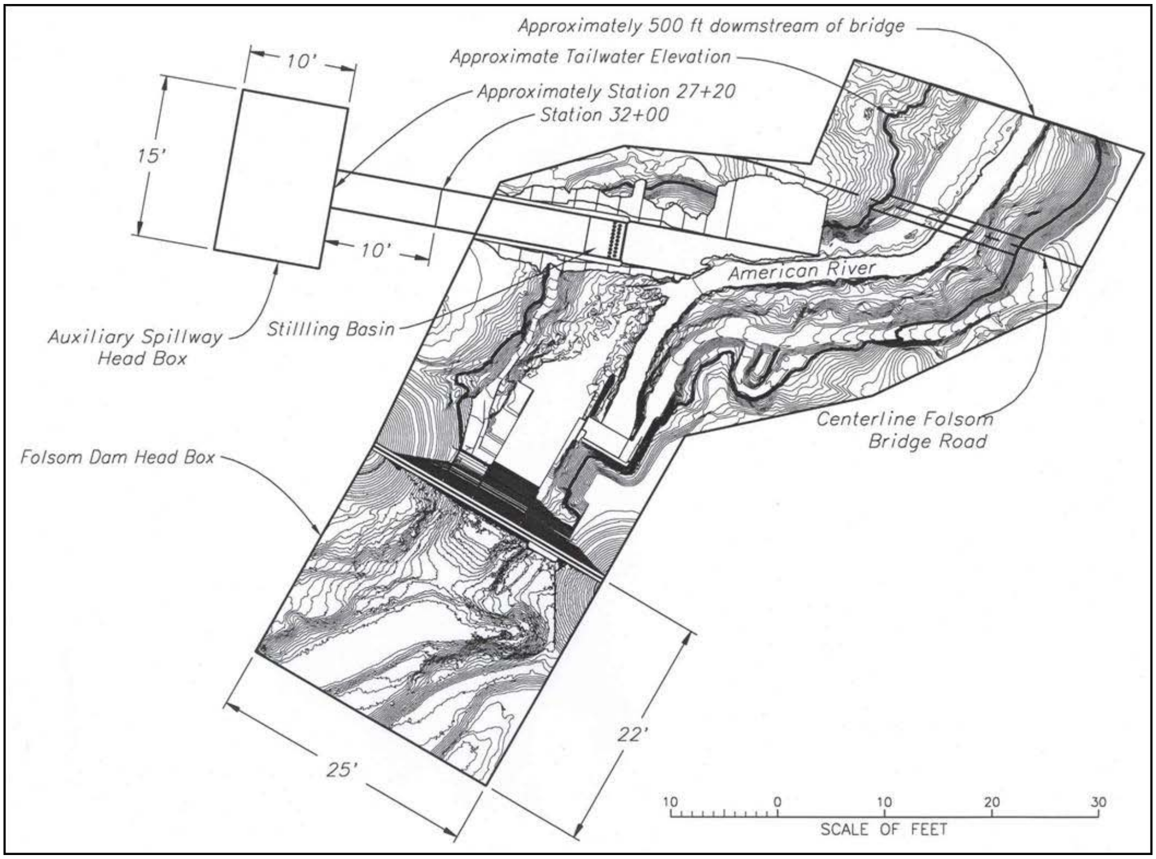

Figure 5. Plan View of 1:48 Scale Model of Folsom Dam Auxiliary Spillway Confluence Model.

Original Baffle Blocks

The original baffle blocks are a standard shape baffle block as shown in Figure 6, with a frontal area of 16 feet high by 12 feet wide, a flat top of 3 ft, a depth of 19 ft, and a 1:1 sloping back face to the floor. The original baffle blocks were installed and tested in the confluence model for effectiveness and robustness. The original baffle blocks produced acceptable energy dissipation for discharges up to 160,000 ft^3/s without any flow from the main dam. Tailwater sensitivity tests were conducted for flows of 115,000 ft^3/s and 160,000 ft^3/s. It was found that the tailwater could be lowered as much as 7.1 feet for discharges of 115,000 ft^3/s without significantly affecting the performance of the stilling basin. However at discharges of 160,000 ft^3/s, the stilling basin performance started to deteriorate after lowering the tailwater by only 1 foot (Svoboda et al. 2009). The basin started to surge where the hydraulic jump was rhythmically pushed out past the baffle blocks and then collapsed on itself. There was a point when the original baffle blocks became very sensitive to tailwater between the discharges of 115,000 ft^3/s and 160,000 ft^3/s. Figure 7 shows the flow scenario of 135,000 ft^3/s from the auxiliary spillway and 25,000 ft^3/s from the main dam for comparison of flow scenarios in following sections.

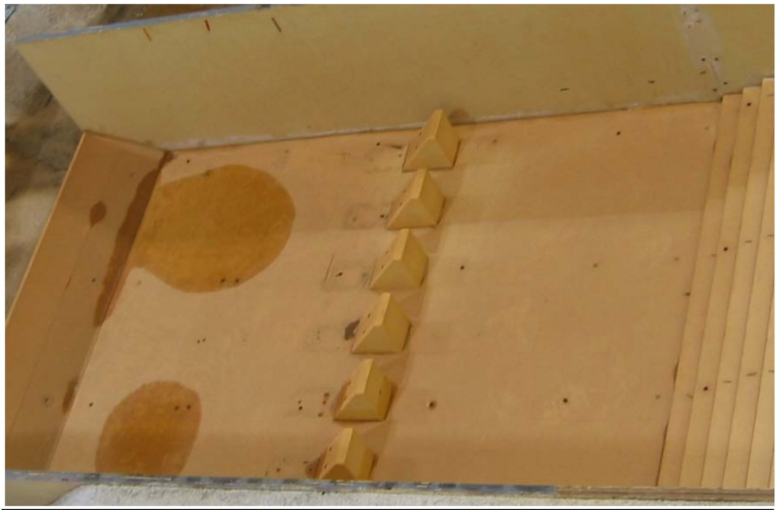

Figure 6. Original Baffle Blocks as installed in Confluence Model.

Figure 7. Original Baffle Blocks with an Auxiliary Spillway Flow of 135,000 ft^3/s and a Main Dam Flow of 25,000 ft^3/s.

Super-Cavitating Baffle Blocks

The super-cavitating baffle blocks have the same frontal area as the original baffle blocks with the face being 16 feet high by 12 feet wide and a 1:2 sloping back face. The super-cavitating block tapers from a width of 12 ft at the front face to a width of 4 ft. The tapered tail extends to a total block depth of 32 ft. The super-cavitating baffle blocks were installed with a ramp on the stilling basin floor to lift the cavitation away from the basin floor. The first round of testing incorporated the ramp in front of the super-cavitating baffle blocks, since this configuration produced the best cavitation reduction potential (Figure 8). However the performance of the stilling basin significantly changed from the performance observed earlier with the traditionally-shaped baffle blocks (Figure 7). The 4-foot-high ramp in front of the blocks was sufficient enough to create a large boil in the stilling basin that overtopped the walls (Figure 9). Numerous modifications to the 1:48 scale model were tried from reducing the height of the ramp to 2 feet and reducing the ramp from 3:1 to 1:1 slope with both the 4 foot and 2 foot high ramp were investigated. However, none of these modifications reduced the boiling to an acceptable level. The ramps were then placed in between the baffle blocks (Figure 10) as previously tested in the LAPC. A small boil still existed in the basin, but the stilling basin performance was deemed to be satisfactory (Figure 11). The selected combination of ramp and baffle block resulted in the best cavitation characteristics while still providing adequate energy dissipation.

Performance of the stilling basin with the super-cavitating baffle blocks and ramp appears to be less dependent on tailwater than the traditional baffle block configuration. During testing it appeared that the ramp deflected the flow at such an angle that the flow collapses backward toward the spillway. This seems to lessen the direct impact of flow on the blocks when the tailwater is low. For this specific application with discharges at 160,000 ft^3/s, the tailwater elevation could be lowered by 9 feet with acceptable stilling basin performance. The super-cavitating baffle blocks with a ramp appear to be more robust when it comes to sensitivity of basin performance in regard to tailwater elevation. Further research is needed to determine if this occurrence applies to typical Reclamation Type III stilling basin geometries and unit discharges.

Figure 8. Super-Cavitating Baffle Blocks with Ramp in Front of Blocks.

Figure 9. Super-Cavitating Baffle Blocks with Ramp in Front of Blocks, with an Auxiliary Spillway Flow of 135,000 ft^3/s and a Main Dam Flow of 25,000 ft^3/s.

Figure 10. Super-cavitating Baffle Blocks with Ramp in between the Blocks.

Figure 11. Super-Cavitating Baffle Block with Ramp in between the Blocks, with an Auxiliary Spillway Flow of 135,000 ft^3/s and a Main Dam Flow of 25,000 ft^3/s.

Summary

Physical cavitation modeling has shown that super-cavitating baffle blocks with a 1:3-sloped ramp on the basin floor reduces cavitation damage potential on the blocks and the stilling basin floor for high stilling basin entrance velocities of 83 to 109 fps. A 1:48 scale physical model of the Folsom Dam auxiliary spillway confluence area showed that there was a difference in the energy dissipation characteristics of a traditional baffle block and a super-cavitating baffle block with a ramp. Placement of a ramp upstream of the super-cavitating baffle blocks produced a large boil that overtopped the stilling basin sidewalls. When the ramp was moved in between the super-cavitating baffle blocks, the stilling basin performance was acceptable. Cavitation and energy dissipation goals were both achieved with this configuration.

Some unexpected results were observed during testing of the traditional baffle block and the super-cavitating baffle blocks and ramp in the 1:48 scale physical confluence model. The traditional baffle block shape design resulted in good energy dissipation with a well behaved hydraulic jump without excessive boiling in the basin. However, the potential cavitation on the stilling basin and baffle block concrete surfaces was unacceptable. A super-cavitating baffle block and ramp system with the ramps between the blocks was found to be superior (to the traditional shaped baffle blocks) from a cavitation potential standpoint and more robust in terms of tailwater sensitivity. The energy dissipation characteristics of super-cavitating baffle blocks (when ramps are included to ensure super-cavitating characteristics) are significantly different than the traditional baffle blocks of the same size. Additional research is warranted on the subject.

References

1. Svoboda, Connie D., Robert F. Einhellig, and K. Warren Frizell. (2009). "Hydraulic Model Study of Folsom Dam Joint Federal Project Auxiliary Spillway Confluence Area." Bureau of Reclamation, Hydraulic Laboratory Report HL-2009-05, Denver, Colorado.
2. Frizell, K.W. (2009). "Cavitation Potential of the Folsom Auxiliary Spillway Stilling Basin Baffle Blocks." Bureau of Reclamation, Hydraulic Laboratory Report HL-2009-06, Denver, Colorado.
3. Peterka, A.J. (1984). "Hydraulic Design of Stilling Basins and Energy Dissipators." United States Department of the Interior, Bureau of Reclamation, Engineering Monograph No.25.