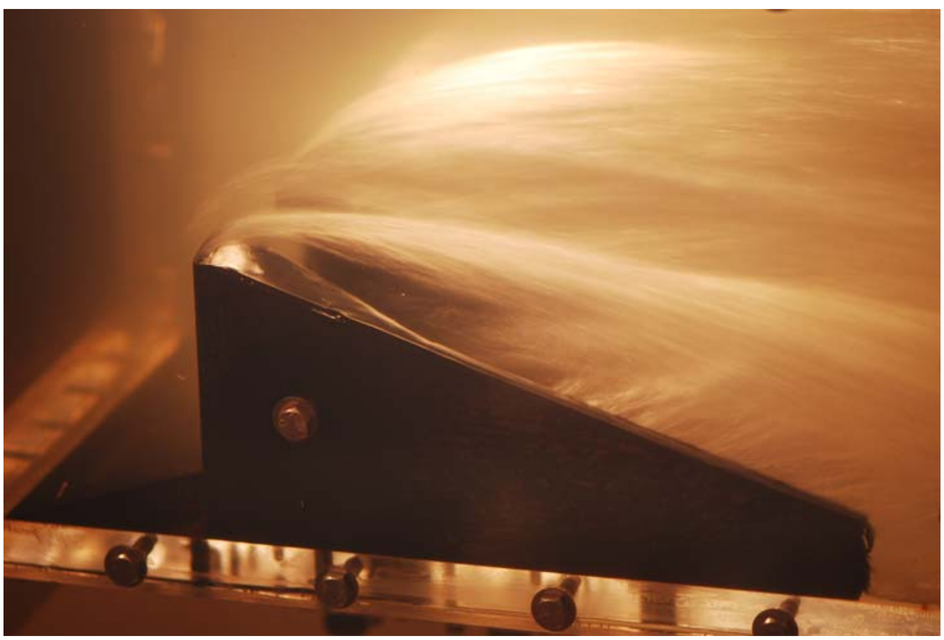
RECLAMATION

Managing Water in the West

Hydraulic Laboratory Report HL-2009-06

Cavitation Potential of the Folsom Auxiliary Spillway Stilling Basin Baffle Blocks

Laboratory Studies



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

December 2009

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
December 2009	**Technical**	n/a

4. TITLE AND SUBTITLE **Cavitation Potential of the Folsom Auxiliary Spillway Stilling Basin Baffle Blocks**	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) **K. W. Frizell**	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of the Interior Bureau of Reclamation, Technical Service Center Hydraulic Investigations and Laboratory Services Group DFC, 86-86460, PO Box 25007, Denver, CO 80225-0007	**8. PERFORMING ORGANIZATION REPORT NUMBER** **HL-2009-06**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Corp of Engineers Sacramento District – American River Design Section CESPK-ED-DR 1325 J Street Sacramento, CA 95814	**10. SPONSOR/MONITOR'S ACRONYM(S)** USACE **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161. http://www.ntis.gov

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Model studies were completed in Reclamation's hydraulic laboratory to evaluate the cavitation potential for the baffle blocks within the stilling basin of the new Folsom auxiliary spillway. Cavitation and resulting damage is expected from the standard block design, with the study goal to find a block shape that will minimize damage to the blocks themselves and the surrounding concrete floor. Reclamation's Low Ambient Pressure Chamber (LAPC) was used to evaluate the cavitation potential for various combinations of blocks and floor ramps. Finally once a block design was selected based on cavitation performance, the blocks were installed in the stilling basin of the 1:48 Froude-based scale model in Reclamation's laboratory. These tests showed that the block that performed best in the cavitation tests was unacceptable in the stilling basin tests. The floor ramp was moved downstream and between the blocks providing acceptable energy dissipation at the auxiliary spillway design flow of 135,000 ft^3/s. The cavitation characteristics were almost identical, with slightly higher potential for vortices to contact the floor near the blocks.

15. SUBJECT TERMS
Folsom Dam, Joint Federal Project, stepped spillways, energy dissipation, computational fluid dynamics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**a. THIS PAGE**			Robert Einhellig, Group Manager Hydraulic Investigations and Laboratory Services Group
UL	UL	UL	SAR	28	**19b. TELEPHONE NUMBER** *(Include area code)* 303.445-2151

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Hydraulic Laboratory Report HL-2009-06

Cavitation Potential of the Folsom Auxiliary Spillway Stilling Basin Baffle Blocks

Laboratory Studies

Prepared: K.W. Frizell
Research Hydraulic Engineer, Group 86-68460

Technical Approval: Robert F. Einhellig, P.E.
Group Manager, Group 86-68460

Peer Review: Joseph Kubitscheck, P.E.
Hydraulic Engineer, Group 86-68460

12/31/2009
Date

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

December 2009

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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.

Acknowledgments

Dane Cheek, Research Machinist constructed the lab model.

Hydraulic Laboratory Reports

The Hydraulic Laboratory Report series is produced by the Bureau of Reclamation's Hydraulic Investigations and Lab Services Group (Mail Code 86-68460), 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/HL/HL-2009-06.pdf**

Disclaimer

Cover Photo: New baffle block design in Reclamation's Low Ambient Pressure Chamber under supercavitating conditions.

Funding was provided by the USACE-Sacramento District

Contents

Figures

Summary

Model studies were completed in Reclamation’s hydraulic laboratory to evaluate the cavitation potential for the baffle blocks within the stilling basin of the new Folsom auxiliary spillway. This spillway features a novel design, combining high velocity flow on a smooth chute terminating in a stepped spillway section leading to a modified type III stilling basin. Velocities entering the stilling basin are over the recommended range for a basin with internal baffle blocks (>50 ft/s). Cavitation and resulting damage is expected from the standard block design, with the study goal to find a block shape that will minimize damage to the blocks themselves and the surrounding concrete floor.

Reclamation’s Low Ambient Pressure Chamber (LAPC) was used to evaluate the cavitation potential for various combinations of blocks and floor ramps. The LAPC is a closed system that allows the lowering of the ambient pressure within the model, enabling cavitation to form and be visualized at much reduced flow velocities. For a given block geometry, the cavitation parameter at various levels of cavitation activity (from incipient to super-cavitation) can be measured and used to predict prototype behavior. A sectional closed conduit model that featured a full central block with scaled spacing on either side and a half block against the side walls was used to evaluate cavitation properties of several block/ramp combinations. Incipient cavitation of bluff bodies (i.e. baffle blocks) is known to occur at relatively high cavitation numbers as compared to what is typical of cavitation along typical flow surfaces. An acoustic emissions sensor was used to evaluate the cavitation activity, and high-speed video allowed capturing of the cavitation type and location near the blocks.

A new style block with cut away sides and top and a floor ramp between the blocks was chosen as having the best combination of cavitation performance and basin performance. This second criteria was tested as the various blocks were installed in the stilling basin of the 1:48 Froude-based scale model in Reclamation’s laboratory. These tests provided verification that the energy dissipation characteristics were similar to the standard block design and that the stilling basin performance was acceptable at the auxiliary spillway design flow or 135,000 ft^3/s.

Background

Folsom Dam is located on the American River upstream and approximately 20 miles northeast of Sacramento, California. The dam was designed and built by the Corps of Engineers (Corps) as part of the Central Valley Project and transferred to the U.S. Bureau of Reclamation (Reclamation) for operation and maintenance in 1956. The dam is a concrete gravity structure 340-ft high and impounds a reservoir of a little more than one million acre-ft. Folsom Dam is a multipurpose facility providing hydropower generation, flood control, water supply storage, and recreational opportunities. Folsom Dam's active storage capacity (El. 329.3-468.3 ft, NAVD 88) of approximately 900,000 acre-ft provides the primary source of flood control storage in the American River basin.

The dam features include two tiers of four outlets each, controlled by 5- by 9-ft slide gates. The outlets consist of rectangular conduits of formed concrete passing through the dam and exiting on the face of the service spillway. As a result of legislation approved in 1999, the Corps of Engineers secured funding to begin studies and designs that included enlargement of the outlets at Folsom Dam. The main objective of the enlargement was to reduce the risk of flooding in the Sacramento area by increasing the release capacity of the dam to 115,000 ft^3/sec for a reservoir level at the spillway crest elevation of 420.3 ft (NAVD 88). Physical hydraulic modeling of the proposed outlet enlargements was conducted at Reclamation's hydraulic laboratory in support of this design effort. This plan was subsequently abandoned over concerns related to the uncertainty and costs of constructing these enlarged outlets.

Legislation approved in 2002 authorized the Corps to begin additional flood-protection studies and designs that included a possible raise of Folsom Dam. Concurrently, Reclamation began evaluating dam safety concerns related to the ability of Folsom Dam to safely pass the revised Probable Maximum Flood (PMF). The need to provide additional discharge capacity at Folsom Dam was identified as a requirement for both of these efforts. It was decided that the Corps and Reclamation would combine the two studies and come up with a solution that would safely pass the PMF as well as meet flood-damage reduction objectives.

The resulting project concept includes constructing an auxiliary spillway near the left abutment of the main dam embankment. The auxiliary spillway would include a gated control structure, an approach channel from the reservoir to the control structure, a 169-foot-wide rectangular, concrete-lined chute, a stilling basin, and an exit channel back to the American River. The final 600 feet of the chute will be stepped as it drops into the stilling basin to aid in energy dissipation.

Several physical hydraulic model studies have been conducted in support of the auxiliary spillway design effort. These studies included a 1:30-scale model of the auxiliary spillway control structure, a 1:26-scale model of the auxiliary spillway channel and stilling basin, and a 1:48-scale model of the confluence area where the auxiliary spillway channel rejoins the American River channel. Cavitation related studies for the auxiliary spillway stepped chute and the stilling basin baffle blocks have been completed.

This report will summarize the studies of the cavitation potential of several baffle block configurations within the modified type III stilling basin. These studies were performed in Reclamation's hydraulic laboratory using the low ambient pressure chamber (LAPC) at the Technical Service Center (TSC) in Denver, CO.

Methods and Materials

The low ambient pressure chamber is a unique facility that allows the ambient pressure within a model to be reduced such that cavitation can form and be observed at reduced flow velocities. The LAPC is a large elevated steel tank that can accommodate both free surface and closed conduit-type hydraulic models, figure 1. The closed circuit hydraulic system features a pump with a capacity of 10 ft^3/s and a vacuum pump that will allow the ambient pressure within the chamber to be reduced to between 0.08 and 0.1 atm (around 1 lb/in^2 absolute on a typical day in Denver).

The Folsom auxiliary spillway stilling basin has extremely high flow velocities entering the basin. At the design specific discharge of 800 ft^2/s (discharge per foot of width), the resulting calculated mean velocity entering the basin is about 85 ft/s and at the maximum specific discharge of 1775 $ft^2/2$ the velocity reaches above 120 ft/s. In order to model the corresponding cavitation parameters appropriately, a closed conduit was chosen over an open channel model to ensure high enough model velocities and minimize problems that would be associated with free surface air entrainment. The test section was constructed of clear acrylic and the baffle blocks machined from aluminum. Well into the test program, we modified a half block, machining it from clear acrylic to allow observation of the area between the blocks. The basic dimensions of the test section were 12-in by 8-in. The block height was one-half that of the test section and with a full block and two half-blocks modeled, 25-percent of the cross-sectional area was effectively blocked. When a 4-ft-high ramp was added, an additional 6.26-percent was blocked for a total of 31.25-percent blockage. Resulting velocities at the test section were calculated based on this reduced area. The cavitation parameter is defined as: $\sigma = \frac{\left(P_{amb} + P_o - P_v\right)}{\rho V_o^{\,2} / 2}$, where P_{amb} is the reduced ambient pressure in the chamber, P_o is a reference pressure, P_v is the vapor pressure of water, ρ is the water density, V_o is a reference velocity. The reference pressure was measured just downstream from the baffle blocks and the reference velocity was simply the mean velocity with blockage included.

The test section was located between a pressure tank and a bulkhead wall within the chamber. The area downstream from the bulkhead allowed the reduced ambient pressure to act on about 10 ft^2 of water free surface, figure 2.

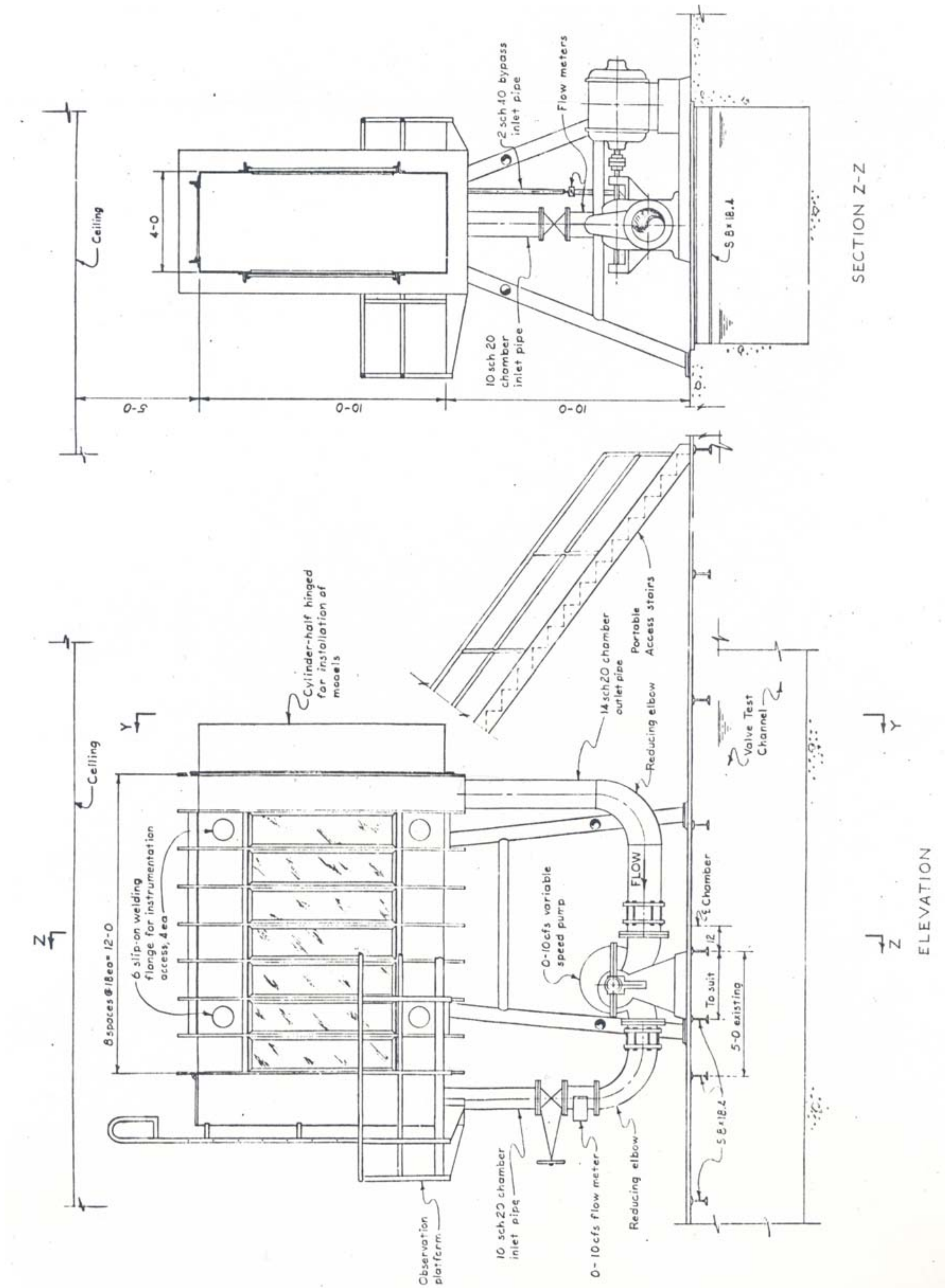


Figure 1: Low ambient pressure chamber (LAPC) in Reclamation's hydraulic laboratory.

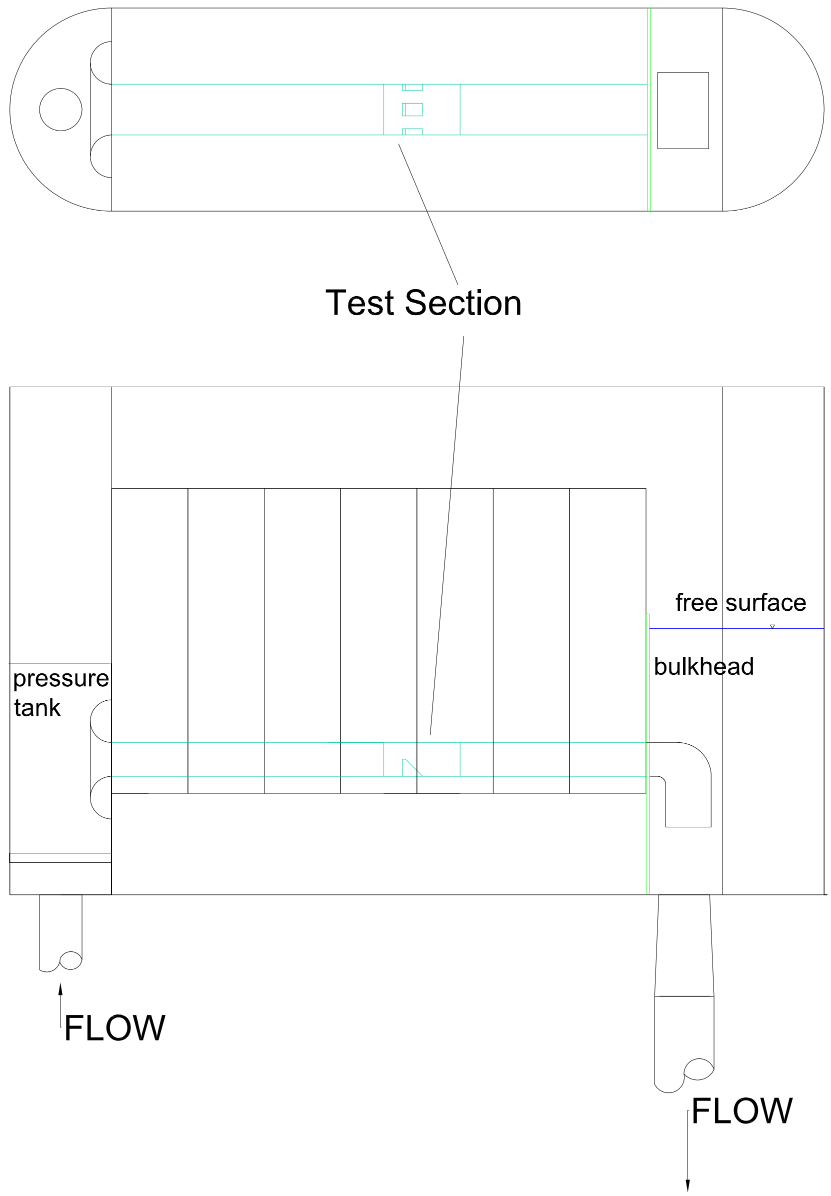


Figure 2: LAPC with test section noted, showing closed conduit operation.

Operation of the LAPC for testing consisted of filling the model with Denver city tap water. Once the pressure tank was filled and the free surface well above the crown of the outlet (about 1.5-2 ft), the vacuum pump was started and the water was circulated at a slow rate. Ambient pressure reduction occurs quickly at first and then slows as the chamber pressure nears 0.1 atm. As the vacuum is applied, free gas is pulled from the fluid and escapes into the reduced atmosphere at the free surface downstream from the bulkhead wall. Typically de-gassing of the water was performed for 6-8 hours prior to the collection of any data, this time varied somewhat depending on water temperature and atmospheric conditions. A test run began with reading the barometer, the chamber vacuum gage and then setting the discharge to 1.75 ft^3/s. The laboratory barometer is a Fortin-type NovaLynx Model 230-7410 with accuracy of ±0.01 in Hg. The vacuum gage and flow meter are permanent instruments of the LAPC. The discharge was increased by increments of 0.35 ft^3/s up to the maximum flow possible, usually about 10 ft^3/s. Data were collected at each flow condition using a laptop computer and data acquisition equipment from IOTech. The center block featured a stinger that was connected to a load cell arrangement. Load cells from Transducer Techniques (10 lb) were connected such that relative loading due to flowing water could be sensed in the vertical and streamwise directions. The arrangement did not allow measurement of the pure directional load as moments were also included in the measurements. Relative comparisons were all that were attempted due to these limitations. Placement of the ramps, particularly in-between the blocks restricted the movement in both directions such that the load cell data was meaningless (i.e. block movement was restricted). Acoustic emission signals were used to sense cavitation activity. Data were recorded over a period of about 45 seconds. During this time period the RMS signal levels of two different frequency ranges were recorded along with the number of counts exceeding a threshold level of activity. The AE sensor and conditioning equipment were manufactured by DECI. The sensor was a model SE9125-M, a hybrid transducer that is mass loaded with a large aperture in order to be equally sensitive to both extensional and flexural waves. The signal conditioner, a model AE1000 provided splitting of the signal into the two different frequency ranges, 20 kHz -70kHz (LF), and 100kHz-1 MHz (HF). The extensional and shear waves always appear in the high frequency bandpass and the flexural wave in the low frequency bandpass. In plane and out-of-plane noise sources both produce shear waves that are nondespersive which are typically higher in amplitude than extensional waves if present. A reference pressure level just downstream from the block location was measured with a 10 psid Sensotec model KZ pressure transducer (accuracy 0.25-percent full scale). High-speed video was acquired using a Vision Research, Inc. Phantom v4.2 digital camera and associated software. A macro/zoom lens allowed close ups to be recorded from outside the chamber through the acrylic windows. The videos were shot at 2000 frames/s and replayed at much slower rates to allow for observation of flow details.

Testing and Results

The test program consisted of several different block configurations. They are shown in figures 3-7. The original blocks featured a frontal area of 192 ft^2 (12-ft-by-16-ft). The preceding ramp encroached on this area, reducing it by 25-percent. The ramp was intended to lift the flow from the floor in the area of the block to reduce the chance that cavitation damage would occur close to the blocks. The original block design featured 6-in chamfers on all sharp edges. In the development of the structural design for the modified blocks, this chamfer was reduced to only 0.75-in prototype and thus was completely left out in the modified model blocks due to scale.

The reasoning to prefer a supercavitating condition around each baffle block is to negate the possibility of cavitation damage on the blocks themselves. Supercavitation is a term used to describe the use of cavitation effects to create a gas filled bubble or cavity within the flowing water. Traditional applications have largely been in the area of high-speed water vehicles (hydrofoil-based) and torpedoes. The increase in speed is possible due to a reduction of almost 1000 times in the drag of the object in a gas versus liquid. In our case, enveloping the baffle block within a vapor/gas filled cavity essentially removes the possibility for cavitation damage on the blocks. As the majority of the drag on the blocks (i.e. energy dissipation) is due to the block shape and not due to friction on the block surfaces themselves, then the energy dissipation characteristics of a supercavitating block should be similar to a block operating in a normal flow regime.

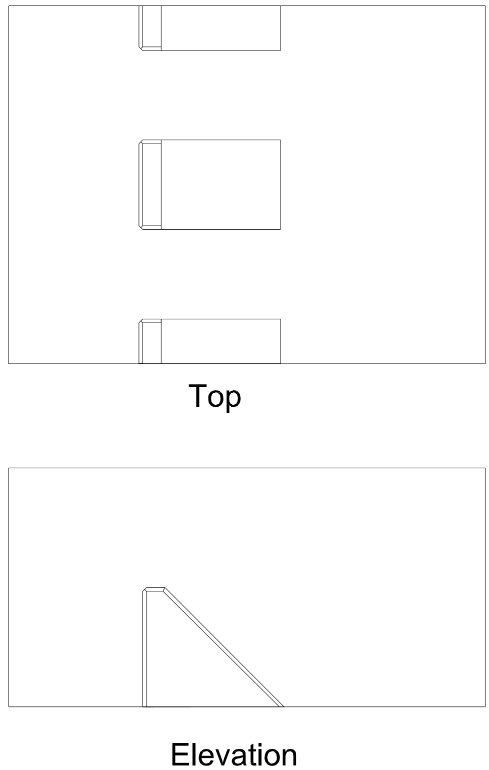


Figure 3: Original block design. Figure shows configuration tested in the LAPC.

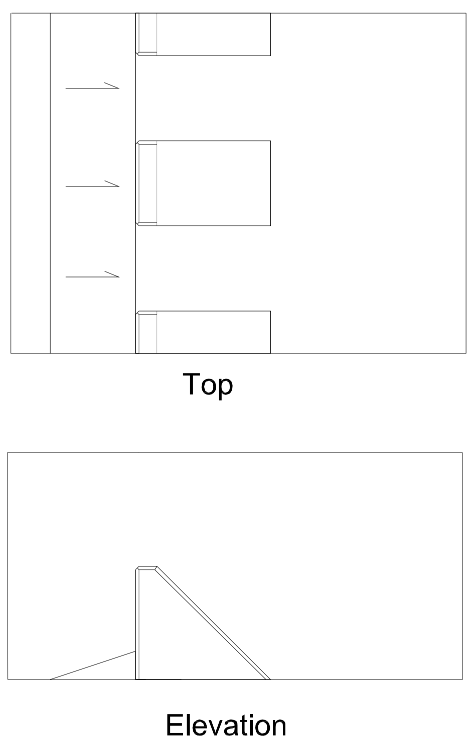


Figure 4: Original block design with a 1V:3H ramp preceding the blocks. Ramp is 4 ft high.

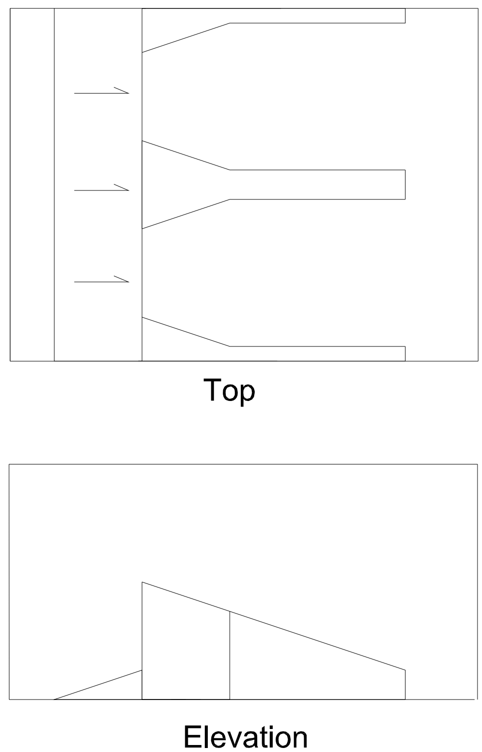


Figure 5: New block design with preceding ramp. Block features a shape that will provide for supercavitation. Ramp is 1V:3H and is 4 ft high.

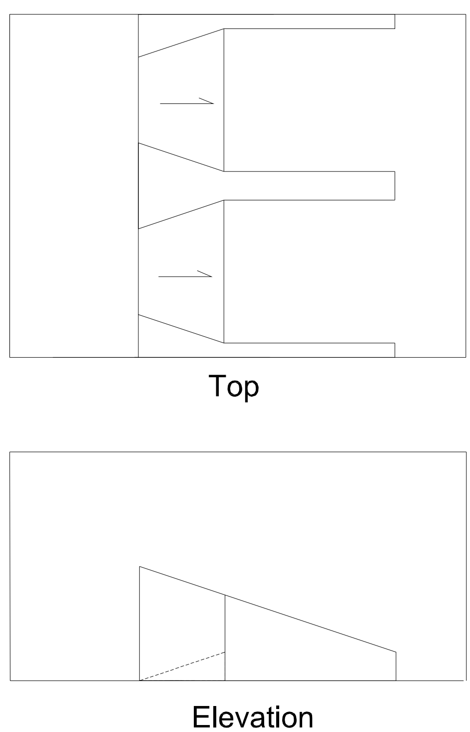


Figure 6: New block design with a 1V:3H ramp placed between the blocks. Ramp begins at block face and is 4 ft high.

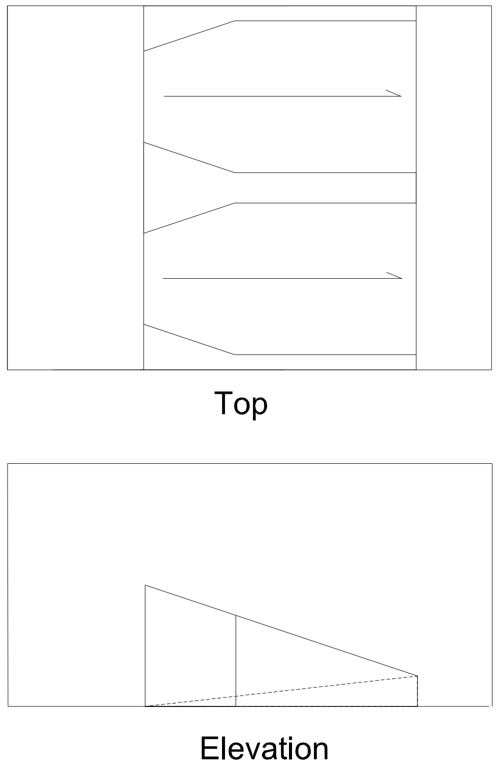


Figure 7: New block design with a 1V:9H ramp place between the blocks. Ramp begins at block face and is 4 ft high.

Incipient cavitation in all cases began with the formation of a horseshoe vortex on the center block, slightly above the floor (or ramp) elevation. This vortex began at relatively high values of the cavitation parameter and became visible, most likely with a combination of water vapor and free gas. Initial thoughts that the horseshoe vortex would be responsible for likely damage downstream from the block were dispelled with the aid of the high speed videography, indicating that the vortices were simply carried downstream, remaining about the same elevation above the floor. The horseshoe vortex is shown in figure 8 and the formation of the damaging cavitating vortices downstream of the blocks is shown in a series of photos in figure 9.

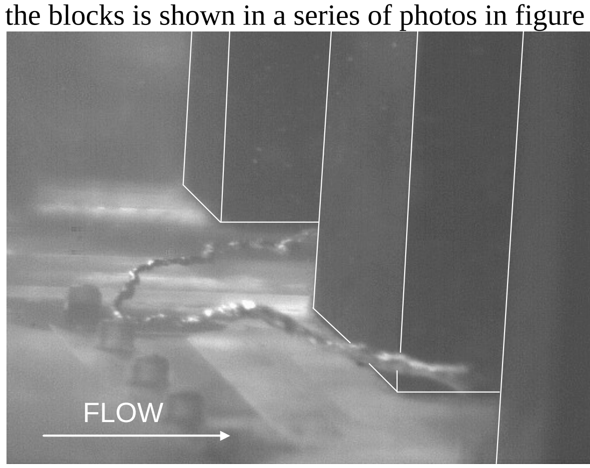


Figure 8: Horseshoe vortex at inception, in front of center block - original design. Front of blocks are outlined in white. Vortex is approximately 0.5 inches above the floor in the model.

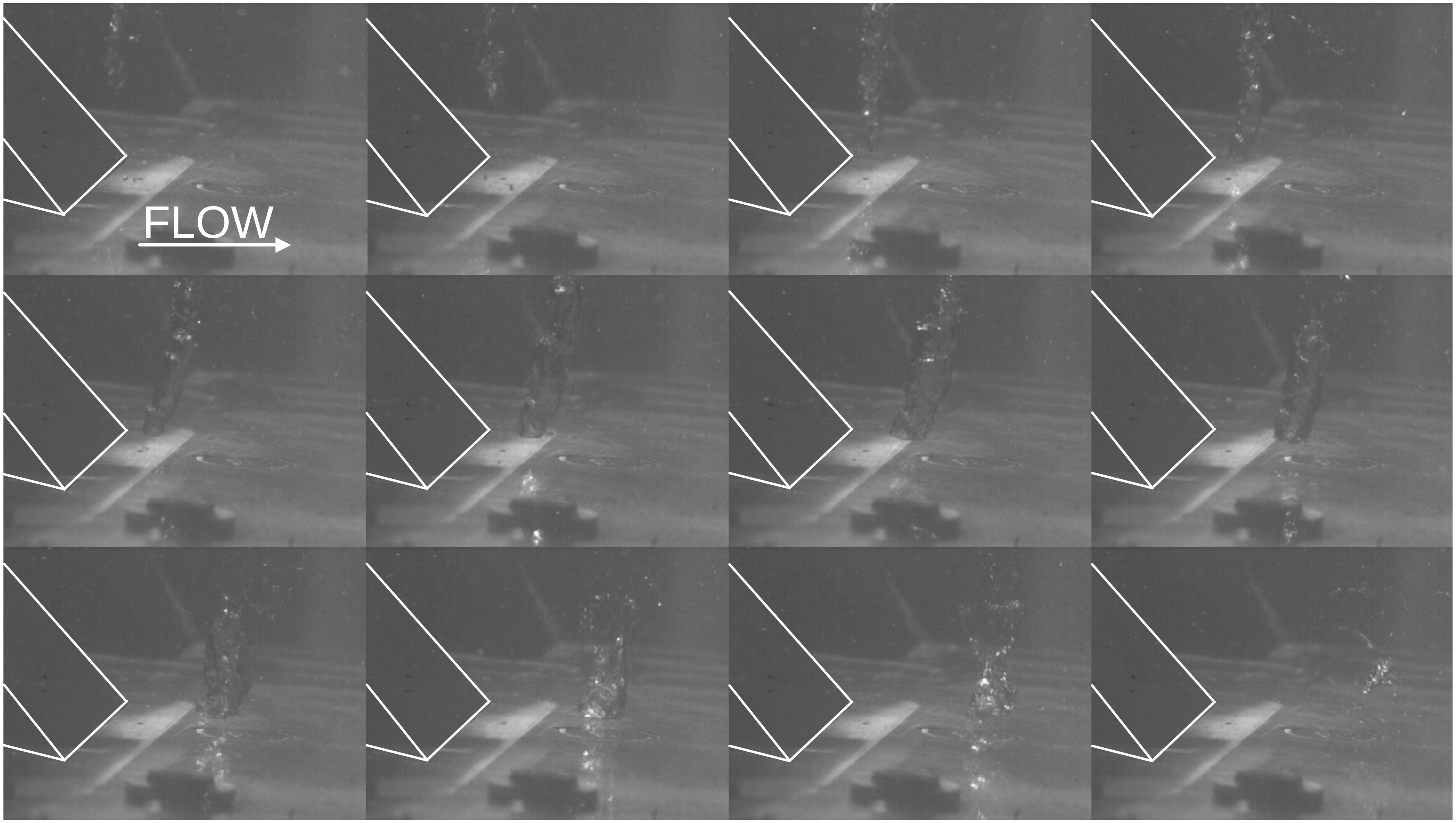


Figure 9: Series of snapshots showing the formation of a floor-attached traveling vortex downstream from the back corner of the center block. Rear portion of the center block is outlined in white. The frame order is left to right, top row, middle, then bottom (time between frames is 0.0005 s).

As the cavitation parameter is reduced further (increasing velocity), attached bubble cavitation forms on the horizontal portion of the tops of the blocks and sporadically along the vertical side leading edges, figure 10. At the point of maximum velocity and minimum ambient pressure (minimum σ), heavy cavitation is formed in all the shear layers surrounding the blocks and on the blocks themselves, the floor attached vortices are especially large and intense, figure 11. This standard design block did not form a completely ventilated cavity characteristic of super cavitation within the flow conditions possible in the LAPC.

The second condition tested (figure 4) added a 1V: 3H ramp preceding the standard block. The ramp resulted in some similarities but also provided some improvements. The horseshoe vortex was still the first type of cavitation to occur. However the floor attached vortexes downstream from the block corners did not form. There was some evidence of the vortex formation well up on the block but they did not attach to the floor and travel downstream, figure 12. The influence of the ramp also allowed a ventilated cavity to form, figure 13.

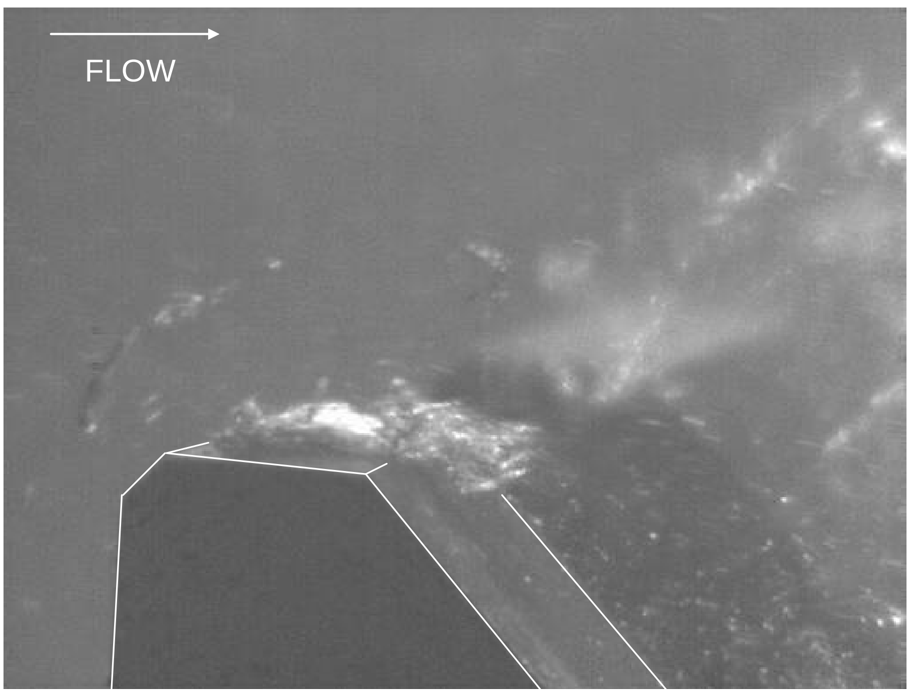


Figure 10: Bubble cavitation attached to the horizontal surface of the block top. View shows a half block adjacent to the side wall for clarity.

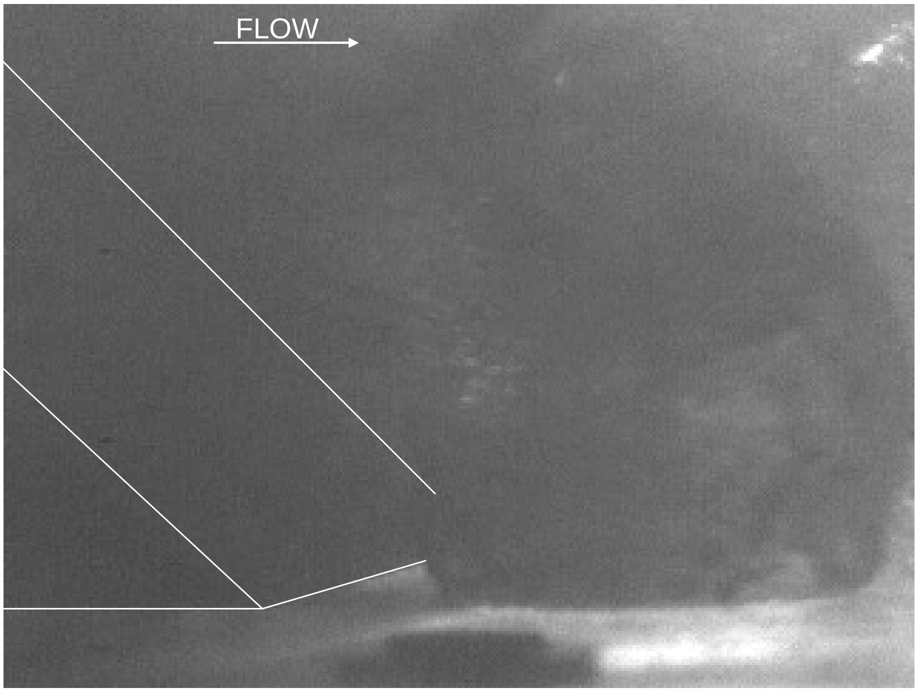


Figure 11: Heavy cavitation downstream from center block. Note the size of the floor-attached vortex, a significant damage producer.

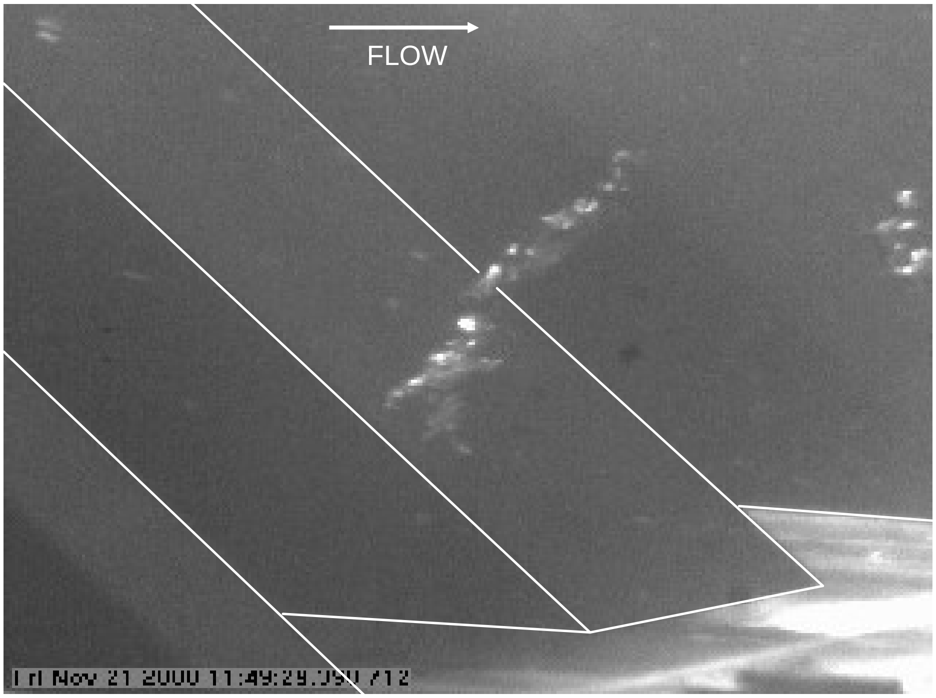


Figure 12: Downstream from original block with preceding ramp. Note vortex formation is well above the floor and moves downstream without attaching to the floor.

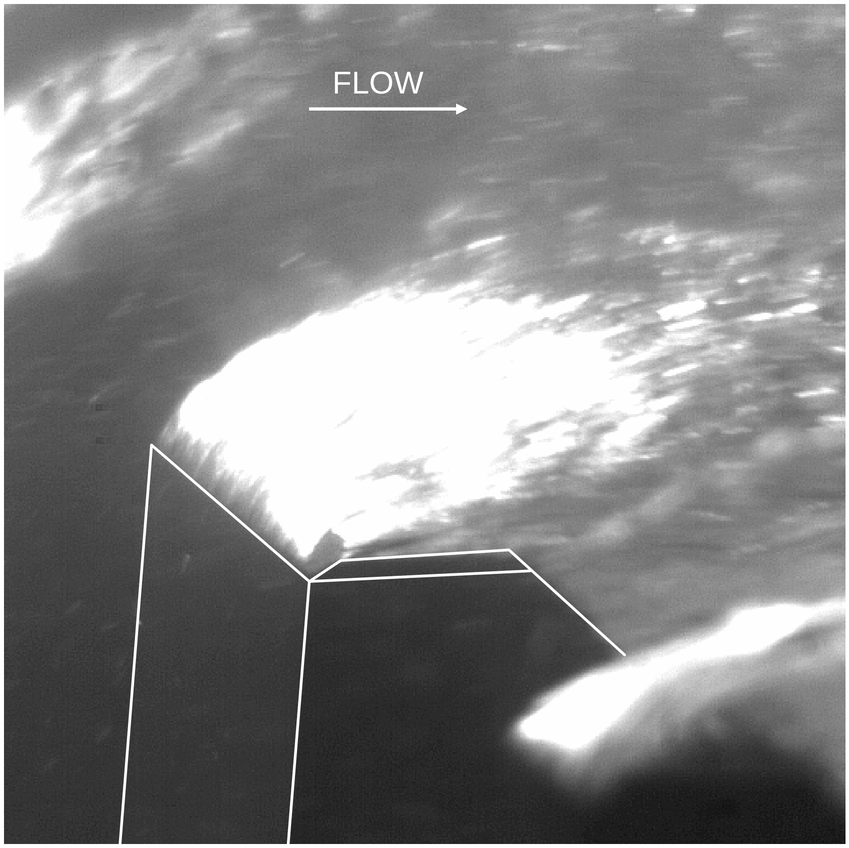


Figure 13: Original block with preceding ramp. Middle block front showing ventilated cavity (wake) supercavitation.

Both the standard block design options (w/wo ramp) were not able to operate free from cavitation. The original block had cavitation attached to the block surfaces that would likely result in damage to the block. In addition, floor-attached vortices that formed in the free shear layers downstream from the block will damage the basin floor. With a ramp preceding the standard block, the floor attached vortexes downstream from the blocks were negated; however there was still attached cavitation on the block top and side surfaces.

The modified block shape was a combination of various ideas, some previously tested by others, some not. The main goal was to provide a sharp edge for separation and then cut away the side and top surfaces such that any cavitation would not attach, with a final goal that the block operate with a supercavitation "bubble" enveloping the entire block. This phenomenon, typically used for high-speed underwater propulsion, would create a damage-free zone around the baffle block.

Incipient cavitation on the modified block was again in the form of a horseshoe vortex out in front of the block near the ramp surface. This was expected as the frontal projection of the block was unchanged from the standard design. As the velocity is increased (σ reduced), cavitation forms within the free shear layers in the wake of the block (figure 14). As the testing progressed, we modified the half-block on the right wall by constructing it from clear acrylic in order to improve visibility between blocks. This enabled observation through the block and into the area between the blocks, revealing an area that had been hidden previously. Figure 15 shows a similar flow condition but with the clear block in place. There are many vertically oriented vortices that form in the shear layer downstream from the vertical side edges of the blocks and these get stretched and pulled (angled) downstream when they encroach on the main flow above the blocks (figure 15). Supercavitition conditions for all combinations of the new block and ramp configurations were steady and highly repeatable, figure 16.

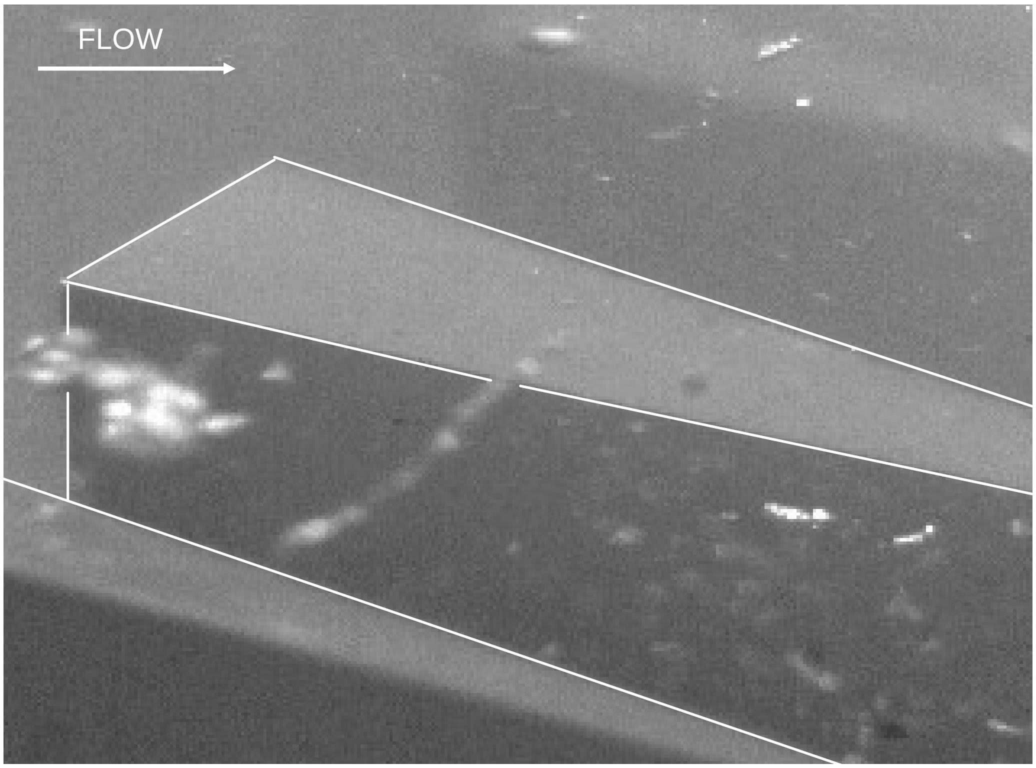


Figure 14: New tapered block with incipient cavitation. All cavitation appears within the free shear layers in the wake of the block with no attachment to solid surfaces.

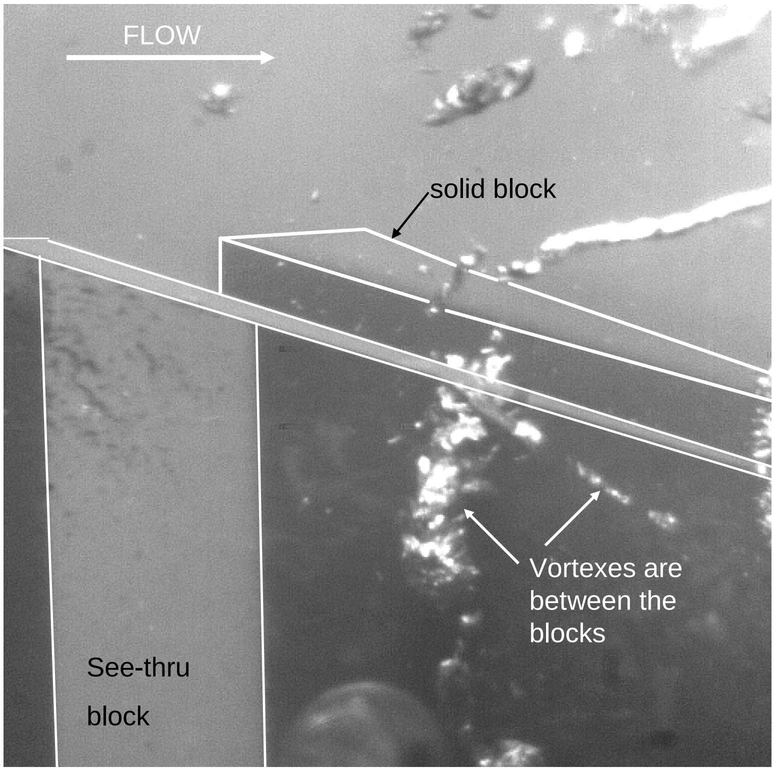


Figure 15: New tapered block with see-thru half-block. Incipient cavitation in the shear layer - note vortex formation between blocks that was hidden from view previously. some distortion due to refractive index of the acrylic block.

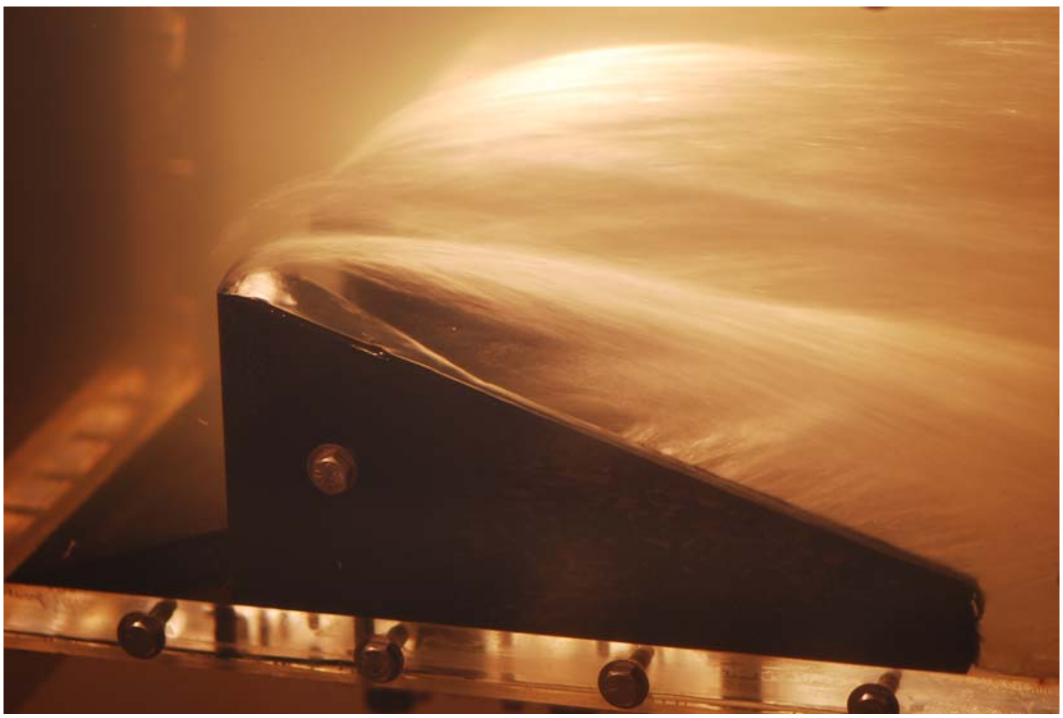


Figure 16: Supercavitaiton with new block and preceding ramp. Note blocks are "dry" beneath a cleanly separated cavity boundary with the main flow.

As noted previously, several block/ramp configurations were tested. In general the main part of the flow field was identical to that shown in figures 14 and 15. Differences in the placement and inclination of the floor ramp did cause some differences in the flow patterns near the floor. The shorter length ramps appeared to do a better job in disrupting the flow patterns with only some random attachment of vortices. The long 1V:9H ramp between blocks protected the area downstream from the blocks, however, the area between blocks along the ramp surface had many vortices attach and dissipate near the ramp surface.

The use of acoustic techniques has been a proven and accepted method for determining incipient and or desinient cavitation levels. Incipience is the beginning of cavitation while desinience is defined as the end of cavitation; typically there is some hysterisis in these values. Usually a hydrophone, dynamic pressure transducer, or high-frequency accelerometer are used as the sensor in this technique. We began using acoustic emissions sensors several years ago to determine cavitation activity within hydro machinery with the intention of being able to separate cavitation within the fluid stream from cavitation that was impacting physical parts of the turbine that could result in damage. We've had varying levels of success, mostly due to the complex geometries of most Francis turbines and the inability to easily locate the sensor on the rotating part of the turbine. We found good correlation with AE activity and damage to draft tube liners as these were relatively easy to instrument.

The technique we used involved looking at two band limited frequency ranges. Initially we used the ASL (average signal level or RMS) as a means to document acoustic emission activity. Figure 17 shows the comparison between the original design and the new block, with a couple ramp configurations, using the average signal level in the high frequency bandwidth (100 kHz – 1 MHz). There is a clear determination when vortex formation begins. In addition, you can clearly see when the cavity vents and envelopes the block (about $\sigma = 0.88$). The original block design did not vent, i.e. supercavitation did not occur for the range of conditions possible within the model. The new block with the short ramp between the blocks transitioned to supercavitation at a slightly lower sigma value (0.78), likely due to the modified flow field between the blocks.

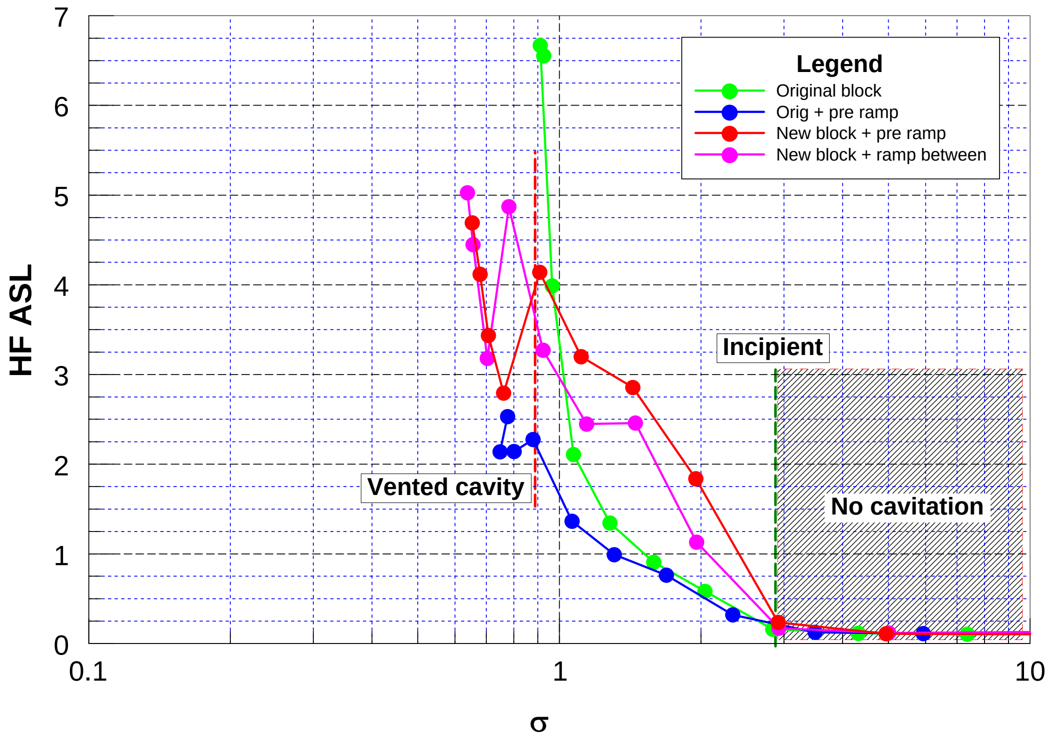


Figure 17: Comparison of the HF average signal level over about 30 s for four different configurations tested.

The AE technique was refined somewhat as the testing progressed. We settled on a counting method – fairly typical of acoustic emission processing for other types of data. The most repeatable and sensitive method was to count the occurrences that the rectified waveforms of the HF signals exceeded a threshold value. In addition collection of data at finer increments of changes in the cavitation parameter (discharge) proved valuable in refining the data. Figure 18 shows an interesting comparison of the use of a more traditional pressure transducer technique compared to this revised AE sensor technique for the new block with preceding ramp. Interesting to note here is the increased sensitivity of the AE technique. The pressure transducer did not pick up the formation of the horseshoe vortex or the initial formation of vortexes in the free shear layers surrounding the block. They both indicated the beginning of the attached cavitation (AE sensor by an increase in rate of counts) and the onset and establishment of supercavitation (dynamic pressure counts dropped off and the AE count rate decreased).

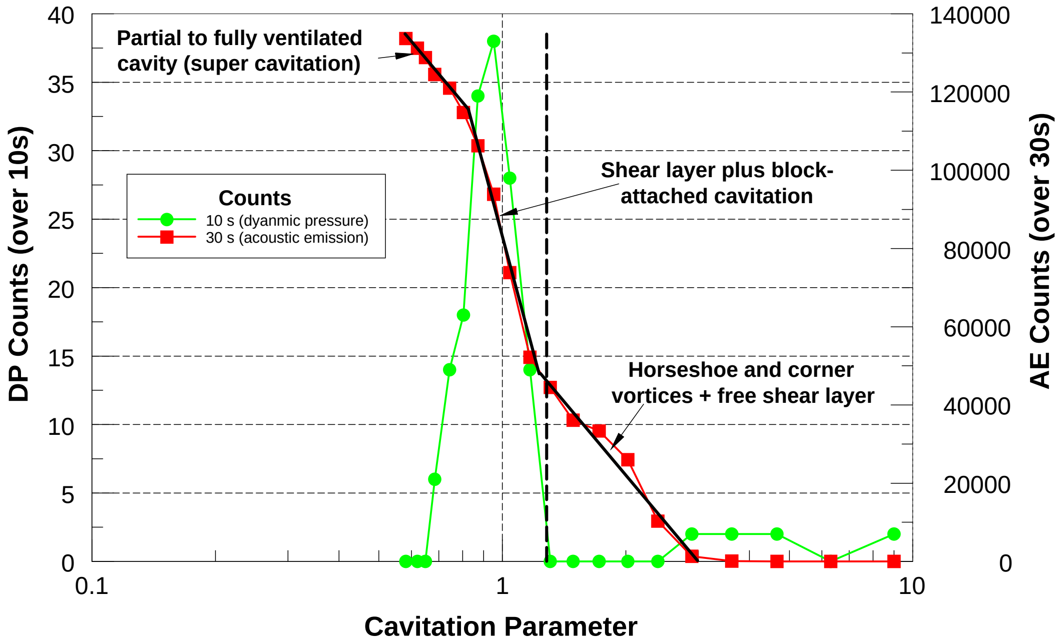


Figure 18: Comparison of refined AE counting technique to more traditional dynamic pressure sensor.

The long ramp, a modification of the floor area between the blocks, showed only slight differences in the shape of the curve but no differences in the important points, i.e. inception and transition to a vented cavity. From the testing completed in the LAPC using a combination of AE data and model high-speed videos, the new block design with preceding ramp seems to have the best performance from the standpoint of minimizing organized cavitation activity in areas near the block that could possibly be damaged. When the short ramp moved between the blocks only slight differences were noted in actual performance. The long ramp definitely had more bubbles, cavities, and vortices close to the ramp surface, possibly indicating a higher probability of damage. The new cut-back block design did not have any attached cavitation for any of the flow conditions or ramp configurations tested.

Application and Discussion

Application of the new block designs and cavitation inception are really two fold. One problem is to apply the data that was collected in the sectional closed conduit model to the actual open channel stilling basin that will be built at Folsom. The other issue is how the new blocks will perform regarding stilling of the flow within the basin. The COE provided a slightly modified block shape (slope on top of block was steepened from 1:3 to 1:2 resulting in a shorter overall length) and we tested this block and various block/ramp configurations in the stilling basin of the 1:48 scale model in the Denver laboratory.

Initially the new block design with a 1V:3H, 4ft-high preceding ramp was installed in the model, figure 19. When operating at the design discharge of 135,000 ft^3/s in the auxiliary spillway and 25,000 ft^3/s coming from the main dam, basin performance was deemed not acceptable. The preceding ramp raised the water surface just downstream from the blocks, overtopping the basin walls, figures 20 and 21. In addition a secondary hydraulic jump formed over the end sill.

Figure 19: New block design with 1V:3H, 4-ft-high ramp preceding the blocks.

Figure 20: Basin performance at Q_{aux} = 135,000 ft^3/s, Q_{main} = 25,000 ft^3/s. Note undulating water surface and secondary hydraulic jump.

Figure 21: Side view of basin performance, showing extent of water surface above basin walls.

Tests with a 1:1 4-ft-high preceding ramp as well as a 12-ft-long by 2-ft-high preceding ramp did not show improvement. Overall, the best basin performance was noted with the new block with the 1V:3H, 4-ft-high ramp between the blocks, figure 22.

Figure 22: New block with 1V:3H, 4-ft-high ramp between the blocks, beginning at the upstream face of the blocks.

The basin performance at the design discharge was much improved and acceptable. There was little difference noted between this and the performance with the standard baffle block originally installed. Figures 23 and 24 show views of the basin performance in the 1:48 model at the design discharge conditions.

Figure 23: New block with 1V:3H, 4-ft-high ramp between blocks at the design discharge.

Figure 24: Side view of basin performance with new block and internal 1V:3H ramps. The ramps are 4-ft-high and begin at the upstream face of the blocks. Note improved uniformity in water level downstream from the blocks. Secondary jump still present.

The cavitation data that were collected are characteristic of particular block geometries. Incipient cavitation and the development of cavitation up to and including the transition to supercavitation can all be tied to dimensionless parameters. The key is to correctly apply the cavitation parameter to discern at what conditions similar behavior can be expected in the prototype stilling basin. More specifically, the reference pressure and velocities are needed at various flow conditions in order to evaluate the prototype cavitation number.

For the auxiliary stilling basin, the reference pressure can be chosen as the depth in the stilling basin just downstream from the blocks. The reference velocity is a bit harder to specify. For design purposes, it is reasonable to assume the mean velocity of the flow entering the basin. This will in turn be conservative as the velocity that is felt at the baffle blocks likely will have decayed some prior to impact. Blockage effects are not important to the prototype basin as the water surface is free to adjust to any such effects. So by using model data and some flow parameters from a 1-D water surface profile program, a curve of velocity versus the cavitation parameter can be calculated for the auxiliary spillway operation up to its maximum flow. In calculating the prototype cavitation parameter, we assumed standard atmospheric pressure as well as vapor pressure of water and used the reference quantities described previously. On this curve then the cavitation parameter values for inception and transition to supercavitation can be noted and thus the tie-in to actual spillway operation can be observed, figure 25.

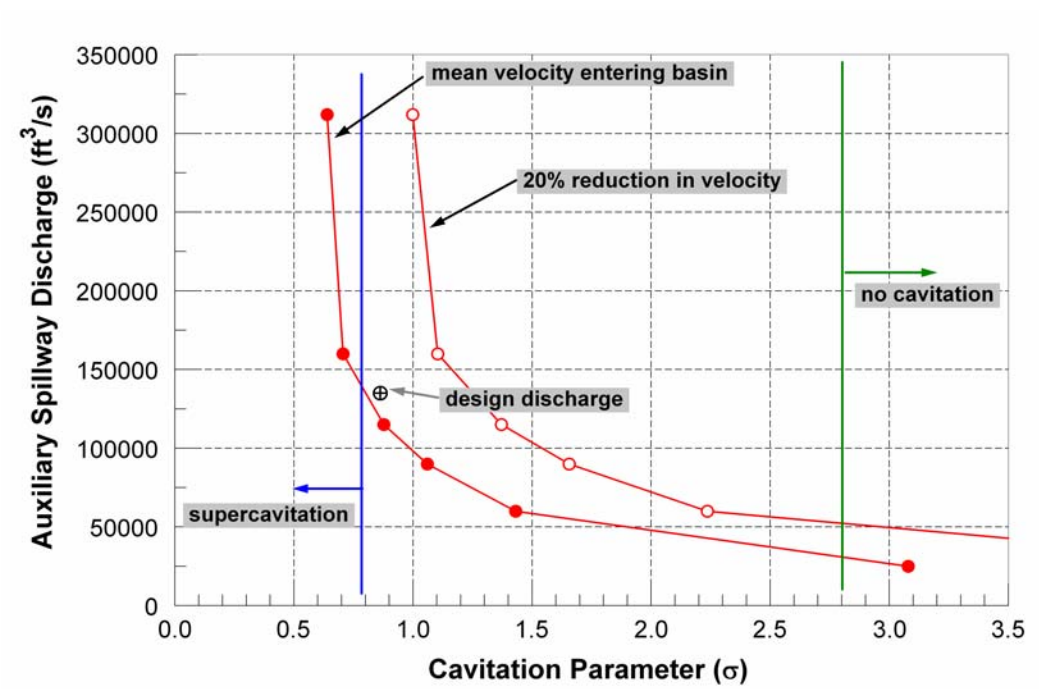


Figure 25: Using LAPC cavitation data to observe conditions within the prototype auxiliary stilling basin. Inception and transition to supercavitation values were chosen based on the new block design with internal 1V:3H, 4-ft-high ramps.

In addition on figure 25 we have shown a sigma curve based on a 20-percent reduction in the incoming velocity. This may be characteristic of a typical decay within a hydraulic jump based on the longitudinal location of the baffle blocks (Rouse et.al. 1958). This reduced velocity would cause a later transition to cavitation (~50,000 ft^3/s), and would not transition to a fully ventilated cavity.

The design featuring ramps in between the blocks resulted in a slightly lower sigma value before the transition to a fully ventilated cavity (supercavitation). The preceding ramp designs, whether with the new block or the standard block, would have both indicated a transition to supercavitation at or slightly below the design discharge (~110000 ft^3/s). This feature while it may be a desirable condition resulted in non-containment of the flow at the design discharge of 135,000 ft^3/s (figure 21).

In all block designs, the first visual evidence of cavitation was in the form of a horseshoe vortex slightly above the floor or ramp and wrapping around the central block. The standard block design also had damaging floor attached vortices form at almost the same time with intensity and size steadily increasing with velocity (reduction of the cavitation number). These vortices are formed in the free shear layers on the sides of the block but travel down along the sloping back of the block and attach to the floor near the intersection of the corners of the block and the floor. These vortices remain attached and travel downstream a short distance before implosion. The location of these vortexes and the implosion zones are characteristic of previous damaged areas that have been noted in prior studies and prototype installations. In addition to these traveling vortices downstream from the block, at lower sigma values, attached cavities form on the top and sides of the block and reattach to the block surfaces – also indicative of damage zones reported on similar designs. When a preceding ramp is added to the standard design, little is changed with the exception that the floor attached traveling vortices downstream from the blocks are eliminated and tend to form and dissipate within the fluid stream above the floor. Attached cavitation still forms on the block top and side surfaces and would likely result in damage to the blocks at flows above about 60000 ft^3/s.

The new cut-back block design eliminated all attached cavitation on the block itself. Consistent attached floor vortices were also not observed. There are still substantial cavitating vortices that are formed within the shear layers around the block structures, especially vertically oriented vortices between blocks. Occasional contact with the floor was observed. When the transition begins to a ventilated cavity, clean lines of separation off the top and side block surfaces as well as the horizontal surface of the ramps was observed. When the cavity was fully vented, the blocks were essentially dry, enveloped with in a steady cavity of water vapor and free gas mixture. In this condition, damage to the blocks is not possible and dissipation of the cavity at the downstream end has shown to be a zone of minimal damage, however some interaction with the floor is likely and some damage could occur.

References

Falvey, Henry T., ***Cavitation in Chutes and Spillways***, Bureau of Reclamation, Engineering Monograph 42, Denver, Colorado, April 1990.

Khatsuria, R.M., ***Hydraulics of Spillways and Energy Dissipators***, Marcel Dekker, New York, 2005; ISBN 0-8247-5789-0; 649 pp.

Cai, W., “Acoustic Method for Measuring Cavitation and Impulse Counting of its Noise,” ***Shuili Xuebao***, No. 3, pp. 49-54, China, 1983 (USBR Translation)

Hamilton, W.S., “Preventing Cavitation Damage to Hydraulic Structures – Part 2,” ***Water Power and Dam Construction***, pp. 46-52, December 1983.

Jin, G., “Cavitation Characteristics of Baffle Blocks in the Downstream Part of a Hydraulic Structure,” collected research papers, ***Academia Sinica***, Ministry of Water Resources, Water Conservancy and Hydroelectric Power Research Institute, vol. 13, pp. 237-254, China, (USBR Translation).

Michel, J.M., “Some Features of Water Flows with Ventilated Cavities,” ***Journal of Fluids Engineering***, American Society of Mechanical Engineers, vol. 106, pp. 319-326, September 1984.

Rouse, H., Siao, T.T. and S. Nagaratnam, “Turbulence Characteristics of the Hydraulic Jump.” ***Journal of the Hydraulics Division***, Vol. 84, No. HY1, pp. 1528-1-1528-30, February 1958.