Presented at:
33rd IAHR Congress
August 9-14, 2009
Vancouver, British Columbia, CANADA

Studies Evaluate Cavitation Potential of Baffle Blocks within a Stilling Basin on a Novel Stepped Spillway Design

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ABSTRACT

Studies were completed at Reclamation's hydraulic laboratory to evaluate the cavitation potential for baffle blocks within a modified type III stilling basin at the terminus of a novel stepped spillway. The spillway features a smooth chute section and a stepped portion, leading to the stilling basin and the largest design unit discharges for a stepped chute to date.

Several combinations of block shapes and floor ramps were testing in Reclamation's Low-Ambient Pressure Chamber (LAPC). Reduced atmospheric pressure allows for the evaluation of the cavitation index for a particular block shape, which can then be applied to the design. The goal was to produce block designs that will supercavitate at the design discharge, causing the dissipation of the vapor cavity to be well downstream from the block structure. Cavitation detection and intensity measurements were done using a mass-loaded acoustic emission transducer mounted on the test section. Visual observations were possible using a high-speed video camera and frame rates up to 2000 Hz.

The design of a supercavitating block was accomplished using the LAPC and a partial sectional model. A tapered block and floor ramp combination should eliminate damage to the blocks and the floor in close proximity. There is some uncertainty about the possible damage that could occur at the closure of the ventilated cavity downstream from the row of blocks, however if damage does occur at this location, the magnitude is expected to be less, and it would be limited to the floor and more easily repaired.

BACKGROUND

The Bureau of Reclamation and the US Army Corps of Engineers have joined together to build a new Auxiliary Spillway on Folsom Dam to comply with dam safety requirements and reduce the flood risk in Sacramento. Folsom Dam is located on the American River approximately 32 km (20 miles) northeast of Sacramento California. The Auxiliary Spillway consists of six submerged tainter gates, each 7 m

(23 ft) wide by 10 m (33 ft) high, with a maximum discharge greater than 8,495 m^3/s (300,000 ft^3/s).

Baffle blocks designed for a unique stilling basin have been tested in Reclamation's Low Ambient Pressure Chamber (LAPC) to evaluate their cavitation potential and to compare modified block designs for possible prototype use. Standard block designs have long been known to be susceptible to cavitation damage and are not recommended for designs where the baffle blocks are exposed to velocities of 15 m/s (50 ft/s) and above without realization that cavitation and resulting damage will occur.

The proposed spillway design features a control structure of 6 top-seal tainter gates (maximum head 34.4 m (113 ft)) discharging into a 51.5-m (169 ft)-wide smooth channel. The smooth channel continues on a 0.02 slope for about 640 m (2100 ft) and then transitions into a stepped channel, passing through a parabolic drop ending in a constant slope of 0.40 with 0.91-m (3 ft)-high steps, resulting in a total drop of 60 m (197.07 ft). The spillway terminates in a stilling basin that while it has the elements of a traditional type III basin (minus the chute blocks), is considerably longer (76.2 m (250 ft)) than one would expect based on the incoming Froude number of the design flow. The mean velocity entering the basin at the design flow is about 24.4 m/s (80 ft/s) with velocities over 30.5 m/s (100 ft/s) expected at the PMF discharge.

A sectional model was constructed in Reclamation's LAPC to evaluate the cavitation potential of several different baffle block configurations. A closed conduit section included a full block with two half-blocks. The water tunnel could be exposed to a reduced ambient pressure by applying up to 74 kPa (10.7 lb/in^2) vacuum. Velocities up to 6 m/s (19.7 ft/s) were possible. Instrumentation allowed for relative comparisons of forces on the center baffle block, detection of cavitation inception, and some evidence of the type of cavitation present. Visual observations of cavitation were performed with the aid of a high-speed video camera. Three configurations were tested, the standard "original" baffle block design, the original block with a 1V: 3H ramp upstream from the blocks, and a modified block shape with various ramp combinations. Elimination of cavitation is not possible under the flow conditions that are present, so creating supercavitation, or the formation of a large vapor cavity that envelopes the entire baffle block is desired in order to prevent typical damage that would occur with the standard block shape. Baffle blocks with the addition of the upstream ramp were able to achieve supercaviting conditions at much lower velocities and this condition was much more stable than the blocks without ramps.

FACILITIES AND MODELS

The testing was carried out in Reclamations hydraulic laboratory within the LAPC, figure 1. This chamber is a recirculating facility and allows for testing at reduced ambient pressures. A partial sectional model was constructed featuring a full block and two half blocks within a clear acrylic test section. The height of the test section was twice the block height. The blocks were geometrically scaled at 1:48.

The incipient cavitation index for the specific block/ramp combinations tested were computed using actual quantities of pressure and velocity. Incipient cavitation on bluff bodies (such as baffle blocks) occurs at relatively high cavitation indices compared to typical hydraulic applications involving isolated roughnesses on a smooth high-velocity spillway. The cavitation index is given by:

$$\sigma = \frac{P_o - P_v}{\frac{1}{2}\rho V_o^2};$$

where P_o is the absolute reference pressure, P_v is the vapor pressure of water, ρ is the density of water, and V_o is the reference velocity. Both pressure and velocity are corrected for blockage area in the test section. Since the flow around the baffle blocks creates a ready source of cavitation nuclei due to the forced separation, tight control over nuclei size and concentration is not as critical within the test chamber and limited scale effects are expected.

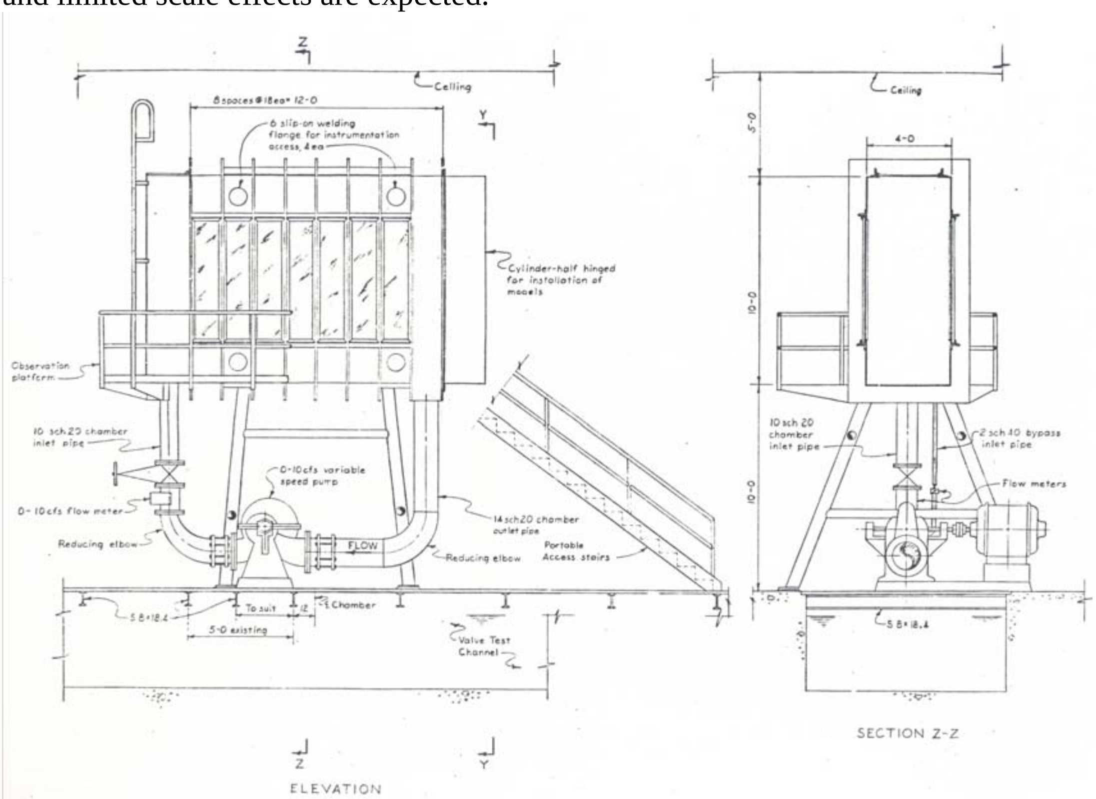
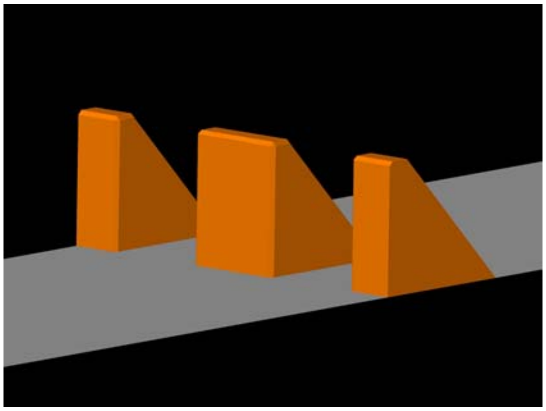
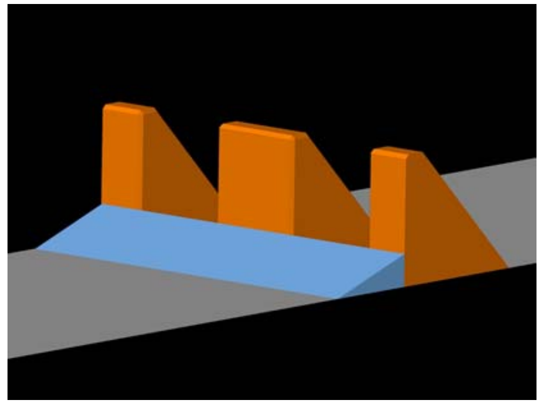


Figure 1: Low Ambient Pressure Chamber in Reclamation's hydraulic laboratory.

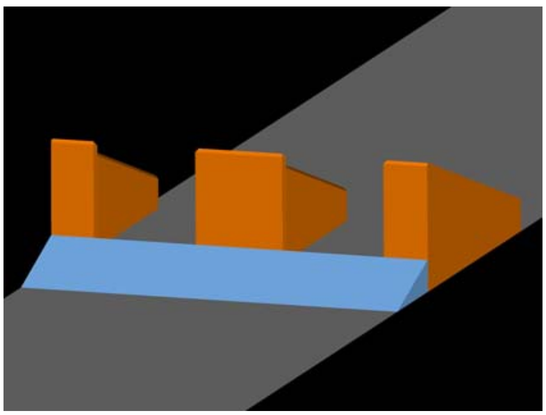
Schematic views of the block and ramp configurations tested appear in figure 2 a-e. These views show the central full block with a half-width block on either side.



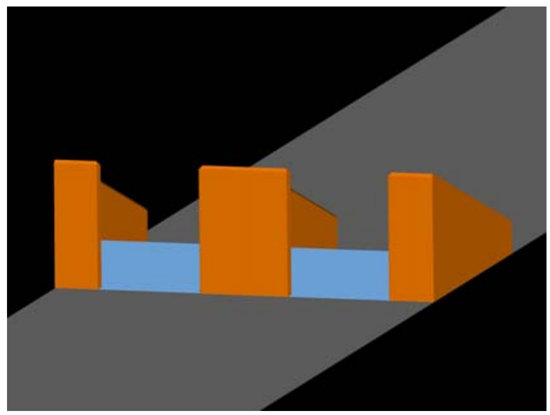
a.) original block design



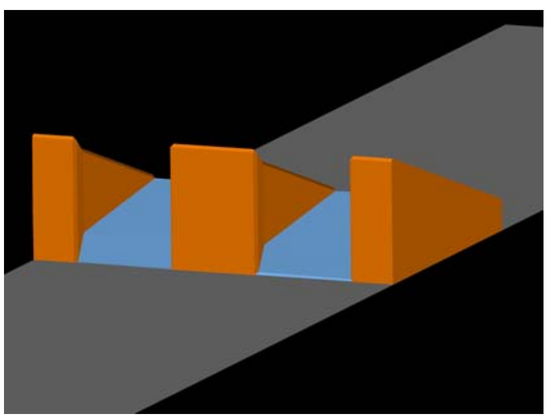
b.) 1V:3H ramp (1.22-m-high (4-ft-high))



c.) tapered block with ramp preceding



d.) tapered block with 1V:3H ramp inside



e.) tapered block with 1V:9H ramp between

Figure 2: Block/ramp combinations testing in the LAPC.

RESULTS AND OBSERVATIONS

The original block design did show substantial cavitation potential. As with all the blocks, the first sign of cavitation takes the form of a horseshoe vortex out in front of the blocks, near the floor, figure 3. This vortex is formed by the interaction of the streamlines due to the stagnation at the block face and the floor intersection. This vortex occurred for all block/ramp combinations that were tested. The ramp location preceding the block caused the horseshoe vortex to be slightly closer to the ramp surface due to the change in pressure gradient over the flat floor approach.

High-speed video allowed the observation of attached vortices at the downstream corners of the blocks, figure 4. These vortices were formed in the shear layer of the block but attached to the floor and remained attached until dissipation or implosion. This location is typical of where damage at previous locations with similar designs has occurred. These vortices intensified in strength with lowering of the cavitation parameter. In addition, this shape would not pass into a supercavitating regime within the operating range of the facility. Addition of the ramp to the original block reduced the intensity and consistency of the floor attached vortices, however it transferred the attachment point up onto the down sloping edge of the block itself, still creating the potential to severely damage the baffle blocks during operation. On a positive note, the ramp prompted supercavition at the design condition.

Figure 3: Horseshoe vortex upstream from baffle block face.

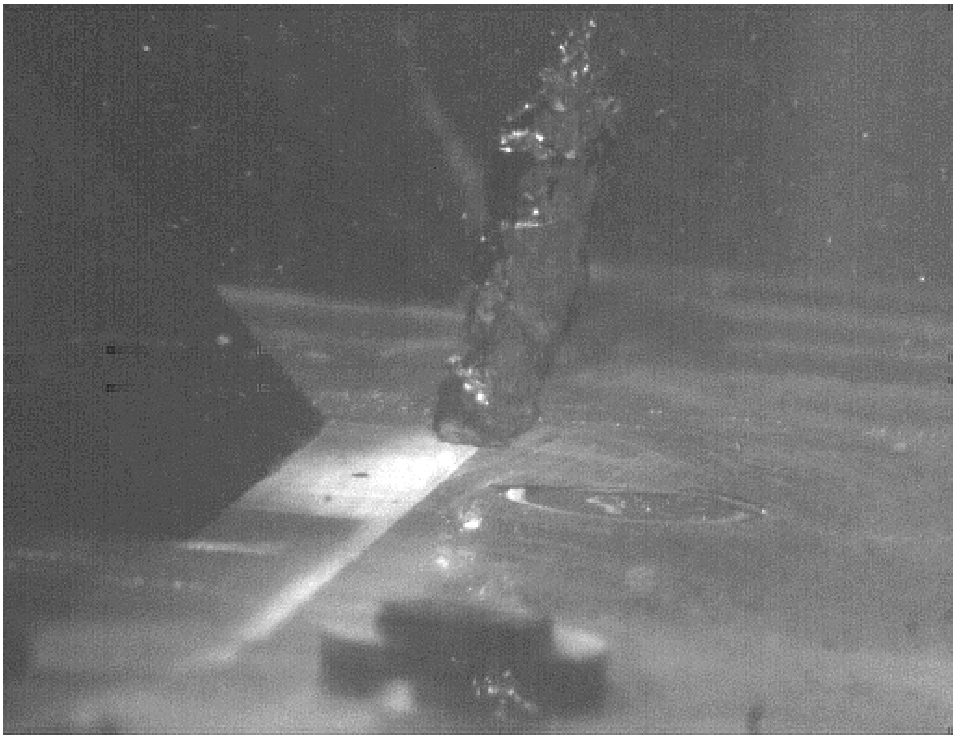


Figure 4: Floor attached vortex at downstream corner of baffle blocks.

Testing of the new tapered block design was accomplished in three steps, each with a different ramp configuration. The first configuration was with a 1V:3H ramp preceding the block. All ramps had a maximum height of 1.22 m (4 ft). The general flow conditions featured many vertically oriented free stream vortices that traveled downstream from the front edge of the block, figure 5. The floor attached vortices observed with the original design were not present. There was still indication of vortices that contacted the floor between the blocks even during ventilated supercavitation. Top and side views of this block/ramp combination in a supercavitating condition are shown on figure 6.

Two ramp configurations were tested, the same 1V:3H ramp as previously tested placed between the blocks starting at the front edge, and a 1V:9H ramp that began at the front edge and ended at the rear edge of the blocks. The first ramp showed general improvement but there was still visual evidence of possible vortex collapse on the floor between the blocks. The extension of the ramp to the end of the blocks lessened the occurrence of collapse or possible implosions on the blocks and floor ramp. For the design condition, any chance of damage with this final configuration will be relegated to downstream from the blocks on the floor of the basin.

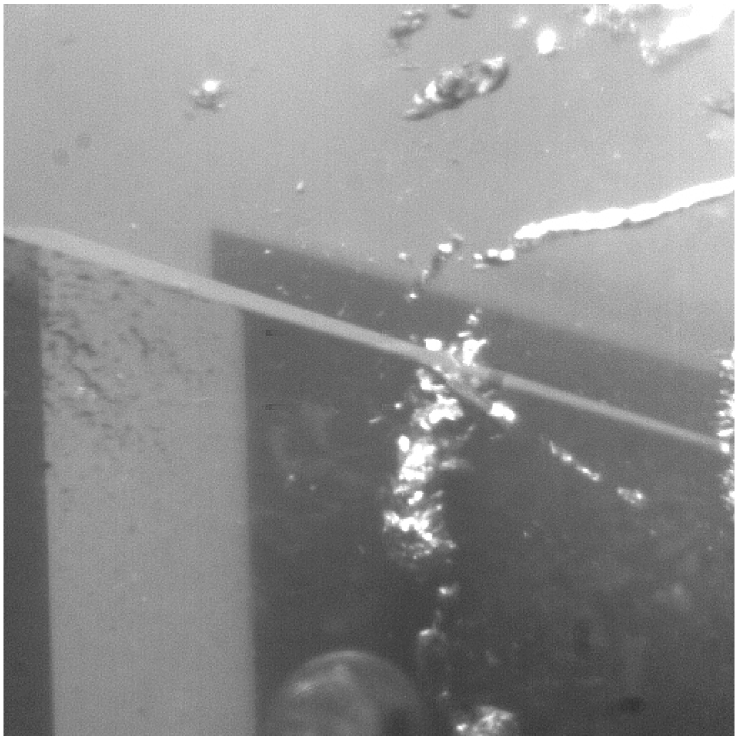
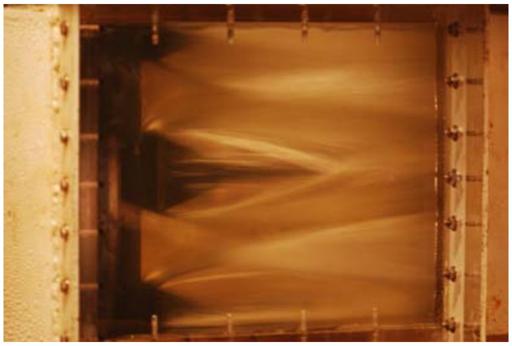


Figure 5: Near vertically oriented vortices in the shear layer between blocks. Half block against wall in clear acrylic to facilitate viewing between the blocks.

a) side view



b) top view

Figure 6: New block with preceding ramp in a supercavitating – ventilated cavity condition

DISCUSSION

Testing of the baffle blocks inside the LAPC proved to be a valuable technique in the development of a baffle block/ramp combination that will keep cavitation damage to a minimum and away from the appurtenances. The use of acoustic emission techniques to detect and categorize different types of cavitation that were present within the model also worked well. Incipient cavitation is often detectable with instrumentation prior to visual corroboration and this was proved out here. Inception of the horseshoe vortex was very evident (marked increase in acoustic emission activity) as were changes in the types of cavitation (changes in slope or rates of activity), figure 7.

The original goal was to produce a baffle block that would not have cavitation damage during basin operation. The velocities entering the basin for almost all flow conditions are well above any recommended values so to accomplish this; the block must operate within a supercavitating regime with the cavity enveloping the entire block. This was accomplished with the new tapered block design that was tested. Possible collapse of shear layer vortices on the floor between the blocks was addressed by moving the ramp such that it fills the entire area between the blocks, resembling an “oversized” dentated endsill. Supercavitation resulted in a very stable condition and should be present at the design condition for the basin. Smaller flows leading up to the transition to supercavitation could possibly result in some minor damage to the floor downstream from the baffle blocks if operated for a long durations.

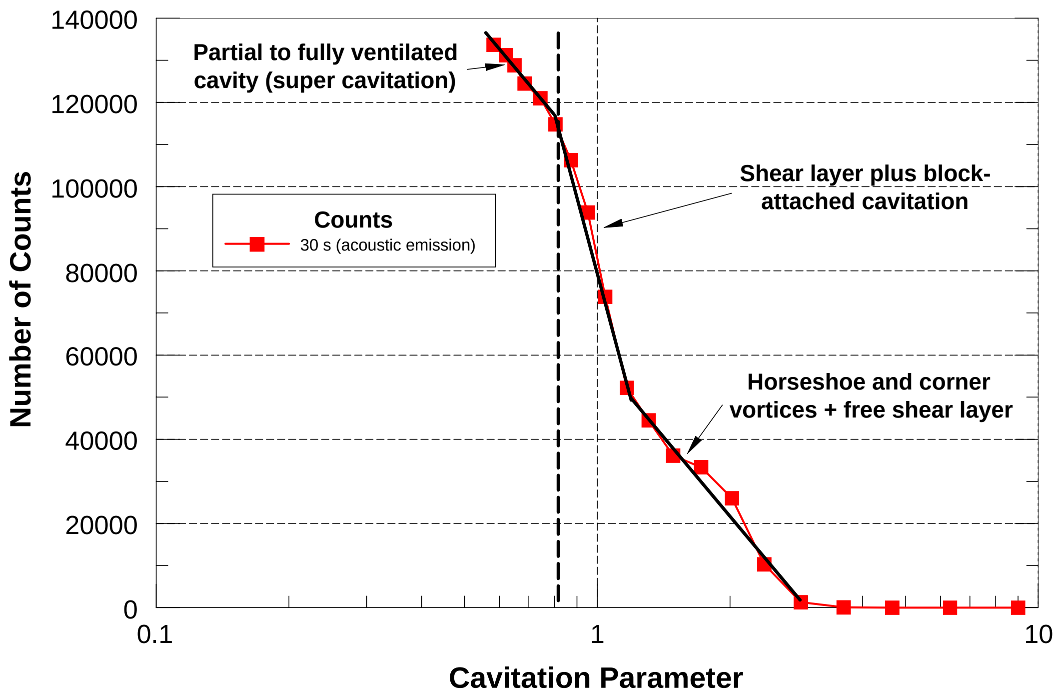


Figure 7: Acoustic emission signature for cavitation on the tapered block design with preceding ramp.

The use of supercavitating planforms is somewhat novel in civil engineering applications; however the application to a baffle block within a stilling basin of a high velocity spillway chute has shown to be an economical solution to an issue that typically would have resulted in a much longer and/or deeper stilling basin. The use of reduced atmospheric modeling and high-speed video has proved to be an effective method to verify design parameters and conditions. The low ambient pressure chamber was effective in validating a satisfactory design through the use of a partial sectional model in a flow dominated by separation and free shear layers.