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Cavitation In Hydraulic Structures-Bridging the Gap Between the Laboratory and the Real World

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KEYNOTE LECTURE

CAVITATION IN HYDRAULIC STRUCTURES – BRIDGING THE GAP BETWEEN THE LABORATORY AND THE REAL WORLD

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ABSTRACT: Recollections of a thirty-five-year career at the hydraulic laboratory of the Bureau of Reclamation are presented within the context of using all the tools at your disposal to reach the best possible answer to your research questions. Cavitation in hydraulic structures will be the main topic used to illustrate this premise, using historic examples and current research to demonstrate study approaches, testing techniques, and applied solutions to real world problems.

Keywords: cavitation, hydraulic structures, tunnel spillways, baffle blocks, stepped spillways.

INTRODUCTORY REMARKS

On the occasion of the opening of the 4th International Junior Researcher and Engineer Workshop on Hydraulic Structures, I'd like to thank the IAHR Hydraulic Structures Committee and the workshop organizers for inviting me to speak here today. I would also like to welcome all of you that are participating and hope that these next few days will be a valuable and enriching experience and that you'll have some fun as well. As with the three previous International workshops, the goal of this meeting is to provide young researchers and engineers the opportunity to present and discuss their research in a friendly environment and to receive constructive criticism and suggestions from their peers and a committee of senior researchers on both their written and oral presentations. Hopefully it will help to generate some new ideas, not necessarily directly related to the technical parts of your work but to help you to better convey your ideas and results—a worthy topic in these days of increased competition for research dollars and clients. This is the first workshop to be held outside of Europe and it's nice to see a good group of participants.

I began my engineering career as a student trainee in the hydraulic laboratory of the Bureau of Reclamation in 1976 while working on my undergraduate degree in Mechanical Engineering. After graduation and working for a few years, I returned to the University of Minnesota and the

St. Anthony Falls Laboratory to work on a graduate degree in Civil Engineering. Throughout my early career in Reclamation and at St. Anthony Falls, I had the good fortune to have some great mentors and colleagues. It feels a bit like "old home" week here as the other invited keynote speaker, Professor Rollin HOTCHKISS, was at University of Minnesota at the same time I was, back in the 1980s. I've continued to work at the lab in Denver and can say that I could not have imagined anything much better from the standpoint of working on a huge variety of "real world" problems in the area of hydraulics and, in particular, hydraulic structures. I'm thinking about retirement now after more than 35 years at the lab and I certainly have many fond memories of engineering and research with Reclamation.

This phrase, "the real world"—it isn't a fictional place. I don't want to give the impression that academia isn't the real world, but generally it's rare at the university to get the chance to work on solving problems specific to a facility and then get to see if your recommendations really worked! We usually think of the university as a place where more "basic" or general research is performed. Perhaps research can best be defined as seeing what everyone has seen, and then doing what no one else has done. Begin with the end in mind! This is one of the things that I was fortunate to observe during my graduate studies. In general an incredible amount of work went into formulating and writing proposals for research dollars. When I first arrived I thought, they already knew the answer—what's the point? I soon learned that taking this approach led to success in the lab, and while the strides forward were not always monumental, they seldom were backwards.

Much of the work that we do at Reclamation's lab is a direct result of some type of problem. Our agency has a relatively short history—just over 110 years—but no lack of issues and problems to address. Damage and/or failures are often the most common study drivers; however, it may also be a new application of existing technology or a search of how to renew an aging structure using state-of-the-art practices. Results from this type of "applied" research are often site-specific but can still be valuable to the engineering community. We are less involved in generalized studies these days due to changes in funding and a shift in our mission; however, depending on how clever you are in planning and performing a study, the final product may provide a wealth of data, a new understanding of the problem, and spur on new studies in the future.

Since most of my career has been involved with testing and applied research, I'm going to discuss how those paths can occasionally grow to allow generalization and advance the state-of-the-art on a particular topic. I will present some "real world" problems that involve cavitation in hydraulic structures and show the importance of how those observations, along with the specific laboratory studies and studies of the phenomena, can all be pulled together to enrich the final solution. The first topic will be cavitation in tunnel spillways, followed by a quick overview of cavitation on baffle blocks in stilling basins, and finally some recent laboratory work on cavitation potential in stepped spillways.

CAVITATION

Cavitation is generally defined as the formation of the vapor phase of a liquid. The word can be used to describe everything from the initial formation of small bubbles (inception) to large attached cavities (supercavitation). Unlike boiling which is induced by raising the vapor pressure of the liquid through heating, cavitation is induced by lowering the local hydrodynamic pressure to the liquid's vapor pressure. Cavitation can affect performance in turbomachinery, thrust in propulsion systems, accuracy of fluid meters, and cause extreme noise and vibration. Perhaps the issue we are most concerned about with hydraulic structures is the possibility of cavitation erosion (or damage). Damage is generally thought to be the result of the implosion or collapse of cavitation bubbles or cavities of vapor as they travel to areas of increasing pressure. If the implosions are near solid boundaries, the sudden collapse can generate shock waves with pressures rises of many orders of magnitude—large enough to cause material bonds to be destroyed, resulting in a process usually called "pitting." Increased time and intensity of this pitting can result in complete failure of structural components.

Tunnel Spillways

As I began my career, Henry FALVEY was at the lab and was our "cavitation expert." He was beginning to write a monograph on cavitation in chutes and spillways (FALVEY 1990) and introduced me to the subject of cavitation in tunnel spillways by predicting that when Glen Canyon Dam filled and they used the spillways, there was going to be significant damage. Reclamation's first tunnel spillways constructed were for Hoover Dam. During the first extended operation (4 months in 1941 at a mean discharge of 383 m^3/s), a post release inspection revealed a large eroded hole (9 m x 35 m x 14 m deep) near the end of the vertical bend, Figure 1. Engineers deduced that a hump in the tunnel profile just upstream from the hole was responsible for initiating the cavitation and resulting damage. They recommended that the hole be filled and the surface made smooth as possible. In addition a suggestion was made to study some method to inject air into the flow near the area that had been damaged. BRADLEY (1945) documented a 1:60 scale Froude-based model to study a variety of methods to cause enhanced air entrainment in the Hoover spillways in 1945. The ability to provide enough air near the boundary of the vertical curve, even for the best performing arrangements, was less than acceptable. He realized that while the model measurements were accurate, scale effects were present due to the inability to scale viscosity and surface tension, and that prototype entrainment rates would likely be much higher. Uncertainties in what the actual aeration rates might be, resulted in abandoning this plan as unfeasible. The hole was filled and the surrounding concrete was "polished" using grinding (terrazzo machine).

Figure 1 – Hoover Dam tunnel spillway following first substantial flows, 1941.

These guys had definitely been on the right track. They believed that air would "cushion" the surface being attacked and lessen the damage. They had also realized that their scale model had issues due to the inability to properly scale the two-phase flow properties. While their reasoning was not entirely correct about the true physics of the problem, it led to continued investigations. Just a few years after this, in 1953, PETERKA (1953) published the first true laboratory evidence that air mixed in with the water had an influence on the damage that results from cavitation. He showed that in a qualitative way, entrained air reduced the severity of the pitting on a test sample within an oscillator vibrating at 7800 Hz. In addition he used a venturi-type device with concrete test blocks and flow velocities of over 30 m/s to conclusively show that air content reduced the amount of cavitation pitting (loss of material) and reduced the noise associated with cavitation. Entrained air of 7.4% resulted in no measurable loss of material. He showed in his test rig, by measuring appropriate pressures, that the cavitation index varied linearly with increasing air entrainment, ranging from 0.109 with no air to 0.288 for 7.1% air, without any other changes to the flow conditions (see Figure 2).

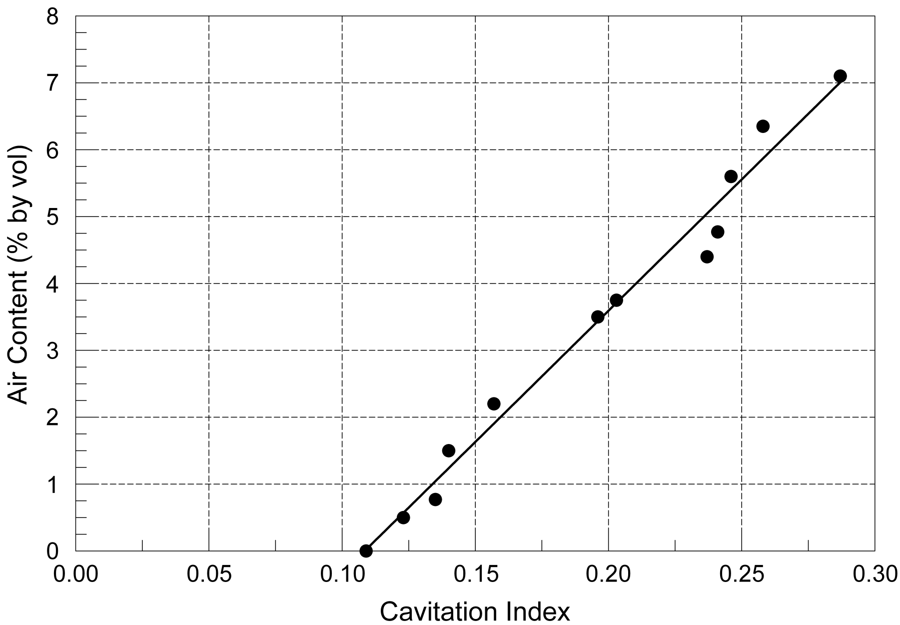

Figure 2 – Air content effects on the cavitation index.

Subsequent damage, model studies, and prototype testing at Yellowtail Dam and Glen Canyon Dam solidified the use of aeration slots in the control of cavitation damage in large tunnel spillways. During this same time frame in the 1980s, other researchers were also working on aerator designs for a variety of high-head chute type spillways, especially in South America. There had been several occasions of significant damage (Tarbela, Karun) to tunnels and spillways around the world, and it became an important design challenge for the times.

Cavitation in the laboratory

Specific cavitation studies in the laboratory to this point had rarely directly addressed cavitation in hydraulic structures. Although EULER first postulated about the possibility of cavitation in 1754, it was near the turn of the 20^{th} century before actual studies of the phenomenon began. REYNOLDS observed cavitation in tubular constrictions, and PARSONS was the first to use a water tunnel and reduced pressures to study the loss of thrust to a ship whose propeller was "cavitating." Many institutions around the world used water tunnels and specialized chambers that allowed the study of cavitation. From the 1940's thru the 1960's, there was extensive work on cavitation inception, bubble dynamics, collapse dynamics, and damage due to all sorts of hydrodynamic cavitation applied to all different fields of interest.

Researchers quickly found that cavitation was not a simple process. Multitudes of scale effects have been discovered; including Reynolds number (velocity), vaporous versus gaseous cavitation, correctly modeling transition to turbulence and turbulent pressure fields, nuclei size and distribution, and dissolved gas content. With these scale effects present, we could question, what can we learn from laboratory experiments that will help us predict full-scale prototype performance? We may still be in the clouds a bit but with proper care, we trudge on. The next topic will be a look at model testing of cavitation on stilling basin baffle blocks.

Stilling basin baffle blocks

The use of baffled stilling basins in high-head, high velocity flows has often lead to problems with cavitation damage to the blocks and surrounding floor areas. Some of the first evidence was the stilling basin at Bonneville Dam. This COE dam is on the Columbia River and features an overflow spillway with a short stilling basin that features a couple of rows of baffle blocks. The structure was completed in the late 1930's and shortly after it was put into service, considerable damage to the blocks and surrounding invert was observed. A lab study at Carnegie Institute of Technology in a "vacuum tank" was one of the first documented studies of cavitation in hydraulic structures. Much of the previous and ongoing work had been concerning cavitation of propellers, and cavitation on bodies of revolution – or just basics such as offsets into/away from the flow, gate slots, and singular irregularities. These tests showed evidence of the type and location of the cavitation on this particular geometry, which correlated nicely with damage observed in the field, Figure 3. Attempts to "streamline" the blocks to reduce the damage were somewhat successful, but not entirely.

Reclamation's standard baffle block design (used in the type III basin) was based on creating the most energy dissipation possible. So the use of these blocks in a high velocity flow might pose some cavitation issues. They were not recommended for velocities >15 m/s and in order to keep dissipation at a maximum, the front face should be vertical and rounding corners or other streamlining was discouraged. In the late 1970's Reclamation constructed a "vacuum chamber" geared at studying cavitation in hydraulic structures. This chamber was called the Low Ambient Pressure Chamber or LAPC. It provided the ability to model a structure (or part of a structure) using typical "Froude-based" techniques but also could provide equal cavitation indices in the model and prototype. This was accomplished by lowering the "ambient" pressure within the chamber – such that lower velocities could generate the hydrodynamic pressures capable of causing cavitation.

Figure 3 – Laboratory tests (Carnegie) and resulting damage pattern in the Bonneville Dam prototype structure, early 1940's.

A recent study (FRIZELL, 2010) looked at a modified type III stilling basin for the Folsom Auxiliary spillway. The cavitation potential of the standard block shape was studied with the goal of modifying the shape to be free from cavitation damage. Incoming velocities to this basin are in the 25–37 m/s range, so the presence of cavitation is highly likely, realizing that if damage is to occur we would prefer that it be downstream from the blocks and not on or around the blocks themselves. Initial tests in a sectional model of the LAPC showed the locations for cavitation formation and actually cleared up a couple of misconceptions about the type of forms of cavitation that have resulted in previous damage to similar block shapes out in the field. Real time visualization can be problematic, as often cavitation is not a steady process. However, details can be revealed when taken at high-speeds and slowed down for viewing. We initially see a horseshoe vortex form near the invert. This vortex contains a vapor core and is very stable, but following the vortex downstream reveals that it does not impact any of the solid boundaries within the basin. Bubble cavitation and attached sheets of bubbles are present on the blocks, and damage has been observed in these areas. But perhaps the most interesting find was the vortices that form in the shear layers downstream from the blocks and actually attach to the floor, move downstream and implode. The floor damage that had been observed (as in the Bonneville basin) was once thought to be the result of the horseshoe vortex interacting with flow coming around the blocks—not really the case.

These insights gave us some ideas about keeping energy dissipation at a maximum while trying to remove cavitation damage from the immediate vicinity. Due to the extreme velocities, we thought that formation of a ventilated cavity or supercavitation may be possible with the right shape. Ideally the cavity would envelope the entire block downstream from the rectangular vertical face, yielding no possible damage to the blocks themselves. We did manage to find a shape that kept traveling cavitation away from solid flow boundaries throughout the flow ranges and transitioned to supercavitation near the maximum flow rate, Figure 4. Through the use of the lab model, we were able to verify the incipient cavitation index for both the standard and new block shapes and at what flow index a ventilated cavity would form.

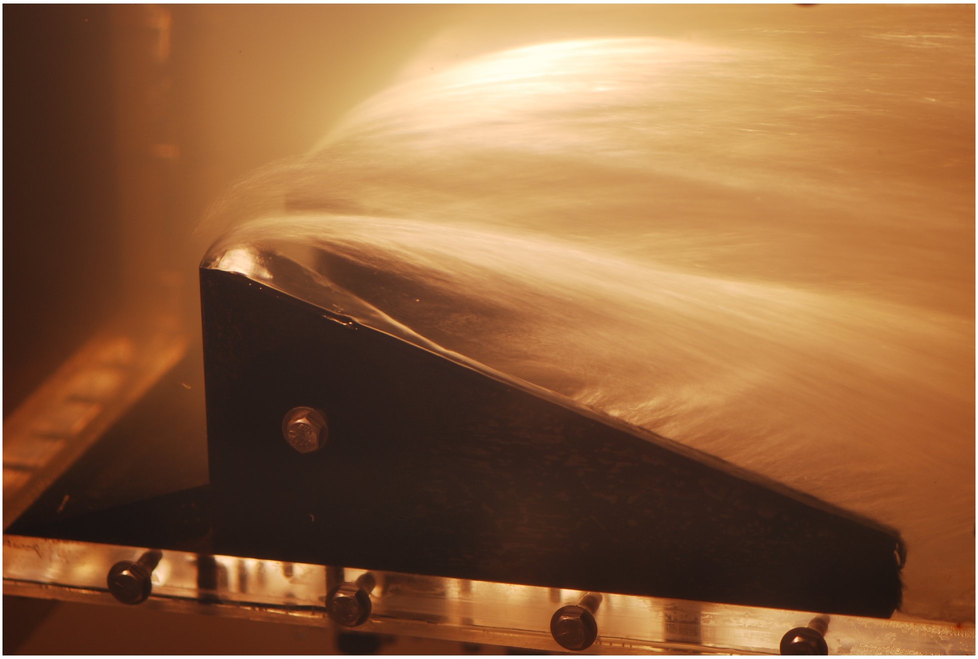

Figure 4 – Ventilated cavity forming around new baffle block design.

The Folsom auxiliary spillway studies provided yet another opportunity to study something that really has only been picked around previously—cavitation potential in stepped spillways. This proposed structure has some rather unique design features: an inlet structure of top-seal radial gates with 30 m head, design specific discharge of 74 m^2/s, maximum specific discharge of 172 m^2/s, and a combination smooth and stepped chute terminating in a modified type III stilling basin. Velocities in excess of 30 m/s on the spillway and depths over 6 m have the designers concerned about possible cavitation damage.

Cavitation on stepped spillways

Cavitation damage has not been reported in previously constructed stepped channels. Reasons are probably two-fold: (1) design recommendations have been conservative based on lab studies, and the measurement of pressures on the steps (limiting unit discharge to 30 m^2/s) and (2) steps are known for substantial self-aeration—triggered much more quickly than on a smooth chute (studies and experience with aeration preventing cavitation damage). If cavitation can form, then where would the cavitation initiate and what possible damage may occur.

Our studies began with a plan to evaluate the flow field present and then observe and measure creation of cavitation by testing the channel in the LAPC. Measurements at atmospheric pressures were completed to characterize the channel (measure pressure gradient, pressures on steps, complete PIV measurements). Once these tests were completed for slopes of 21.8 degrees and 68.2 degrees for two step heights (relative roughnesses), the channel was moved into the LAPC.

Each of the four cases was tested in the LAPC (2 slopes, 2 roughness heights). The chamber was initially filled with city water and then circulated while under vacuum for a period of about 8 hours. By doing this "degassing" process, the water was slightly under saturated at the reduced operating pressure—a condition where cavitation inception has been shown to be less dependent on total dissolved gas content. The flow rate (velocity) was then incrementally increased, and acoustic data and high-speed video were recorded. We used an acoustic emissions sensor to indicate critical conditions within the model, such as inception, in much the same manner as hydrophones or dynamic pressure transducers have been used in the past. We discovered that cavitation could indeed form on stepped channels. The initial formation was within the high intensity shear layer that is associated with the step tips (the pseudo-bottom). There was some formation of bubbles on the step tips themselves, but the bubbles were quickly carried into the shear layer and either appeared as a swarm of bubbles or organized into stream wise vertex-like structures, Figure 5.

Our goal was to see if the critical cavitation data from a stepped spillway would follow the model proposed by ARNDT and IPPEN (1968) for cavitation on uniformly rough surfaces. This required us to interpret our data in a manner to extract the friction factor so that we could compute the coefficient of friction. We ended up using the velocity profiles that were extracted from the PIV measurements and applying a method suggested by NIKURADSE and later applied by CHAMANI (1997) to calculate the friction factor. Then plotting the C_f versus our critical cavitation indices from the experiments, we found they fit reasonably well with the model of ARNDT and IPPEN. From a designers standpoint this was great news! Although the implication of a friction factor to the macro-roughness elements of a stepped spillway is still just an "approximate" way to handle the complex flow, we can now predict the critical cavitation index based on this friction factor.

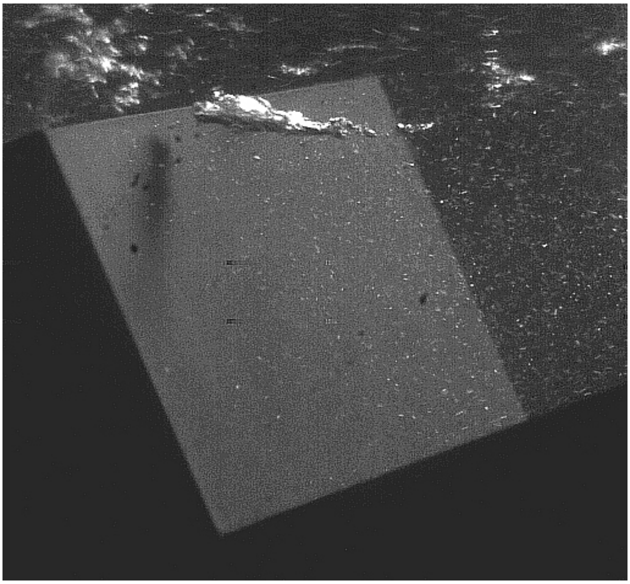

Figure 5 – Photo of cavitation formation within the shear layer of the 21.8-deg stepped channel.

The site-specific studies concerning cavitation potential on the new Folsom auxiliary spillway, along with some additional research funds, ended up expanding the state of knowledge concerning cavitation on uniformly rough surfaces. From the small triangular grooves tested by Arndt and Ippen to these large macro-roughness elements tested at Reclamation's laboratory, in the end, it is the design engineer that is the "winner." Careful consideration in the design of the model and test program yielded a result that was not entirely unexpected. Reclamation and others had assumed that cavitation in stepped spillways might be described by the same "theory" as the uniformly rough boundary layer work revealed 40 years earlier, but the experiments are the key to actually show that the theory is supported by data.

CLOSING

In closing, I have presented several topics related to cavitation in hydraulic structures and hope that I have illustrated the value in looking not only to specific examples previously studied but also delving into related testing and research of the general phenomena. Using all that is available just might help explain and enhance your present work. Research doesn't always go as planned; sometimes your best attempts to prove out a hypothesis come crashing down, but then there can also be that serendipitous moment of discovering something totally unexpected! I remember being told once that it was better to be clever than smart; however, achieving meaningful results in your research can be enhanced by cleverly applying your (and others') knowledge to the topic.

ACKNOWLEDGMENTS

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