RECLAMATION
Managing Water in the West

Concrete Cavitation Resistance – Scoping Study

Research and Development Office
Science and Technology Program
Final Report ST-2017-1786-01 (8530-2017-37)

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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It has long been know that both concrete strength and concrete surface tolerances affect resistant to cavitation, but little guidance or tools are available to help the designer's choose both a technically adequate and economical concrete mix. This scoping study was initiated to perform a literature search on concrete mix specific information for cavitation resistance and to identify partners for continued collaboration on the topic of cavitation in the future.

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Acronyms and Abbreviations

ACI	American Concrete Institute
AERC	abrasion erosion resistant concrete
ASTM	American Society of Testing Materials
CR	Comprehensive Review
H	horizontal
LAPC	Low Ambient Pressure Chamber
m/s	meters per second
PFR	Periodic Facility Review
V	vertical
w/cm	water to cementitious ratio

Executive Summary

It has long been know that both concrete strength and concrete surface tolerances affect resistance to cavitation, but little guidance or tools are available to help the designer's choose both a technically adequate and economical concrete mix. This scoping study was initiated to perform a literature search on concrete mix specific information for cavitation resistance and to identify partners for continued collaboration on the topic of cavitation in the future.

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Purpose

Cavitation occurs in hydraulic structures as water vapor bubbles form and then collapse, creating a very high local pressure drop which can damage concrete. Reclamation has many concrete conveyance structures where velocities, geometries and elevation changes make cavitation a concern. It has long been known that both concrete strength and concrete surface tolerances affect resistant to cavitation, but little guidance or tools are available to help the designer's choose both a technically adequate and economical concrete mix. This scoping study was initiated to perform a literature search on concrete mix specific information for cavitation resistance and to identify partners for continued collaboration on the topic of cavitation in the future.

Background

Reclamation has been an industry leader in the field of cavitation and spillway/stilling basin design. The Hydraulic Investigation and Lab Services Group has published over 70 reports on cavitation since the 1950’s [1]. It has been well established that the shape and size of spillway and stilling basin components can affect the cavitation potential of a given design. The 1990 Engineer Monograph No. 42 *“Cavitation in Chutes and Spillways”* [2] led to great advances in spillway design and the understanding of cavitation indices.

From early studies of Hoover Dam it was learned that “imperfections in the concrete, such as rock pockets, cold joints, porous areas, lack of bond, etc, all made the concrete more vulnerable to [cavitation]” and that new concrete should be “finished carefully to produce a sound, continuous, uninterrupted surface [3]”. The cover photo of this report showing the damage caused at Glen Canyon Dam during severe flooding and extreme spillway use in the 1980’s is proof enough of the damage that can be caused if cavitation potential is overlooked or misunderstood.

Cavitation and erosion are often cited together, as “cavitation erosion”, or “erosion caused from cavitation.” This generally explains why testing for concrete abrasion is the typical accepted indicator of a concrete mixtures’ performance against cavitation. Because much work has been done to look at what hydraulic configurations minimize cavitation, little has been studied on what effect mixture proportions and concrete compressive strength have on actual cavitation bubble collapse resistance.

Previous Cavitation Work

A 1947 study reported by the Bureau of Reclamation summarized the effects of mix proportions, materials, finishing operations, curing procedures, etc. on the erosion resistance of the concrete. No detailed test data was presented in either the ACI Journal article on the subject [4] or the Reclamation companion report [5]. By today's standards, the mixtures used were of a relatively low strength and high w/cm. The conclusions state that erosion resistance is a function of strength, lower water-to-cementitious ratio (w/cm) and good curing. They also state that concrete over seven sacks (658 pounds) of cement performed better. However the data to support these conclusions was not shown, limiting the usefulness to today's designers.

The Army Corps of Engineers has reported that Libby Dam had concrete strengths roughly 10,000 psi at the time that cavitation damage occurred [6], leading to the thought that severe cavitation potential cannot be overcome by strength alone. However detailed mix design information or geometries in the cavitated zone for Libby Dam were not provided. Abrasion resistance of high-strength concrete was further tested and reported in 2001 [7]. Concrete in the 11,000 psi to 18,000 psi compressive strength ranges were found to have six to ten times lower wear due to abrasion when tested using ASTM C 1138, "Abrasion Resistance of Concrete Underwater" and also ASTM C779, "Abrasion Resistance of Horizontal Concrete Surfaces" [8]. The cost and practically of using concrete above 10,000 psi has limited it use in Reclamation projects to date. The question still remains, when design steps have been made to reduce cavitation potential, but there is still some concern that cavitation could occur, how can designers select a compressive strength that can reduce this potential without adding an unnecessary cost burden on the project.

American Concrete Institute's (ACI) 207 Mass Concrete Committee, and the author of this scoping study, recently revised Erosion of Concrete in Hydraulic Structures [9] which discusses cavitation at length. It notes that cavitation erosion in concrete has not been as thoroughly studies or documented as cavitation in metals has been. In addition, the previous work by the Bureau of Reclamation resulted in a better understanding of the cavitation index and its effect on damage rate (from minor to major) [2]. The ACI 207 documents' only guidance for concrete that has failed due to cavitation is to "replace the damaged concrete with more erosion-resistant materials." This does not leave the designer or specifier with specific helpful guidance.

In 2009, model studies were completed in Reclamation's Hydraulic Investigation and Lab Services Group to evaluate the cavitation potential for the stepped chute and baffle blocks within the stilling basin of the new Folsom Auxiliary Spillway using the Low Ambient Pressure Chamber (LAPC). In the model, the steps were made from aluminum, pitting and elongated holes were noted on the tops of the stairs with near prototype velocities of >20 m/s on the 1V:2.48H steps. Consistent damage from step to step was observed [10]. For the final design and subsequent construction of the stepped chutes, a layer of high strength abrasion-resistant concrete (AERC) containing silica fume, one-foot thick, was cast monolithically with the underlying portion of the steps to create a more durable top surface[11]. It was thought that AERC would resist the effects of cavitation and/or any abrasion erosion for debris or sediment transport. The strength of the AERC was selected based on testing of regional materials which found that the average percentage of loss due to abrasion (using ASTM C1138) seems to increase with an increase of w/cm [12]. Ultimately a limit of 4% maximum volume loss for abrasion resistance was required for the AERC which resulted in a specified concrete compressive strength of 8,000 psi at 90 days. However, no cavitation testing was performed on the project concrete. It is thought that the LAPC and High Head Pump facilities, could be used for validation testing purposes of a range of concrete strengths and w/cm's to be compared to traditional erosion testing methods.

Reclamation's Materials and Corrosion Laboratory has been restoring a Venturi-type materials cavitation testing apparatus for testing of coatings under the Science and Technology Program (S&T) project "Evaluation of Field Repairable Materials and Techniques for Cavitation Damage"[13]. This machine was used for cavitation testing at Reclamation in the 1960's on a variety (of mostly non-cementitious) materials. This equipment, once restored, could also be considered for validation testing if it aligns with the finalized scope of the proposed research.

Future Research

This scoping study evaluated previous research efforts and provides some recommendation for future research. Although there is a lot of information available to the author and Reclamation designer's, there are some gaps worth pursuing. This study was a means to obtain a collection of past research papers from which future work could benefit, and also to identify potential research partners for any new pursuits.

Collaborators

Two main collaborators were identified as potential partners. Brazilian engineering consultant Mr. Selmo Kuperman is a professional colleague of this author through shared involvement in ACI. Mr. Kuperman is a Civil Engineer, ACI Honorary Member, and Brazilian expert on concrete technology, dam design, dam safety appraisal, repairs and rehabilitation of concrete structures.

The second is the FURNAS Laboratories in Brazil. FURNAS is one of the largest Brazilian agencies of hydroelectric energy generation. It is under the control of the Brazilian Federal Government, Centrais Elétricas Brasileiras S.A. - Eletrobras, associated with the Ministry of Mines and Energy. The company has two laboratories, the Experimental Hydraulic Lab (LAHE) which runs studies on reduced scale models on FURNAS' hydroelectric power plants, located in Rio de Janeiro, and a Concrete and Soil Lab located at the city of Goiania, in midwestern Brazil that focuses on the concrete and soil materials studies.

Both the Brazilian and United States government water resource facilities are faced with erosion of the concrete surface of spillways and stilling basins and each have made many costly repairs that impact operations. At some of FURNAS' hydroelectric power plants, they are faced with erosion of the concrete surface of spillways and stilling basins that have complicated repairs which were necessary to perform during plant operation. Reclamation is familiar with the phenomena of erosion of the concrete surface of spillways and stilling basins. Canyon Ferry Dam, Yellowtail Dam, and Buffalo Bill Powerplant are a few structures that have had recent repair work.

Compressive Strength versus Cavitation Resistance

Can the relationship between concrete compressive strength versus concrete cavitation resistance be quantified and presented in terms of durability and economy?

We know from the ACI 350 - Environmental Structures Code and Commentary [14] code document that "Structures exposed to cavitation erosion shall be constructed with high-strength, low water-cementitious materials concrete..." No clear guidance is given to the designers for selecting high-strength boundaries and if a selected strength is unnecessarily high, this can add costs to a project for materials and special construction considerations. There is much information on mixtures and erosion resistance, but most of the testing focus has been on erosion type testing. True cavitation testing of a variety of concrete materials has been limited and no validation of the assumption that erosion testing is representative of cavitation by model testing could be found.

Through the collaboration between the Concrete, Geotechincal and Structural Laboratory and the Hydraulic Investigation and Lab Services Group, and the Brazilian partners, there is the potential to create a testing matrix to look at various high-strength concrete mixes in a cavitation environment. If additional records from the 1947 Reclamation testing program can be located they could be used to evaluate and plan for future testing as well.

Scaled Hydraulic Modeling and Materials

Can tests be developed to examine different concrete materials and surfaces subjected to real scale flow to evaluate which combinations reduce the damage from cavitation and erosion on concrete surfaces in spillways and stilling basins?

FURNAS's two prestigious concrete and hydraulics laboratories are proposing to partner with Reclamation's concrete and hydraulic experts to study real scale cavitation testing on concrete materials coupled with scaled hydraulic modeling to evaluate solutions for long-term, cost-saving remediation options.

Reclamation could collaborate with the FURNAS Laboratories in Brazil to study concrete surface problems encountered in spillways and stilling basins by combining concrete materials testing with hydraulics lab studies. Reclamation could provide guidance and technical assistance to the FURNUS led laboratory efforts. The research FURNAS is naming "Hydraulic Surface" is the result of many years of observations of concrete surfaces problems at the spillways and stilling basins of Furnas hydroelectric plants and at other energy companies they work with. They are still detailing the research plan and have reached out to Reclamation for this partnership. Their efforts will be performed at two Furnas laboratories, in the cities of Goiania and Rio de Janeiro, Brazil.

The Brazilian government will be funding the FURNAS laboratories for a sizeable three years study to investigate this problem. Reclamation's timely commitment to participate in this study, provide feedback, and review of testing plans and results could allow us to use our decades of expertise to help shape the research in a way most useful to FURNAS, Reclamation, and the international water resource community. FURNAS is expecting to start this research in FY18.

The FURNAS Hydraulic Lab has researched macro turbulent flow on stilling basins and downstream of ski jump spillways. The FURNAS Concrete and Soil Lab has experience on the concrete behavior and its characteristics on the same structures. This is the first time their research laboratories are combining materials testing with hydraulics from both of their labs to study the real action of the macro turbulent flow on concrete surfaces. The research goals are to conduct real scale cavitation testing on concrete specimens (with varied material strength) and scaled hydraulic modeling (estimate / quantify cavitation levels and locations). Reclamation has experience with both of these approaches and unique facilities such as the LAPC and High Head Pump Facility to help validate and supplement FURNAS findings.

Need and Benefits

Canyon Ferry Dam (~$1.2M), Yellowtail Dam (~$95K), Buffalo Bill Powerplant (~$800K) and Lahonton Dam (May 2017 emergency repair), are a few structures that have recently had extensive concrete repair work to fix eroded dam stilling basins and powerplant tailrace exit concrete. A feasibility level concrete repair design is currently underway for Boysen Dam and Powerplant where concrete has eroded past the top layer of reinforcing steel in both the spillway stilling basin and the outlet works stilling basin under the powerplant. It is in Reclamation's best interest to make sure these repairs remain in good condition and prevent, if possible, continued erosion from the same cavitation and particle transport mechanisms.

Concrete repair of the affected areas is very costly to Reclamation. High construction costs are attributed to the building of a coffer dam to unwater the repair area and short construction schedules that are necessary to reduce the impacts on irrigation deliveries and power generation, and to assure emergency releases are able to provide adequate flood control during construction. A better understanding of real scale cavitation testing on concrete materials and scaled hydraulic modeling to estimate and quantify cavitation levels and locations could result in longer lasting repairs and the implementation of new design approaches for new water resource structures.

FURNAS's large financial contribution to this research and the dedication of their two prestigious laboratories combined with the expertise of Reclamation's Concrete Geotechnical and Structural Laboratory and Hydraulic Investigation and Laboratory Services, with the support of other industry organizations such as the American Concrete Institute, create a strong partnership. Reclamation and FURNAS Laboratories have a long history of working together. Mr. Timothy P. Dolen most recently visited the FURNAS Laboratories in 2008 to collaborate on roller compacted concrete design and direct tensile testing of concrete.

Next Steps

A FY2018 proposal was presented to the Research and Development Office which included a detailed list of the assumed tasks and scope of work, collaborative partnership and key personnel information, and a detailed budget. This scope and budget could change based on the level of partnership desired by FURNAS and/or based on initial meetings and should be reevaluated prior to beginning any formal collaboration.

Results of a study could be worked into the design alternatives used to address facility recommendations that are created during the Periodic Facility Review (PFR) and Comprehensive Review (CR) process for Reclamation's Water Infrastructure and Power projects, or for new projects.

Additionally successful results for this research could impact Reclamation in the following ways:

- Extending the life, or increasing the reliability of our water storage, water delivery, and power generation facilities so that continued beneficial uses of project waters are dependable.
- Decreased outage time or reduced likelihood of an emergency shutdown
- Reduced water delivery interruptions
- Reduction in maintenance, inspections, repair times needed for a facility
- Reduced costs compared to current business practices
- Lower life-cycle costs

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