Collaborative Studies to Reduce Flow-Induced Damage on Concrete Hydraulic Surfaces

Science and Technology Program
Research and Development Office
Final Report No. ST-2020-1885-01
Hydraulic Laboratory Report HL-2020-05

U.S. Department of the Interior September 2020

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

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30-09-2020	Research	01-10-2018 to 30-09-2020

4. TITLE AND SUBTITLE
Collaborative Studies to Reduce Flow-Induced Damage on Concrete Surfaces

5a. CONTRACT NUMBER
FA710

5b. GRANT NUMBER
n/a

5c. PROGRAM ELEMENT NUMBER
1541 (S&T)

6. AUTHOR(S)
Josh Mortensen, P.E.
Hydraulic Engineer,
Hydraulic Investigations and Laboratory Services, 86-68560

5d. PROJECT NUMBER
ST-2020-1885

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Technical Service Center
Denver Federal Center
Denver, CO 80225

8. PERFORMING ORGANIZATION REPORT NUMBER
n/a

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Science and Technology Program
Research and Development Office
Bureau of Reclamation
U.S. Department of the Interior
Denver Federal Center
PO Box 25007, Denver, CO 80225-0007

10. SPONSOR/MONITOR'S ACRONYM(S)
Reclamation

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Final Report ST-2020-1885-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Cavitation and erosion damage to concrete hydraulic surfaces such as spillways and stilling basins are a problem for facilities operated by the Brazilian Government and Reclamation. A collaboration was begun in 2018 between FURNAS in Brazil and Reclamation to study the complex relationships between concrete properties and hydraulic conditions that induce damage. The aim of this study is to improve guidance for concrete design and repair procedures. This study combines technical expertise and laboratory capabilities of concrete and hydraulics laboratories from Brazil and Reclamation. The focus of this report is cavitation damage testing conducted in Reclamation's labs in 2020. Quantitative data and visual observations suggest correlations exist between cavitation damage and concrete strength as well as air entrained into the flow which reduced the aggressiveness of the cavitation. Further work is planned for similar laboratory testing in Brazil through 2022 and comparisons to historic field data of cavitation damage on spillways to improve overall findings and application of the study.

15. SUBJECT TERMS
Air entrainment, cavitation, concrete, spillway

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U			

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Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. Special thanks to the laboratory shop staff for their expertise in fabricating, installing, and maintaining the venturi cavitation test facility.

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JOSHUA MORTENSEN

Digitally signed by JOSHUA MORTENSEN
Date: 2020.09.30 15:52:52 -06'00'

Prepared: Josh Mortensen, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, 86-68560

CATHERINE LUCERO

Digitally signed by CATHERINE LUCERO
Date: 2020.09.30 15:59:02 -06'00'

Checked: Catherine Lucero, P.E.
Civil Engineer, Concrete and Structural Laboratory, 86-68530

KATIE BARTOJAY

Digitally signed by KATIE BARTOJAY
Date: 2020.09.30 16:03:02 -06'00'

Technical Approval: Katie Bartojay, P.E, FACI
Manager, Concrete and Structural Laboratory, 86-68530

Tony L. Wahl

Digitally signed by TONY WAHL
Date: 2020.09.30 15:46:14 -06'00'

Peer Review: Tony Wahl, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, 86-68560

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

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JOSHUA MORTENSEN

Digitally signed by JOSHUA MORTENSEN
Date: 2020.09.30 15:53:19 -06'00'

Prepared: Josh Mortensen, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, 86-68560

Digitally signed by TONY WAHL
Date: 2020.09.30 15:50:18 -06'00'

Peer Reviewed: Tony Wahl, P.E.
Technical Specialist, Hydraulic Investigations and Laboratory Services, 86-68560

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Acronyms and Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
EM	Engineering Monograph
FURNAS	FURNAS Centrais Elétricas
psi	lbs./in^2
MPa	Mega Pascals
Reclamation	Bureau of Reclamation
UFRGS	Universidade Federal do Rio Grande do Sul

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Executive Summary

Cavitation and erosion damage to spillways and stilling basins are a problem for both the Brazilian Government and Reclamation, and each have made many costly repairs that impact operations. Reclamation's typical approach to cavitation has been to mitigate the source, if possible, (i.e. geometry, aeration slots, etc.) and then line the structure with steel, high strength concrete, or other durable materials in locations where mitigation through design is not possible. However, there is no clear guidance for engineers and designers for selecting concrete strength parameters for repairs or new designs. Specialized materials and construction techniques are needed when concrete strengths go above about 8,000 psi and selecting an unnecessarily high value can significantly increase repair and construction costs.

Reclamation began collaborating in 2018 with materials and hydraulics laboratories at FURNAS of the Brazilian Government and their partner Federal University of Rio Grande do Sul to study flow induced damage to concrete surfaces. The approach to this study, which is planned to continue through 2022, includes three main steps: literature review, analysis of historical field data, and laboratory testing of concrete cavitation damage.

The main objective of this collaborative study is to develop a reliable correlation between concrete properties and local hydraulic conditions that enables design engineers to choose the most cost-effective concrete design for the application.

While this report summarizes literature review and analyses of field data to date, its focus is on concrete cavitation testing conducted in Reclamation's Concrete and Hydraulics Laboratories in 2020. Parallel testing in Brazil's laboratories is planned for 2021, in addition to ongoing efforts by both Reclamation and Brazil in 2022 to further analyze historical field data and develop correlations to laboratory results.

Main conclusions from cavitation testing at Reclamation's Laboratories in 2020 include:

- Air flows as low as 0.15% of the water discharge significantly reduced the level of hydrodynamic pressure fluctuations on the concrete surface, which continued to decrease for air flows up to about 2%. Air flows greater than 2% had little additional influence on pressure fluctuations at the surface.
- Concrete damage was correlated with air flow. Damage was significantly reduced with air flows as low as 0.25% There was practically no damage to the samples with a strength of 3800 psi for air flows of 2% and for higher-strength samples (4600 – 8100 psi) for air flows of 0.5% and greater. This is most likely due to the air's influence on hydrodynamic pressure fluctuations as shown by hydraulic measurements.
- Concrete damage was also correlated with concrete strength. Cavitation at the baseline condition without airflow caused significant damage and material erosion on the 3800 psi samples. At the same condition mass loss and visual damage decreased for greater concrete strength with only light pitting on the surface of the 8100 psi test samples. The exception

was the 5400 psi samples which sustained more mass loss and visual damage compared to the weaker samples of 4600 psi. While the cause is not known it may be due to variabilities in the paste content near the formed surface and uneven settlement of the aggregate between mixes with slightly different workability.

- Results provide a method to estimate the extent of concrete surface damage in the field based on concrete strength and a pressure coefficient describing localized hydraulics. These results are limited to a single operating condition with intense cavitation (cavitation index of 0.06) and application to other conditions should be approached with caution. It is hoped that additional testing at laboratories in Brazil and proposed efforts to further correlate lab testing with field data will help extend the application of this research.

The following recommendations and next steps are proposed to be addressed by the ongoing collaboration with Brazil to the extent possible.

- Further refine the pressure coefficient or develop a more effective parameter by improved prediction of localized pressure fluctuations on the concrete surface in order to predict concrete surface damage on prototype structures in the field.
- Conduct similar cavitation damage tests on concrete samples of a similar range of compression strength at a different operating condition of cavitation intensity.
- Further analyze data and experience from the field to correlate with results from both Brazilian and Reclamation laboratories.
- Improve methods of predicting air concentration and pressure fluctuations at the surface boundary of prototype spillways. A field test on a prototype spillway would be the most ideal scenario for this research.

Introduction

Water resource facilities operated by the Brazilian and United States Government are faced with cavitation and erosion of concrete surfaces of spillways and stilling basins and each have made many costly repairs that impact operations. The Bureau of Reclamation (Reclamation) is collaborating with FURNAS Centrais Elétricas (FURNAS) and their partners in Brazil to study flow induced problems encountered at concrete surfaces in spillways and stilling basins by combining concrete materials testing with hydraulic laboratory studies. This partnership, which is planned to continue through 2022, includes parallel efforts of literature review, analysis of historical field data and experience, and laboratory testing of cavitation damage to concrete. This report summarizes the findings of research performed to date by Reclamation with a focus on the 2020 laboratory testing.

The main objective of this collaborative study is to develop a reliable correlation between concrete properties and local hydraulic conditions that enables design engineers to choose the most cost-effective concrete design for the application, be it a repair of an existing structure or new design.

Project Background

Reclamation has been an industry leader in the field of cavitation and spillway/stilling basin design. The 1990 *Engineering Monograph No. 42 "Cavitation in Chutes and Spillways"* (Falvey, 1990) led to great advances in spillway design and the understanding of cavitation indices. Reclamation also contributed greatly to the 2017 revisions to the American Concrete Institute's (ACI) "*207.6R-17 Report on Erosion of Concrete in Hydraulic Structures"*. Reclamation's approach to cavitation has been to mitigate the source, if possible, (i.e. geometry, aeration slots, etc.) and then line the structure with steel, high strength concrete, or other durable materials in locations where mitigation through design was not possible. During the revision to the ACI document it became evident that much of the research performed to date on the cavitation of concrete hydraulic structures subject to high velocity flows was establishing critical cavitation indices with little consideration for concrete erosion resistance, and when concrete erosion resistance was being considered it was being evaluated using abrasion-erosion testing, instead of test methods based on cavitation erosion itself. This was primarily due to the complexity of cavitation testing and the ease and low cost of concrete abrasion-erosion testing.

The current guidance for cavitation prevention was to use higher strength concretes in areas subjected to increased risk. The *ACI 350 - Environmental Structures Code and Commentary* (ACI 350-6) code document states that "Structures exposed to cavitation erosion shall be constructed with high-strength, low water-cementitious materials concrete..." No clear guidance is given to engineers and designers for selecting specific strength values. Specialized materials and construction techniques are needed when concrete strengths go above about 8,000 psi and selecting an unnecessarily high value can significantly increase repair and construction costs.

There is much information on concrete mixtures and their relationship to abrasion-erosion resistance. Strength requirements for hydraulic structures are selected somewhat arbitrarily from samples that performed well using ASTM C1138 (2019), Standard Test Method for Abrasion

Resistance of Concrete. This test is meant to evaluate the relative durability of different concretes exposed to abrasion from particles suspended in water. The unproven hypothesis is that resistance to abrasion-erosion damage will imply resistance to cavitation damage. True cavitation resistance research was limited to the 1960's work of one Russian researcher, R.S. Galperin. Galperin published a study of the relationship between water velocity of a cavitation flow, concrete strength, and air content (air content referring to the naturally occurring or injected air into the water flow known to decrease the effects of cavitation as the content of air to water increases). The accuracy and reliability of this relationship was considered limited, as only 8 data points were presented in the published data.

In 2017, Reclamation's Concrete and Structural Laboratory completed Concrete Cavitation Resistance – Scoping Study report (Bartojay, 2017) to identify partners for research in the area of cavitation of concrete hydraulic structures and to evaluate previous cavitation work done by Reclamation, the Army Corps of Engineers, and ACI.

Mr. Selmo Kuperman, a Civil Engineer, ACI Honorary Member, and Brazilian expert on concrete technology, dam design, dam safety appraisal, repairs and rehabilitation of concrete structures made the initial introductions between Reclamation and FURNAS research laboratories. FURNAS was in the infant stage of a research project they named "Hydraulic Surfaces," a result of many years of observations of problems with concrete surfaces at spillways and stilling basins of Brazilian hydroelectric plants. In conjunction with their partner Federal University of Rio Grande do Sul (UFRGS), their research laboratories are combining materials testing with cavitation damage testing as well as physical hydraulic modeling of spillways with historic damage to study the real action of the macro turbulent flow on concrete surfaces. The research goals are to conduct live cavitation testing on real concrete specimens (with varied material strength) and to perform scaled hydraulic modeling to estimate cavitation levels and locations of potential damage.

In 2018, Reclamation's Materials and Corrosion Laboratory and Hydraulics Laboratory completed the restoration of a Venturi-type cavitation generator apparatus for testing cavitation-repair coatings under the Science and Technology Program (S&T) project "Evaluation of Field Repairable Materials and Techniques for Cavitation Damage" (Daniels, 2018). This machine was used for cavitation testing at Reclamation in the 1960's on a variety of materials. This equipment was an important tool for Reclamation's collaboration with FURNAS, enabling actual concrete testing under cavitating conditions.

In September 2018, the first year of the project, Reclamation researchers Janet White and Josh Mortensen traveled to Brazil with the purpose of meeting with partners to clearly communicate objectives and approaches of this research project. This meeting took place at the 2018 Dam World Conference in Foz do Iguaçu, Brazil and included a site visit to the FURNAS hydraulics laboratory in Rio de Janeiro. The trip report that summarizes the visit and discussions is found in Appendix A.

In January 2020 Alba Valéria Canellas, a hydraulic engineer from FURNAS, and Marcelo Marques a hydraulic engineer from UFRGS visited Reclamation's Laboratories in Brazil. The purpose of their visit was to participate in initial cavitation damage testing of variable-strength concrete samples and help define the test procedure before the commencing the entire test matrix. Their participation was helpful to Reclamation researchers in deciding which test variables and parameters would be the most useful and for the Brazilian researchers as they were still in the process of developing and designing their test facility. Their visit included many discussions on various aspects of the collaborative study and how it could be best conducted and applied for the greatest benefit of both entities as well as industry.

Previous Work

The literature describes a variety of approaches and test methods for assessing cavitation damage to different materials including concrete surfaces. Findings from this literature review are summarized in Appendix B. Two studies are discussed in detail here.

A Russian researcher named R.S. Galperin completed many studies on cavitation effects to hydraulic equipment and structures. One study (Galperin, et al, 1977) included laboratory testing of concrete samples with a range of compression strengths under cavitating hydraulic conditions with varying flow velocity and amount of air injection. Test results were used to form the "Galperin Graph" which is shown in Figure 1. Data points represent initial damage that was visually observed on the concrete surface for the given hydraulic conditions. Details about the amount of time for each test are not clear in the report.

Information included on this graph make it user-friendly, as concrete strength and flow velocity are easily estimated as well as the concentration of air in the flow, although air near the surface is difficult to predict with any degree of certainty. This plot has been used by design engineers in Brazil, but they have recently called into question its reliability with only 8 data points used to develop the plot and trend lines. The lack of information from this study, as well as uncertainty from current abrasion methods identified from revisions to the ACI report (ACI 207.6R-17, 2017) helped provide initial motivation for the current collaborative study with Brazil.

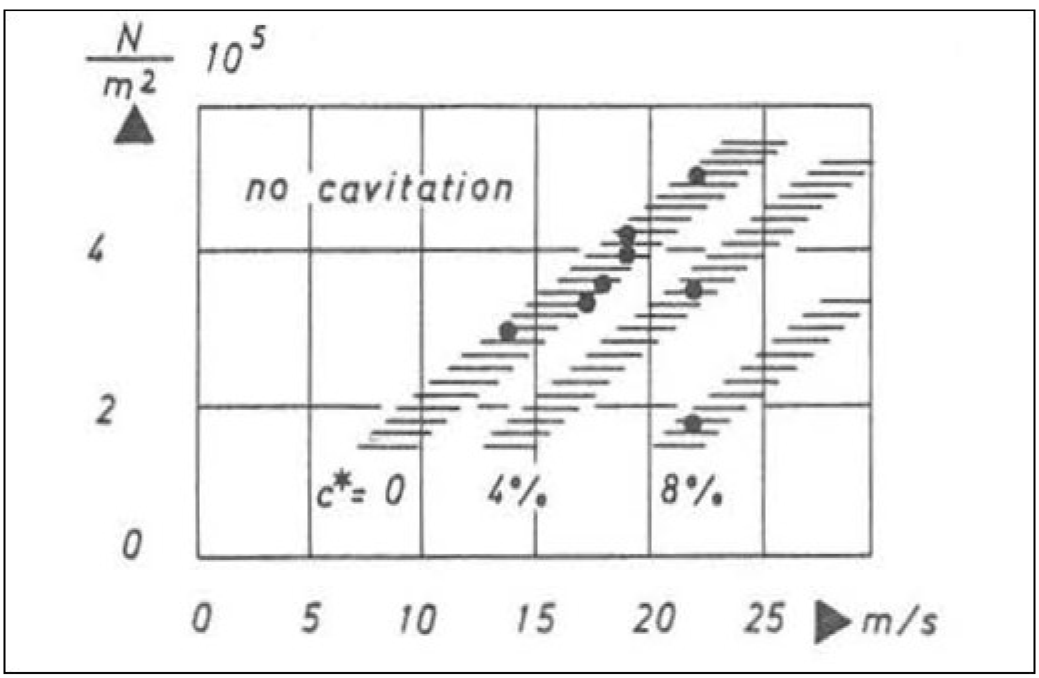

Figure 1 Galperin's Graph showing relationship of damage for concrete strength with flow velocity and air injection (in the flow of water).

In the early 1950's researchers in Reclamation's laboratories conducted studies on cavitation damage to concrete. Peterka performed laboratory tests that showed the significant affect that air (in the flow of water) has on reducing cavitation damage to concrete surfaces (Peterka, 1953). Concrete test samples were placed in a venturi type device, similar to the one used in the current study, and exposed to cavitation for a 2 hour period under varying percentages of air injected upstream. Test data from his study show that air mixtures as little as 1-2% (percentage of water flow by volume) significantly reduced the amount of damage sustained by the concrete and that damage was almost entirely eliminated with approximately 7-8% air in the water flow (Figure 2). The study was limited to a single concrete strength and cavitation condition. While the concrete strength was not reported it was likely very low as the mix had only cured for 7 days before testing and did not contain coarse aggregate, and damage to the concrete at low air flow conditions was quite extensive (Figure 3).

Results from this study were significant for that time and helped point to the development of aerators and slot designs that have been successfully used in spillway modifications and new designs to prevent cavitation damage. Air flow results were also instrumental in guiding the range of conditions to be considred in the current laboratory testing.

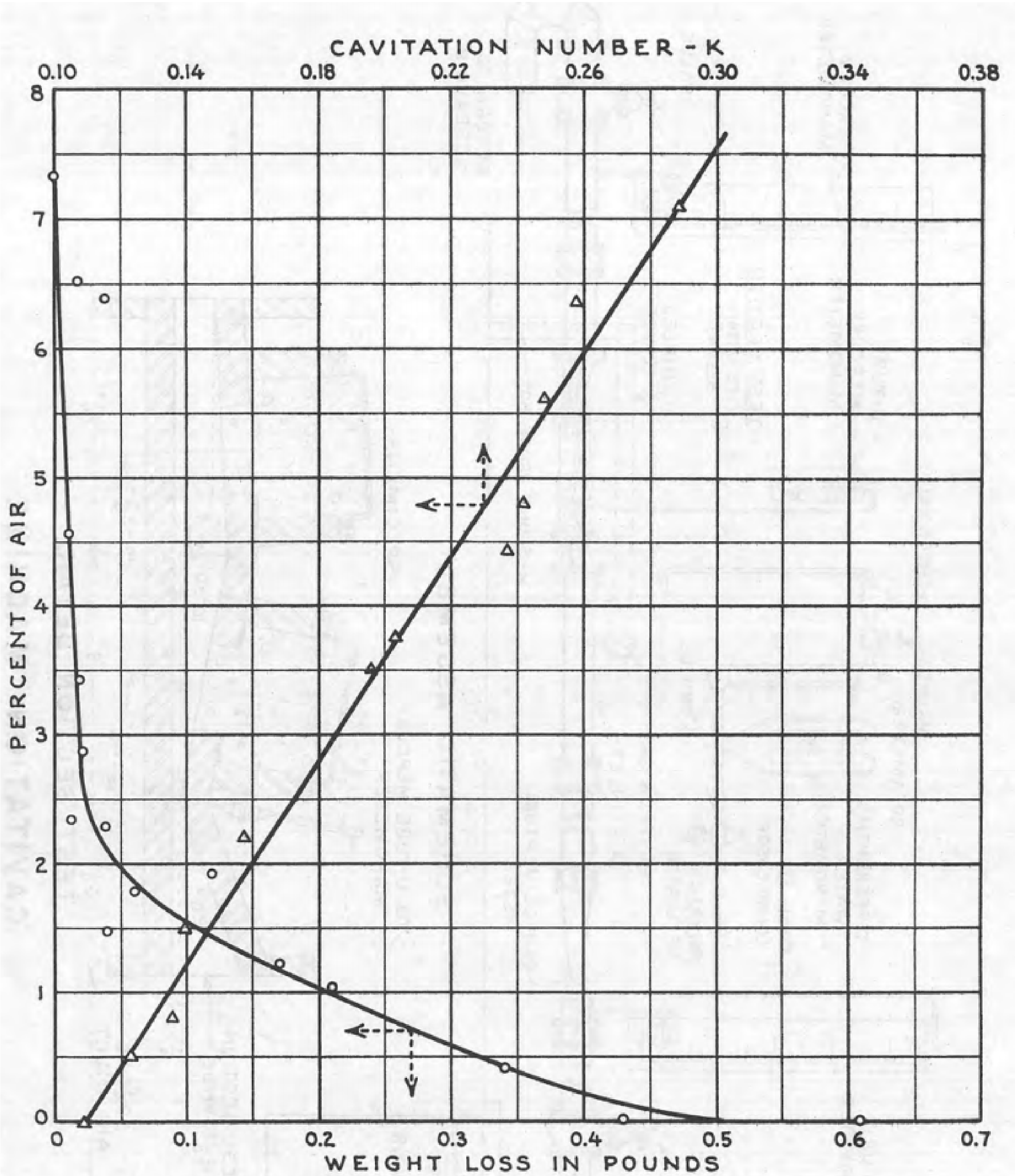

Figure 2 Test data from Peterka's 1953 laboratory study showing significant decrease in concrete damage from cavitation with percentage of air in the flow of water.

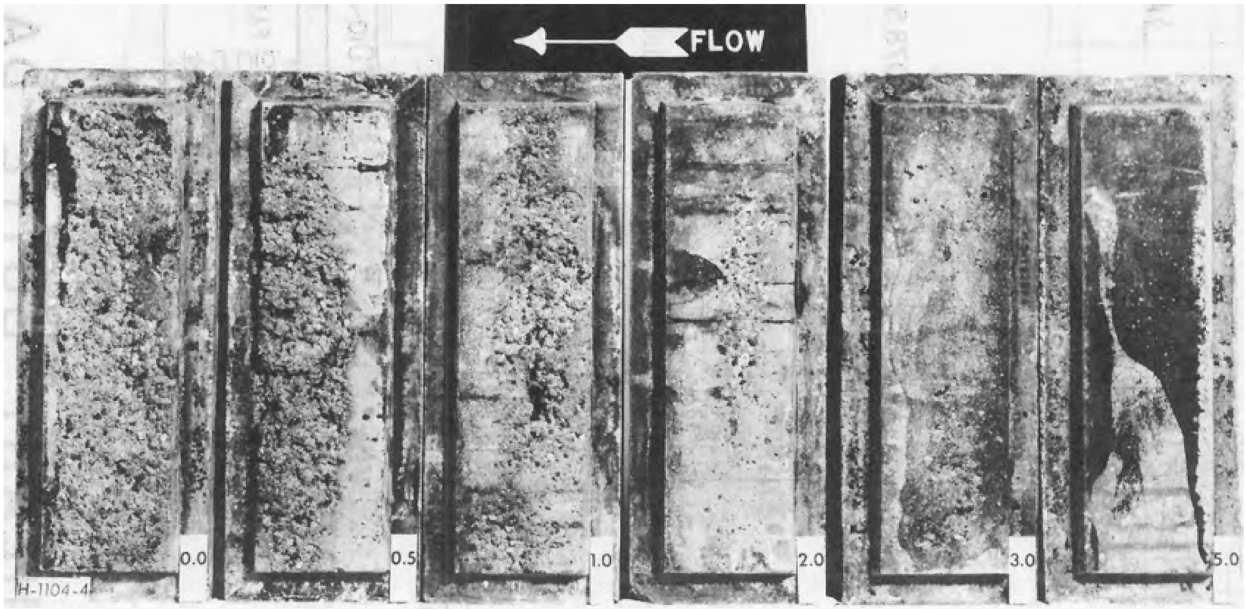

Figure 3 Photograph from Peterka's 1953 laboratory study showing differences of cavitation damage on concrete surfaces with injected air percentages.

Approach and Methodology

Researchers from Brazil and Reclamation agreed upon a research plan that included three main steps – Literature Review, Analysis of Historical Field Data, and Laboratory Testing involving concrete and hydraulics laboratories from both Brazil and Reclamation. The plan provided that researchers from both countries would engage these steps independently but in parallel with open lines of communication. The hope of this collaborative approach was to improve the overall quality of the study by correlating field and laboratory data and extend the application of results to a greater range of spillway designs, operating conditions, and concrete strengths than could be done independently.

Analysis of Historical Field Data

For FURNAS and UFRGS, this step included site visits to several Brazilian facilities with cavitation damage on concrete surfaces, mainly spillways. Data on the material properties of the concrete were gathered as well as historic operating records to be used to simulate hydraulic parameters. Hydraulic simulations were completed using numerical hydraulic modeling software Ansys Fluent (Ansys, 2020) to identify hydraulic parameters at the location of reported damage. In addition to numerical modeling, a couple of the Brazilian facilities will be modeled physically at the FURNAS Hydraulics Laboratory in Rio de Janeiro to measure localized hydraulics parameters with greater spatial and temporal resolution to compare to numerical results. Physical and numerical modeling tasks will continue through 2022.

For Reclamation, this step included gathering information on Reclamation facilities that have sustained cavitation damage on concrete surfaces. These were mainly emergency spillways that have passed a flood event. Data included concrete material properties from historical records (Bureau of

Reclamation, 2020-a) as well as hydraulic data. Hydraulic data were produced by simulating the flow event using Spillway Pro (Bureau of Reclamation, 2020-b) which is a spreadsheet tool that models the flow in one-dimension using the approach described in Engineering Monograph 42 (EM 42) (Falvey, 1990). Parameters such as depth, velocity, and cavitation index at the location of reported damage were used for preliminary analysis. More thorough analyses with three-dimensional hydraulic modeling software Flow3D (Flow Science, 2020) are proposed through 2022 to better correlate with laboratory results.

Laboratory Testing

Laboratory testing of actual cavitation damage to concrete surfaces is a key component of this study and the focus of this report. Due to the immediate access of the cavitation venturi test facility and advantage of having both concrete and hydraulics laboratories at the same location it was decided by the research team that Reclamation would be the first to conduct laboratory testing. Brazilian collaborators will conduct laboratory cavitation damage testing in 2021 and 2022 after development and construction have been completed of a cavitation test facility similar to Reclamation's. Also, significant logistical planning will be required between concrete and hydraulic laboratories that are in different locations in Brazil.

Laboratory tests included the design and mixing of concrete samples, hydraulic measurements of cavitation conditions within the venturi facility and cavitation damage testing where concrete blocks of different strengths were exposed to cavitation under the same hydraulic conditions for 4 hours each (Table 1). The concrete samples featured a raised test surface, 3 inches by 10.5 inches and 3 inches thick, that fit flush with the inner surface of the cavitation machine with the bottom formed side of the concrete is exposed to the water flow(Figure 4).

The testing matrix developed by Reclamation and FURNAS

- 5 mixes
- 5 air injection hydraulic test conditions
- 3 samples per mix – total of 75 tests
- 4-hour test period to run samples in the cavitation machine

Table 1 Target air flow injection rates and concrete strength for laboratory cavitation damage testing.

<table>
<tr><td></td><td colspan="5">Volumetric Air-Water Ratio</td></tr>
<tr><td></td><td>0%</td><td>0.25%</td><td>0.50%</td><td>1.00%</td><td>2.00%</td></tr>
<tr><td rowspan="5">Concrete Target Strength</td><td colspan="5">3,000 psi (20 MPa)</td></tr>
<tr><td colspan="5">4,500 psi (30 MPa)</td></tr>
<tr><td colspan="5">6,000 psi (40 MPa)</td></tr>
<tr><td colspan="5">8,000 psi (55 MPa)</td></tr>
<tr><td colspan="5">10,000 psi (70 Mpa)</td></tr>
</table>

Figure 4 High density foam mold used for casting concrete test samples (left) and load of concrete samples ready for cavitation testing (right).

Concrete Design

Reclamation and FURNAS discussed concrete mixture options and availability of materials in each country. The goal was to choose materials that were similar so that results could be compared for validation testing. Straight cement mixtures were selected to eliminate the variables associated with supplementary cementitious materials. The 10,000-psi concrete mixture included 7% silica fume (>98% SiO_2) to achieve high strength.

The concrete mixtures prepared at Reclamation contained a ¾-inch (19 mm) crushed granite coarse aggregate from Morrison, CO and natural sand fine aggregate source from deposits near the Platte River, Milliken, CO. Fine aggregate is primarily quartzite and granite with smaller percentages of sandstone, chert and andesite. Aggregate was proportioned about 45% sand and 55% coarse as seen in the gradation curve (Figure 5).

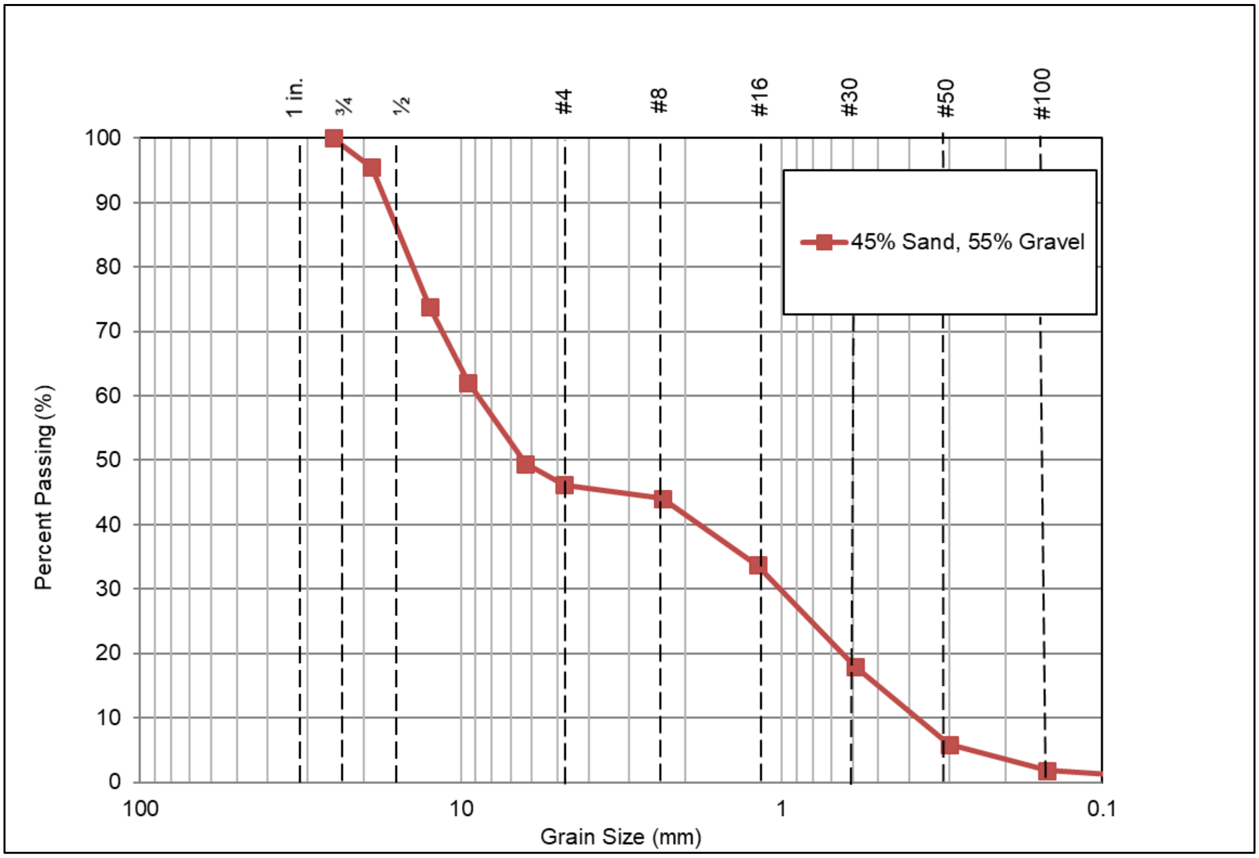

Figure 5. Combined fine and coarse aggregate gradation

All concrete contained ASTM C150 Type I/II cement. Lower strength concrete contained a slightly higher percentage of sand compared to the mixtures ranging from 6,000 to 10,000 psi (20 -70 MPa). Reclamation decided to add one high strength concrete mix for the US research to set a higher strength upper boundary. This mix contained ASTM C1240 Silica Fume, which is not widely available in Brazil. Concrete contained a mid-range or high-range water reducing admixture in order to achieve a slump of 4 to 5 inches (100 to 125 mm) when tested in accordance with ASTM C143 as shown in Figure 6. Trial batches were made prior to casting the final specimens, with results plotted in Figure 7.

Figure 6. Concrete trial batch with a 4-inch slump

Final concrete specimens were cured in lime water baths at 73 °F (22.7 °C) until removed for strength or cavitation testing. Compressive strength was tested on 4-inch (100 mm) diameter cylinders at 7 days after casting and at the start and end of the cavitation testing (approximately 26 days and 36 days after casting) in accordance with ASTM C39.

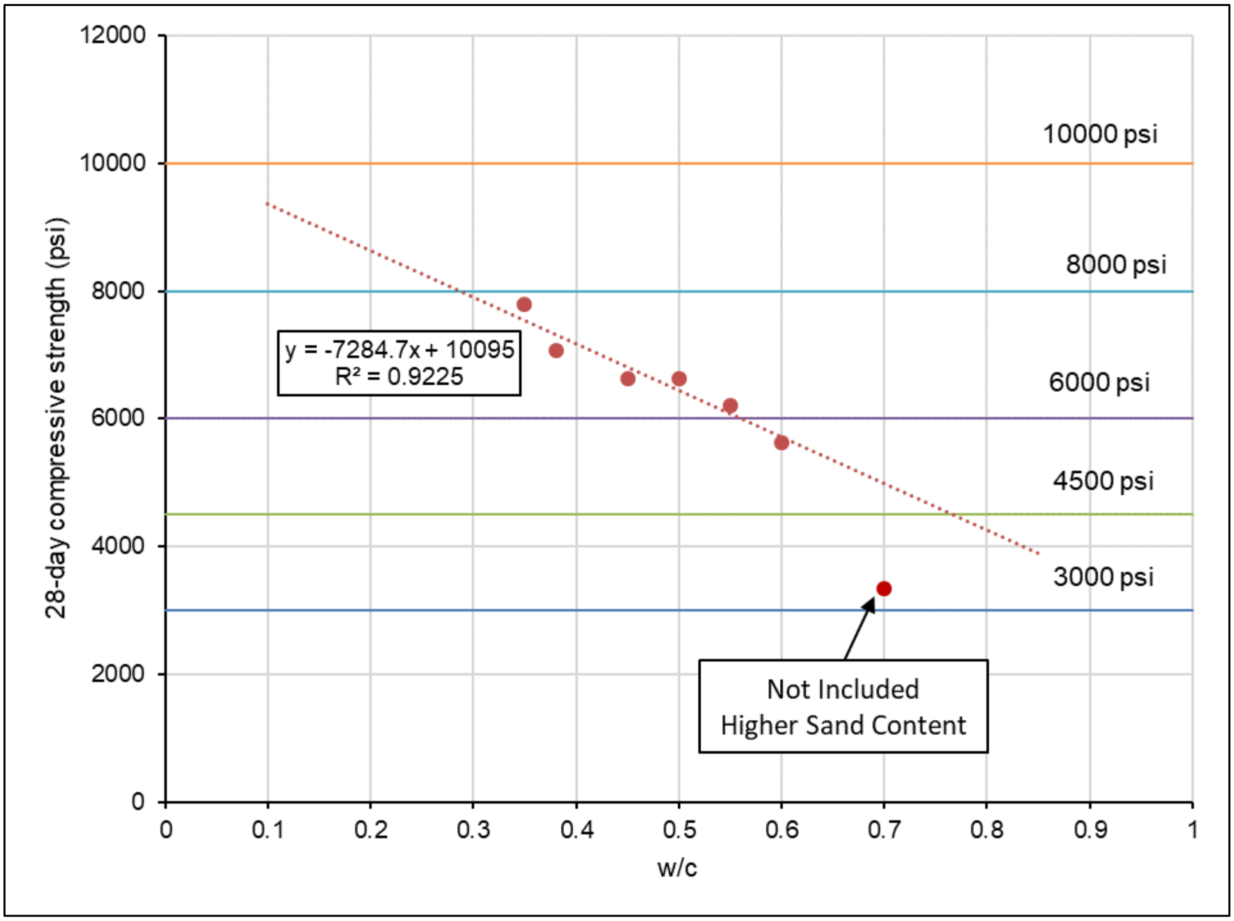

Figure 7. Trial batch strength results to determine proportions for final specimens.

Hydraulic Testing

The cavitation test facility consists of an inline stainless-steel venturi that induces cavitation damage on a test sample. Cavitation is induced at the throat of the converging section and damage occurs where high intensity implosions of the cavitation bubbles occur adjacent to a test surface immediately downstream (Figure 8). Details of its construction and operation are found in report PAP-404 (Bureau of Reclamation, 1963). Water flow was delivered to the cavitation facility from a large sump beneath the lab floor via a high-head pump with a variable frequency drive, and a gate valve downstream from the facility was used to control discharge and pressure profiles within the cavitation venturi. Pressure control points upstream and downstream were matched to those used during the original 1963 test. Water was discharged from the cavitation facility into a large head tank which returned water back to the lab sump.

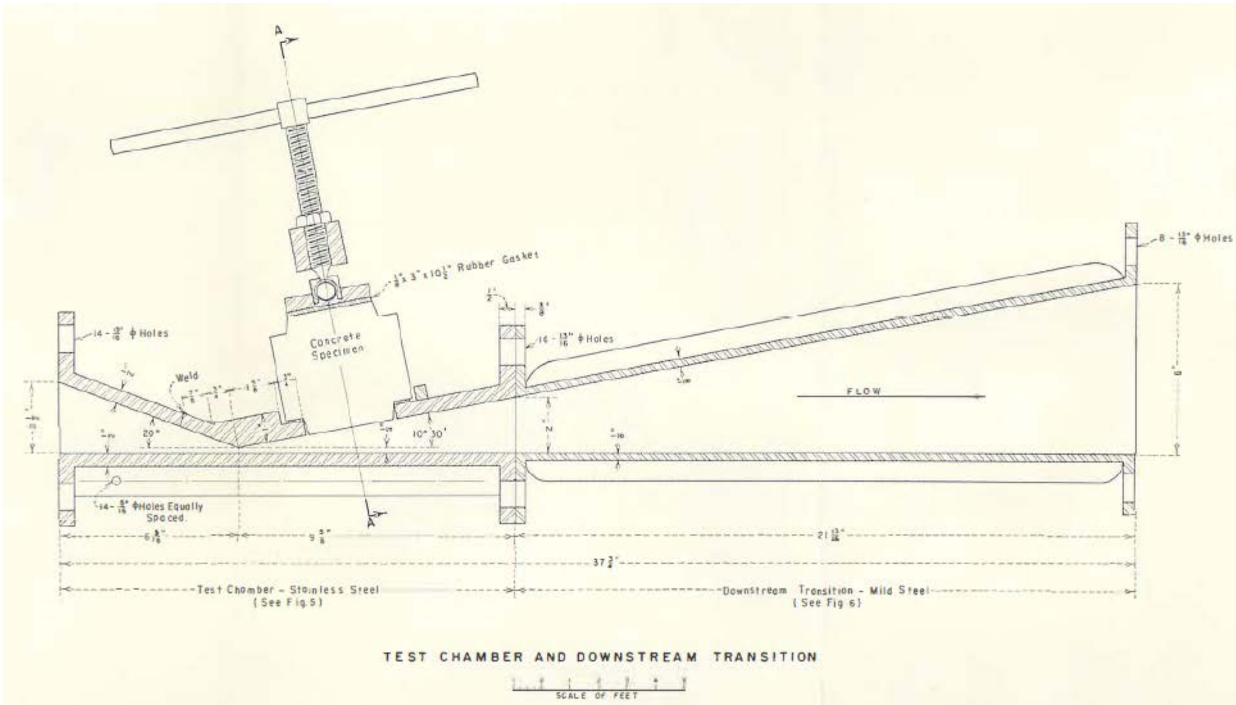

Figure 8 Original drawing of the cavitation venturi machine used in the current laboratory testing. Drawing is in profile view with flow going left to right.

Water discharge was measured using a venturi meter and mercury manometer upstream from the cavitation facility. Air was injected into the water pipe immediately upstream from the cavitation venturi (and downstream from the venturi meter) from the building's house compressed air system and was controlled and measured using the system shown in Figure 9. Water discharge was recorded manually from the mercury manometer and all other pressure and air flow measurements were recorded with an analog to digital converter data acquisition system and laptop computer. Descriptions of instrumentation used for hydraulic measurements are shown in Table 2.

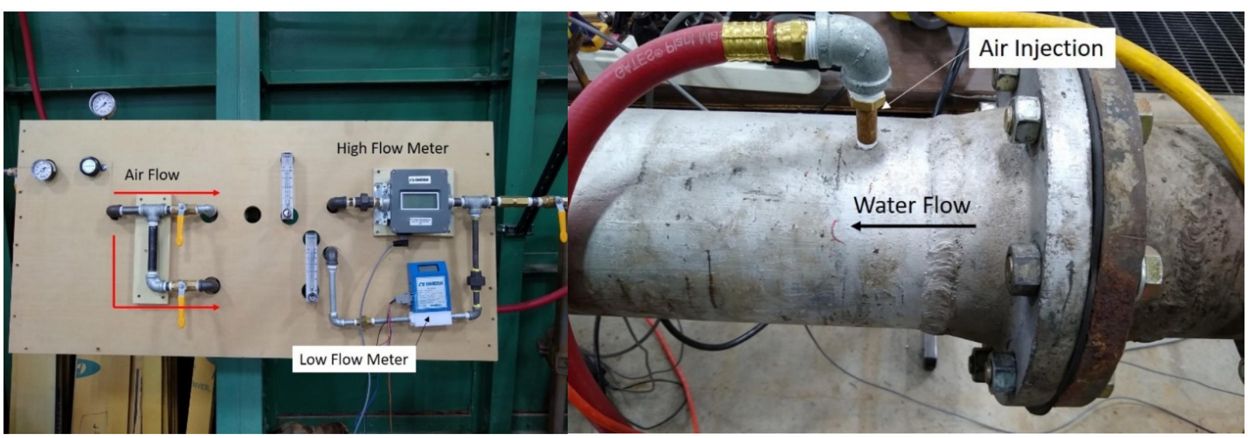

Figure 9 Air injection and measurement system (left) and air injection tap immediately upstream cavitation facility.

The cavitation facility was installed in a sound-reducing box due to the high levels of vibration and noise during operation. Before concrete test blocks were tested, hydraulic measurements were made which included static pressures from pressure taps at several locations along the flow path (Figure 10). A metal plate of the same surface dimensions as the concrete test blocks was used to house static pressure taps and dynamic pressure sensors. Two flush-mounted dynamic pressure sensors were installed in the plate as well as three pressure taps (Figure 11) to directly measure hydrodynamic pressure fluctuations on the surface of the test sample for the range of air injection conditions.

Table 2 Description and location of pressure and air flow instrumentation used for hydraulic measurements and cavitation damage testing. Negative distances indicate locations upstream from the throat.

Sensor Label	Description	Brand and Model	Measurement Range	Distance from Throat	Sampling Rate
			-	*inch*	*sample/sec*
P1	upstream piezo ring on pipe	Omega PX309	0-100 psig	-46.00	100
P2	upstream converging section, static	Omega PX309	0-100 psig	-4.21	100
P3	upstream converging section, static	Omega PX309	0-100 psig	-2.22	100
P4	immediately upstream throat, static	Omega PX309	0-30 psia	-0.23	100
P5	test sample - upstream, static	Omega PX309	0-30 psia	2.76	100
P6	test sample - mid, static	Omega PX309	0-30 psig	3.88	100
P7	test sample - downstream, static	Omega PX309	0-30 psig	5.00	100
P8	downstream diverging section, static	Omega PX309	0-30 psig	6.78	100
P9	downstream diverging section, static	Omega PX309	0-30 psig	8.26	100
P10	downstream piezo ring on pipe	Omega PX309	0-30 psig	30.50	100
D1	upstream dynamic - D1	Kistler 603CBA	0-5000 psi	3.33	1M
D2	downstream dynamic - D2	Kistler 603CBA	0-5000 psi	4.46	1M
Air flow	meter upstream from injection point	Omega FMA-A2000	0.75-75 SLPM	-104.0	100

The venturi test facility was limited to a single operating condition with a water discharge of 1.96 ft^3/s, which translates into 92 ft/s average throat velocity and cavitation index of 0.06. Hydraulic measurements were made for air injection flow conditions of 0% to 2% (airflow/waterflow). Measurements were recorded at 100 samples/second for five minutes at each condition, except for dynamic pressures which were recorded at 1 million samples/second for five seconds at each condition. These measurements were used to guide the selection of operating conditions for cavitation damage testing with the concrete test samples.

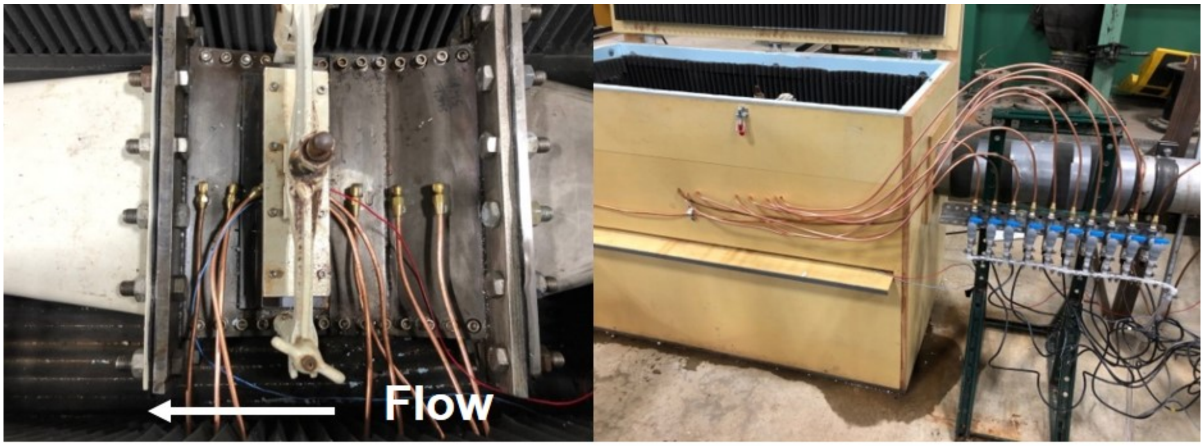

Figure 10 Photographs of the cavitation venturi showing top view with yoke and pressure taps (left) and upstream pipe entering the box to reduce noise (right).

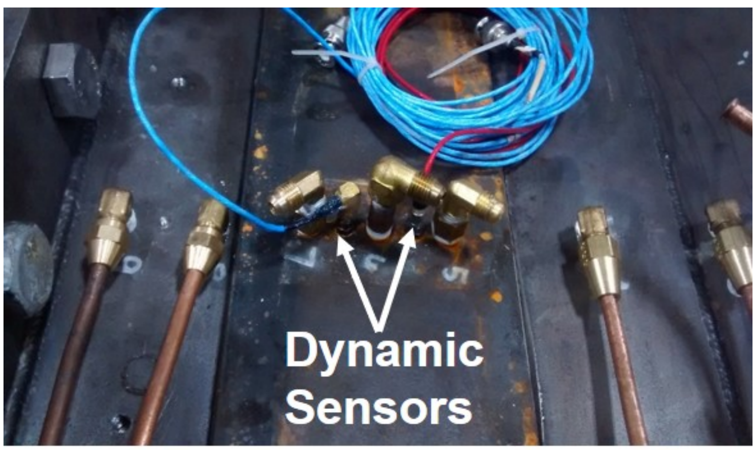

Figure 11 Photograph showing pressure taps and dynamic pressure sensors mounted on the metal block used for hydraulic measurements.

Cavitation Damage Testing

Following the hydraulics testing the metal test sample with pressure sensors was replaced by concrete block test samples (Figure 12). Each sample was tested under the same conditions of 1.96 ft^3/s water flow with air injection settings of 0, 0.25, 0.5, 1, and 2% (air flow / water flow). Each block was tested for 4 hours while the upstream and downstream pressure points, air flow, and water flow readings were monitored and recorded throughout each test.

The mass of each test block was measured in the saturated surface dry condition both in air and submerged before and after each test. A scale was used with a basket hanging in a water tank to allow the apparent mass of the sample to be measured when completely submerged. These measurements were used to calculate mass and volume loss of each test sample.

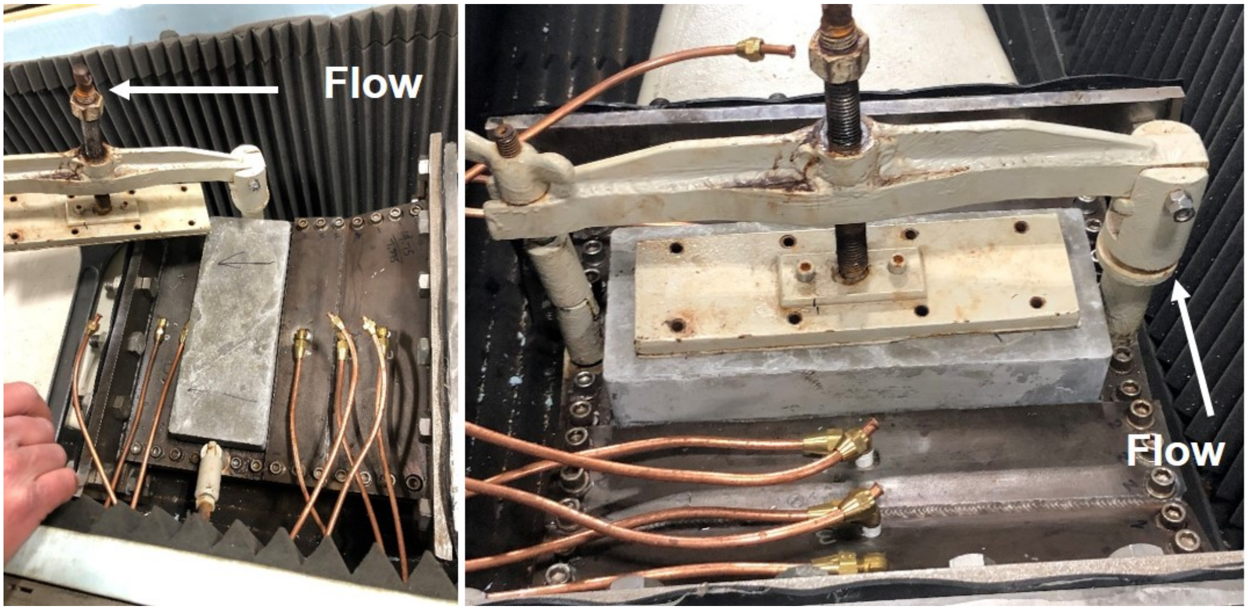

Figure 12 Photographs showing concrete test block mounted in the cavitation venturi for testing.

Results

Field Experience and Historical Data

Data were gathered from eight cavitation damage events at five Reclamation facilities summarized in Table 3. Descriptions of operating conditions, locations, exposure time, and extent of the damage were mainly obtained from EM 42 (Falvey, 1990). Using this information, the flood events were analyzed using Spillway Pro to compute the hydraulic conditions at the location of concrete damage. Concrete data (mainly compression strength) were obtained from historical records (Bureau of Reclamation, 2020-a). No attempts were made to estimate actual concrete strength at the time of the event. These field results are preliminary and further work has been proposed to analyze concrete damage and hydraulic data with a more robust and detailed numerical hydraulic model correlated to laboratory findings (from both Reclamation and Brazilian labs).

Table 3 Hydraulic and concrete strength data for flow events that caused cavitation damage in Reclamation spillways. Hydraulic data are results from Spillway PRO simulations and concrete data were provided from the historical database (Bureau of Reclamation, 2020-a).

Facility Name	Flow Rate during damage	Station of Damage	Slope	Depth	Velocity	Froude Number	Flow Sigma, σ	Exposure Time	Concrete Strength
	cfs	*ft*	*ft/ft*	*ft*	*ft/s*	-	-	*hr*	*psi*
Blue Mesa	3500	1,489.6	0.6	3.1	108.1	14.7	0.190	49.0	
Flaming Gorge	4000	325.0	1.4	3.5	111.4	16.9	0.149	20.0	4,340.0
Glen Canyon (1)	7250	2,300.0	1.4	3.7	120.5	18.3	0.127	450.0	3,570.0
Glen Canyon (2)	7250	2,495.7	0.4	3.5	134.3	16.8	0.127	450.0	3,570.0
Hoover AZ SW	13000	1,200.0	0.1	4.6	145.1	15.3	0.156	3,000.0	3,056.0
Kortes	15000	273.0	0.4	8.4	92.2	7.3	0.436		4,692.0
Yellowtail	15000	944.9	0.2	6.2	136.2	12.0	0.166	420.0	6,160.0
Yellowtail	15000	1,036.8	0.0	6.2	137.1	11.8	0.122	450.0	6,160.0

Efforts from Brazilian collaborators to gather and analyze field data has been quite extensive. They have made site visits to ten facilities to personally inspect concrete surface damage and gather additional information from facility operators. Several locations of damage have been identified at each of these facilities and have been classified into damage type (i.e. abrasion, erosion, cavitation – see Table 4) and extent (i.e. minor surface wear, aggregate exposed, major pitting and material loss). Most of these damaged surfaces were due to cavitation at concrete joints. Efforts to simulate the hydraulics at damage locations with numerical and physical hydraulic models will continue through 2022.

Table 4 Definition of abrasion, erosion, and cavitation terminology used throughout this report.

Abrasion	associated with impact of solid particulate matter carried by the flow, characterized by linear damage patterns aligned with flow direction
Erosion	damage caused by flow forces against protruding forms of a previously roughened flow surface. Forces causing damage are from normal stresses and shear stresses associated with flowing liquid water, not water vapor bubble implosions.
Cavitation	damage characterized by divots or pockmarks created by intense pressure spikes at distinct "point locations". Damage that expands in the downstream direction (Christmas tree pattern as initial damage serves as catalyst for subsequent damage at downstream locations).

Field experience from Brazilian facilities are important to extend results to facilities with a different operational range. Most Brazilian spillways are low head and high discharge, and operate frequently as part of normal operations, in contrast to Reclamation's spillways which typically operate infrequently during emergency conditions. Comparing findings from both agencies shows that cavitation damage happens in a variety of spillway types and over a broad range of Froude numbers of the spillway flow ($Fr \approx$ 2-11 for Brazil and $Fr \approx$ 7-16 for Reclamation).

Laboratory Testing

Concrete

Final concrete proportions are summarized in Table 5. Eighteen cavitation test blocks were cast along with eight 4-inch by 6-inch strength-test cylinders for each mix. Cylinders were capped with sulfur in accordance with ASTM C617 and tested in compression in accordance with ASTM C39. The compressive strength was measured on the first and last days of cavitation testing, as shown in Table 6, to evaluate any variations in strength due to hydration over the testing period. The compressive strength development is plotted in Figure 13.

Table 5. Concrete mixture proportions

		Amount, lb/yd^3 (kg/m^3)				
Material	**Description**	**HydroSurf-0.35-SF**	**HydroSurf-0.35**	**HydroSurf-0.50**	**HydroSurf-0.65**	**HydroSurf-0.70**
Cement	ASTM C150 Type I/II	785 (465.7)	830 (492.4)	650 (385.6)	500 (296.6)	475 (281.8)
Silica Fume	ASTM C1240 Densified Silica Fume	60 (35.6)	None	None	None	None
Coarse Aggregate	Crushed Granite C33 No. 67 (19mm)	1627 (965.3)	1602 (950.4)	1625 (964.1)	1633 (968.8)	1618 (959.9)
Fine Aggregate	Natural Washed Concrete Sand	1286 (763.0)	1293 (767.1)	1392 (825.8)	1526 (905.3)	1502 (891.1)
Water	Denver Tap Water	294 (174.5)	290 (172.0)	324 (192.2)	326 (193.4)	334 (198.2)
Water Reducing Admixture	GCP Applied Technologies Zyla 625 ASTM C494 Type A&D	5 oz/cwt (325 mL/100 kg cement)	5 oz/cwt (325 mL/100 kg cement)	3 oz/cwt (195 mL/100 kg cement)	1.5 oz/cwt (98 mL/100 kg cement)	None
High Range Water Reducing Admixture	GCP Applied Technologies EXP 950 ASTM C494 Type F	4 oz/cwt (260 mL/100 kg cement)	4 oz/cwt (260 mL/100 kg cement)	None	None	None

Table 6. Final cavitation specimen strength

MIX ID	**7-Day Strength**		**Strength - Start of Cavitation Testing**		**Strength - End of Cavitation Testing**		**Average Strength During Testing Period**	
	psi	*MPa*	*psi*	*MPa*	*psi*	*MPa*	*psi*	*MPa*
HydroSurf-0.35 + SF	7910	55	7760	54	8480	58	8120	56
HydroSurf-0.35	6880	47	7770	54	7930	55	7850	54
HydroSurf-0.50	4630	32	5390	37	5470	38	5430	37
HydroSurf-0.65	3820	26	4550	31	4640	32	4600	32
HydroSurf-0.70	2950	20	3840	26	3940	27	3890	27

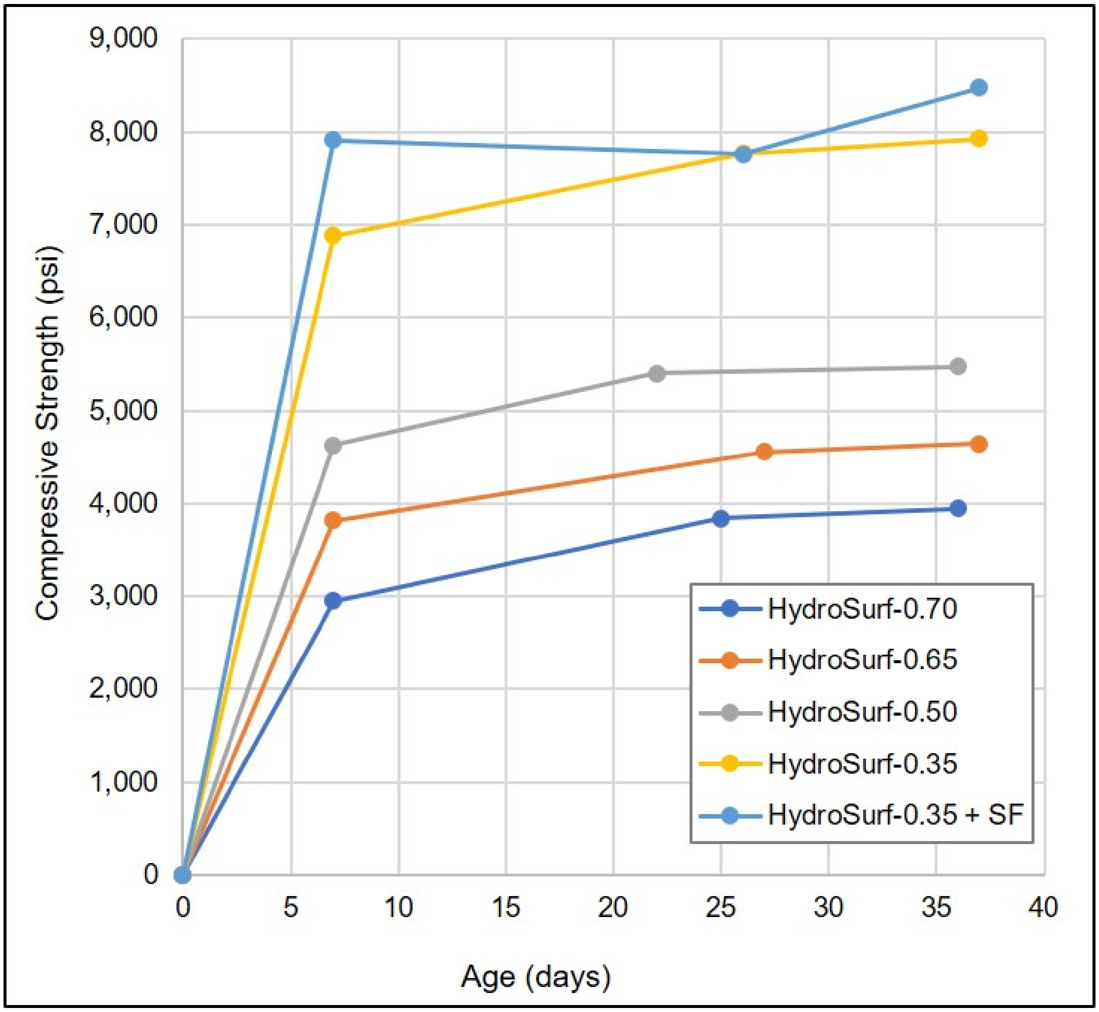

Figure 13 Compression strength results over time for concrete samples used for cavitation damage testing.

Hydraulic Testing

Hydraulic measurements were used to quantify the cavitation conditions at the surface of the test sample and to confirm proper operation and function of the venturi test facility. This was done by comparing average static pressure readings along the facility to the original 1963 test (without air injection) when the facility was first commissioned (Bureau of Reclamation, 1963). Results are compared in Figure 14 and show good agreement over the location of the test sample surface where the pressure gradient is quite steep forcing the majority of the cavitation pitting to occur at that location. A pressure reading at the throat of the venturi was not available in the current study due to the complex geometry at that location making machining a reliable pressure tap very difficult.

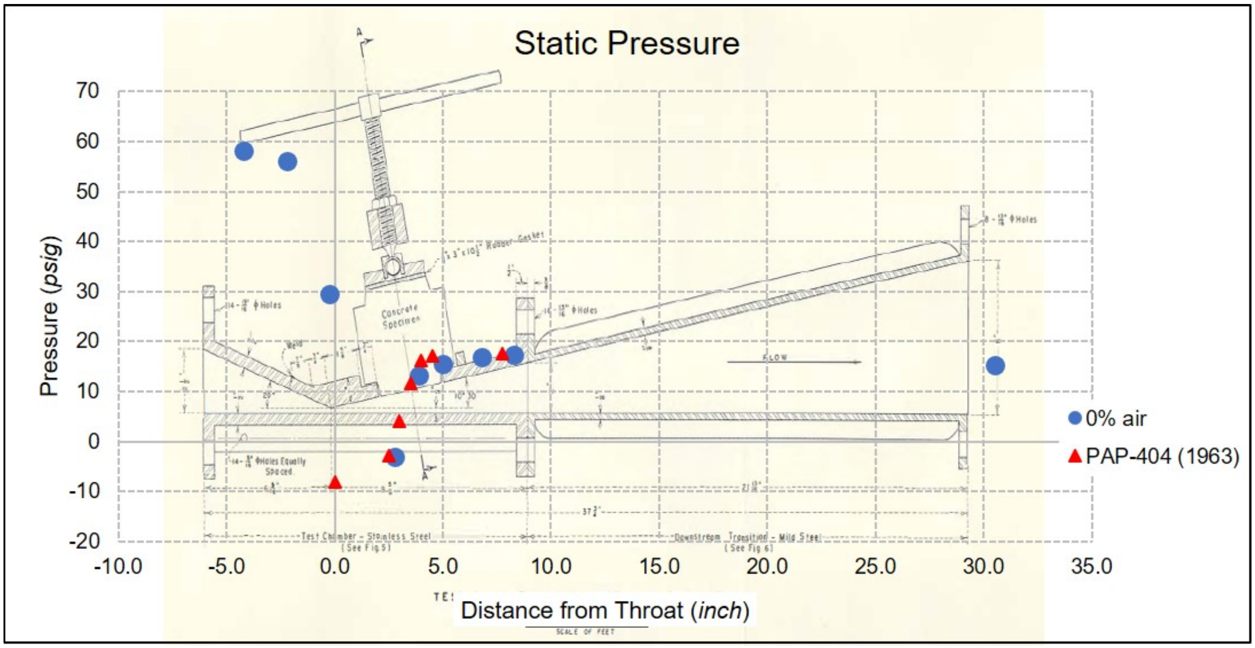

Figure 14 Average pressures measured in the cavitation venturi for the single flow condition used for all cavitation damage testing.

The measurements were repeated at each air flow condition and are shown for 2% air in Figure 15. Static pressure measurements with air were not significantly different than those without air, except for the midpoint of the test sample 3.88 inches downstream from the throat. The reason for the measurement with air being much less at this location is unknown. In general, it was assumed that pressure measurements with air were less reliable due to air bubbles entering the pressure tap lines. Had the pressure taps been installed on the invert of the venturi rather than the top, this problem may have been reduced.

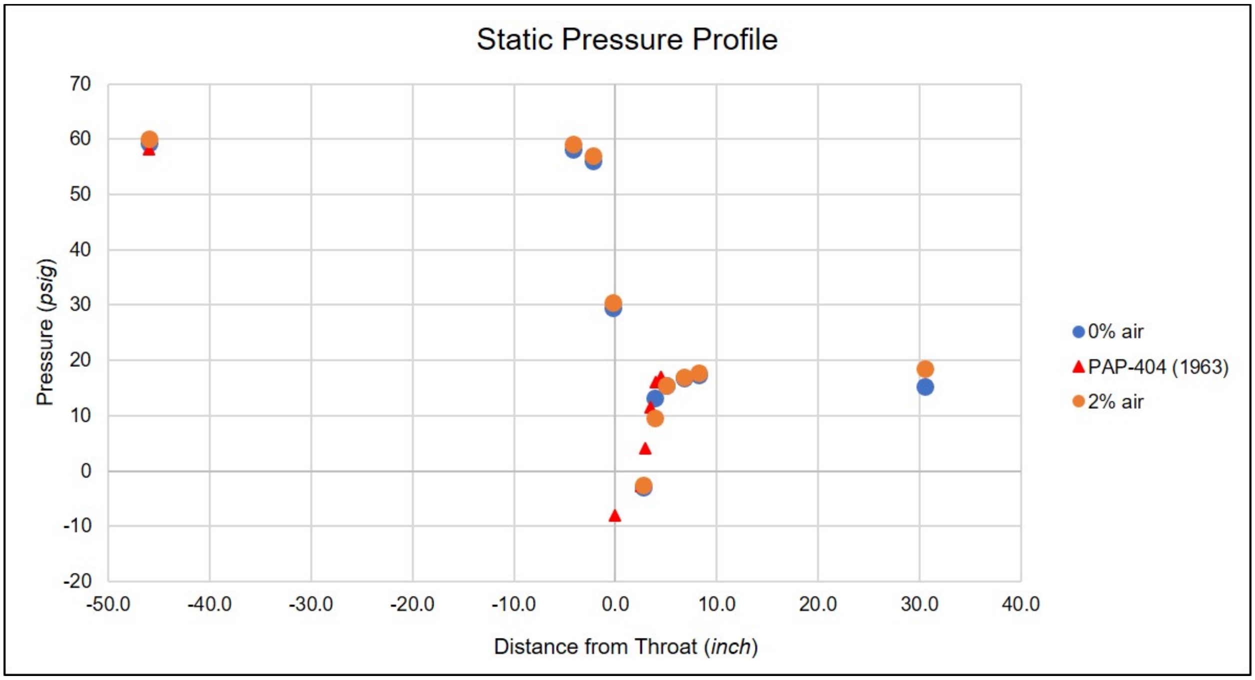

Figure 15 Comparison of average pressures measured upstream, downstream, and in the cavitation venturi for 0% and 2% air and the 1963 test (0% air).

Figure 16 shows the standard deviation of both flush mounted dynamic pressure sensors which is an indicator of the level of pressure fluctuations at the test surface for several air flow conditions between 0 and 2.5%. Maximum pressure fluctuations up to 4,500 psi occurred almost regardless of the quantity of injected air, but the standard deviation of the 5-second time series of dynamic pressures reduced consistently as air flow was increased and provided a good indication of the cavitation severity. Vibration and sound measurements were not made during these tests, but observations showed that the noise from the venturi was greatly reduced for even the smallest amount of air injection and the "banging sound" was almost eliminated entirely at 2% air.

For D1 (dynamic sensor near the upstream edge of the test sample) the pressure fluctuations were significantly reduced for air flows as little as 0.15% compared to cavitation with no air injection. The trend of reduced dynamic pressure with increasing air percentage continued to about 2% air where it then began to level out, similar to Peterka's findings (Peterka, 1953). This trend was also seen for D2 although standard deviations were lower and the change in standard deviation per unit of air flow was also reduced, suggesting that most cavitation implosions occurred on the upstream half of the test sample.

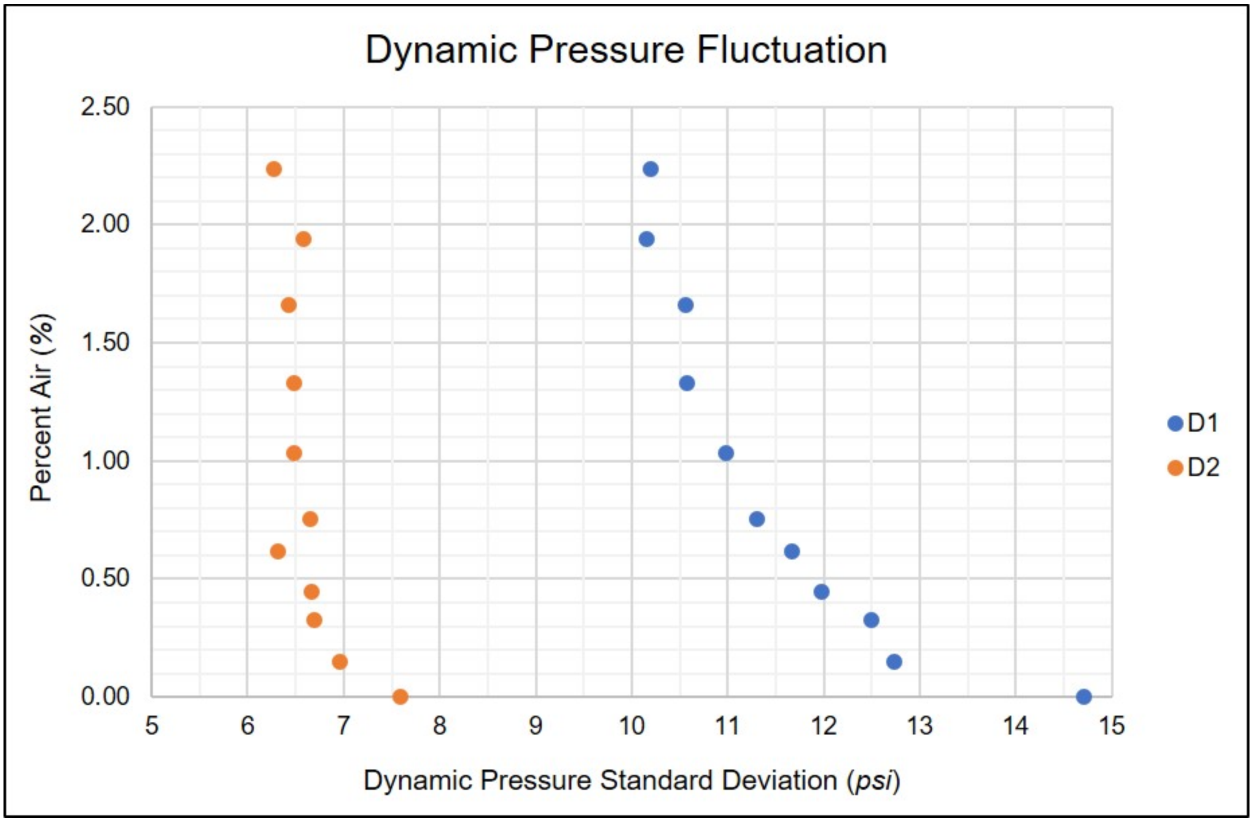

Figure 16 Plot showing effect of air percentage on hydrodynamic pressure fluctuations (standard deviation) on the test surface.

Cavitation Damage Testing

The significant effect that air injection had on noise and dynamic pressure fluctuations was also demonstrated in the cavitation damage sustained on the concrete test samples. Figure 17 shows air percentage vs. mass loss for the five concrete strengths tested. Each data point is the average of three concrete samples showing that cavitation damage was dependent on both concrete strength and air injection up to about 1 percent air. The same result is shown by volume loss in Figure 18. The exposure time in each test was 4 hours.

The trend of reduced cavitation damage with concrete strength held true except for the case of 4,600 and 5,430 psi which was opposite. It is unknown why this result is opposite from what was expected as both hydraulic test conditions and concrete mixes were confirmed to be consistent. One explanation may be the relative proportion of paste in the concrete mix. The HydroSurf-0.50 (5430 psi) mixture contained a higher percentage of paste compared to the HydroSurf-0.65 (4600 psi) mixture, which could erode more quickly. Variabilities in the paste content near the formed surface and uneven settlement of the aggregate between mixes with slightly different workability are also potential contributors. While every effort was made to eliminate variables in the concrete mixtures, ultimately, they were designed to meet a specified strength.

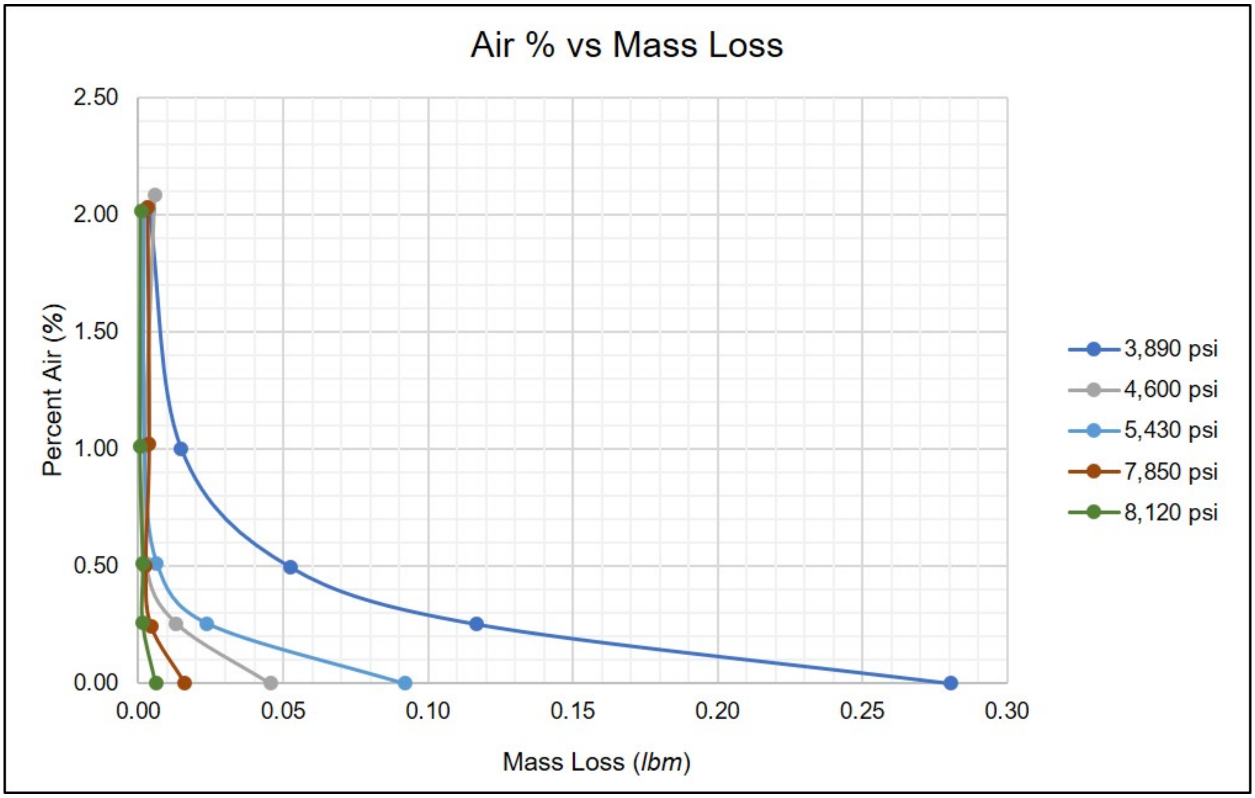

Figure 17 Plot showing effect of air percentage in the flow of water on cavitation damage during a 4 hour test period to concrete test blocks (mass loss) for the range of concrete strengths.

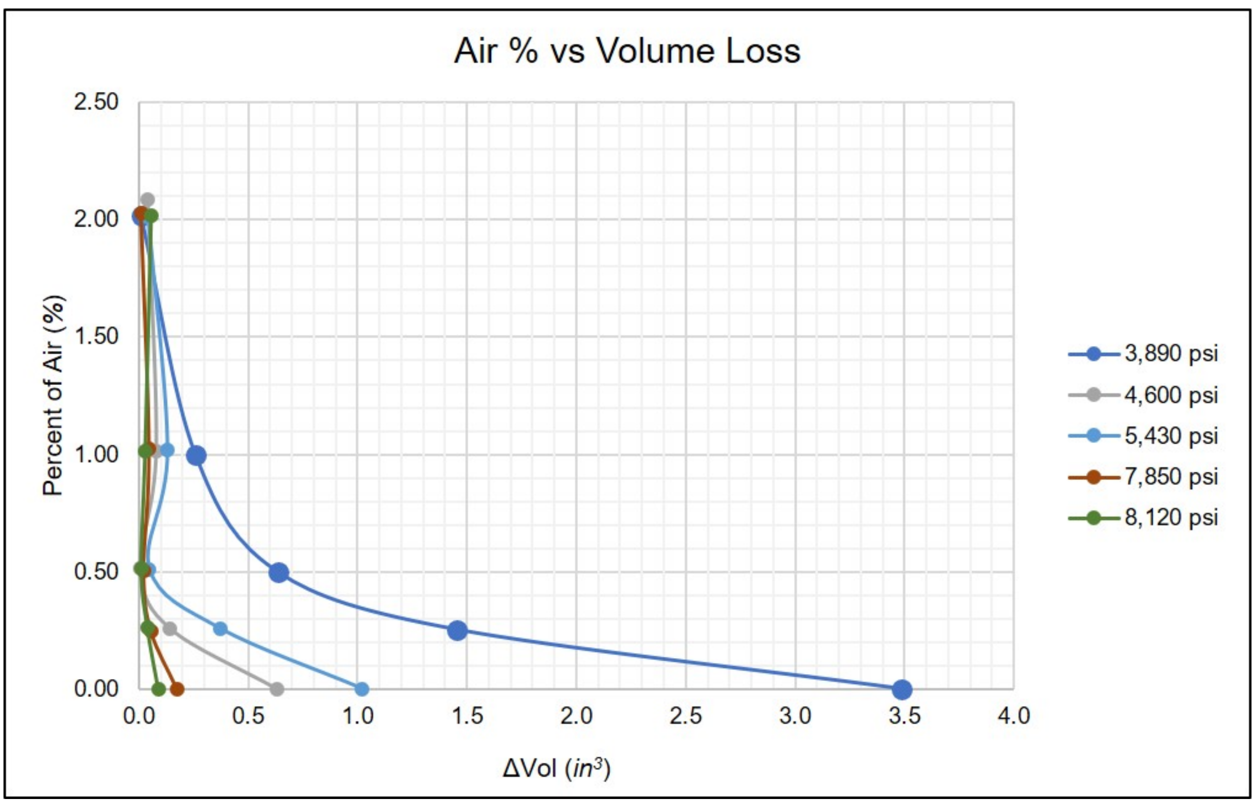

Figure 18 Plot showing effect of air percentage in the flow of water on cavitation damage during a 4 hour test period to concrete test blocks (volume loss) for the range of concrete strengths.

A comparison of the current study results to Peterka's work (1953) is made in Figure 19. In addition to expanding the results to a broad range of concrete strengths, the intent of the current testing was to obtain additional test data for air flows less than 2% since Peterka already showed great success above that level and significant changes in effectiveness below that level. Also, for actual flows on prototype spillways it is difficult to predict the amount of air near the concrete boundary, but it is believed to be quite low, which is why the current test range focused on air flows less than 2% and especially less than 1%. The increased cavitation damage and weight loss of Peterka's results compared to the current study are likely due to lower levels of concrete strength. While the actual concrete strength was not reported it was likely very low as it had only cured for 7 days before testing.

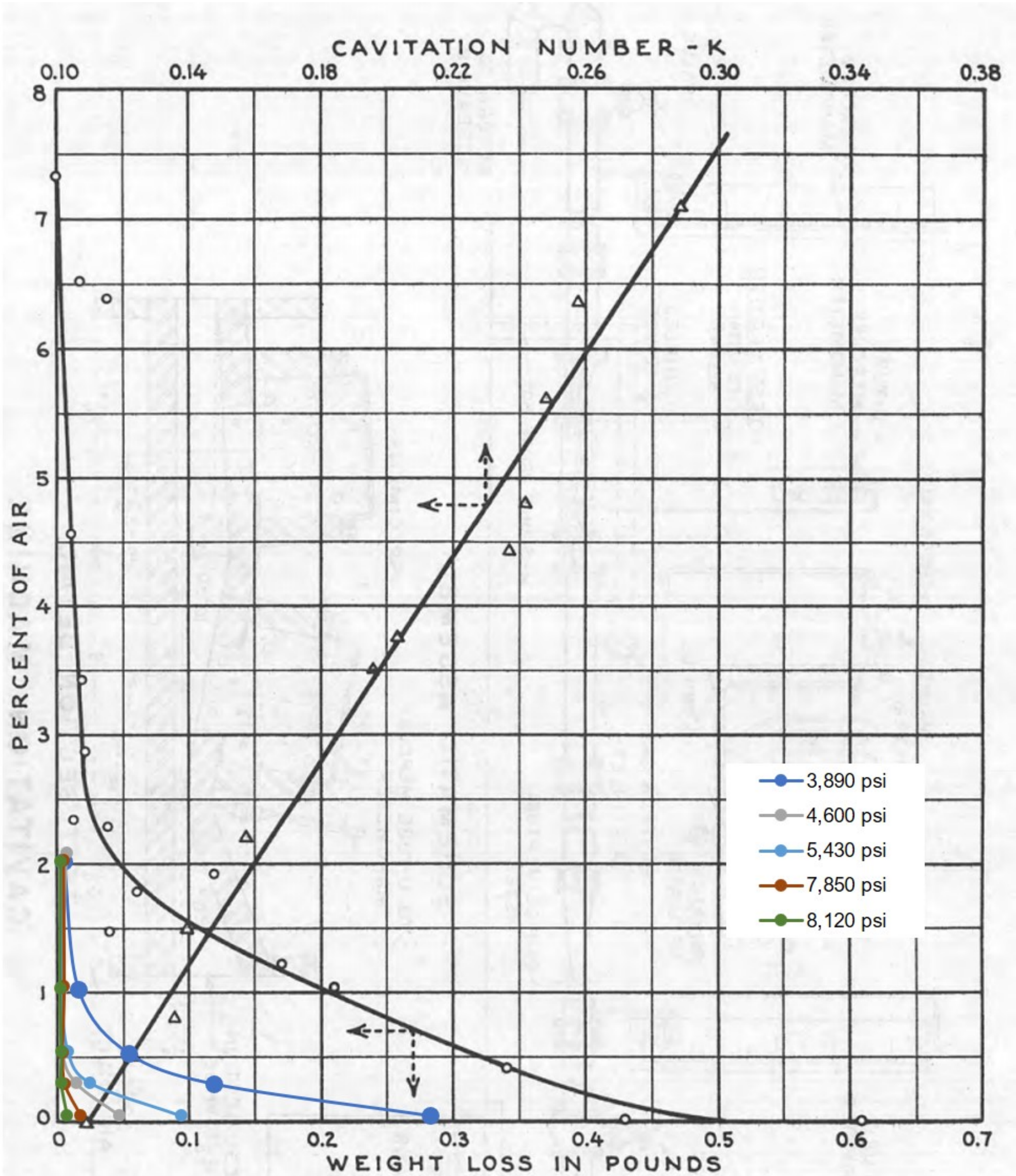

Figure 19 Plot comparing concrete damage results of current study to that of Peterka in 1953. Percent of air pertains to air in flow of water. The present tests used a 4-hour exposure time. Peterka's tests used a 2-hour exposure time and concrete samples of unmeasured strength (and no coarse aggregate) cured for only 7 days.

Photographs of the damaged test samples agree with the trends found from the quantitative data for both air injection and concrete strength. Figure 20 shows test samples with a strength of 3,890 psi for each of the five air flow conditions. The significant difference in damage to the concrete test surface is visually apparent as air flow increased with essentially no surface damage at 2% air.

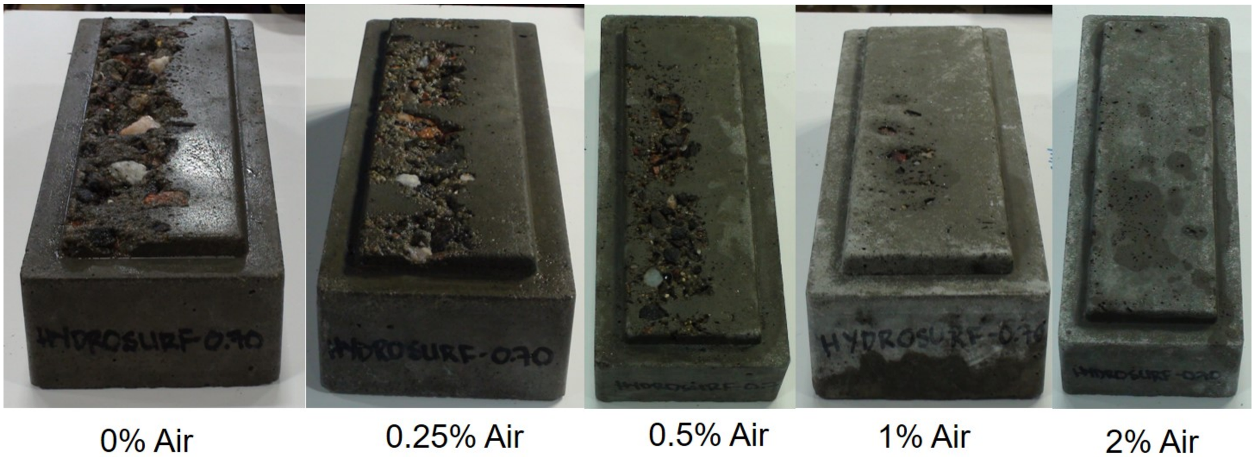

Figure 20 Photographs showing extent of cavitation damage with air percentage (in flow of water) to concrete test blocks with the lowest strength (average of 3,890 psi).

Similarly, Figure 21 shows test samples of the five concrete strengths for the single condition of cavitation with no air injection. Surface damage decreases dramatically with increasing compression strength of the concrete, with only light pitting on the sample with the highest strength (8,120 psi). Again, the exception to this trend for 4,600 and 5,430 psi can be seen visually, with more damage on the 5,430 psi sample, which is consistent with the measured data. This finding suggests that cavitation surface damage may depend on other concrete mix properties and not compression strength alone.

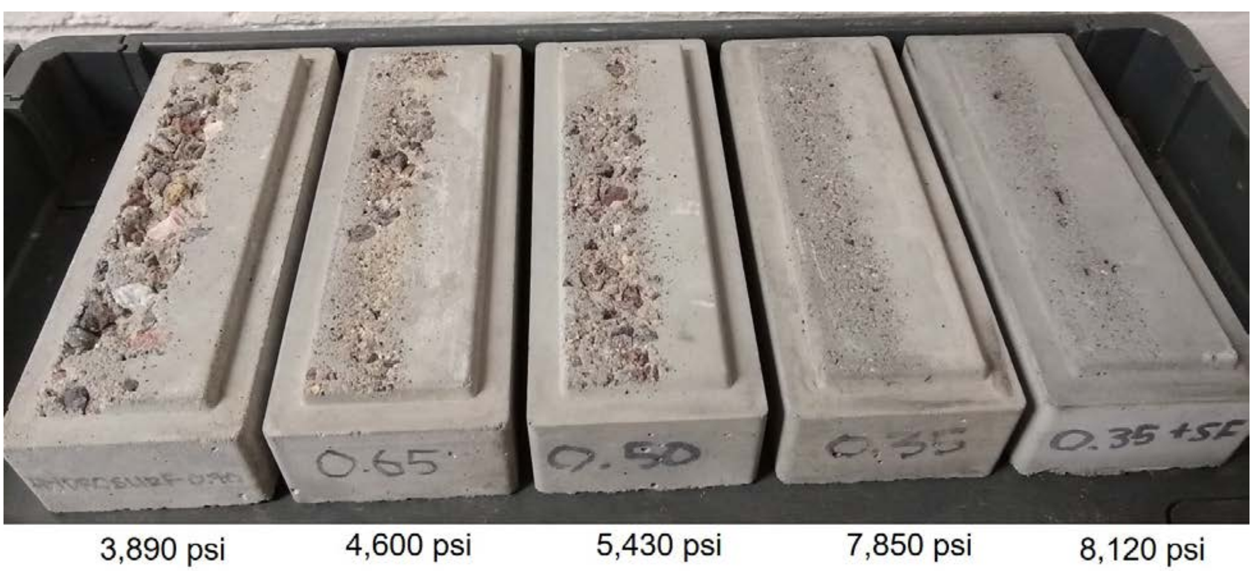

Figure 21 Photographs showing extent of cavitation damage with concrete strength to concrete test blocks with no air injection.

Analysis and Discussion

The aim of this collaborative research is to develop a reliable correlation between cavitation damage rates, concrete properties, and local hydraulic conditions that enables design engineers to choose the most cost-effective concrete design for the application, be it a repair of an existing structure or new design. Ideally this correlation would be obtained from both laboratory testing and field data over a broad range of concrete properties and hydraulic conditions represented by easily applied dimensionless parameters. While analyses of field and laboratory data are still in preliminary stages, attempts have been made to begin the development of such a correlation. Additional field analysis and laboratory testing in Brazil are planned through 2022 and proposed work to relate lab results to Reclamation field data will help further develop this correlation.

One preliminary attempt to utilize field data is shown in Figure 22 which includes data from both Brazilian and Reclamation facilities for cases with a similar "classification" of significant cavitation damage. Data for other facilities with different extents or "classifications" of damage could be plotted in a similar way. A dimensionless concrete parameter is defined below combining concrete and hydraulic properties. Figure 22 shows values of this parameter plotted against the Froude number.

$$Concrete\ parameter = \frac{f_c}{\gamma V^2/2g}$$

and

$$Fr = \frac{V}{\sqrt{gh}}$$

f_c = compression strength of the concrete (lb/ft^2)
γ = specific weight of water (62.4 lb/ft^3)
V = average velocity at the location of damage (ft/s)
Fr = Froude Number (-)
g = acceleration due to gravity (32.2 ft/s^2)
h = average flow depth at location of damage (ft)

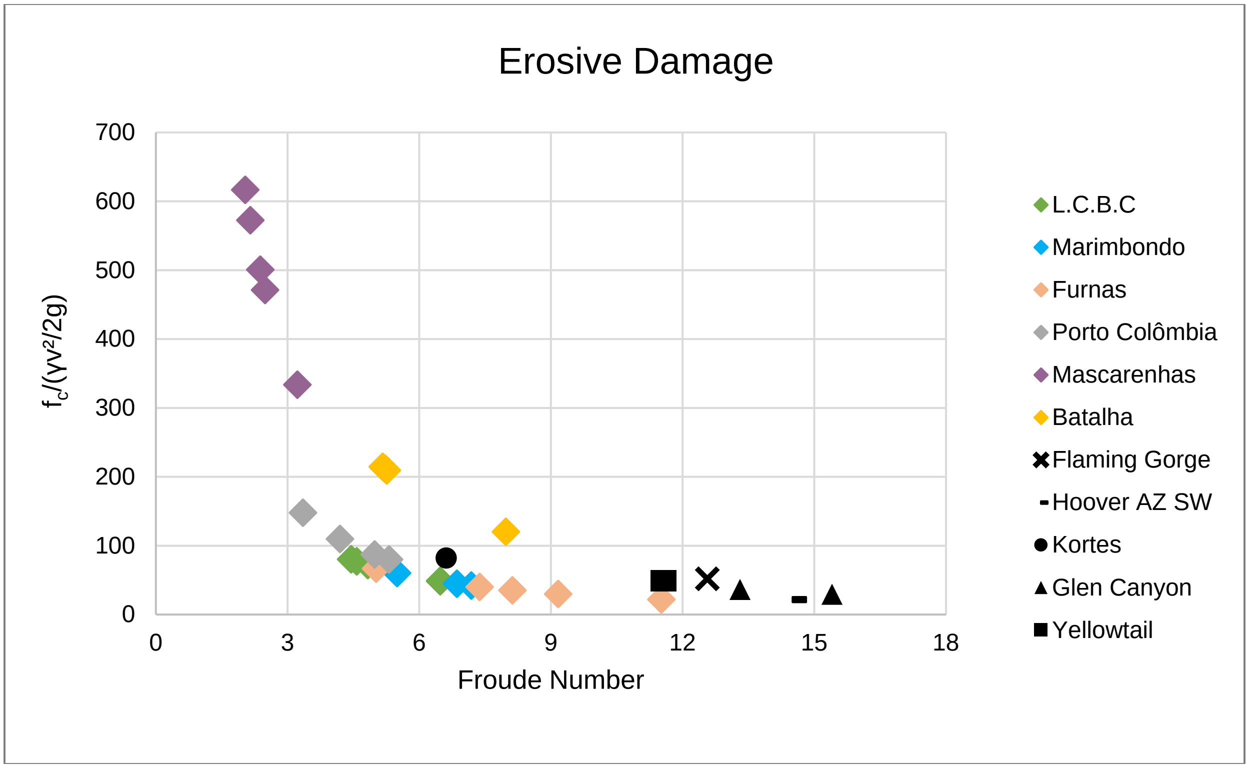

Figure 22 Plot showing preliminary method with historical field data from Brazilian and Reclamation spillways to compare hydraulic conditions at the spillway surface with concrete strength for severely eroded concrete damage.

Another preliminary attempt to correlate hydraulics and concrete damage uses results from the laboratory tests. These are plotted in Figure 23 with a damage rate in inches per hour (from volume loss over 4-hour test) vs a pressure coefficient. Dimensionless parameters from the lab data, and visual observations from the test results, help predict the level of surface damage expected for a given concrete strength and hydraulic conditions at the surface (which are a function of air percentage). Both parameters are defined below:

$$Damage\ Rate = \frac{\Delta Vol}{\frac{A}{t}}$$

and

$$P_c = \frac{P_{dynamic}}{P_o - P_{vapor}}$$

Where:

ΔVol = volume loss of concrete (in^3)

A = specific area of concrete (in^2 – area of test blocks in laboratory case)

t = time of exposure (hr)

$P_{dynamic}$ = standard deviation of pressure fluctuations on surface (lb/in^2)

P_o = average pressure at location of damage (lb/in^2)

P_{vapor} = vapor pressure of water (lb/in^2)

While Figure 23 presents a useful way to utilize the laboratory data there are currently limitations that restrict its use and application to prototype structures. Hydraulic data for the parameters presented were obtained at a single operating condition (standard cavitation index of 0.06) where the intensity of cavitation was changed only by injection of air rather than changes in local velocity and pressure. It is expected that hydraulic conditions near an actual concrete boundary in a prototype spillway will vary due to both local velocity and air entrainment that affect the pressure fluctuations on the surface.

In addition, it is very difficult to predict the level of air entrainment and pressure fluctuations on the concrete surface of a prototype structure in the field with a degree of certainty comparable to the direct measurements made in the laboratory tests. Thus, a pressure coefficient based on dynamic pressure fluctuation at the surface may not be practical. However, since laboratory results showed a direct correlation of these pressure fluctuations (controlled by air entrainment) with concrete damage, additional study must focus on better prediction of this parameter.

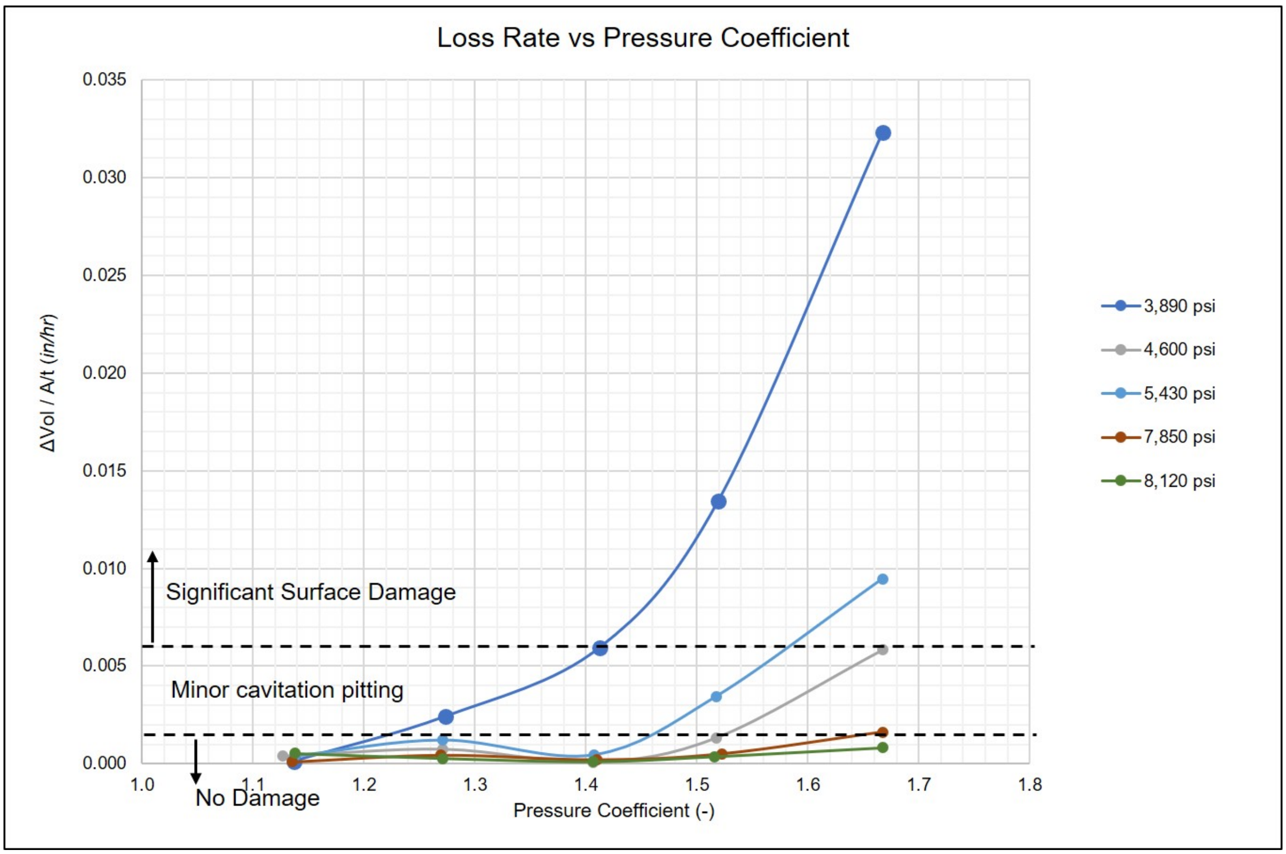

Figure 23 Plot showing preliminary method from current laboratory data to compare the degree of cavitation damage with localized hydraulic conditions at the surface and concrete strength.

Improved prediction of localized pressure fluctuations can be addressed to a large degree by tasks planned for the remainder of this study. Numerical simulations of the hydraulics at facilities with damage will provide more insight into localized conditions near damaged concrete surfaces. Simulations of Reclamation facilities proposed in 2021 are important to help complete this task. Physical hydraulic model studies planned in FURNAS's hydraulics lab through 2022 to determine local pressure fluctuations at locations of historic damage will provide very valuable information in correlating cavitation damage from the laboratory to historic field events. Also, to expand the testing range, the cavitation machine being constructed at the laboratory at UFRGS could be modified to operate at different hydraulic conditions than the tests conducted in Reclamation's laboratory.

The most ideal test scenario would be to collect both hydraulic and cavitation damage data from a prototype field test. While such a test is difficult to achieve due to logistics and ability to control test conditions, it would provide the most complete data set for both hydraulic conditions and concrete damage. Concerns with size-scale effects and air entrainment could be eliminated and parameters of local pressure, air entrainment, and actual concrete damage could be directly measured to help improve validity of predictions made through hydraulic models and laboratory scale testing. A field test should be undertaken if the right opportunity arises.

Conclusions and Recommendations

Laboratory testing of cavitation damage to concrete surfaces of varying strength was completed as part of an ongoing collaborative study with the Brazilian government to reduce damage to concrete surfaces in hydraulic structures. Test samples with five different compression strengths ranging from about 3900 psi to just over 8000 psi were exposed to high intensity cavitation in a venturi-type test chamber in Reclamation's Hydraulics Laboratory. Tests were repeated at five different conditions of air injection ranging from 0 to 2 percent of the water discharge which reduced the intensity of the cavitation and damage to the concrete samples. Each sample was exposed to the same cavitation condition (i.e. velocity & pressure) for a period of four hours. Damage from the cavitation was quantified by mass and volume loss. Key conclusions from this study include:

- Air flows as low as 0.15% of the water discharge significantly reduced the level of hydrodynamic pressure fluctuations on the concrete surface, and this trend continued for air flows up to about 2%. Air flows greater than 2% had little additional influence on pressure fluctuations at the surface.
- A correlation was found between concrete damage and air flow rates. Damage was significantly reduced with air flows as low as 0.25%. For samples with a strength of 3800 psi there was practically no damage for air flows of 2% or more. For higher strength samples (4600 – 8100 psi) there was no damage for air flows of 0.5% and greater. This is most likely due to the air's influence on hydrodynamic pressure fluctuations as shown by hydraulic measurements.
- A correlation was found between concrete damage and concrete strength. Cavitation at the baseline condition without airflow caused significant damage and material erosion on the 3800 psi samples. At the same flow condition, mass loss and visual damage decreased for greater concrete strength, with only light pitting on the surface of the 8100 psi test samples.

The exception was the 5400 psi samples which sustained more mass loss and visual damage than the weaker 4600 psi samples. While the cause is not known, variabilities in the paste content near the formed surface and uneven settlement of the aggregate between mixes with slightly different workability are potential contributors.

- Results provide a method to estimate the extent of concrete surface damage in the field based on concrete strength and a pressure coefficient describing localized hydraulics. At this time, these results are limited to a single operating condition with intense cavitation (cavitation index of 0.06) and application to other conditions should be approached with caution. It is hoped that additional testing at laboratories in Brazil and proposed efforts to further correlate lab testing with field data will help extend the application of this research.

The following recommendations and next steps are proposed to be addressed by the ongoing collaboration with Brazil.

- Further refine the pressure coefficient or develop a more effective parameter by improved prediction of localized pressure fluctuations on the concrete surface in order to predict concrete surface damage on prototype structures in the field.
- Conduct similar cavitation damage tests on concrete samples of a similar range of compression strength at a different operating condition of cavitation intensity.
- Further analyze data and experience from the field to correlate with results from both Brazilian and Reclamation laboratories.
- Improve methods of predicting air concentration and pressure fluctuations on the flow surfaces of prototype spillways. A field test on a prototype spillway would be the most ideal scenario for this research.

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Appendix A – 2018 Brazil Trip Report

United States Department of the Interior

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Denver, CO 80225-0007

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MEMORANDUM

To: Program Manager, Native American and International Affairs Office
Attn: 96-43000 (Morris)

Through: Thomas A. Luebke THOMAS LUEBKE Digitally signed by THOMAS LUEBKE Date: 2018.10.05 13:43:41 -06'00'
Director, Technical Service Center

From: Ms. Janet White, P.E. JANET WHITE Digitally signed by JANET WHITE Date: 2018.10.05 12:14:35 -06'00'
Manager, Concrete, Geotechnical, & Structural Laboratory, Technical Service Center

Mr. Josh Mortensen, P.E. JOSHUA MORTENSEN Digitally signed by JOSHUA MORTENSEN Date: 2018.10.05 11:43:34 -06'00'
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, Technical Service Center

Subject: Control Number 18-266 and 18-267, International Trip report for Brazil

1. **Location:** Rio de Janeiro and Foz do Iguaçu, Brazil

2. **Dates of Travel:** September 16-23, 2018

3. **Attendees:** Janet White and Josh Mortensen

4. **Purpose of Trip:** Reclamation is collaborating with the FURNAS Laboratories and other parties in Brazil to study concrete surface problems encountered in spillways and stilling basins. The purpose of this trip was to meet with partners and clearly communicate objectives and approaches of this research project as well as visit the FURNAS hydraulics laboratory in Rio de Janeiro where some of the testing may take place.

5. **Synopsis:** On September 18 we met with engineers from FURNAS at LAHE – Experimental Hydraulics Laboratory in Rio de Janeiro. We toured their hydraulics laboratory facility where we learned more of their capabilities in physical hydraulic modeling and hydraulic research. We also discussed the research capabilities of their concrete and materials laboratory facilities, located in Goiânia, Brazil. In turn, we briefed them on our hydraulic and concrete laboratory capabilities in Denver CO, and discussed how to best utilize the capabilities of both Reclamation and FURNAS laboratories for the current research.

On September 19 we traveled by air from Rio de Janeiro to Foz do Iguaçu, Brazil where we met with the entire research team who were there attending the 2018 Dam World Conference. The research team included concrete and hydraulic engineers from FURNAS, a hydraulic researcher from the Federal University of Rio Grande do Sul, and a technical expert in concrete from DESEK (private firm in Brazil). Discussions included the background and need of this research from the Brazilian's point of view as well as the potential application to and benefit for Reclamation infrastructure.

Discussions continued into the evening of September 20th which focused on the approach and steps of the research. These included first conducting a thorough literature review and gathering information of past issues with concrete hydraulic surfaces from both Reclamation and FURNAS facilities. Findings from this effort will then be used to guide the experimental design for testing to be conducted in both Reclamation and FURNAS laboratories. The entire study is expected to last 3 years, with completion by the end of 2021. At the end of the meeting it was decided that FURNAS would provide a draft study plan which would then be reviewed by Reclamation before official testing begins. There was a caveat that Reclamation's direct involvement in the testing portion of the research would depend on outcomes from the initial review of literature and field data to ensure efforts can be made with potentially limited resources and are in line with Reclamation's research priorities.

6. **Trip Agenda**:

Josh Mortensen**:**

Sept 16 **–**	departed Denver for overnight flight to Rio de Janeiro
Sept 17 **–**	arrived in Rio de Janeiro, Brazil
Sept 18 **–**	toured FURNAS hydraulics laboratory and discussed research with FURNAS engineers.
Sept 19 **–**	traveled by air from Rio de Janeiro to Foz do Iguaçu, Brazil and met with entire research team
Sept 20 **–**	continued discussions with research team and made plans for next steps
Sept 21 **–**	stayed at Foz do Iguaçu, reviewed and summarized meetings of trip
Sept 22 **–**	departed Foz do Iguaçu for a connection flight in Rio de Janeiro and departed for Denver
Sept 23 **–**	cleared customs in Houston (flight connection) and arrived in Denver

Janet White:

Sept 16 **–**	departed Denver for overnight flight to Rio de Janeiro
Sept 17 **–**	arrived in Rio de Janeiro, Brazil
Sept 18 **–**	toured FURNAS hydraulics laboratory and discussed research with FURNAS engineers.
Sept 19 **–**	traveled by air from Rio de Janeiro to Foz do Iguaçu, Brazil and met with entire research team
Sept 20 **–**	continued discussions with research team and made plans for next steps
Sept 21 **–**	reviewed and summarized meetings of trip in Fox do Iguacu
Sept 22-26 **–**	on leave
Sept 27 **–**	departed Rio de Janeiro for Denver.
Sept 28 **–**	cleared customs in Houston (flight connection) and arrived in Denver

7. **Benefit to Reclamation:** The initial steps of this research will benefit Reclamation by offering an opportunity to review the state-of-the-art in concrete design and help determine if there is a need or benefit for changes to Reclamation's current design and specifications. Active testing of concrete surface performance under a range of hydraulic conditions will help to advance the state-of-the-art in concrete surface design and keep Reclamation on the forefront in this critical infrastructure area.

8. **Benefit to Traveler:** We gained significant knowledge of materials and hydraulic research activities being conducted in Brazil which has a wide fleet of dams, hydropower plants, and hydraulic structures which are similar to Reclamation. We benefitted from many formal and informal discussions regarding research methods and technology related to the current research project as well as other potential opportunities to collaborate in the future. These included different test methods for durability of concrete surfaces, deflectors for better air entrainment on stepped spillways, evaluating size-scale effects in physical hydraulic modeling, collecting physical data from actual field structures, and comparison of physical and numerical hydraulic models.

9. **Conclusions and Recommendations:** The interactions with FURNAS and other partners, in face-to-face meetings that helped overcome the language barrier, were invaluable to understanding FURNAS's background and prioritization of this research. The research approach was agreed upon and a draft of the study plan was developed by FURNAS and sent to Reclamation for review and comments.

10. **Actions Required:** The research approach was agreed upon and a draft of the study plan was developed by FURNAS and sent to Reclamation for review and comments. The initial steps of the study will begin after that plan is finalized.

cc: 08-10000 (Whitler) 96-43000 (Morris), 96-43100 (Nugent, Medina, Vigil),
86-68500 (Baumgarten), 86-68530 (White, Bartojay), 86-68560 (Einhellig, Mortensen)

Appendix B – Literature Review Summary

AUTHOR	TITLE AND REFERENCE	NOTES
Falvey, Henry T.	Engineering Monograph No. 42 (Reclamation) https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/EM/EM42.pdf	Most field data / experience comes from EM42. Is basis for Spillway Pro program used for much of the hydraulic analyses.
Colgate	HYD-543, Resistance of Selected Protective Coatings for Concrete to High-Velocity Water Jets https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HYD/HYD-543.pdf	Describes test method and results for cavitation damage to coatings using a submerged jet.
Frizell, Kathy	PAP-665, Hydraulic Model Study Results for Black Rock Dam (Kathy Frizell) https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0665.pdf	
Frizell, Kathy and Mefford, Brent	PAP-581, Avoiding cavitation damage on spillways https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0581.pdf	
Colgate	PAP-88, Cavitation Damage of Roughened Concrete Surfaces (Colgate) https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0088.pdf	Study looked at the potential from rough concrete surfaces to induce cavitation (previous damage, pitting, etc.). Used surface molds from Davis and Grand Coulee inside of a laboratory test to look at conditions that produce incipient cavitation. Measured vertical velocity distribution to estimate shear velocity near the boundary of different roughness's. Scope does not include surface resistance of concrete.
Colgate	PAP-349, Cavitation Damage in Hydraulic Structures https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0349.pdf	Overview of cavitation issues in hydraulic structures. Mentions 3 laboratory test approaches for evaluating cavitation. Mentions testing of damage resistance of construction materials –not sufficient data to form correlation.
Hanna, Leslie	PAP-918, Hydro Review – Preventing Abrasion Damage in Stilling Basins: Controlling the Flow (Leslie Hanna – she also has many other reports on flow deflectors for stilling basins) https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0918.pdf	Description of flow deflector method to alter the hydraulics in order to reduce abrasion to concrete surfaces. No mention of cavitation erosion.
Simmons, W.P.	HYD-423, Erosion Studies on Sandstone Through Which Glen Canyon Dam Diversion Tunnels Will Pass, Glen Canyon Dam, Colorado River Storage Project https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HYD/HYD-423.pdf	Description of tests using a submerge jet to erode sandstone. Compared clean water and suspended sediment rather than cavitation erosion.

AUTHOR	TITLE AND REFERENCE	NOTES
Peterka, A.J.	PAP-38, The Effect of Entrained Air on Cavitation Pitting https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0038.pdf	Describes effect of air on both cavitation index and damage to concrete surfaces. Describes the old venturi test rig and its use for studying cavitation damage to concrete. Found that air as low as 1-2% (air volume/water volume) has a significant reduction of damage and damage can be almost eliminated with 7% air. Test methods and information about concrete mixes are given (but not strength) but did not vary. Describes cavitation damage on Heart Butte and Grand Coulee spillways.
F.E. Causey	REC-OCE-70-51, Evaluation of Materials for Cavitation Resistance https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/REC/REC-OCE-70-51.pdf	
E.M. Harboe and L.J. Mitchell	Design and Construction of New Cavitation Machine https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0404.pdf	Description and Drawings of the cavitation venturi that was refurbished and used in current laboratory testing
Mortensen	Resistance of Protective Coatings to High Pressure Water Jets for Invasive Mussel Removal https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-1074.pdf	Describes a test method for cavitation damage on mussel resistant coatings from a submerged jet
Volkart, Peter	Air Entrainment Devices (Air Slots)	
Galperin, R.	Hydraulic Structures Operation under Cavitation Conditions	Describes the “Galperin’s graph” which is a plot of concrete strength vs flow velocity of different air concentrations near the boundary layer of the flow. Not much detail is given about the experiment other than what’s on the plot. Assumes that Damage Resistance = f (strength, velocity, air concentration)

Appendix C – Results from Reclamation Field Experience with Cavitation Damage

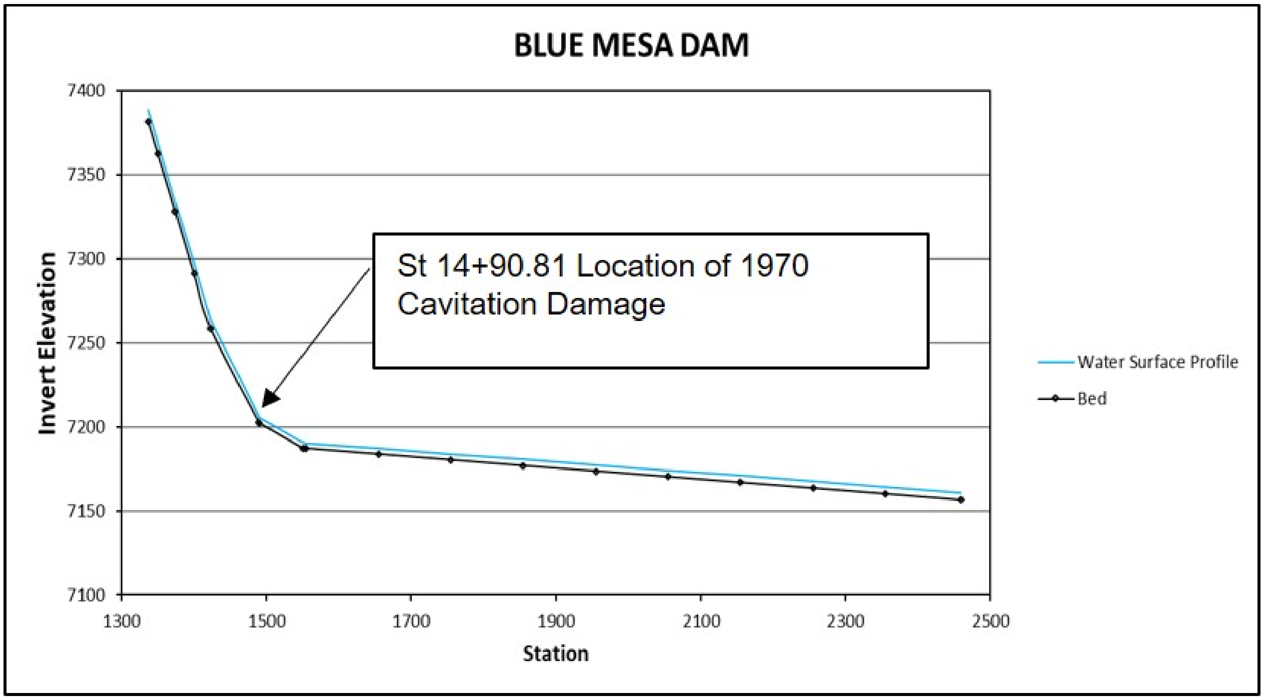

Figure 24 Water surface profile plot from Spillway Pro and location of cavitation damage observed at Blue Mesa Dam.

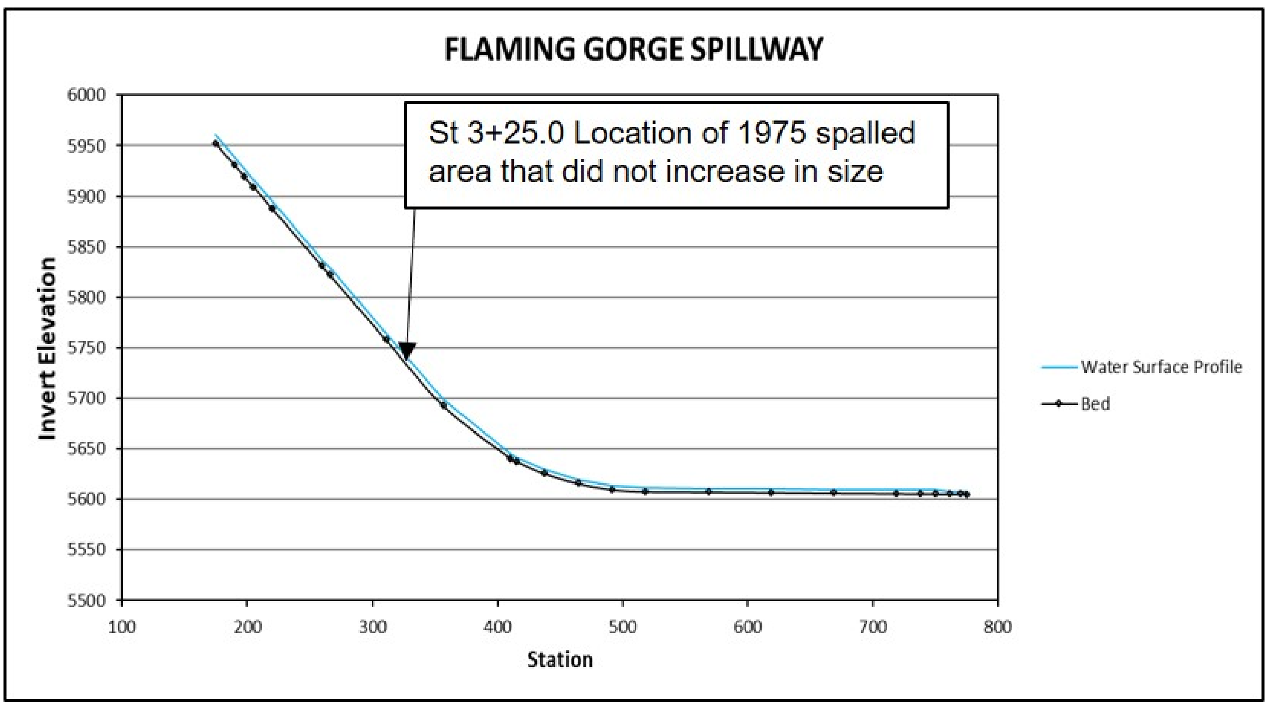

Figure 25 Water surface profile plot from Spillway Pro and location of cavitation damage observed at Flaming Gorge Dam.

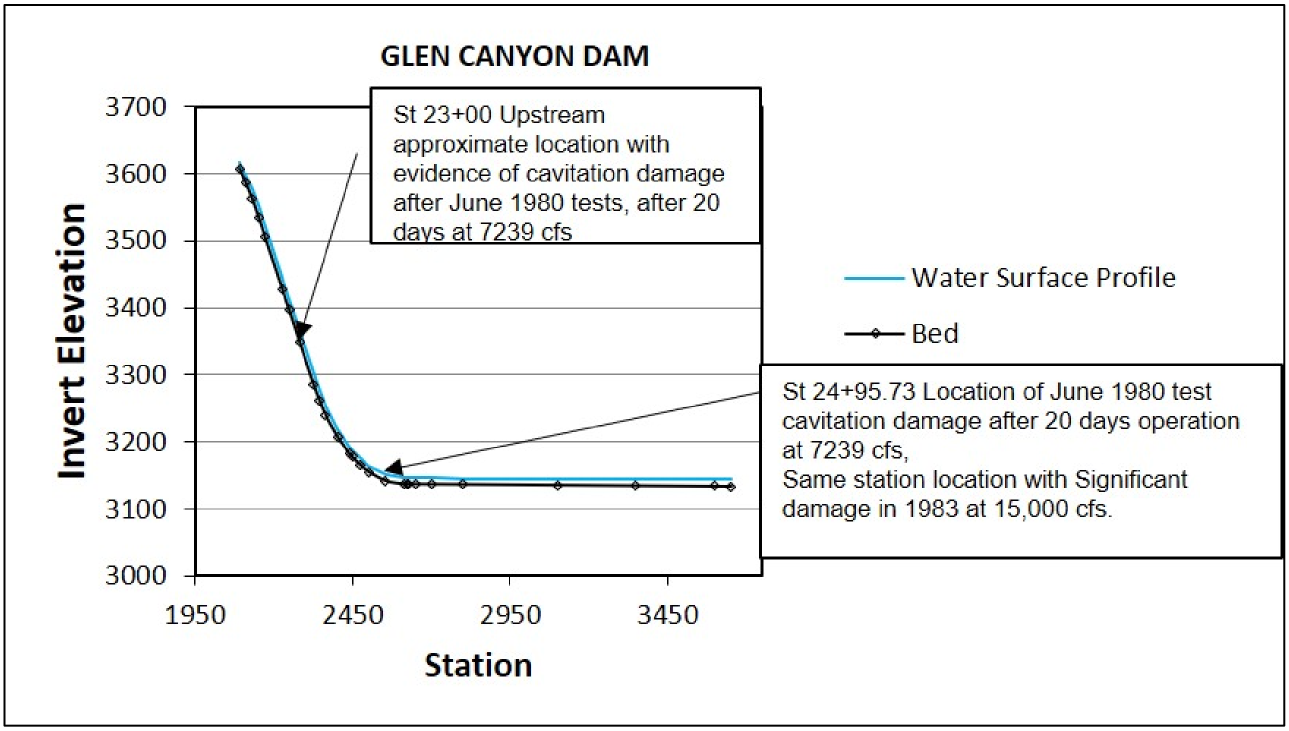

Figure 26 Water surface profile plot from Spillway Pro and location of cavitation damage observed at Glen Canyon Dam.

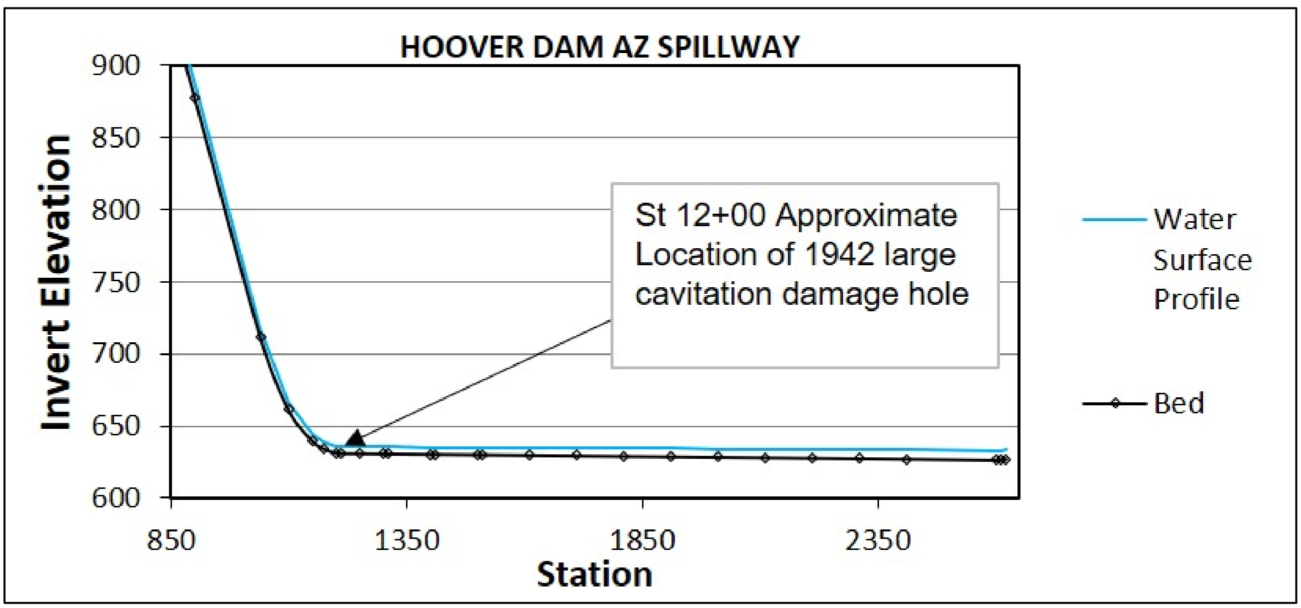

Figure 27 Water surface profile plot from Spillway Pro and location of cavitation damage observed at Hoover Dam.

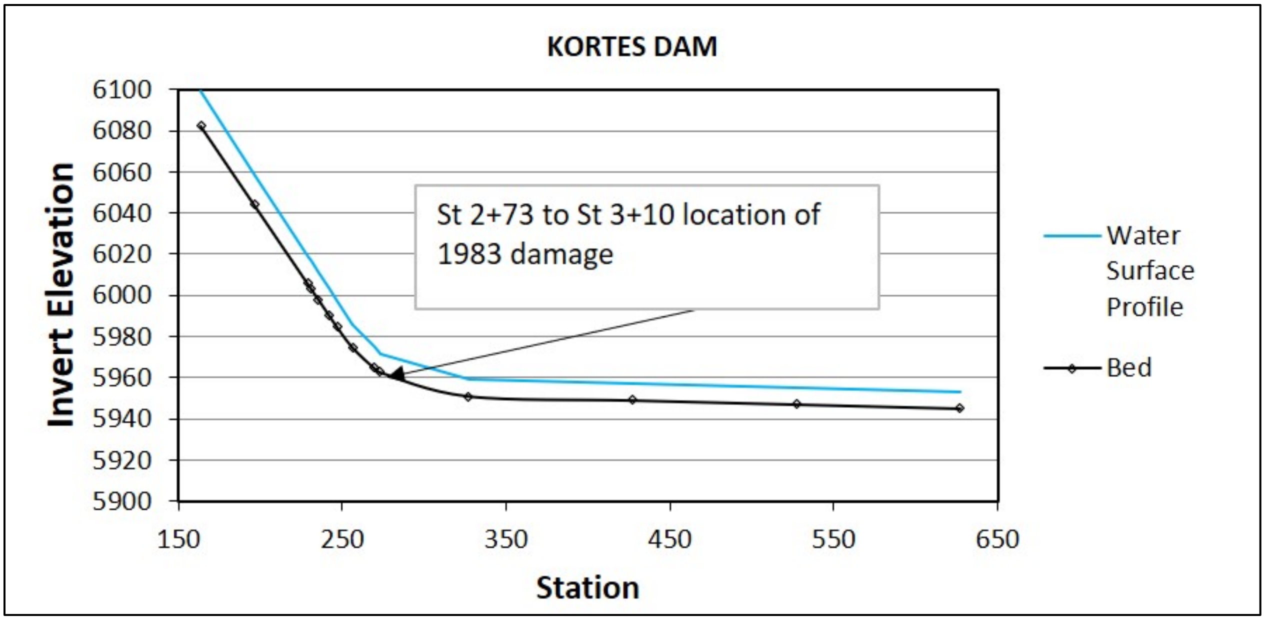

Figure 28 Water surface profile plot from Spillway Pro and location of cavitation damage observed at Kortes Dam.

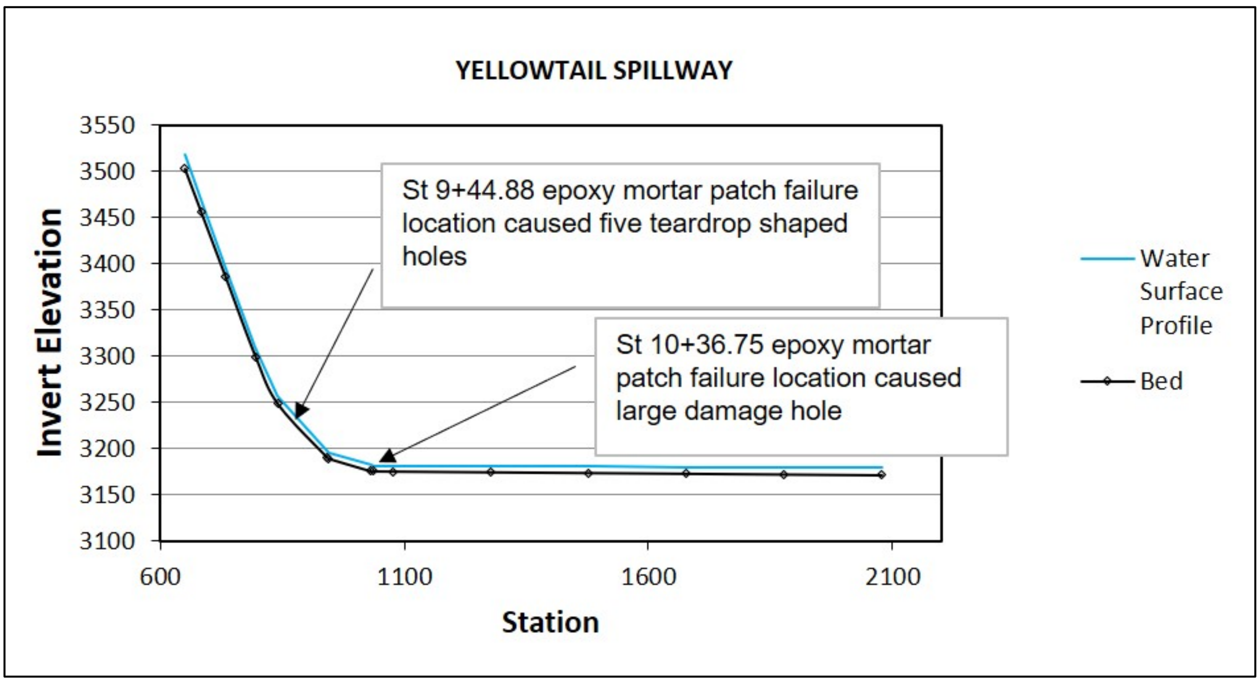

Figure 29 Water surface profile plot from Spillway Pro and location of cavitation damage observed at Yellowtail Dam.

DATA

Data identified of created for this project is available upon request.

Keywords: Air entrainment, cavitation, concrete, spillway

Point of Contact Katie Bartojay, kbartojay@usbr.gov, 303-445-2374:

- Short description of the data: Key Hydraulic Calculations and Cavitation Measurements, Concrete Mix Proportions and Strength Data

<1MB of data