BUREAU OF RECLAMATION

Hydraulic Concrete Surfaces for Water Resource Structures – Continued Collaboration

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Research and Development Office
Final Report No. ST-2023-21051
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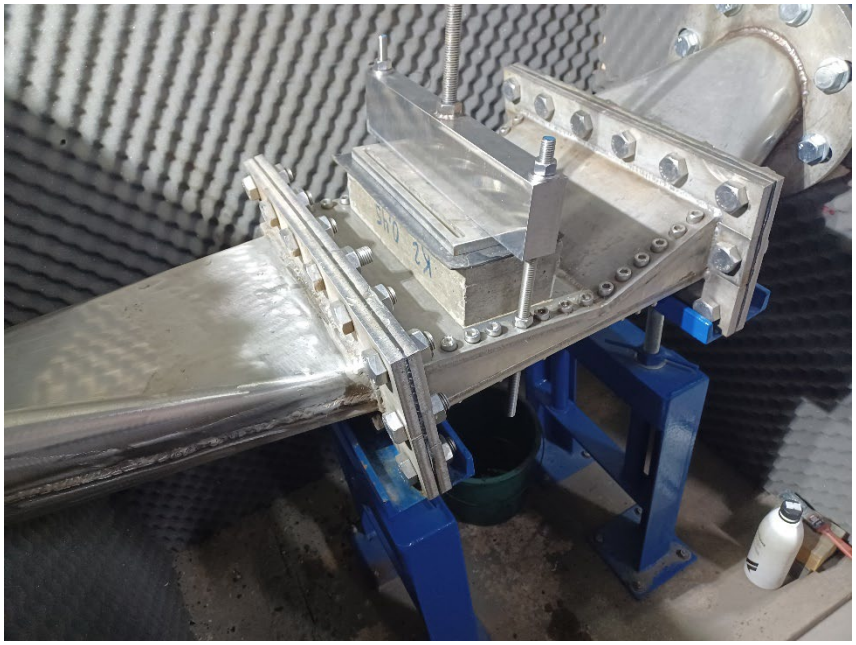

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14. ABSTRACT
Water resource facilities operated by the Brazilian and United States Government are faced with cavitation and erosion of concrete surfaces of spillways and stilling basins and each have made many costly repairs that impact operations. The Bureau of Reclamation has been collaborating with Brazilian government companies and universities to study flow induced problems encountered at concrete surfaces in spillways and stilling basins by combining concrete materials testing with hydraulic laboratory studies. This report summarizes research efforts made to date and highlights laboratory testing in Brazilian laboratories in 2023 which culminated in a Reclamation site visit to Brazil to witness laboratory testing.

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Cavitation, concrete, damage, concrete repair, spillway, stilling basin

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Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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prepared by

Technical Service Center
Josh Mortensen, Hydraulic Engineer

Peer Review

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Research and Development Office
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Hydraulic Concrete Surfaces for Water Resource Structured – Continued Collaboration

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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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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. Since 2018, the Bureau of Reclamation (Reclamation) has been collaborating with FURNAS Centrais Elétricas (FURNAS) and the Federal University of Rio Grande do Sul (UFRGS) 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 has continued through 2023, includes parallel efforts of literature review, analysis of historical field data and experience, and laboratory testing of cavitation damage to concrete. A detailed report of Reclamation's laboratory testing is provided in (Mortensen, 2020). This report summarizes research efforts made to date and highlights laboratory testing in Brazilian laboratories in 2023 which culminated in a Reclamation site visit to Brazil to witness laboratory testing (Appendix A).

The main objective of this collaborative study is to develop a reliable correlation between concrete properties and local hydraulic conditions to provide updated guidance and advance the state-of-the-art in concrete design.

Collaboration with Brazil

Since 2018 Reclamation and Brazilian laboratories have been collaborating to study flow-induced damage to concrete surfaces. Table 1 summarizes efforts made by each laboratory each year since that time, including delays and roadblocks caused by the Covid-19 pandemic starting in 2020 which particularly affected the Brazilians. Laboratory cavitation damage testing at the UFRGS was finally completed in the summer of 2023, although additional analysis and final results are still pending.

Since the beginning of the study in 2018 the primary role of Reclamation in the collaboration has been laboratory cavitation testing, analysis of Reclamation facilities with cavitation damage, and ongoing technical support for Brazilian laboratories.

Brazilian laboratories are comprised of FURNAS and UFRGS who both played a role in a campaign to visit and document field observations from eleven Brazilian spillways with concrete damage. The FURNAS laboratory constructed and tested physical hydraulic models of three of these facilities and is working with their concrete laboratory for material testing of original facility concrete mix designs in the near future. UFRGS tested concrete samples in a cavitation facility very similar to Reclamation's. In addition, they have analyzed the eleven Brazilian spillways using Computational Fluid Dynamics (CFD) models and continue to compare hydraulic results to field observations and laboratory results.

Table 1. Summary of research efforts for Reclamation and Brazilian Laboratories since 2017.

Year	Reclamation	Brazilian Laboratories
2017	Scoping Level Study (Bartojay, 2017)	Initial contact with TSC laboratories
2018	Initiate collaborative study	Initiate collaborative study
2019	Literature review, field case review, & design of lab testing	Field case review, site visit inspections
2020	Lab testing in cavitation machine, S&T report	Design independent cavitation machine, visit Reclamation labs
2020 - 2022	Support Brazilians, regular email & video calls	Covid shutdown, CFD modeling of field cases
2023	Visit Brazilian labs, witness testing, & discussions	Lab testing in independent cavitation machine

2023 Brazilian Laboratory Testing

A cavitation test facility was constructed in the laboratory at UFRGS and used to test concrete samples which was completed in 2023. The test facility is very similar to the one used in Reclamation's laboratory and tests concrete block samples of the same size (approximately 3-inch long x 12-inch wide x 3-inch deep) and is also limited to a single operating point and cavitation condition (Figure 1).

Figure 1. Photograph of the cavitation test machine at UFRGS within the soundproof box (left) and looking from the top where the cavitation sample is installed (right).

Testing at UFRGS included four concrete mixes (water/cement ratios of 0.35, 0.45, 0.50, and 0.65) which produced compressive strengths at time of testing in the same range as those tested in Reclamation's lab (Figure 2). Also like Reclamation's test plan, UFRGS tests included injecting air upstream of the cavitation machine to evaluate reduction in concrete damage with the percentage of air flow to water flow.

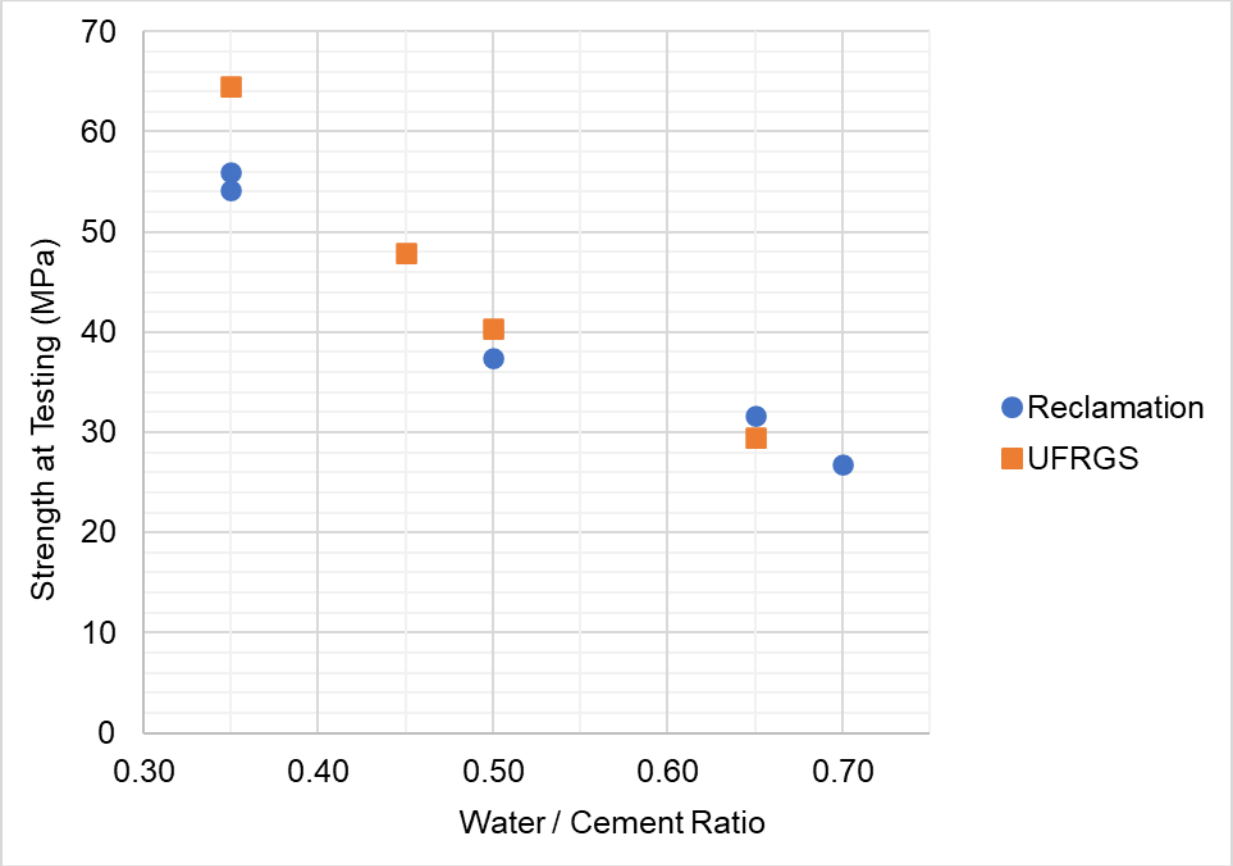

Figure 2. Compressive strength comparison of concrete samples during testing in Reclamation and UFRGS laboratories.

While final results and conclusions are still pending, trends in the test data were similar to those from Reclamation's test results. The effect of air injection in reducing damage to the concrete surface was apparent even at the lowest air flow tested (0.25%) and continued to reduce damage as it increased up to 2% as seen in the photographs in Figure 3. Compressive strength of the concrete was another factor that correlated with damage. Higher strength concrete samples sustained less damage over the same time of cavitation exposure which was also a significant finding in Reclamation's test results.

Testing and analysis were performed at UFRGS beyond what was accomplished at Reclamation. Examples include measuring mass loss over time for a single concrete test sample to determine the damage rate (Figure 4) and using different techniques to measure volume loss and damage depth over time using 3D scanners and profilers. These additional tasks were also performed on a greater number of test samples than what was completed at Reclamation and will help improve understanding of fluid behavior on concrete surface damage and correlation with field and CFD results.

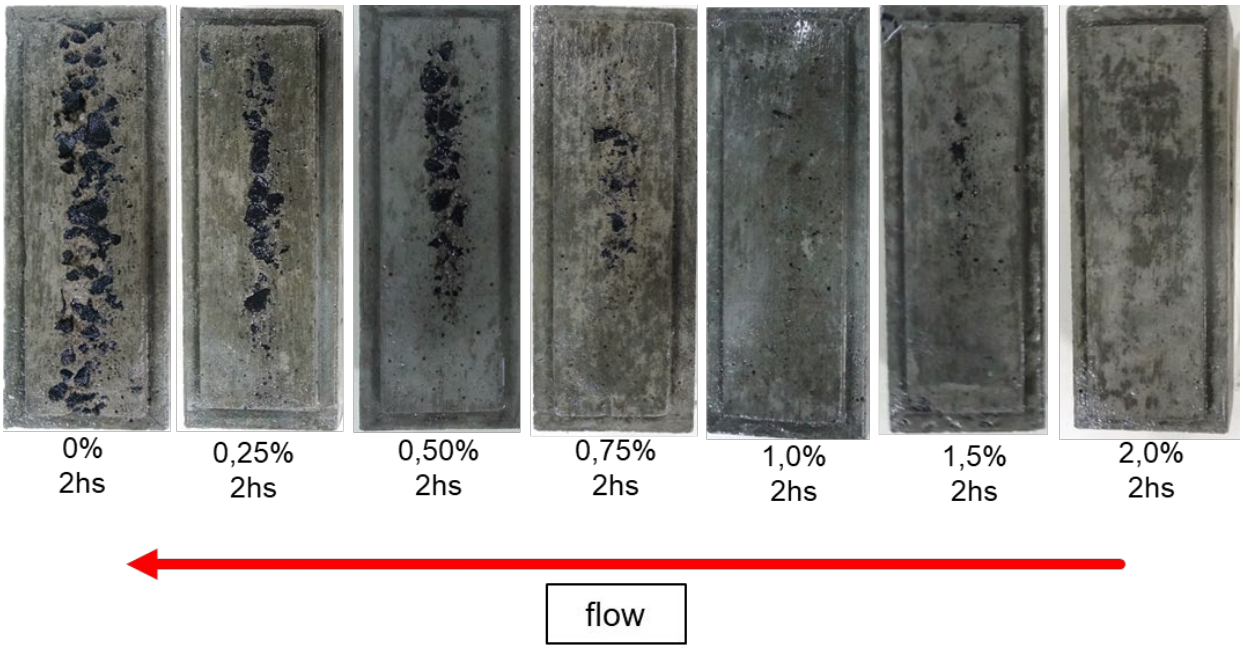

Figure 3. Photographs comparing damage to concrete samples with a water/cement ratio of 0.45 tested at different air injection rates.

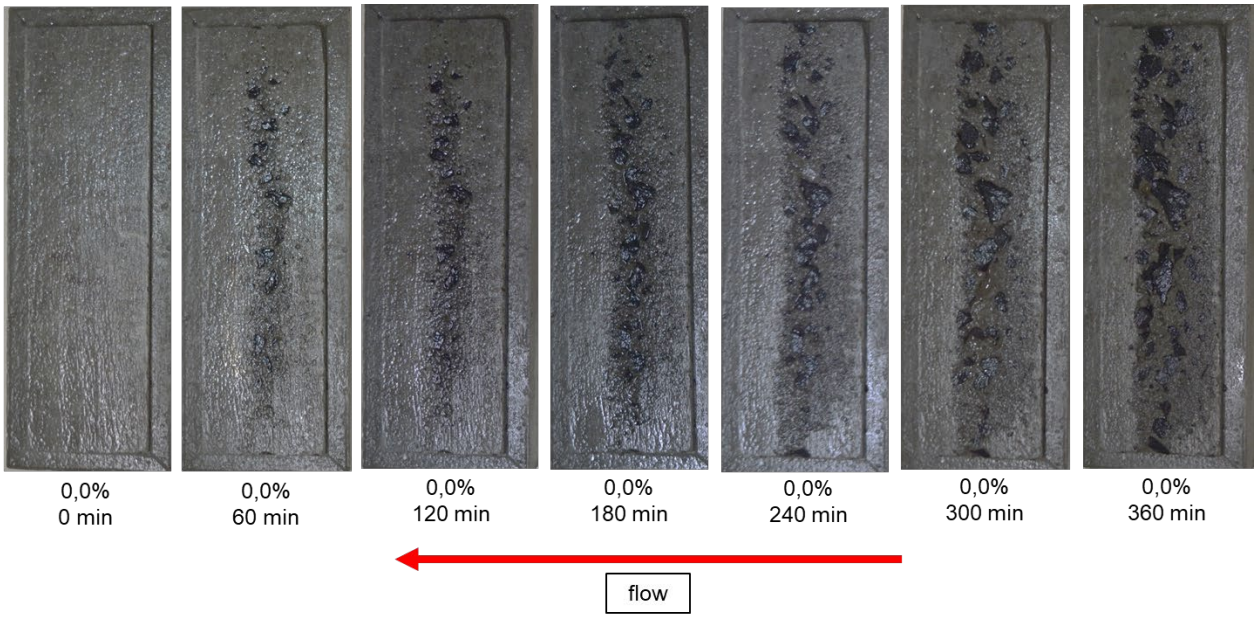

Figure 4. Photographs comparing damage over time of a single concrete test block with a water/cement ratio of 0.35.

Planned Next Steps

Completion of Brazilian laboratory tests and especially the site visit for witness testing helped identify important research gaps and formulate plans to continue this research. Additional testing and analysis are needed to bridge the gap between current results and application to practice. During meetings at the site visit in August 2023 several next steps were identified for both Reclamation and Brazilian collaborators.

Reclamation

Secure additional funding through Reclamation's Dam Safety (already secured for fiscal year 2024) and Science & Technology (proposal to be submitted June 2024) programs to complete the following:

- Improve quantification of concrete damage by using 3D scanning and/or photogrammetry techniques on existing test blocks from previous testing.
- Use UFRGS cavitation damage rate results to predict long term spillway damage depending on flow conditions and concrete material properties. Prediction methods are described in Engineering Monograph No. 42 (Falvey, 1990) but were never verified with test data.
- Develop a test procedure using larger concrete test sample sizes at prototype scale hydraulic conditions to reduce uncertainty in test results and improve correlation of test data to field observations.
- Synthesize laboratory, analytical, and field data to develop clear guidance for concrete design.
- Continue technical support and collaboration with Brazilian partners.

Brazil

Secure additional funding from Brazilian sources to complete the following:

- Complete data analysis of cavitation testing already performed at UFRGS.
- Test high strength concrete repair materials in the cavitation machine at UFRGS.
- Develop and construct a cavitation test machine at the hydraulics laboratory at FURNAS to complement ongoing cavitation at the laboratory at UFRGS.
- Complete concrete testing (structural, abrasion, and cavitation) of concrete samples recreated using original concrete mix designs of Brazilian spillways that have sustained cavitation damage.
- Work with Reclamation to develop a test procedure using larger concrete test sample sizes at prototype scale hydraulic conditions to reduce uncertainty in test results and improve correlation of test data to field observations.
- Work with Reclamation to synthesize laboratory, analytical, and field data to develop clear guidance for concrete design.

Conclusions

Laboratory testing of cavitation damage to concrete surfaces was performed independently at Reclamation and UFRGS laboratories and provides results with similar trends. These results are being compared to observations from field observations and CFD models to develop correlations between fluid behavior and concrete properties. While final analysis and reporting of Brazilian test results are not yet complete, a summary of key conclusions and next steps include:

- Results from both laboratories showed there is a correlation between reduced concrete damage and air content injected into the water flow.
- Results from both laboratories showed there is a correlation between concrete damage and concrete strength.
- There is uncertainty in concrete damage results due to the size of the test samples used at both laboratories. It is important to conduct further testing with concrete samples that have a larger surface area to properly represent the interaction between aggregate and cement, allowing the damage and erosion process to develop without edge effects from the test facility. Also, testing over a range of hydrodynamic conditions, rather than a single cavitation condition, is needed to advance findings from this study. Although challenging, testing at prototype scale would be ideal to quantify key parameters over a range of hydrodynamic conditions and material properties.
- High strength materials used for localized concrete repair were identified that should also be tested in the laboratory.
- Further work is needed to synthesize the results from field observations of concrete damage, CFD analyses, and laboratory results for application to analysis tools and processes to develop clear guidance for concrete design.

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Appendix A – International Trip Report from August 2023 Site Visit

United States Department of the Interior

BUREAU OF RECLAMATION
Washington, DC 20240

IN REPLY REFER TO:

9/12/2023

86-68560
FIN-10.10

VIA ELECTRONIC MAIL ONLY

MEMORANDUM

To: Jeffrey Morris, Program Manager
Native American and International Affairs Office

Through: Richard W. LaFond, Director Acting for
Technical Service Center

From: Josh Mortensen, Hydraulic Engineer JOSHUA MORTENSEN Digitally signed by JOSHUA MORTENSEN Date: 2023.09.12 09:14:57 -06'00'
Hydraulic Investigations and Laboratory Services, Technical Service Center

Catherine Lucero, P.E., Civil Engineer CATHERINE LUCERO Digitally signed by CATHERINE LUCERO Date: 2023.09.12 09:30:04 -06'00'
Concrete and Structural Laboratory, Technical Service Center

Subject: Control Number 23-416, International Trip Report for Brazil

1. **Location:** Porto Alegre and Rio de Janeiro, Brazil

2. **Dates of Travel:** August 19-27, 2023

3. **Attendees:** Josh Mortensen and Catherine Lucero

4. **Purpose of trip:** Discuss collaborative research efforts on cavitation damage to concrete structures. Witness cavitation damage testing and review test results from Brazilian laboratories. Discuss next steps to address remaining research gaps and advance the state-of-the-art in concrete surface design.

5. **Synopsis:** On August 21st in Porto Alegre we met with engineers, professors, post-graduate students, and the director of the Institute of Hydraulic Investigations (IPH), part of the Federal University of Rio Grande do Sul (UFRGS), who presented the history and mission of IPH. Engineers from FURNAS were also in attendance. We toured their laboratory facilities including their sedimentation, river hydraulics, and coastal

engineering lab. In the afternoon we inspected their cavitation test machine and instrumentation which are similar to those used in Reclamation's Hydraulics Lab. The machine was turned on and we witnessed its operation at various test conditions. We inspected various concrete test samples with damage from the cavitation machine. Engineers from IPH presented the latest test results compared to Reclamation's laboratory test results and discussed conclusions and gaps. See photos in Figure 1 through Figure 4.

On August 22nd, engineers from both IPH and FURNAS presented and discussed findings from concrete damage inspections on several Brazilian spillways and hydraulic parameters that may have caused the damage estimated from numerical simulations. There is still difficulty in accurately correlating these results due to unknown hydrodynamic conditions near the spillway surface. Results from concrete material testing and plans for future testing in FURNAS' concrete laboratory were also discussed. That afternoon we toured the UFRGS Concrete and Structural Laboratory where the concrete test samples used in the current study were formed. We learned of the capabilities and experience of their laboratory and discussed potential materials for new concrete design and concrete repair that have not yet been tested. See photos in Figure 5 and Figure 6.

During the morning of August 23rd, we discussed research gaps and potential next steps with IPH staff which included verifying results on larger concrete samples, importance of applying research to concrete repair materials, and correlating damage and hydraulic parameters in the field. We also presented other ongoing projects and capabilities of Reclamation's Hydraulics and Concrete and Structural laboratories and discussed areas of common interest. That afternoon we departed to catch a flight to Rio de Janeiro.

On August 24th, we met with engineers and technicians at the FURNAS hydraulics laboratory in Rio de Janeiro. They presented a brief history and mission of FURNAS and discussed ongoing projects in their hydraulics lab. We discussed findings and plans to continue to use hydraulic data from physical model spillways in their lab to correlate to concrete damage experienced on those spillways. We also discussed plans and inspected their lab space for constructing a cavitation testing machine at the FURNAS lab similar to those at IPH and Reclamation. This in-person discussion was important to ensure the design and function of this facility would complement future study results and not provide redundant information already available from other labs. At their request we presented capabilities, operations, and construction techniques used in Reclamation laboratories to their technicians and craftsmen, many of whom are new to laboratory work and even the water resources industry in general. Meetings were concluded by

reviewing next steps identified the day before in IPH and discussing other potential areas of collaboration. See photos in Figure 7 through Figure 9.

On August 25th, we stayed in Rio de Janeiro reviewing and summarizing discussions and findings from the site visits. August 26th – 27th were spent traveling back to Denver.

6. **Trip Agenda:**
   Aug 19 – departed Denver for overnight flight to Porto Alegre
   Aug 20 – arrived in Porto Alegre, Brazil
   Aug 21 – discussed research with IPH and witnessed testing in cavitation machine
   Aug 22 – discussed research, toured Concrete/Structural and Hydraulic Lab facilities
   Aug 23 – presented ongoing research in Reclamation's Hydraulics and Concrete labs, traveled to Rio de Janeiro
   Aug 24 – toured hydraulics lab at FURNAS LAHE and discussed research, end of meetings
   Aug 25 – stayed in Rio de Janeiro, reviewed and summarized meetings of the trip
   Aug 26 – departed Rio de Janeiro for overnight flight to Houston (flight connection)
   Aug 27 – cleared customs in Houston and arrived in Denver

7. **Benefit to Reclamation:** This trip was extremely beneficial to communicate the results, status, and future steps for this research collaboration. Witnessing the operation of test facilities, seeing actual cavitation damage on concrete test samples, and in-person discussions with the Brazilians was very important to understand their part of the research and how it compares to and complements efforts made in our Reclamation laboratories. Knowledge transfer and mutual understanding were improved with in-person interactions that could not be communicated in virtual meetings, especially with the language barrier. Examples from this trip include potential use of an ultra-high strength concrete repair material, adjusting the design of the new cavitation test facility to be built at FURNAS, and potential test methods at prototype scale to correlate concrete strength hydrodynamics at the surface. This helped clarify remaining research gaps and a path forward to continue this research collaboration in a way that will be applicable to Reclamation facilities.

8. **Benefit to Travelers:** Additional benefits included the opportunity to learn more of Brazilian interests and expertise in hydraulic and concrete research in common with Reclamation and align with current and upcoming research studies in our labs. Examples include sediment removal techniques at intakes to outlet pipes through dams, physical

modeling methods of erosion, and rock scour at plunge pools and spillway exits, stilling basin design for stepped spillways, air entrainment requirements for stepped spillways, and ultra-high strength concrete repair materials and application.

9. **Conclusions and Recommendations:** Discussions and witness testing in Brazilian laboratory facilities were conducted to coordinate and summarize cavitation research efforts to date. These in-person interactions were invaluable in understanding research findings and effectively combining results from Brazilian and Reclamation laboratories to advance the state-of-the-art for concrete design and repair for hydraulic structures. Research gaps that remain were identified (i.e., cavitation resistance of localized repair materials, uncertainty of concrete test sample size, and correlation to field hydraulics). Plans were made to bridge the gap between research results and application to practice.

10. **Actions Required:** Reclamation will summarize technical findings, in conjunction with Brazil's results, in a final report submitted to the Science and Technology Program in September 2023. Additional funding to address research gaps will be pursued through the Dam Safety Technology Development Program and Science and Technology Program in Fiscal Year 2024. Brazilian laboratories are also pursuing independent funding to continue this research.

11. **Security Questions:** We did not receive any questions about classified work and did not feel pressured or coerced in any way to cooperate with a foreign entity.

cc: 86-43200 (Kramer), 86-68000 (LaFond), 86-68500 (White), 86-68560 (Mortensen, Svoboda), 86-69000 (Brekke), 86-69100 (Foraker, Nowak)

Figure 1. Cavitation machine at UFRGS (similar to Reclamation's) used to test durability of concrete to cavitation.

Figure 2. Concrete test samples after cavitation testing at UFRGS.

Figure 3. Hydraulics Laboratory at UFRGS.

Figure 4. Prof. Marcelo Marques explaining past research of stilling basin design downstream of stepped spillways at UFRGS. Reclamation is at the beginning stages of this same research and the insights and information gained from this trip help boost our study.

Figure 5. Concrete and Structural Laboratory at UFRGS.

Figure 6. Mold used to form the concrete test samples of the current research in the Concrete and Structural Laboratory at UFRGS.

Figure 7. Catherine and Josh with engineering and technician staff at the FURNAS hydraulics lab.

Figure 8. Physical model of the FURNAS facility spillway at the FURNAS hydraulics lab. This spillway has suffered cavitation damage and is an important case study of the current research.

Figure 9. The model fabrication shop at the FURNAS hydraulics lab. This section is part of a spillway model that is made of concrete in a plaster mold. It was beneficial to learn of different model construction techniques used in Brazil compared to our methods in Reclamation.