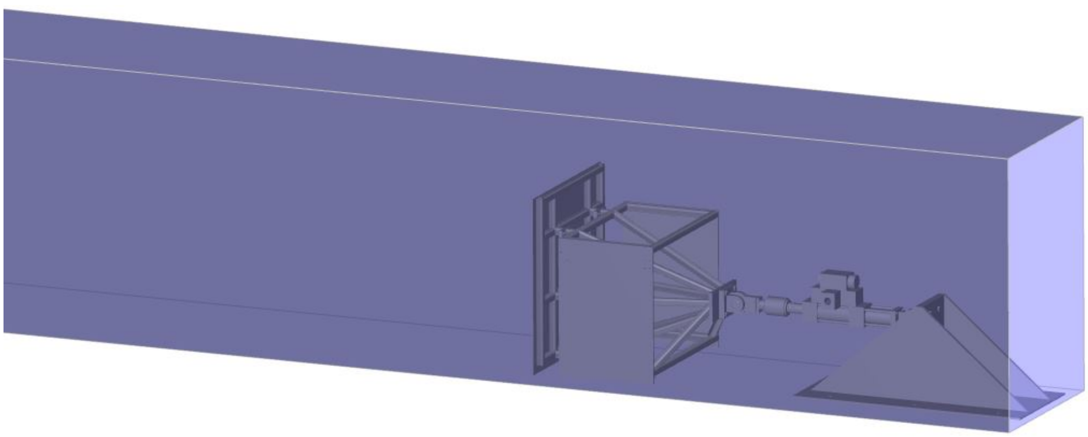
RECLAMATION
Managing Water in the West

Improved Prediction of Hydrodynamic Loads on Dams and Spillway Gates

Research and Development Office
Science and Technology Program
(Interim Report) ST-2018-1836-01

HL-2018-08



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

December 2018

Mission Statements

Protecting America's Great Outdoors and Powering Our Future

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

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A test facility in Reclamation's Hydraulics Laboratory simulates seismic vibrations to induce hydrodynamic loads on lab-scale dam and spillway gate models. The physical data from initial testing in 2018 indicate that the "flexibility" of the model skin plate significantly amplifies hydrodynamic loads. Results highlight the need to account for all important factors such as geometry and structural response when predicting hydrodynamic loads on hydraulic structures. In the next project phase, physical data will be compared to Finite Element models.

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Improved Prediction of Hydrodynamic Loads on Dams and Spillway Gates

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The test facility and model structures were designed by Warren Starbuck, formerly of the Concrete and Geotechnical Lab, and was fabricated, assembled, and installed by Warren Starbuck and Marty Poos of the laboratory shop crew.

Many thanks to Warren Frizell, retired hydraulic engineer from the Hydraulics Lab, who provided much technical guidance and insight, as well as Jerzy Salamon who peer reviewed this report.

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Background

With a large inventory of dams and spillway gates, many in areas of high seismic activity, the Bureau of Reclamation (Reclamation) has a keen interest in improved understanding and prediction of hydrodynamic loads induced during earthquakes. Over the years, Reclamation's Dam Safety Office (DSO) has funded ongoing studies comparing widely-accepted analytical and numerical approaches for hydrodynamic load predictions in an attempt to identify the important factors and limitations of these methods (Reports DSO 11-06, DSO 18-10, and DSO 19-13). Through these efforts, many important factors and limitations have been identified and evaluated, benefiting structural analyses and risk assessment activities. Still, these analytical methods produce significant differences and uncertainty in results (Salamon et al, 2017 and Salamon, 2018). The need was identified to obtain physical hydrodynamic loads and structural response data to compare with analytical and numerical methods in an attempt to account for all the important variables and reduce the uncertainty of dynamic load predictions. By comparing to physical data, the accuracy of hydrodynamic load predictions can be improved and the current state of the art can be advanced.

This report describes a physical test facility in Reclamation's Hydraulics Laboratory in Denver, CO that simulates seismic motion and hydrodynamic loads on laboratory-scale dam and spillway gate structures and documents initial test results. The design, fabrication, and initial testing was completed under DSO's Technology Development Program from 2016-2018, with supplemental funding from the Science and Technology (S&T) Program. This study will continue through 2020 under S&T, to further investigate hydrodynamic loads with various geometrical and stiffness configurations of the test structure. The results from laboratory testing will be compared to numerical Finite Element (FE) analyses conducted by Reclamation's Waterways and Concrete Dams Group 1 under the DSO Technology Development Program.

Introduction

Dam and spillway gate designs must account for both hydrostatic (static pressures from the reservoir) and hydrodynamic loads (due to seismic excitation). While hydrodynamic loads on dams and spillway gates have been investigated since the 1930's, analytical approaches developed over the years produce significantly different results, which creates uncertainty for structural design engineers. Since seismically induced hydrodynamic loads on hydraulic structures depend on several variables such as reservoir depth, water properties, and geometry and stiffness of the structure, it is difficult to accurately predict such loads. Modern sophisticated numerical methods have improved predictions of the hydrodynamic loads by accounting for some of these variables but still need to be verified with reliable physical data to ensure correctness of the analytical models and estimate accuracy of the obtained results. In the current study, a vibrating test facility was used to simulate seismic vibrations to induce and measure hydrodynamic loads on the face of a laboratory-scale [1]model structure.

The primary objectives of these investigations include:

- Obtain physical measurements of hydrodynamic loads and structural response of a laboratory-scaled model of dam and spillway gate configurations under simulated time varying seismic vibrations.

- Evaluate the factors that affect the fluid-structure interaction (excitation frequencies, structure geometry, stiffness, etc.) and the influence of these factors on developed hydrodynamic loads.

- Improve understanding of hydrodynamic loads developed during seismic interaction between a structure and fluid by comparing and validating numerical results with physical data.

[1] *The size, geometry, and hydraulic and structural features of the model configurations tested in this study do not represent a specific prototype Reclamation dam, gate structure, or project in the field. Direct application of scaled physical data from the model to a prototype structure will not yield accurate results due to differences in model-prototype structural characteristics and size-scale effects. Results from this study are only intended for general evaluation and comparison to numerical models.*

Literature Review

While an extensive literature search was made by Salamon (2011), some additional sources were researched to help guide the development of the physical testing approach and correlate it with existing analytical methods. While only two of these sources are mentioned here, findings from all sources that were reviewed are outlined in Appendix A. Any new sources with information relative to this study will be added as this study progresses through 2020.

Structural Analysis

Much of the recent work for Reclamation's DSO related to seismically-induced hydrodynamic loads on dams and spillway gates is summarized by Salamon (2018). The author describes and evaluates the most significant approaches developed in industry, starting with the analytical equations developed by Westergaard in the 1930's. Westergaard's exact and approximate solutions are presented in Equations 1 and 2, respectively. This approach is limited to horizontal vibrations of a rigid, vertical structure.

$$P_{exact} = \frac{8\alpha\gamma h}{\pi^2} \sum_{1,3,5,\ldots}^{n} \frac{1}{n^2\sqrt{1-\frac{16\gamma h^2}{n^2 gkT^2}}} \sin\left(\frac{n\pi y}{2h}\right) \qquad \text{(Eq. 1)}$$

$$P_{approximate} = \frac{7}{8}\gamma\alpha\sqrt{h(y)} \qquad \text{(Eq. 2)}$$

where: γ = specific weight of water (*lb/ft*^{3})
α = maximum horizontal acceleration of dam or gate (*g's*)
h = total depth of the upstream reservoir (*ft*)
y = local depth or vertical distance from top of reservoir (*ft*)
g = acceleration due to gravity (*ft/s*^{2})
T = period of horizontal vibration (*s*)
k = bulk modulus of water (*lb/ft*^{2})

As part of these evaluations summarized by Salamon (2018), Westergaard's solutions were compared to the results from FE analyses for both rigid and flexible dam structures as well as for spillway radial gates. These analytical investigations show the importance of accounting for factors such as the actual geometry and structural characteristics of the dam or spillway gate structure. One of the main recommendations from these investigations was to use physical data from laboratory testing as a primary benchmark in comparison to FE models.

Laboratory Testing

A study to obtain physical data from laboratory-scale dams & gates was conducted in Japan by Nakayama, et.al. (2008). The objective, size of the test setup, and test conditions were quite similar to those implemented in the current Reclamation study. They used a rigid vertical plate (47.25 x 39 x 1.6 inch acrylic sheet) mounted on a shake table submerged in water to measure hydrodynamic pressures and accelerations on the plate caused by horizontal vibrations. Figure 1 shows a schematic of their set up for physical testing.

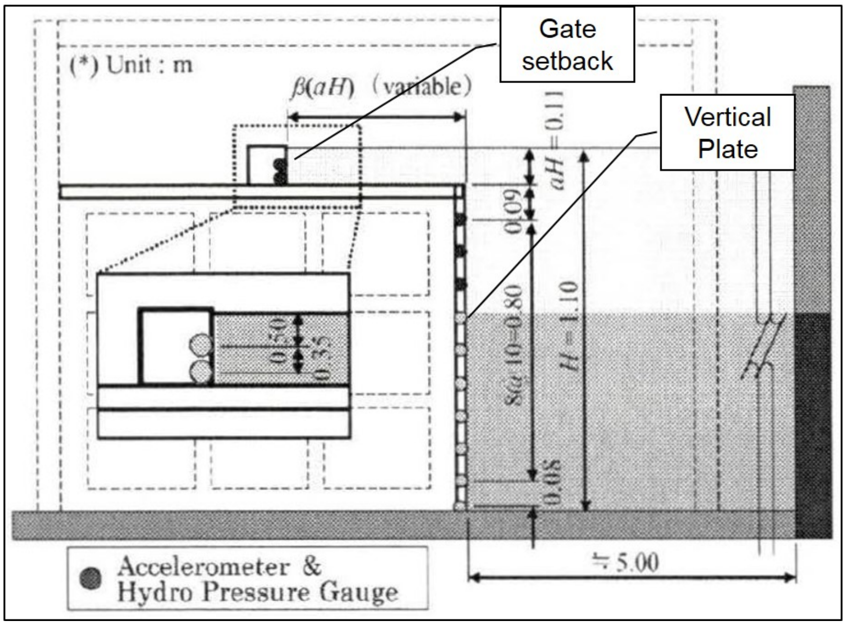


Figure 1 Schematic in elevation view of the physical test setup used by Nakayama et al.

Their results are compared to Westergaard's approximate solution in Figure 2 for a test condition of 5 Hz at 39.4 inch/s^2 (0.1g). Data are shown as the ratio of hydrodynamic pressure to local acceleration for various setback distances for the gate location from the upstream face of the dam (β = gate height / setback distance from dam face). For depths greater than about 0.3m, hydrodynamic loads were not influenced by gate setback. Physical data were slightly less than those predicted by Westergaard, which was attributed to limitations of the physical test facility including boundary conditions and wave reflections. However, the trend was similar for both physical and analytical results, with hydrodynamic loads varying only with reservoir depth. This suggests that their physical test setup was truly rigid, greatly reducing or even preventing localized effects from the structural response of the vertical plate. Testing of other excitation conditions, structural geometries or characteristics, such as gate stiffness, were not mentioned in the report. While 2018 testing in the current study did not include gate setbacks, information from Nakayama's study, with similar size, geometry and test conditions, are interesting for comparison.

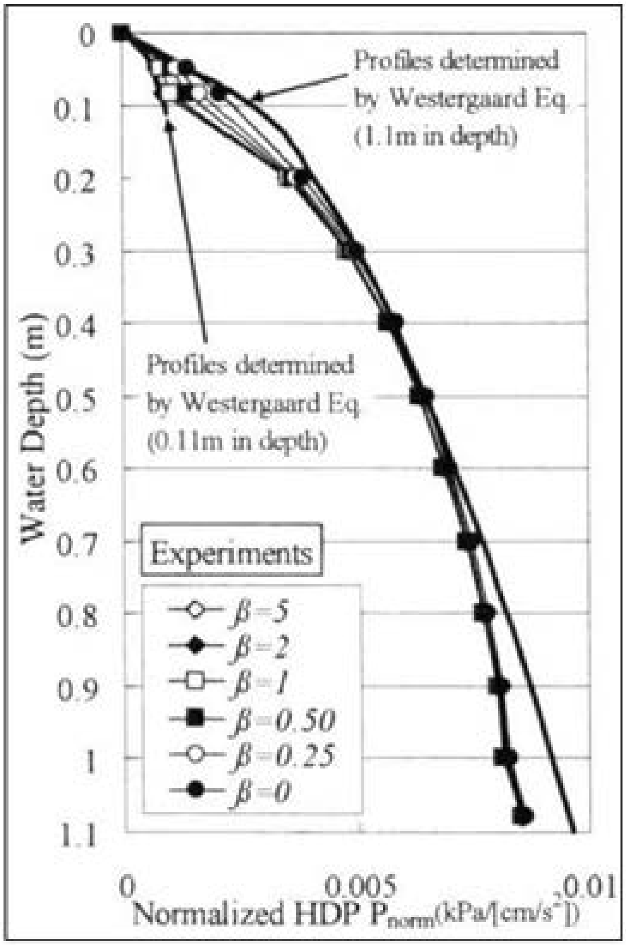


Figure 2 Results of depth vs the ratio of hydrodynamic pressure to acceleration compared to Westergaard's approximate solution.

Reclamation Testing Program

Introduction

The current study utilized a physical test facility to measure hydrodynamic loads and structural response of laboratory-scale dam and spillway gate structures under horizontal vibration. The original intent was to test three different geometries of the model with vertical, sloped, and radial faces (Figure 3). All model configurations were 4 ft high and approximately 3.5 ft wide to allow space for gate seals and the side walls of the buttress frame. A height of 4 ft allowed the largest model size to be tested within the load and space limitations of the hydraulic actuator and 4-ft-wide by 8-ft-deep laboratory flume.

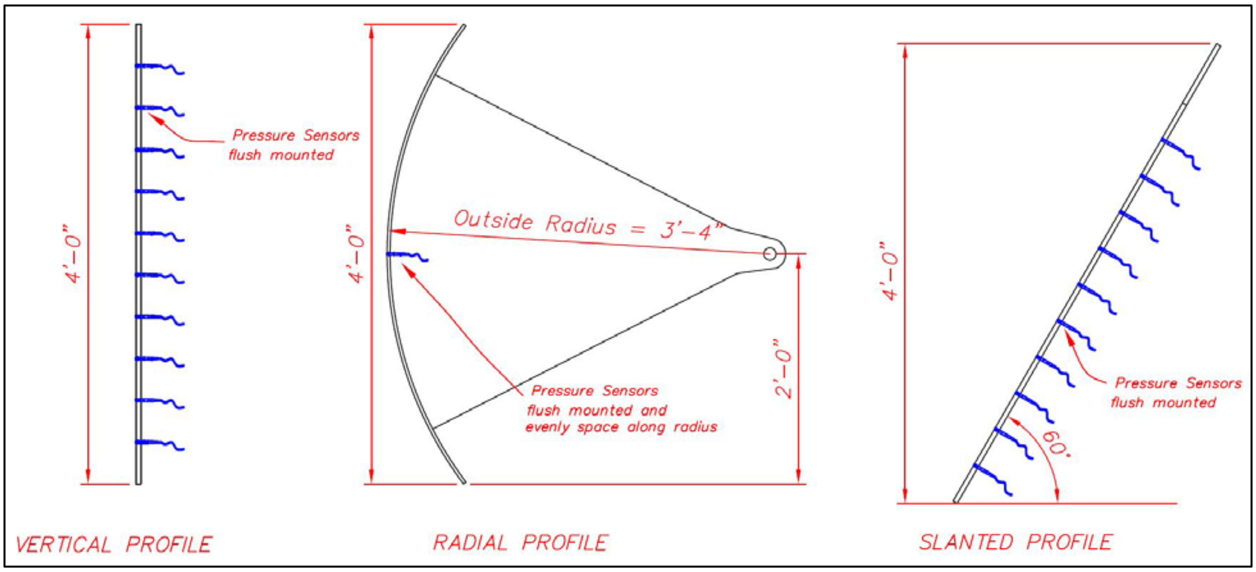


Figure 3 Three shapes of the model faces to be tested as part of the current study. Potential locations of hydrodynamic pressure sensors on each geometry are shown in blue. In 2018, only the vertical model geometry was tested.

Physical Test Facility

The physical test facility is comprised of a model structure, buttress frame, hydraulic actuator, and support frame (Figure 4) designed to be easily removed and re-installed. The model configuration, which is interchangeable for the three geometries, is mounted to the buttress frame which slides on horizontal linear bearings. The model and buttress frame sit inside interior side walls made of metal sheeting which helps stabilize the whole arrangement. Seals between the interior sidewalls and the flume walls prevent the reservoir water from flowing downstream of the model face. The horizontal motion is produced by the hydraulic actuator, which is controlled by a servo motor and controller, and is mounted to a support frame anchored to the concrete floor. This assembly was installed in the 4 ft flume of Reclamation's Hydraulics Laboratory which provided a static water pool on the upstream side of the model. The excitation signature, frequency, and displacement of the hydraulic actuator are controlled by a function generator in the controller. Thus, seismic motion is simulated by horizontal vibrations moving the model in and out of the reservoir which produces hydrodynamic loads on the skin plate.

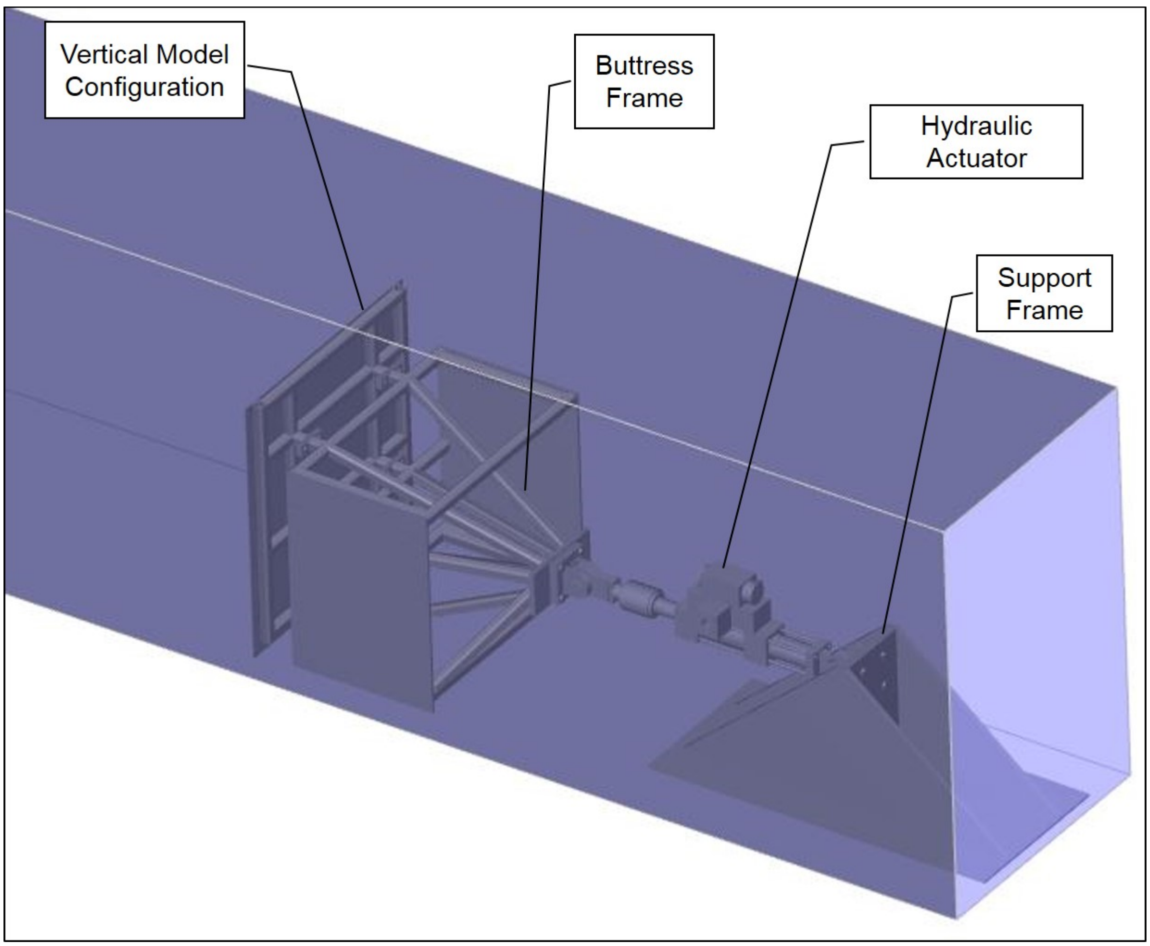


Figure 4 Three dimensional drawing of the test facility assembly as installed in the 4-ft flume. Flume is shown in transparent purple color in the drawing.

Each of the three model structures is made of steel and backed with a ribbed frame to provide stiffness. The model skin plate thickness is 3/8 inch and the ribbed frame is constructed of 2 x 2 x 5/16 inch square tubing that was welded to the back side of the skin plate. The model geometry is bolted to the buttress frame which is also made of the same sized square tubing. The buttress frame, hydraulic actuator, and support frame are attached together by bolted connections. Detailed drawings and dimensions of all three model configurations and other assembly components are shown in Appendix B.

The models and other components were first fabricated and assembled on the main floor of the Hydraulics Laboratory for functional testing before installation in the laboratory flume (Figure 5). The flume is 4 ft wide, 8 ft high and spans approximately 44 ft from the upstream flow baffle to the upstream face of the model skin plate (Figure 6). It is filled by one of the laboratory pumps, drawing water from the 240,000 gallon underground sump, and drained back to the sump through a series of floor drains in the flume.

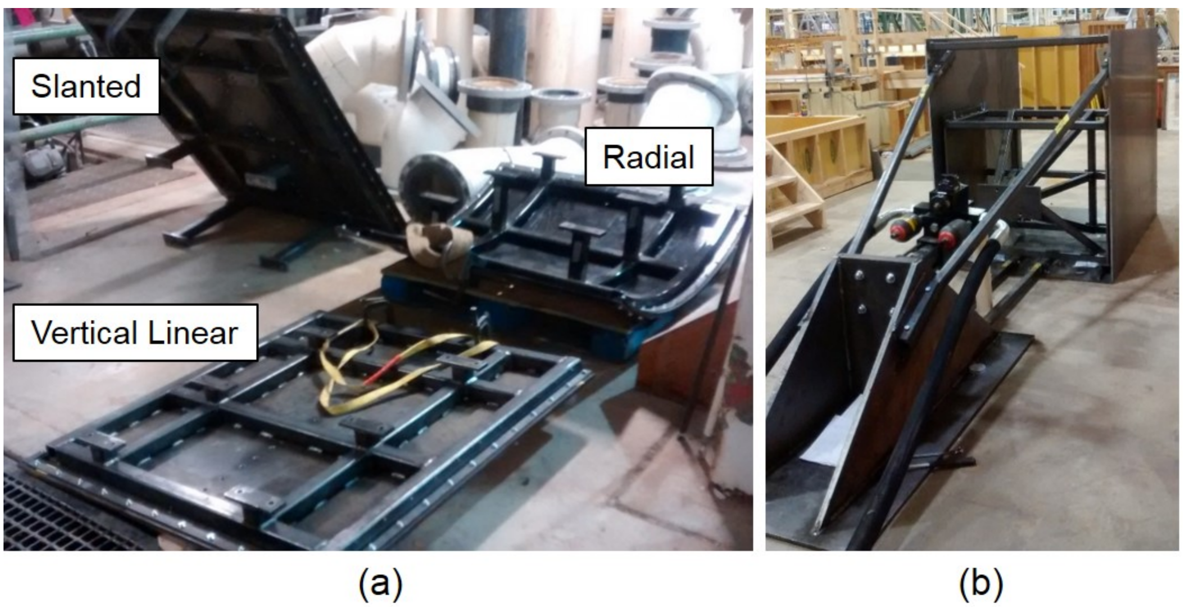


Figure 5 Constructed model configurations on the shop floor before installation (a) and the test facility on the lab floor for functional testing before installation in the flume (b).

(a) (b)

Figure 6 Hydraulic Laboratory's 4 ft flume before test facility installation (a) and after installation (b). Looking upstream.

Instrumentation and Data Acquisition

A series of sensors were used to obtain the physical measurements for this study as outlined in Table 1. All measurement signals were acquired with a Measurement Computing 1616HS data acquisition module connected to a laptop computer and processed using DasyLab 2016 software according to the sequence in Figure 7. All data were collected at a rate of 5k samples/second with the exception of reservoir pressures measured with the hydrophone at a rate of 1M sample/second to detect high frequency acoustic pressure waves and reflections.

Table 1 Information of sensor used to collect physical hydraulic and structural data during testing.

Measurement	Sensor	Range	Qty	Sensitivy or Accuracy
Gate Pressure	Dynamic Flush mount - Kistler 211B6	0-50 psi	10	0.0005 psi resolution
	Static Chamber mount - Omega PX309	0-5 psi	1	0.25% FS accuracy
Reservoir Acoustic Pressure	Hydrophone, Buel & Kjaer Type 8103	210 - 222 dB	1	dB ref. 1V/µPa, 4-200kHz
Gate Acceleration	Accelerometer, Wilcoxon Research 797L	0-10 g	7	5% freq. response 0.6 -850 Hz
Reservoir Depth	Acoustic Downlooker, MassaSonic M-5000	4-40 inch	1	0.01 inch resolution
Actuator Displacement	LVDT, Team Corporation 9565	±3 inch	1	-
Actuator Force	Load Cell, Lebow 3116	0-22 kips	1	-
Impact Hammer	Instrumented Impulse Hammer, DyTran, 5802A	0-5 kips	1	0.3 lb resolution

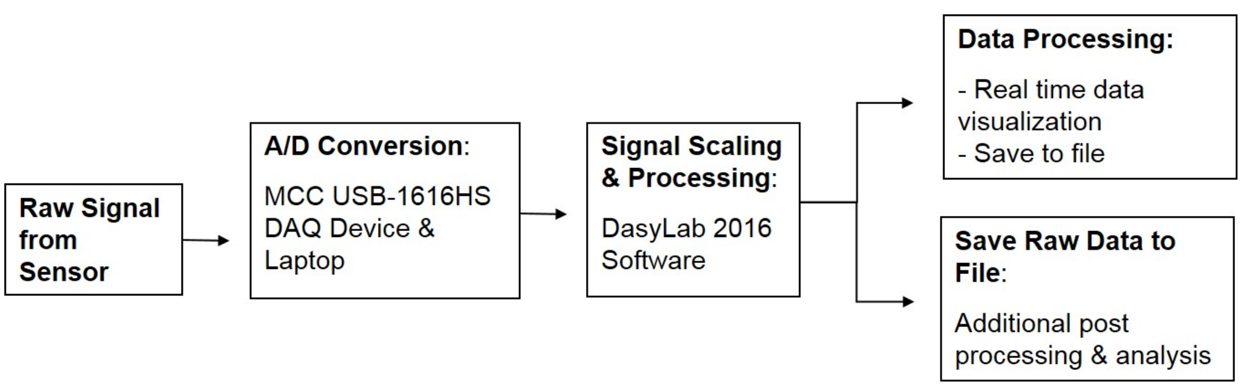


Figure 7 Data acquisition and post processing sequence.

Dynamic pressure sensors and accelerometers were mounted to the skin plate of the model as shown in Figures 8 and 9. The dynamic pressure sensors were flush mounted to measure hydrodynamic pressures directly on the upstream face of the model and accelerometers were mounted with a high strength magnet to the backside of the skin plate to measure accelerations at the same locations. This was done at 10 vertical locations along the centerline of the gate. Mounting holes not in use were blocked with a threaded plug. The reservoir depth was measured with a down looking acoustic sensor at the center line of the flume, 48 inches upstream from the model face.

In addition, a hydrophone was used to measure acoustic pressures in the reservoir upstream of the gate. As shown in Figure 9, the hydrophone was hung vertically from the top of the flume at horizontal positions of 4 and 48 inches upstream of the model. The hydrophone was raised to collect data at the same vertical locations as the dynamic pressure sensors on the model face for comparison. While data from all of the flush mounted pressure sensors and accelerometers were collected simultaneously, hydrophone measurements could only be made one location at a time.

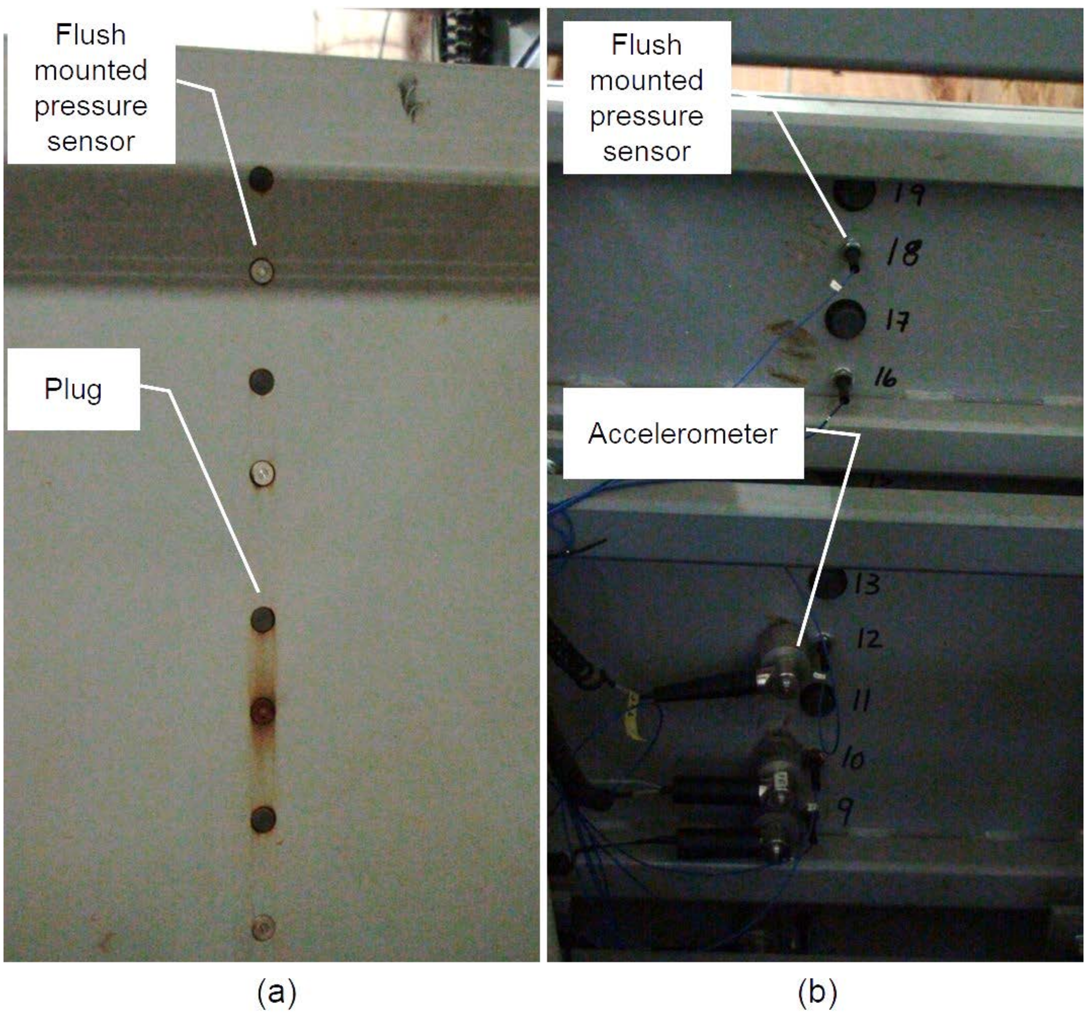


Figure 8 Dynamic Pressure sensors mounted flush with the upstream skin plate (a) and sticking out the back along with magnet-mounted accelerometers on the backside of the model (b).

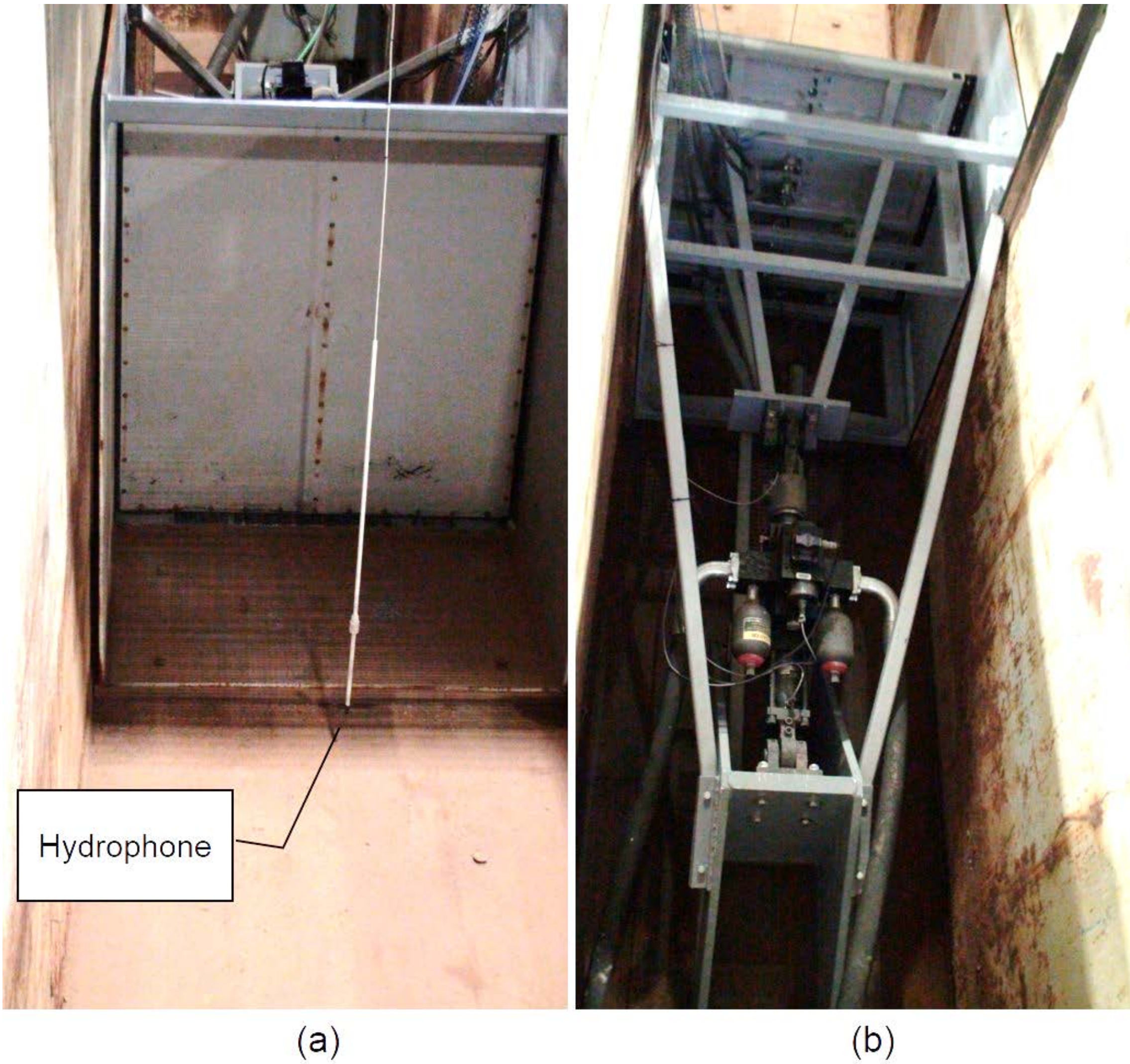


Figure 9 Test assembly installed in the flume with the upstream face of the vertical model (a) and the actuator, support frames, and backside of the model (b).

Operational Testing

Each test run was made by selecting the frequency and displacement input for the actuator and recording data for a minimum of 3 seconds during operation. Initial tests included only sinusoidal excitation signals and reservoir depths near 4 ft. Table 2 shows the 10 vertical locations of hydrodynamic pressure and acceleration measurements made during initial tests. The 10 locations were not equally spaced due to the horizontal ribs along the back side of the model.

One objective of the initial testing was to determine the operational range where reliable test conditions exist and relevant measurements could be made. Table 3 outlines the test conditions attempted and observations made for an upstream reservoir depth of 4 ft. Measurements at test conditions with frequencies of 5, 10, and 50 Hz were used for analysis, with a focus on 10 Hz in this report.

Table 2 Vertical locations of hydrodynamic and acceleration instrumentation installed during 2018 initial testing of vertical linear model.

Sensor	**Vertical Location**
-	*inch from model invert*
Static Pressure	2.375
Dynamic Pressure, Accelerometer, & Hydrophone	5.500
	9.625
	12.375
	16.750
	21.563
	24.000
	28.750
	33.625
	38.750
	43.250

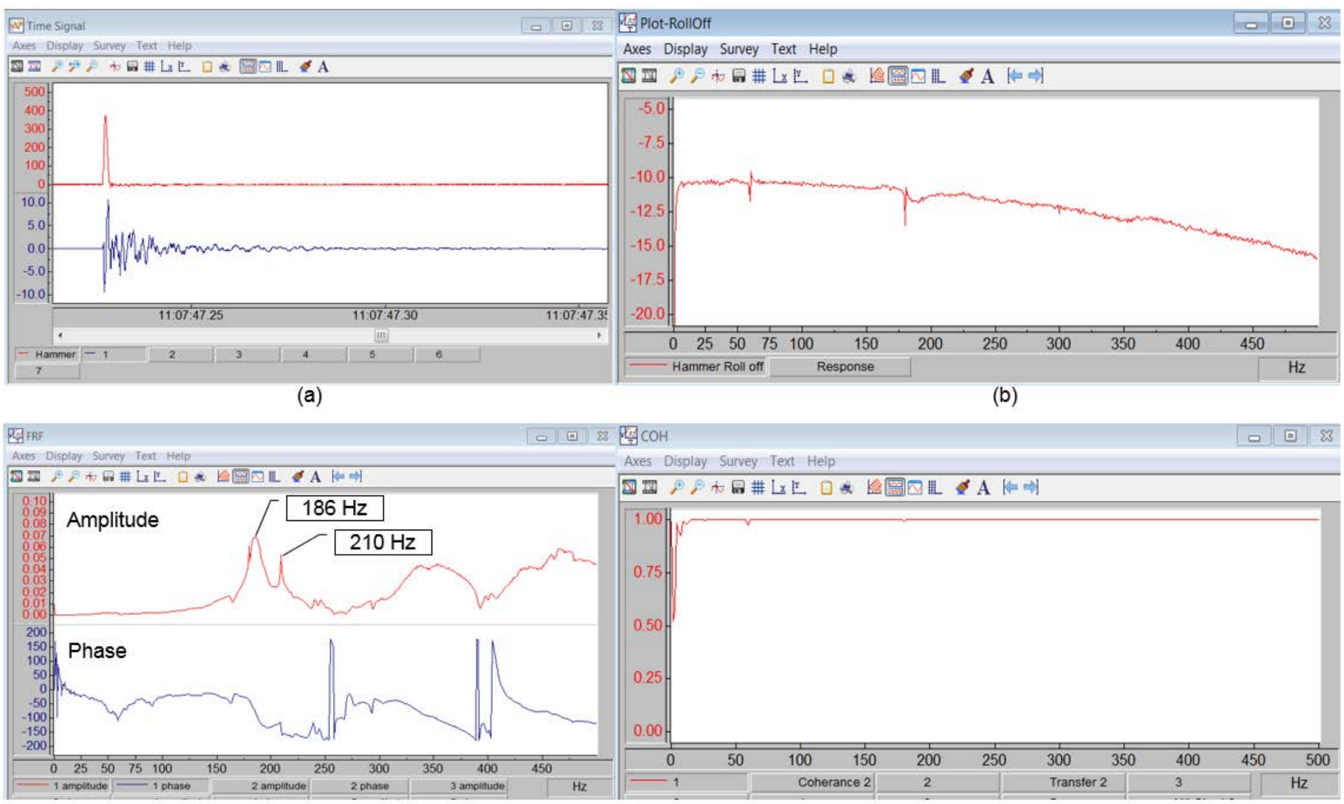
Table 3 Test conditions attempted in initial shakedown testing with 4 ft reservoir depth.

Frequency	**Displacement Range**	**Comments**
Hz	*± inch*	-
1	1	Produces a surface wave rather than acoustic pressures. Not tested further
5	0.005 – 0.250	Clean sinusoidal vibration
10	0.005 – 0.100	Clean sinusoidal vibration
20	0.005 – 0.012	Load noises, may be near subharmonic of natural frequency of reservoir or gate. Limited testing.
30	-	Load noises, may be near subharmonic of natural frequency of reservoir or gate. Not tested further
50	0.002 – 0.050	Max frequency that produces clean sinusoidal vibration.

Modal Testing

Impact testing was used to define the modal shapes of the vertical gate to understand the structural response of the model structure. This was done by striking the back side of the skin plate with an instrumented impact hammer to excite the natural frequencies of the model structure. The response was measured with the accelerometers mounted on the backside of the skin plate to determine the Frequency Response Function (FRF) of the gate. Impact tests were performed both in the dry and with a reservoir depth of 4 ft to see the effect of the “added mass” of the water. Figure 10 shows an example of the measured excitation time signal and model response.

A similar method was used during operational testing, utilizing the excitation from the hydraulic actuator to define the operation deflection shapes of the model structure. For both cases, the mode and operating deflection shapes were compared to hydrodynamic pressure results to determine the influence from the structural response of the model.



(c) (d)

Figure 10 Modal Analysis using an impact hammer and accelerometers. Time series of the excitation force from the hammer and response from an accelerometer (a). Spectral data showing the “roll-off” of the impact hammer (b). The amplitude and phase of the FRF (c). The coherence function where values near 1 indicate good correlation between the input and response (d).

Results and Discussion

Results from 2018 initial testing of the vertical linear model indicated a significant influence of the structural response on hydrodynamic loads for all conditions tested. Figure 11 shows the vertical distribution of hydrodynamic pressures that produce a similar trend for excitation frequencies of 5, 10, and 50 Hz. While there is a general increase of hydrodynamic pressure with depth, a localized influence significantly amplifies the pressure that varies greatly depending on vertical location. These results were dependent on both excitation frequency and displacement. Results from modal testing were helpful in explaining the amplified hydrodynamic pressures.

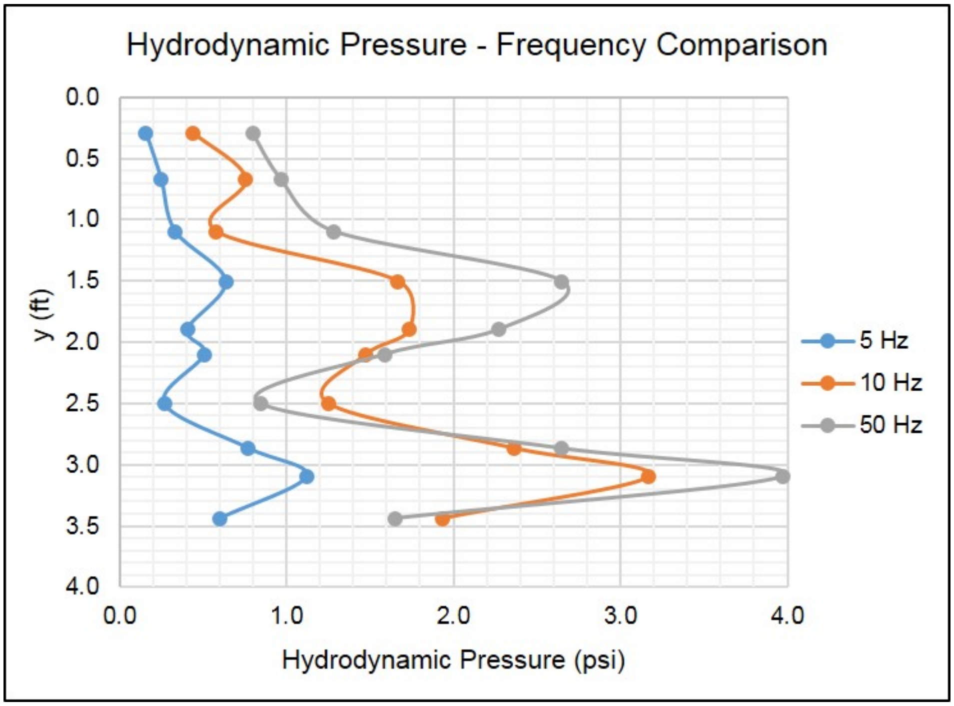


Figure 11 Depth vs maximum hydrodynamic pressures on the gate for input frequencies of 5, 10, and 50 Hz.

Modal test results determined the dominant natural frequency of the model assembly to be 186 Hz by impact testing and 200 Hz by operational testing at a reservoir depth of approximately 4 ft (compared to 243 Hz in the dry). Using Eq. 3, the fundamental frequency of the reservoir, f_{res}, is estimated to be near 300 Hz for a depth of 4 ft which could potentially cause resonance with the gate assembly depending on the excitation frequency, although this did not seem to be the case for operation at 5, 10, and 50 Hz.

$$f_{res} = \frac{c_w}{4\,h} \qquad \text{(Eq. 3)}$$

where: c_w = speed of sound in water (*approximately 4,860 ft/s*)
h = total depth of the upstream reservoir (*ft*)

Plots (a) and (b) of Figure 12 show the modal and operating deflection shapes of the vertical model respectively, both indicating an $n = 2$ mode shape with nodes near the top, center, and bottom of the skin plate. The mode shapes and nodes appear to be modulated by the ribs on the backside of the skin plate. For an excitation frequency of 10 Hz, the influence of the skin plate response is shown by plots of hydrodynamic pressure at the model surface in (c) and (d). A nearly linear relationship of the pressures at the gate ribs at depths of 1.2, 2.6, and 3.5 ft is shown in plot (c). Plot (d) shows the amplification of hydrodynamic pressures in between the gate ribs relative to those at the ribs. Results for this test condition show that hydrodynamic pressures were amplified up to almost 50 percent greater than those near a node with high stiffness. However, this result should not be generalized to all structures due to differences in designs, reservoir conditions and seismic frequencies which should be evaluated individually. Regardless, these results show that hydrodynamic loads are highly dependent on the stiffness and structural response of the structure.

Attempts were made to “normalize” the pressure results with local acceleration data similar to Nakayama et al (2008), but this did not remove the amplifications. The literature and current test results highlight the importance of several factors that influence hydrodynamic loads at the face of dams and spillway gates. These include namely, seismic excitation, reservoir depth, fluid properties, and structural characteristics of the structure. Future efforts with dimensional analysis of the physical data may help pull out the most important variables and show their relationship to each other as it relates to hydrodynamic loads.

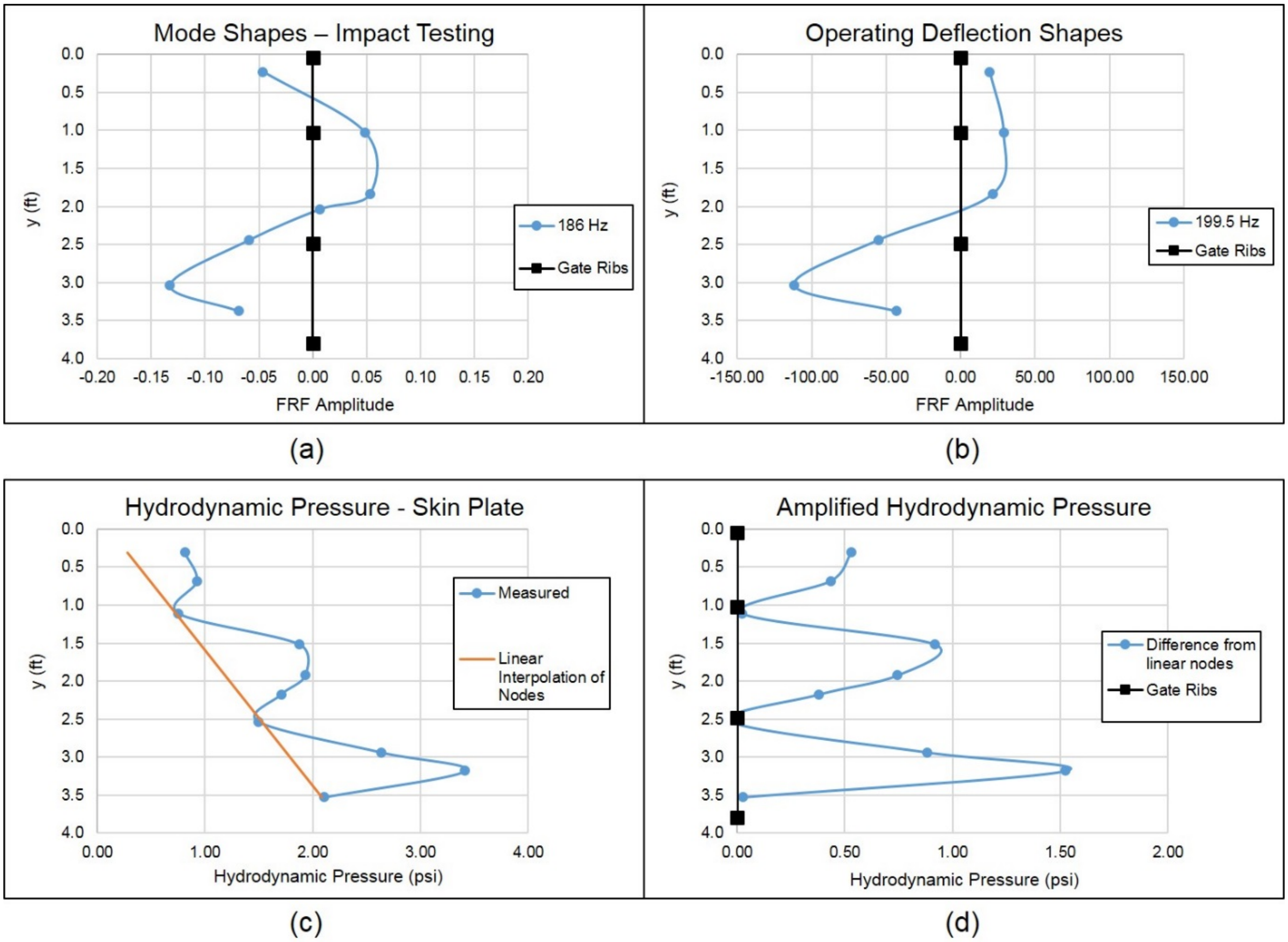


Figure 12 Mode shapes from impact testing (a) and operating deflection shapes (b) of the vertical linear model shown by the depth vs. Frequency Response Function. These are compared to hydrodynamic pressures with a linear interpolation at the structural nodes (c) and relative to the vertical location of the skin plate rib supports (d).

Time series data of hydrodynamic pressure and acceleration on the skin plate and acoustic pressures in the reservoir with their respective frequency spectra were considered. All signals were low-pass filtered at 400 Hz to remove any influence from the hydraulic actuator pump (500 Hz) and other factors such as acoustic reflections of the flume. However, high frequency reflections were not observed in the raw signals. The time series of hydrodynamic pressure and acceleration at a depth of 3.18 ft and excitation of 10 Hz are shown in Figures 13 and 14. Both signals appear to consistently oscillate at 10 Hz and are approximately 180° out of phase with each other. Higher frequency components are also seen in both signals, particularly in the acceleration signal. These frequencies appear in the spectral data in Figures 15 and 16 with greater amplitudes at 200 and 340 Hz, which may be caused by the natural frequencies of the model structure and flume reservoir.

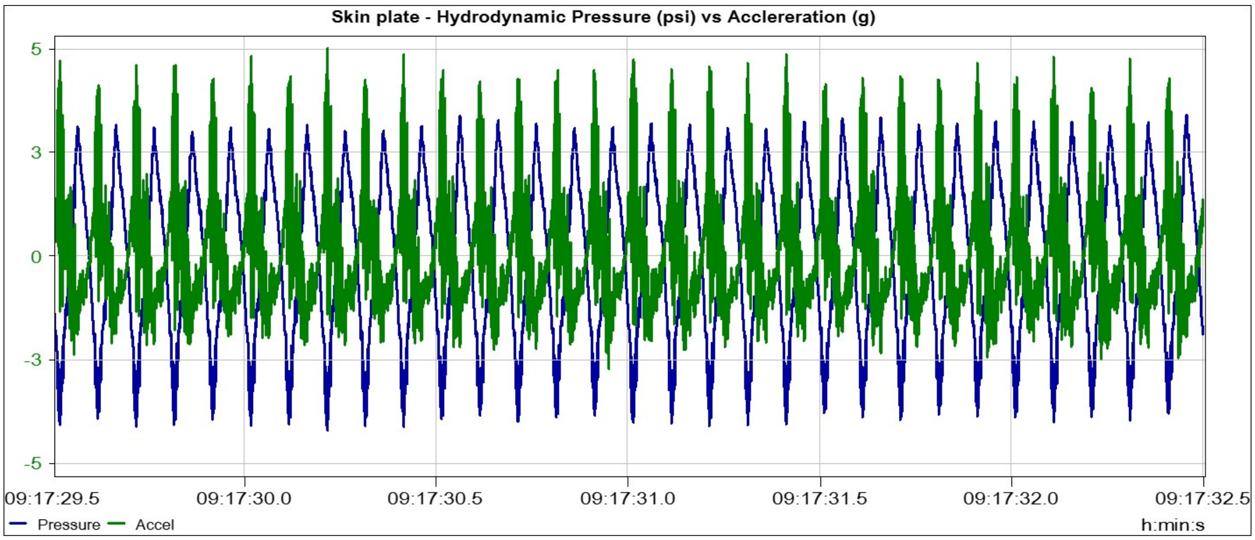


Figure 13 Time series data for hydrodynamic pressure (blue) and acceleration (green) at y = 3.18 ft and input frequency of 10 Hz.

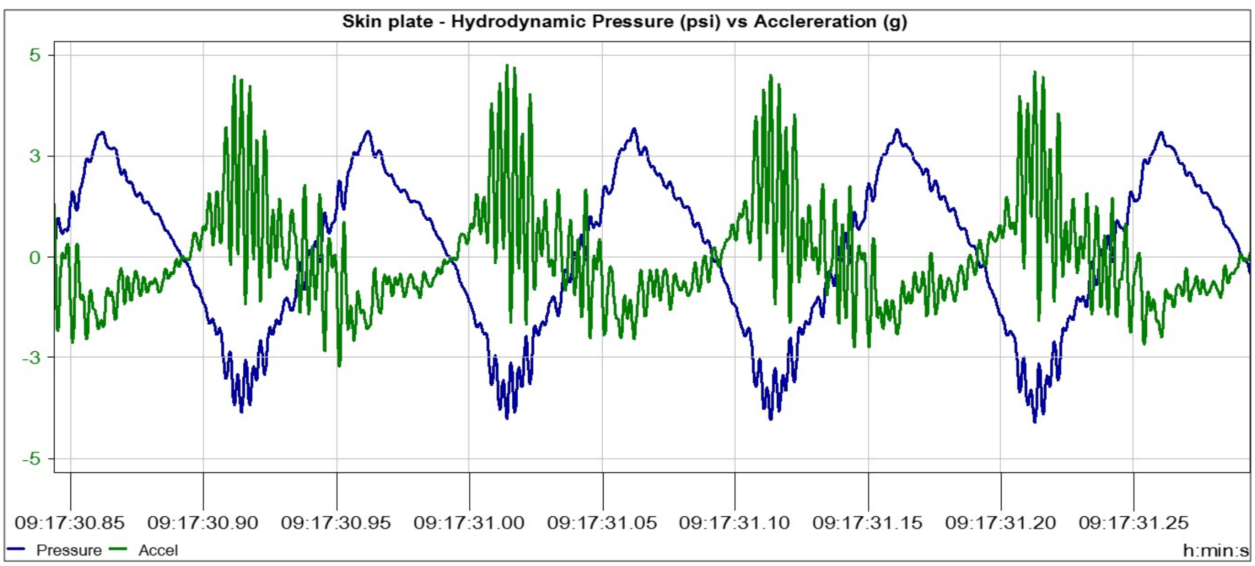


Figure 14 Time series data for hydrodynamic pressure (blue) and acceleration (green) at a depth of 3.18 ft and excitation frequency of 10 Hz, zoomed in to observe five oscillations.

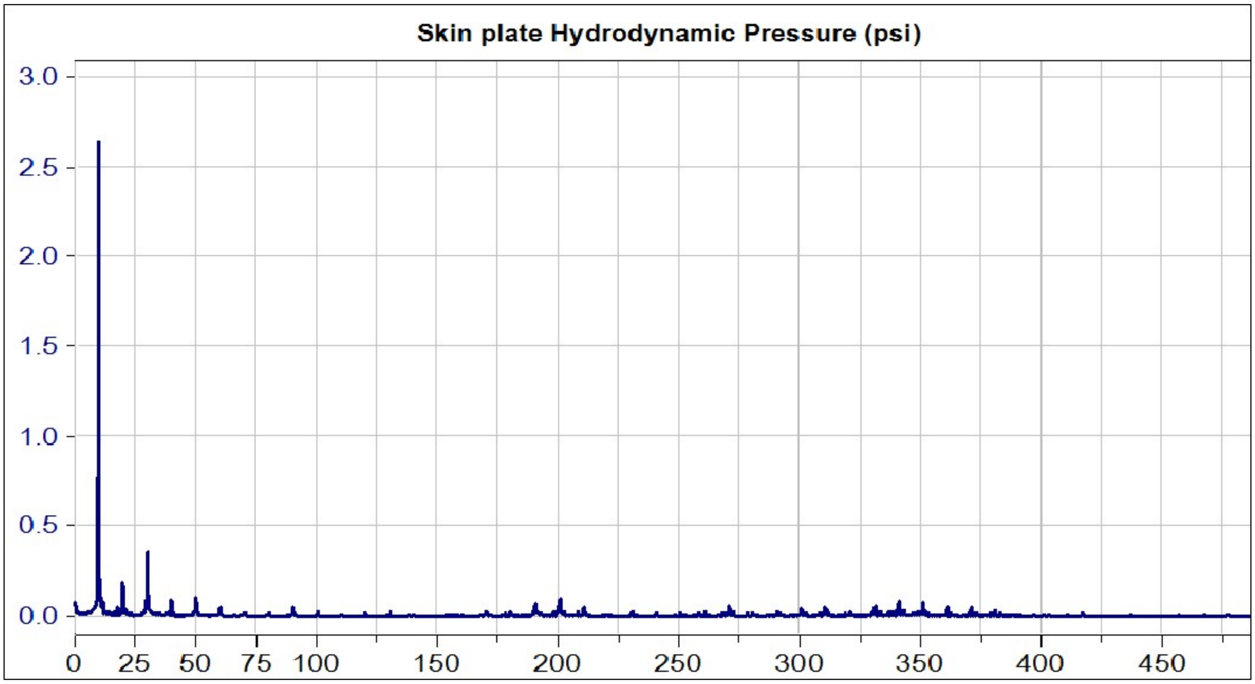


Figure 15 Frequency spectrum of hydrodynamic pressure on the skin plate at a depth of 3.18 ft and input frequency of 10 Hz.

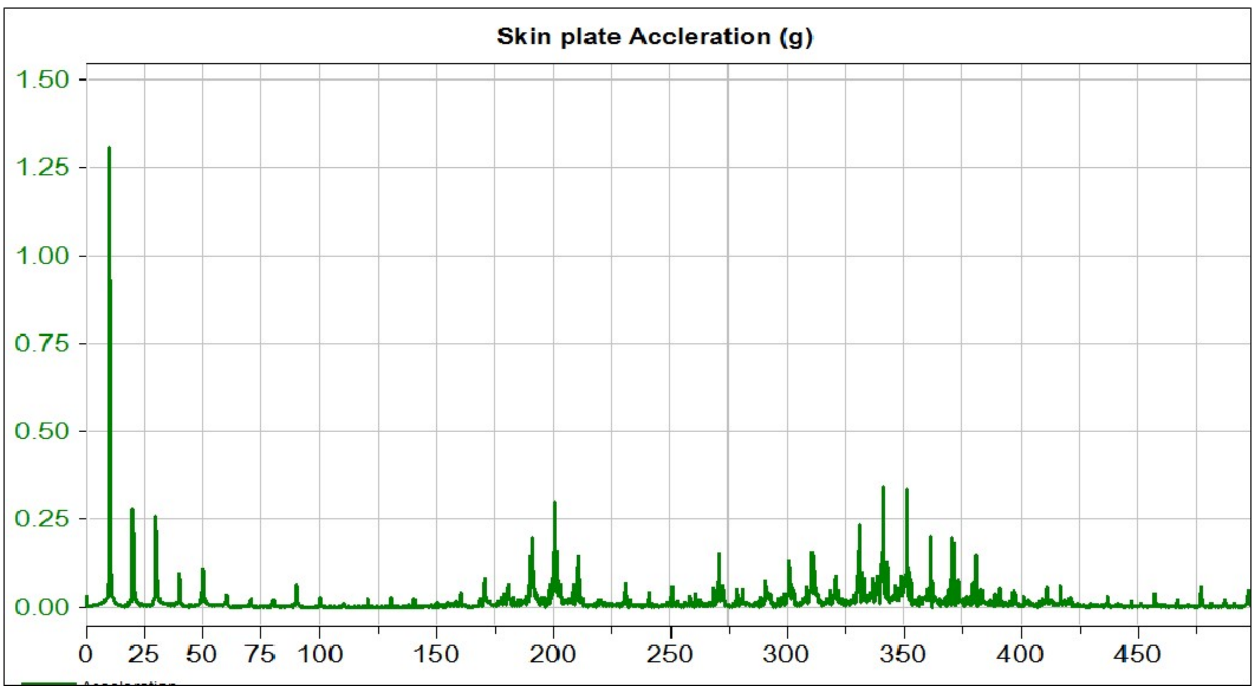


Figure 16 Frequency spectrum of acceleration at a depth of 3.18 ft and input frequency of 10 Hz.

Hydrodynamic pressures in the reservoir, measured with a hydrophone at 4 and 48 inches upstream of the model face, are compared to skin plate measurements in Figure 17. Reservoir data are not influenced by the structural response of the model and vary only with depth. The damping of these acoustic pressure waves is exhibited by the difference in magnitude at both horizontal locations. Maximum pressures near the bottom of the reservoir at 48 inches are approximately ½ of those at 4 inches from the face, where the acoustic waves are generated.

A comparison of the time series and frequency spectra of skin plate and reservoir hydrodynamic pressures is shown in Figures 18 through 20. Again, some frequency content higher than the dominant 10 Hz appears on the skin plate but is not observed in the reservoir. Neither the natural frequency of the reservoir near 300 Hz nor high frequency acoustic reflections were seen in the raw and filtered signals from the hydrophone. Again, this points to the structural response of the skin plate as the main cause of amplified hydrodynamic loads at the model surface.

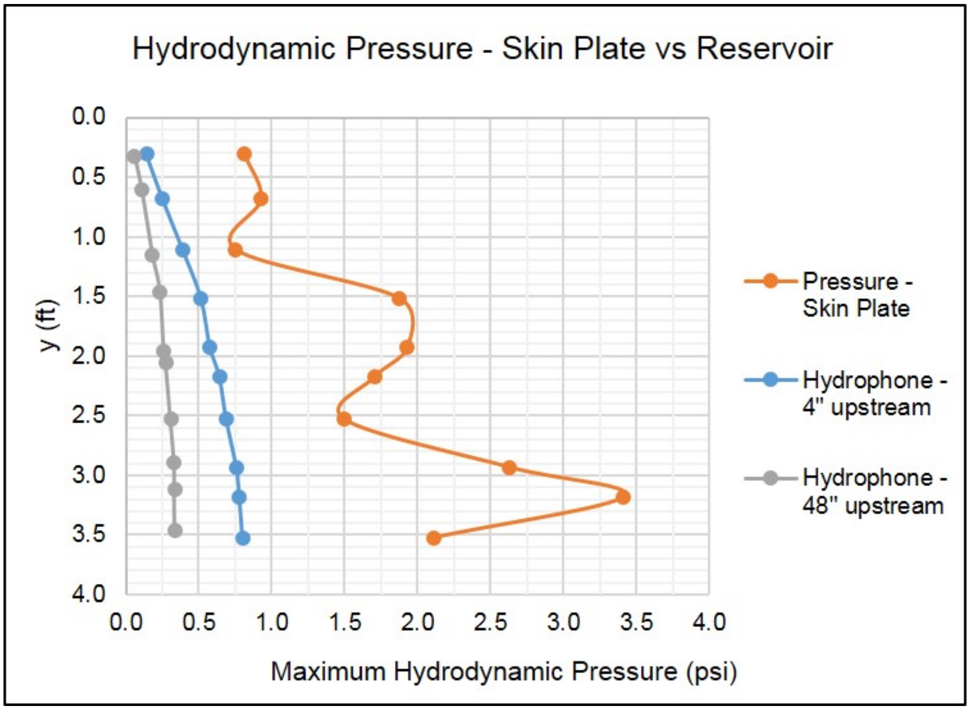


Figure 17 Depth vs hydrodynamic pressure comparison for the model skin plate and two stream-wise locations in the upstream reservoir.

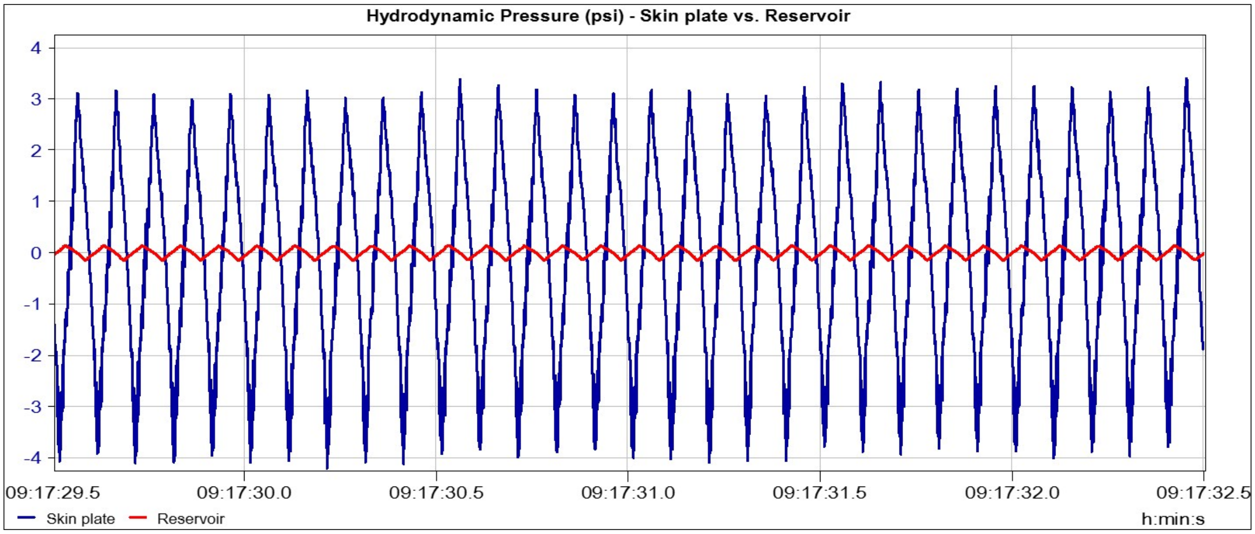


Figure 18 Time series data for hydrodynamic pressure at the skin plate (blue) and reservoir 4 inches upstream of the face (red) at a depth of 3.18 ft and input frequency of 10 Hz.

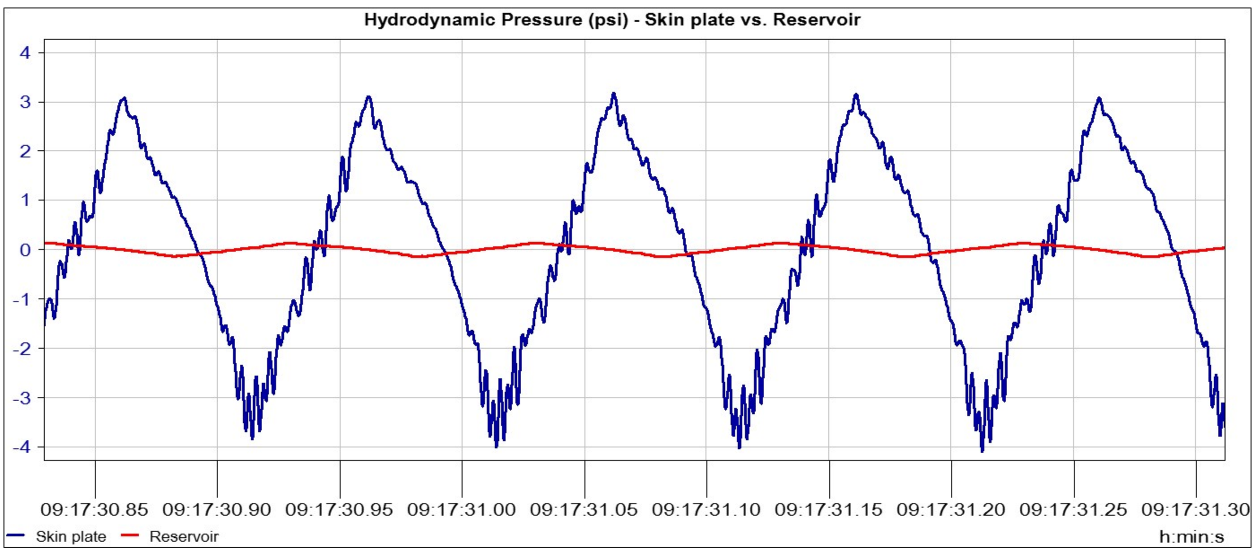


Figure 19 Time series data for hydrodynamic pressure at the skin plate (blue) and reservoir 4 inches upstream of the face (red) at a depth of 3.18 ft and input frequency of 10 Hz, zoomed in to observe five oscillations.

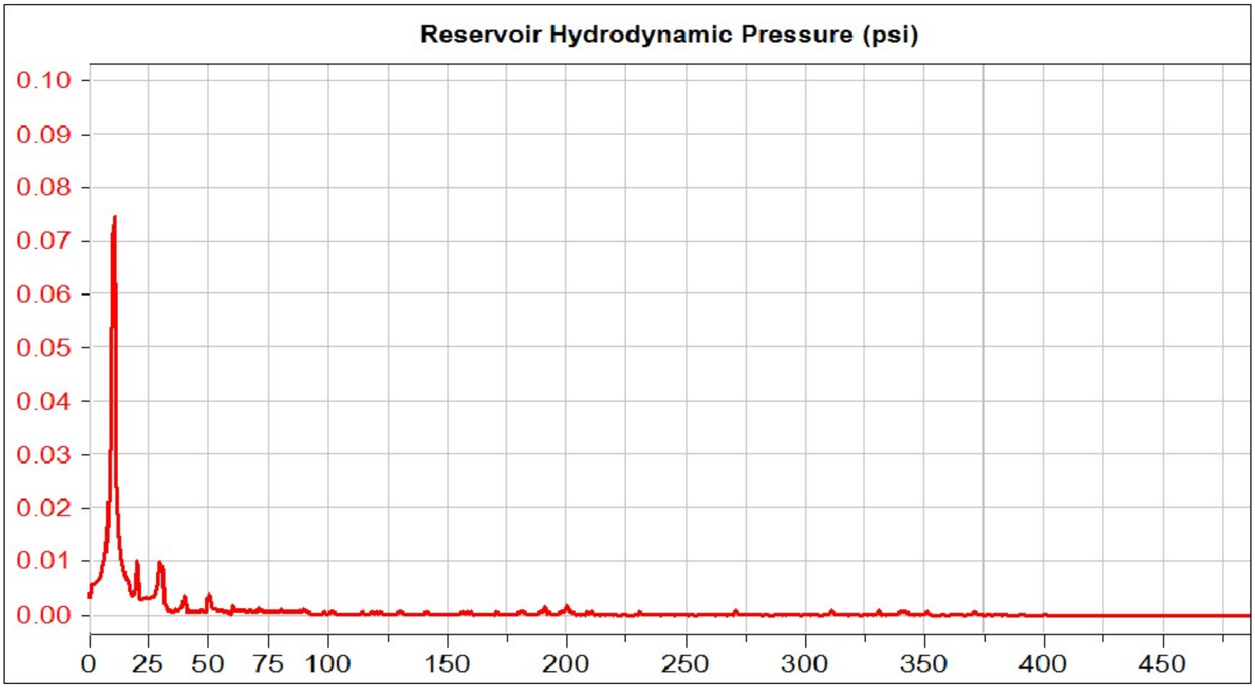


Figure 20 Frequency spectrum of hydrodynamic pressures measured in the reservoir 4 inches upstream of the face at a depth of 3.18 ft and input frequency of 10 Hz.

A comparison of hydrodynamic loads at the skin plate and reservoir to Westergaard's analytical predictions is made in Figure 21. Calculations were made using equations 1 and 2 and assuming h = 3.93 ft, α = 1.02 g, T = 0.1 sec, and k = 315,950 psi to match laboratory test conditions. Both the exact and approximate solutions produced a similar trend but were greater than the reservoir measurements immediately upstream of the model face. This is expected as Westergaard assumes loads on the surface of a rigid structure which produce higher pressures than those in the reservoir due to damping. The comparison to measurements on the skin plate again highlights the influence of a "flexible" structure that amplifies local hydrodynamic loads. While measurements at a few of the model rib "nodes" compare well to the analytical results, there are some differences at the other node locations which are not currently understood. Future comparison of these results with FE models will hopefully shed further light on these results.

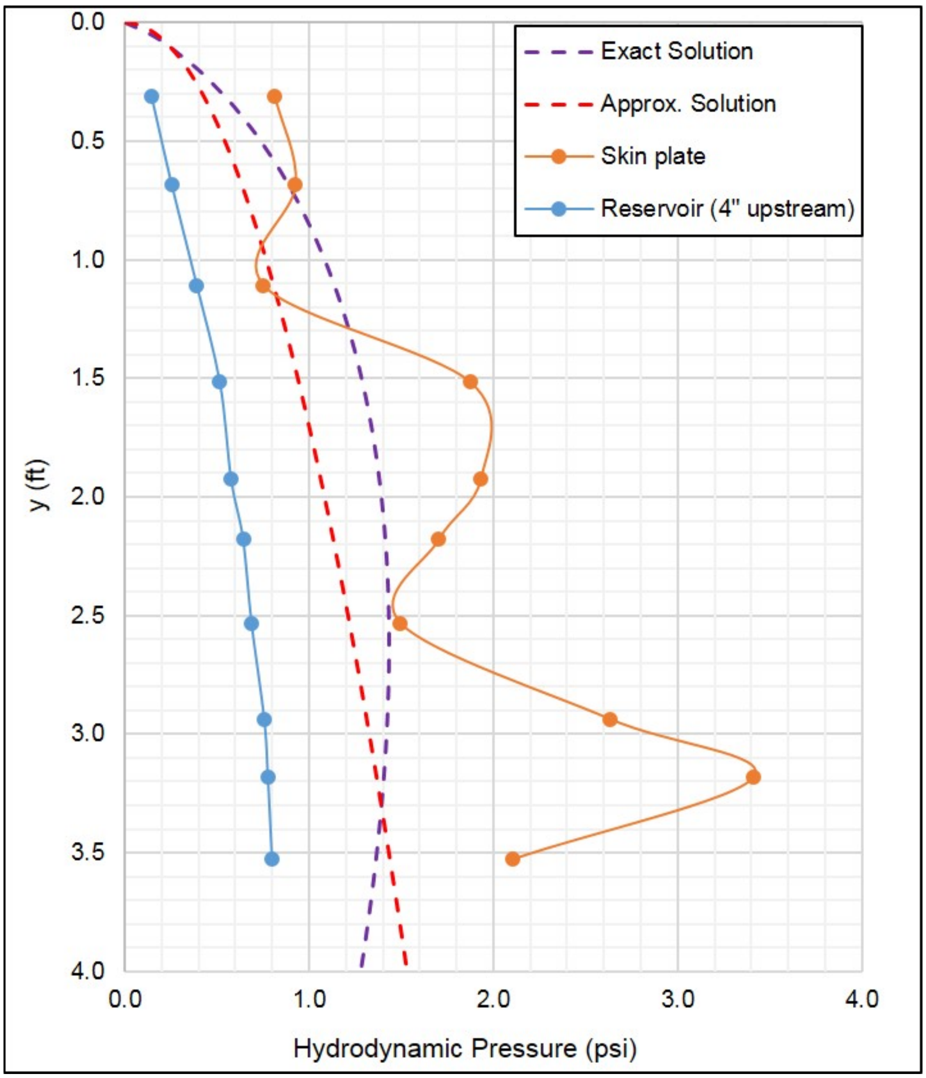


Figure 21 Comparison of measured hydrodynamic pressures on the model face and in the reservoir 4 inches upstream of the model to Westergaard's exact and approximate predictions.

Conclusions of 2018 Investigations

- Installation and initial testing of the seismic test facility to produce hydrodynamic loads on laboratory-scale dam and spillway gate configurations were successful. Initial tests were conducted with a vertical linear geometry with a reservoir head of approximately 4 ft in the laboratory flume. For this head, excitation frequencies of 5, 10, and 50 Hz were most effective at inducing stable hydrodynamic loads on the model.

- The natural frequencies of the model structure and flume reservoir were identified in the time series measurements on the skin plate but did not appear to have a significant influence on the amplitude of hydrodynamic pressures for the range of excitation frequencies tested.

- The structural response of the model had a significant influence on the hydrodynamic loads on the model surface. Hydrodynamic pressures on the skin plate were amplified up to 50 percent by the localized vibration of the skin plate. The result was not the same for hydrodynamic pressures measured in the reservoir immediately upstream of the model; these showed a similar trend with depth but no influence from the "flexibility" of the model face.

- A comparison of Westergaard's solutions to physical measurements showed similar results at some of the model nodes (locations of back side rib supports) and further highlighted how the structural response of the model influences hydrodynamic loads.

Plans through 2020

Investigations with physical testing will continue through Fiscal Year 2020. Plans include repeating tests with a modified vertical linear model with greater stiffness. The radial and slanted geometries will be tested as well. These models will be modified as needed to adjust stiffness or other structural characteristics that may influence hydrodynamic load results. Other configurations that could be tested include a spillway gate offset from the top of a vertical dam, or other geometries as determined necessary. A range of reservoir depths will also be included in future tests. Physical data obtained from each test configuration will be compared to numerical results from Finite Element modeling.

References

Nakayama, Y., Ohmachi, T., & Inoue, S. (2008). Practical Evaluation of Hydrodynamic Pressures on Dam-Gates during Earthquakes. *Doboku Gakkai Ronbunshuu A.*, 64. 959-969. 10.2208/jsceja.64.959.

Salamon, J. (2011). *Seismic Induced Loads on Spillway Gates Phase 1 - Literature Review*. Denver, CO: Bureau of Reclamation, DSO-11-06.

Salamon, J. (2015). Evaluating Seismically Induced Hydrodynamic Loads on Spillway Gates. *USSD.* Louisville, KY.

Salamon, J. (2018). *Evaluation of Numerical Models and Input Parameters in the Analysis of Concrete Dams.* Denver, CO: Bureau of Reclamation, DSO-19-13.

Salamon, J. (2018). *Seismically Induced Hydrodynamic Loads on Concrete Dams and Spillway Gates.* Denver, CO: Bureau of Reclamation, DSO-18-10.

Salamon, J., & Manie, J. (2017). Numerical Assessment of Hydrodynamic Loads Induced during Seismic Interaction between Reservoir and Concrete Dam. *USSD.* Anaheim, CA.

Smith, E. R., & Herrington, C. R. (1992). *Wave Reflection at Tainter Gates.* Vicksburg, MS: U.S. Army Corps of Engineers, CERC-92-6.

Svoboda, C. D., Einhellig, R. F., & Frizell, K. W. (2010). *Hydraulic Model Study of Folsom Dam Joint Federal Project Auxiliary*. Denver, CO: Bureau of Reclamation, HL-2009-05.

Wittler, R. J., & Frizell, K. W. (1990). *Comparison of Flush and Chamber Mounted Dynamic Pressure Transducer.* Denver, CO: National Conference of Hydraulic Engineering.

Zangar, C. N. (1952). *Hydrodynamic Pressures on Dams due to Horizontal Earthquake Effects.* Denver, CO: Bureau of Reclamation.

Appendix A – Literature Review

AUTHOR	TITLE	NOTES
(Nakayama, Ohmachi, & Inoue, 2008)	Practical Evaluation of Hydrodynamic Pressure on Dam-Gates during Earthquakes	Documents an investigation of hydrodynamic pressures on gates using physical measurements very similar to the current study. Using a shake table in a static pool, they measured dynamic pressures and accelerations on a vertical linear plate. The vertical plate was made of an acrylic sheet 4 cm thick. Size and vibration conditions were similar in magnitude to the current study. Pressure distributions from the physical and analytical data were compared. There seemed to be no influence of the structural response of the vertical plate on the physical data, suggesting it was truly rigid. Analytical results produced hydrodynamic pressures that were slightly greater than physical results, particularly greater depths. This was attributed to limitations of the physical test facility including boundary conditions and reflections. Gate setback from the top edge of the dam was investigated. They concluded that hydrodynamic pressures are significantly reduced for gates that are set back from the dam. This finding agrees with conclusions found in the many investigations by Salamon.
(Salamon, 2011)	Seismic Induced Loads on Spillway Gates Phase 1 – Literature Review DSO-11-06	Includes a compilation of several sources that address hydrodynamic loads on dams and spillway gates including Westergaard analytical approaches (most commonly used in industry) and Zangar's experimental results. Concludes that Westergaard's formulas should only be used in preliminary assessments. Outlines plans to further compare using 3D FEA models. The intent was to help develop guidelines for the calculations of hydrodynamic loads on spillway gates that could be adopted by Reclamation's Dam Safety Office.

AUTHOR	TITLE	NOTES
(Salamon, 2015)	Evaluating Seismically Induced Hydrodynamic Loads on Spillway Gates	Study looking at hydrodynamic loads on a vertical spillway gate on a vertical dam using Finite Element modeling. Compares the FE model results to approaches of past studies for various distances that the gate is set back from the dam face. Results include the vertical pressure distribution of the dam and gate for various gate heights (α = gate depth / reservoir depth) and offsets (β = distance back from dam / gate height). Concluded that loads on the gate can be estimated with a modification to the exact Westergaard equation by including β. A comparison to physical data will be helpful in defining hydrodynamic loads for gates that are set back from the dam face. Reclamation's laboratory testing will not include set back testing in 2018, but will hopefully be performed in 2019 or 2020.
(Salamon & Manie, 2017)	Numerical Assessment of Hydrodynamic Loads Induced During Seismic Interaction Between Reservoir and Concrete Dam	Comparison of three different numerical approaches to determine hydrodynamic loads on a concrete arch dam, "added mass", "acoustic fluid", and "fluid-like material". Comparison showed limitations of approaches, particularly the approximate Westergaard solution. Concluded that compressibility of the reservoir is the factor that has the most influence on the hydrodynamic pressure distribution on the dam. Physical results from lab testing should be analyzed in the same way as numerical results for comparison. This includes the vertical pressure distribution of the dam/gate face (depth vs. maximum hydrodynamic pressure) and both time series and frequency domain analyses to compare frequencies from excitation, natural reservoir, and noise.

AUTHOR	TITLE	NOTES
(Salamon, 2018)	Seismically Induced Hydrodynamic Loads on Concrete Dams and Spillway Gates DSO-18-10	Summary report of 3 numerical approaches (Westergaard, Acoustic-fluid, and Fluid-like Behavior). Compares approaches with a case studies of a gravity dam, spillway radial gate, and reservoir-gate-dam system. Presents case studies using the different methods that demonstrate a significant difference when applied to reactions of the structures. Future Research plans include the physical model testing with the assembly in the 4-ft flume of the hydraulics laboratory. This is to be used as the primary benchmark for validation of the FE models.
(Salamon, 2018)	Evaluation of Numerical Models and Input Parameters in the Analysis of Concrete Dams	Summarizes a workshop on Numerical Modeling of seismic activity on dams for the U.S. Society of Dams. The workshop compared results of submitted by eight different contributors for case studies based on Pine Flat Dam. FE results varied greatly based on mesh size, computation methods, damping parameters, and the fluid-structure interaction. A general conclusion was that FE methods produce an “approximation of a solution” rather than an exact solution to seismic effects to dams. Physical model testing can help further refine and understand approximations made by FE numerical models.
(Smith & Herrington, 1992)	Wave Reflection at Tainter Gates	A 1:30 scale physical model study of waves on a large tainter gate conducted by the Army Corps of Engineers. The focus was on wave heights, not dynamic pressures on the tainter gates. Waves were traveling on the surface rather than as acoustic waves in the current study. A Froude scale was applied to convert results to prototype scale since gravity is the dominant force. No guidelines were given on how to prevent size-scale effects. The current study assumes a Froude scale if results were to be applied to an actual prototype structure – however test results may indicate forces other than gravity are dominant and Froude scaling can no longer apply.

AUTHOR	TITLE	NOTES
		Due to wave reflections only 15 wave oscillations were able to be produced at a time before reflections would occur and contaminate test conditions. Acoustic reflections are also a concern in the current test facility and should be monitored and accounted for.
(Svoboda, Einhellig, & Frizell, 2010)	Hydraulic Model Study of Folsom Dam Joint Federal Project Auxiliary Spillway Confluence Area	https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HL/HL-2009-05.pdf Physical hydraulic model study of the confluence of flow from the existing and new auxiliary spillway. The report documents pressure measurements to predict loads on the auxiliary spillway wall that will be impacted by almost perpendicular flows from the main spillway. Flush mounted pressure sensors were used in the study, but static rather than dynamic loads were the focus of the investigation.
(Wittler & Frizell, 1990)	Comparison of Flush and Chamber Mounted Dynamic Pressure Transducer	A comparison of two types of pressure sensor configurations for measuring hydrodynamic pressures. This study was helpful in choosing sensor type and installation during early stages of the current study to ensure accurate dynamic pressure measurements could be made at the fluid-structure interface. Based on this information, and small scale experiments in the lab, flush mounted dynamic pressure sensors were chosen to avoid resonance effects of less-expensive sensors with a chamber mount.
(Zangar, 1952)	Hydrodynamic Pressures on Dams due to Horizontal Earthquake Effects	https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/EM/EM11.pdf An experimental study of hydrodynamic pressures on dams using an electric analog method conducted in Reclamation’s labs in the early 1950’s. Results are used to define pressure coefficients for different dam geometries (mostly linear with varying slopes). Method does not account for structural characteristics of the dam.

Appendix B – Drawings of Test Facility and Model Components

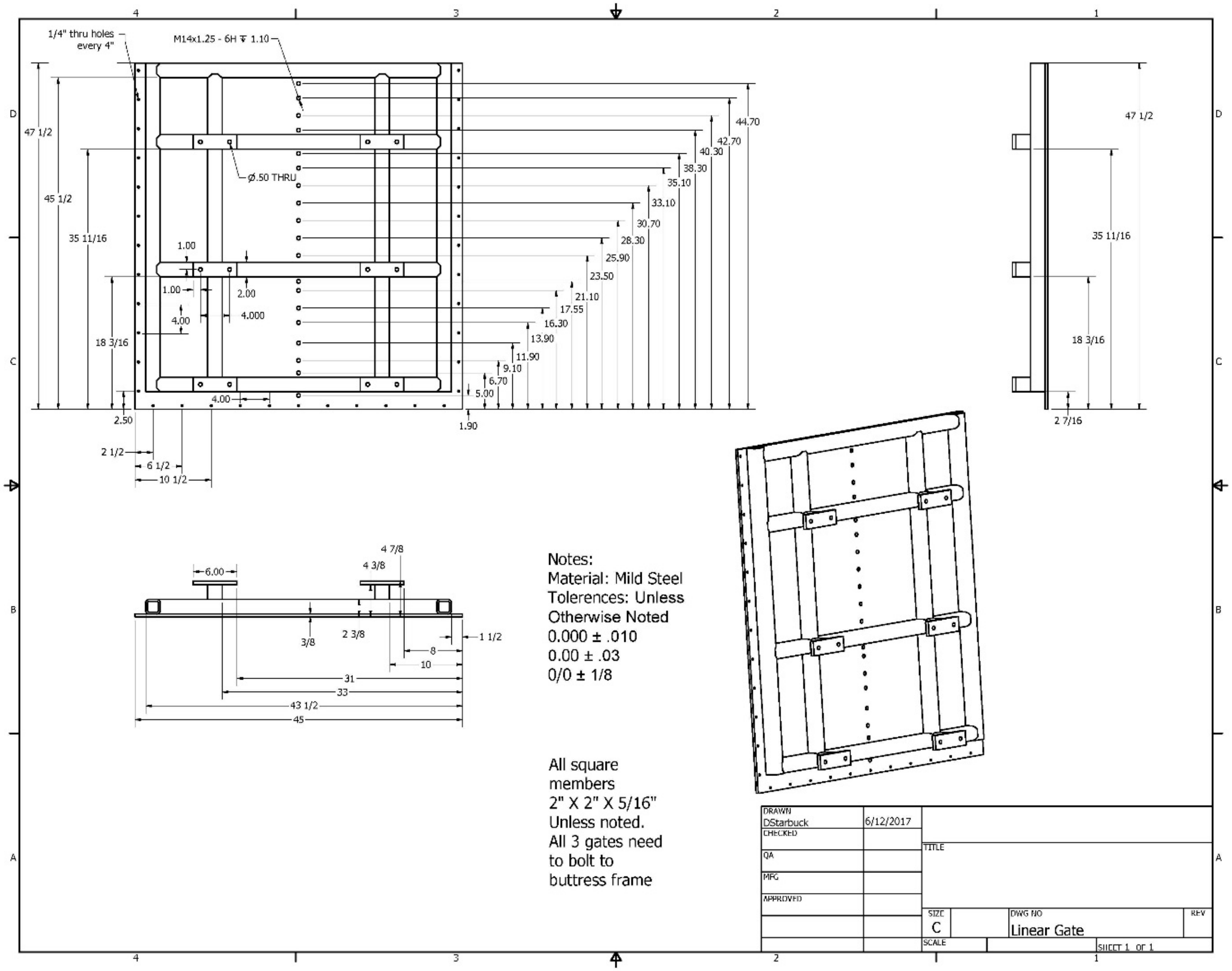


Figure 22 Drawing and dimensions of laboratory-scale vertical linear geometry.

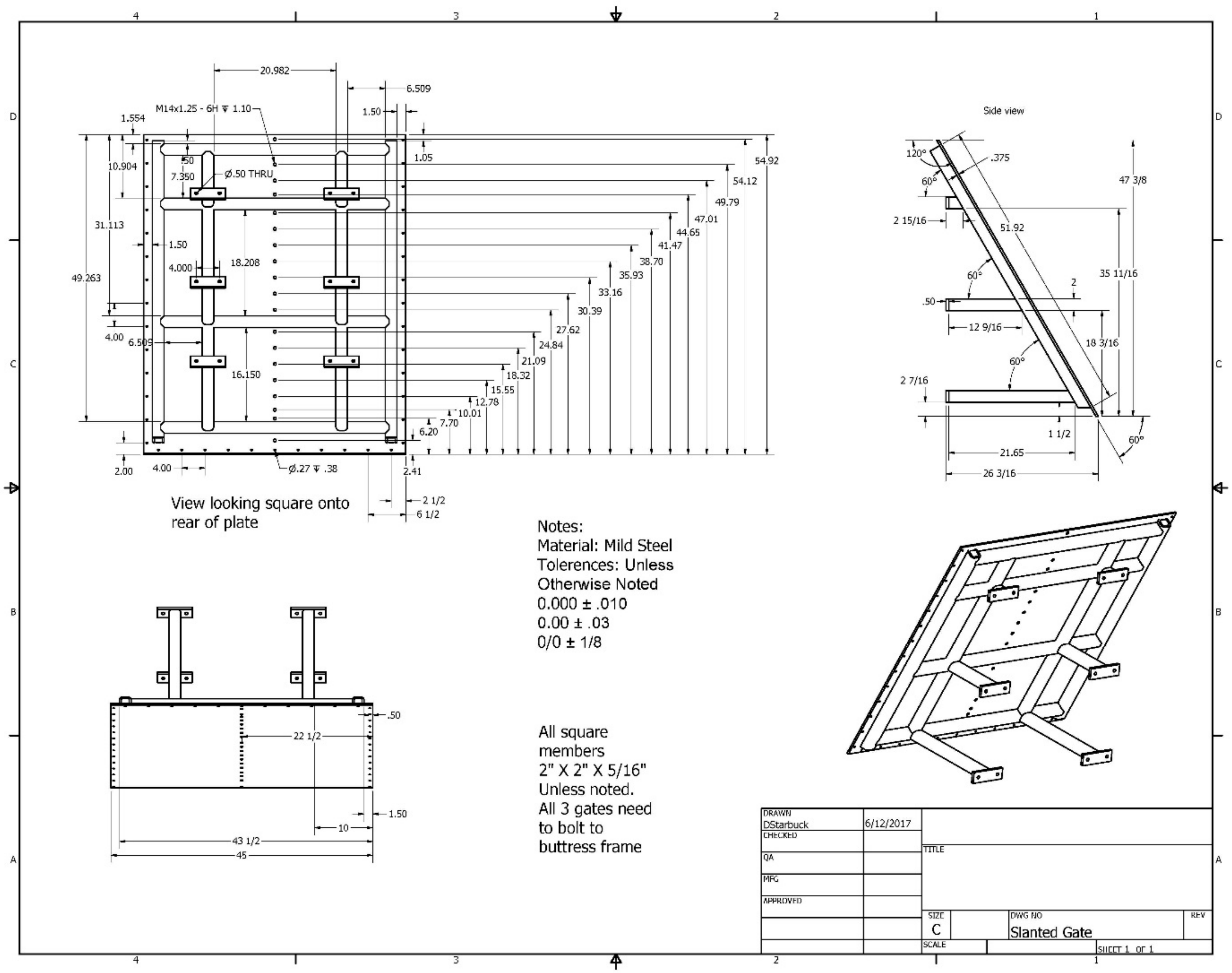


Figure 23 Drawing and dimensions of laboratory-scale slanted linear geometry.

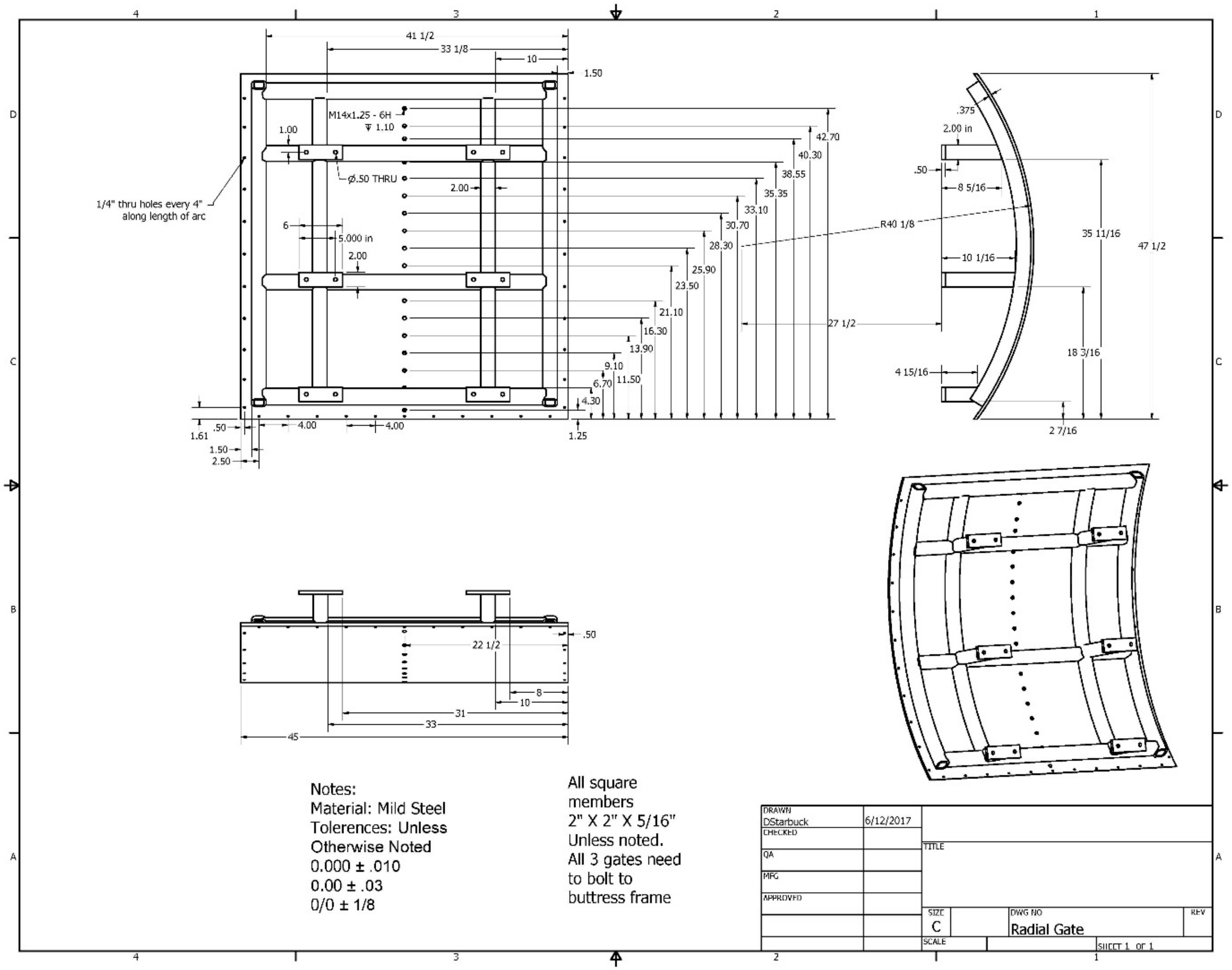


Figure 24 Drawing and dimensions of laboratory-scale radial geometry.

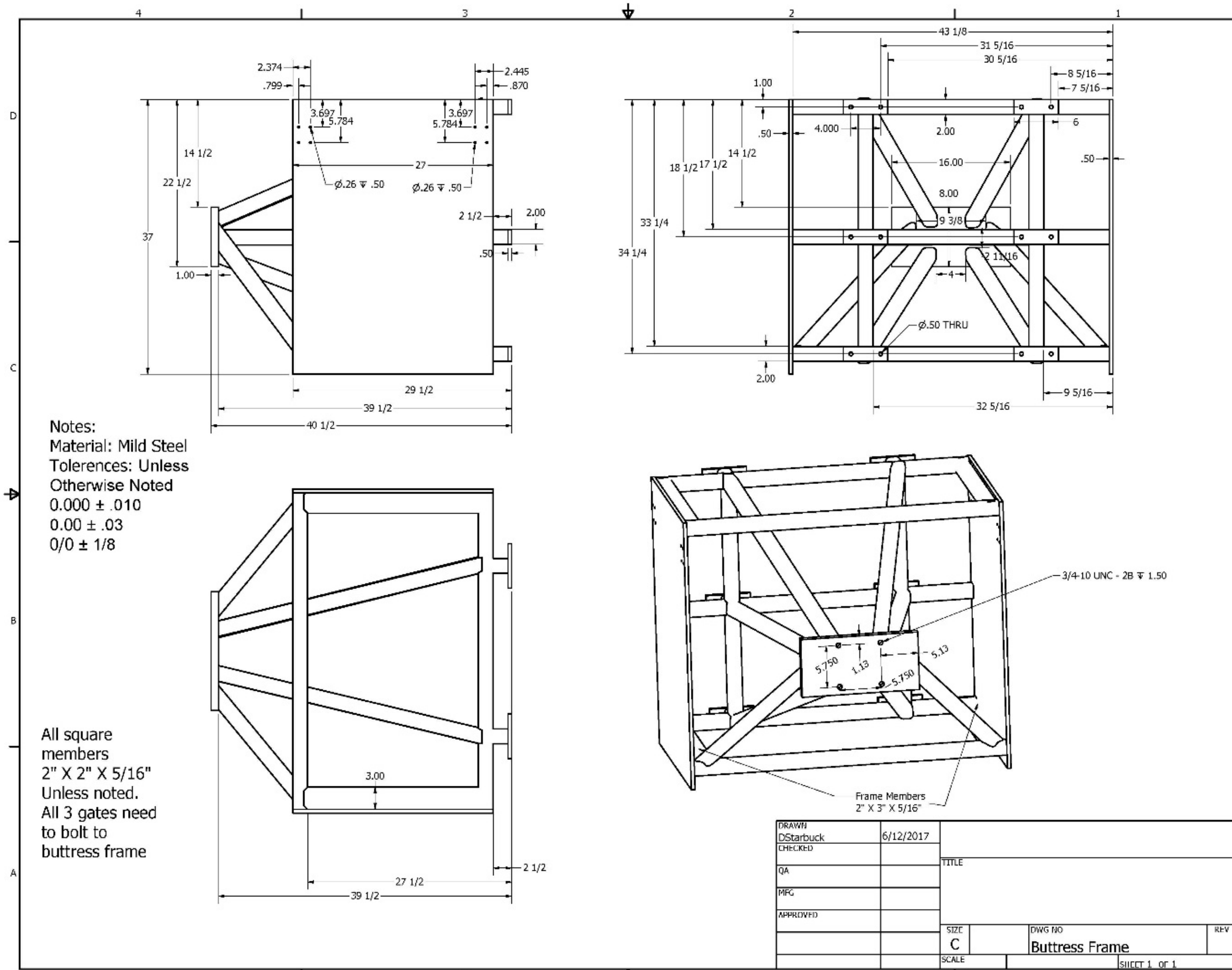


Figure 25 Drawing and dimensions of buttress frame.

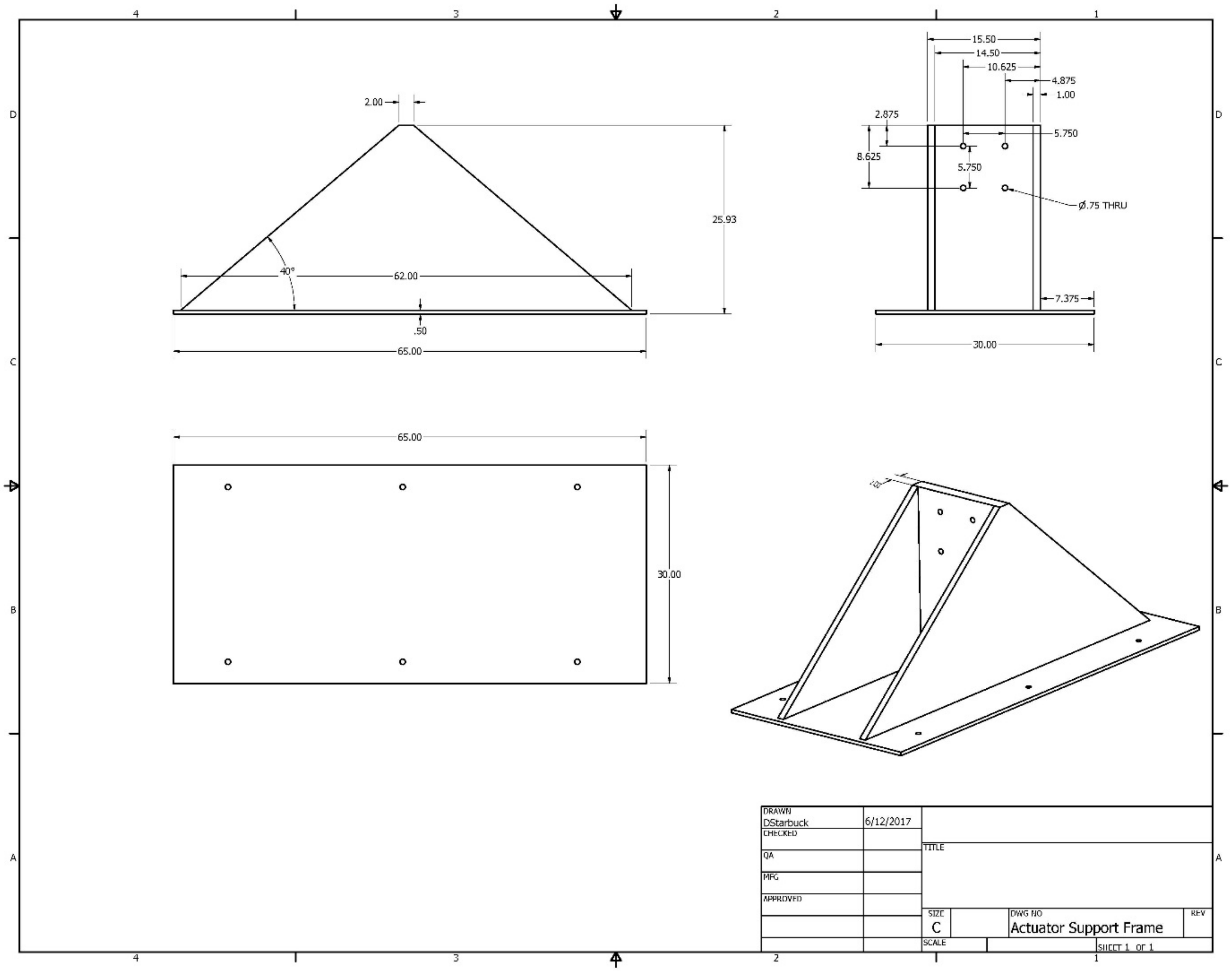


Figure 26 Drawing and dimensions of hydraulic actuator support frame

Data Sets that Support the Final Report

If there are any data sets with your research, please note:

- U:\Active Files\Dam Safety\Hydrodynamic Gate Loads
- Josh Mortensen, jmortensen@usbr.gov, 303-445-2156:
- DasyLab files, spreadsheets, word doc report
- Keywords: Earth quake, dam, hydrodynamic load, seismic, spillway gate
- Approximate total size of all files: 3.36 GB