AMBIENT VIBRATIONS FOR MODEL VALIDATION OF A LARGE DAM: INSTRUMENTATION AND TESTING

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(Part one of a three-part paper series)

ABSTRACT

We present methods, insights, and lessons learned from an ambient vibration testing program that recorded data from 90 unique locations at a large dam in Oregon. This program was designed to validate the dynamic properties of an LS-DYNA model, which is being used to evaluate the dam's response to earthquake ground motions. Results of the dynamic structural analysis will be used to inform an ongoing Issue Evaluation Study by the U.S. Army Corps of Engineers. Conducted over four days during normal operating conditions—including spill and generation—the testing did not require forced excitation. A roadway along the dam's crest remained open for three of the four testing days, resulting in sporadic vehicle-induced excitation of the dam, which proved useful in subsequent analyses. Data were collected from various critical structural components, including rockfill embankments, concrete piers, retaining walls, a tower, a concrete spillway, non-overflow sections, and a bedrock outcrop. Eleven recording instruments—four reference instruments and seven temporary instruments—were deployed for thirteen 40-minute-long test setups. Reference instruments, which remained stationary between test setups, made recordings which were used to synchronize results from across the dam. Temporary instruments recorded data from specific locations on each structural component to identify important local resonances and component interactions. The vibration data collected were successfully used in subsequent operational modal analyses to estimate the dam's dynamic characteristics, such as mode shapes, modal frequencies, and damping.

INTRODUCTION

The Risk Management Center (RMC) of the U.S. Army Corps of Engineers (USACE) is conducting an Issue Evaluation Study (IES) of Foster Dam, located in the Willamette River Valley, in Oregon. One of the primary components of the study is to better characterize the potential seismic risk at the site by conducting a detailed structural analysis of the dam considering static and seismic loading. As part of this assessment,

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linear and nonlinear LS-DYNA finite element models are being used to better understand the seismic performance of Foster Dam within the USACE IES process.

For certain potential failure modes of Foster Dam, the structural demands, failure thresholds, and potential damage are sensitive to the dynamic characteristics of the structural model, in particular: (i) modal frequencies and (ii) damping. Therefore, calibration and validation of the dynamic properties in the finite element model with measured dynamic data is necessary.

To assess and validate the dynamic properties of the LS-DYNA finite element models, a rigorous ambient vibration testing program with a dense deployment of many sensors was undertaken. Ambient vibration data was recorded from various critical components of Foster Dam including the concrete gravity monoliths, an attached reinforced concrete tower, spillway piers, and adjacent embankments including the spillway retaining walls.

In this paper (part one of a three-part series), we focus on the specifics of the testing program: discussing the instruments, test setups, and means and methods, and share successful testing strategies and lessons learned. Two subsequent papers will focus on the important structural component interactions identified (Dupuis et al, 2025) and application of the results of the testing program to validate finite element models (planned for USSD 2026).

BACKGROUND

Foster Dam, shown in Figure 1, is situated approximately 30 miles upstream of Albany, Oregon, on the South Santiam River. Foster Dam is 126 ft tall, 2,985 ft long, and features a 400-ft-long concrete spillway, four spillway gates, a concrete non-overflow segment, and a powerhouse. The dam's construction was initiated in 1964 and completed in 1968. Foster Dam is owned, operated, and maintained by USACE. As part of the Willamette Valley Project, Foster Dam is one of 13 multi-purpose dams contributing to flood risk management while serving secondary roles in hydropower generation, recreation, irrigation, municipal and industrial water supply, and water quality maintenance.

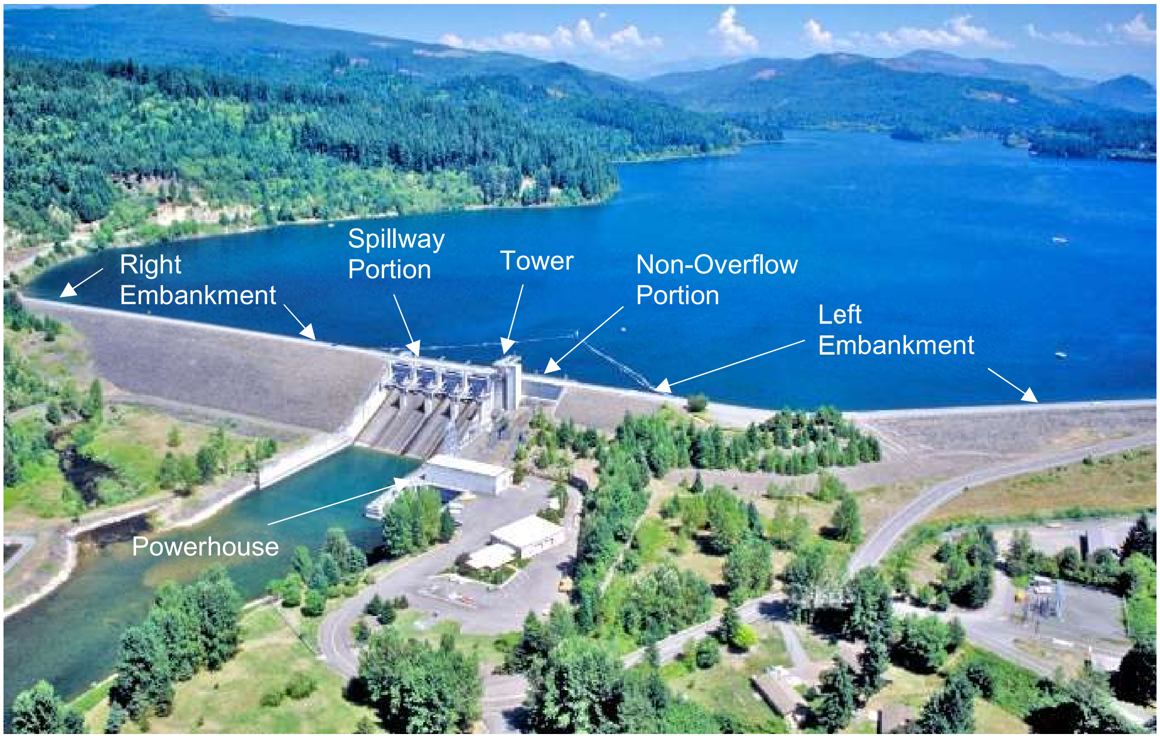

Figure 1. Aerial view of Foster Dam (Recreation, 2024).

DAM FEATURES AND LAYOUT

Foster Dam includes a right embankment, concrete dam with gated spillway and non-overflow portion, and left embankment with skewed alignment. The concrete portion of the dam includes several important structural sub-components. Figure 2 and Figure 3 show adapted drawings of the concrete spillway and non-overflow portions, respectively, with dam block numbering and locations of the drainage galleries.

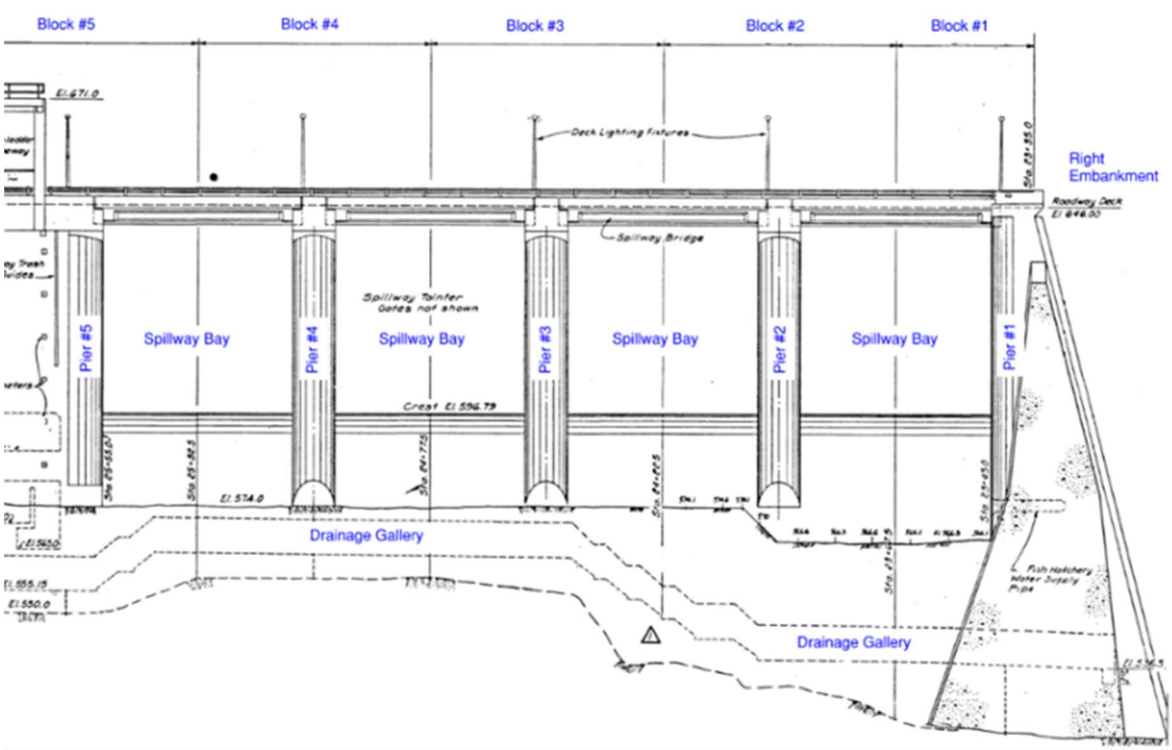

Figure 2. Concrete spillway components of dam looking downstream. Adapted from USACE, 1964.

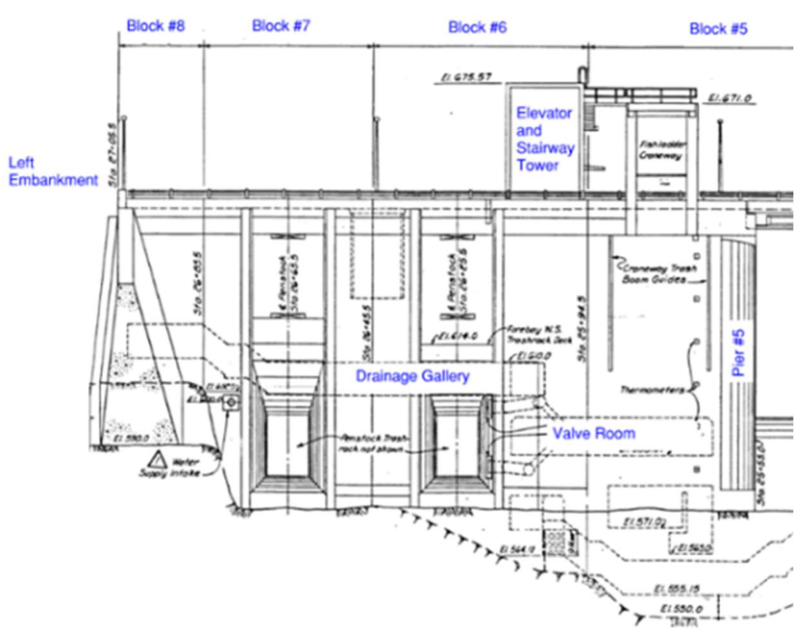

Figure 3. Concrete non-overflow components of dam looking downstream. Adapted from USACE, 1964.

Foster Dam includes the following major features:

Concrete gravity monoliths — There are eight dam blocks, Block #1 through Block #8 from the right to left, which encompass the two spillway retaining walls, four spillway bays, five spillway piers, reinforced concrete tower, and penstock intakes. Contraction joints between the dam blocks are in the center of each spillway bay.

Spillway piers — There are three interior and two exterior spillway piers; all five piers are 10 ft wide. Each pier has ladder access to the upper surface downstream of the gate, including the trunnion anchor block, which is surrounded by a permanent guardrail.

Tainter gates — Four Tainter gates are supported by trunnions and anchor blocks at the downstream end of the piers, all four Tainter gates are 45 ft wide, 47 ft tall, and have a working line radius of 45 ft to their pivot points.

Elevator and stairway tower — There is a large concrete tower structure on the downstream side of Block #6 which encompasses an elevator shaft and stairway with multiple concrete landings and extends above the dam crest roadway.

Right embankment — The right embankment extends approximately 1260 ft with a straight alignment from the right edge of the right spillway retaining wall to bedrock at the right abutment of the entire dam structure.

Left embankment — The left embankment extends straight and then skews upstream over a total length of approximately 1330 ft.

Concrete retaining walls — Block #1 and Block #8 have large concrete retaining walls which retain the embankment material in the cross-valley direction. The retaining walls are tapered up their height, transitioning from a thick base to a relatively thin top.

Drainage galleries — Drainage galleries extend the entire length of the concrete spillway and non-overflow portion of the dam between Block #1 and Block #8.

Penstock gate motor room — There is a penstock gate motor room located within the concrete non-overflow monolith above the penstock intakes in Block #6 and Block #7 with mechanical equipment to operate the intake gates to the penstocks.

Valve room — There is a valve room located in Block #5 and Block #6. The valve room is relatively low within the non-overflow portion of the concrete dam; it is below the elevation of the crest of the adjacent spillway bays and at similar elevations to the adjacent penstock intakes within Block #6 and Block #7.

Publicly accessible two-lane road — There is a publicly accessible two-lane road which extends along the crest of the embankments and across a four-span elevated bridge deck over the spillway.

TESTING PROGRAM

Test Setups

The testing program at Foster Dam made use of multiple test setups (TS), which typically included all eleven instruments deployed together, and stand-alone deployments (SD), which consisted of either one or two instruments. In total, 145 recordings were taken from 90 locations across the dam, as summarized in Table 1.

Simultaneous recording from multiple locations on each structure was done to (i) distinguish between local and global resonances, (ii) distinguish between translational and torsional local resonances, and (iii) improve the ability to differentiate between environmental noise and resonant characteristics of the structures. Recording at many locations simultaneously was particularly effective as it facilitated computation of spectral ratios comparing responses in different directions and at different locations (Dupuis et al, 2025).

Test setups, of which there were 13 in total, focused on each of the five piers, the tower, the non-overflow portions of the dam, as well as the left and right embankments. These were designed to record vibration data from important locations on various structural components and included both (i) temporary and (ii) reference instruments.

Temporary Instruments

Temporary instruments (seven in total) were placed at different locations for each test setup and were used to record vibration data from multiple locations on each component. Important locations to instrument on each structure were selected based on expected resonant characteristics of the structure. Two types of locations were selected: (i) locations which were expected to participate in local resonant interactions, and (ii) locations that were expected to have relatively little dynamic participation or low amplitude responses, such as within the galleries. An example schematic layout, indicating the locations of all sensors for TS-3 is shown in Figure 4.

Reference Instruments

Reference instruments (four in total) were placed at consistent locations across the dam for each test setup. These were used in ARTeMIS Modal (ARTeMIS, 2023) to integrate results from all setups, allowing for analysis of the dam's global response without the need for simultaneous instrumentation at all locations. The number of reference instruments required varies based on the structure's complexity and the needed spatial coverage. A relatively large number of reference instruments—located at Block 1 Pier, Block 4 Pier, Top of Tower, and Upper Gallery—were used to ensure that the test setups could be combined into a global model.

Table 1. Attributes of each test setup (TS) and stand-alone deployment (SD) in the testing program.

Test	**Day Mar 2024**	**Sensors**	**Sampling Frequency (Hz)**	**Duration (minutes)**	**Primary Feature Tested**
TS-1	19th	1-11	400	40	Block 1 Pier
TS-2	19th	1-11	400	40	Block 2 Pier
TS-3	19th	1-11	400	40	Block 3 Pier
TS-4	19th	1-11	400	40	Block 4 Pier
TS-5	19th	1-11	400	40	Block 5 Pier
TS-6	18th	1-11	400	40	Tower
TS-7	18th	1-11	400	40	Non-Overflow
TS-8	20th	1-11	400	40	Right Embankment
TS-9	20th	1-11	400	40	Concrete Roadway
TS-10	20th	1-11	400	40	Left Embankment
TS-A	20th	1-11	400	40	Right Embankment
TS-B	21st	1-8, 10-11[A]	400	40	Galleries
TS-C	21st	1-11	400	40	Right Wall
SD-Tower	19th [B]	1, 11	400	240	Tower
SD-Bedrock	21st	1	1200	40	Bedrock

[A] Sensor 9 malfunctioned and produced no recording; [B] SD-Tower was set to run on 19 March 2024 and recording took place between 1:00 – 5:00 AM on 20 March 2024

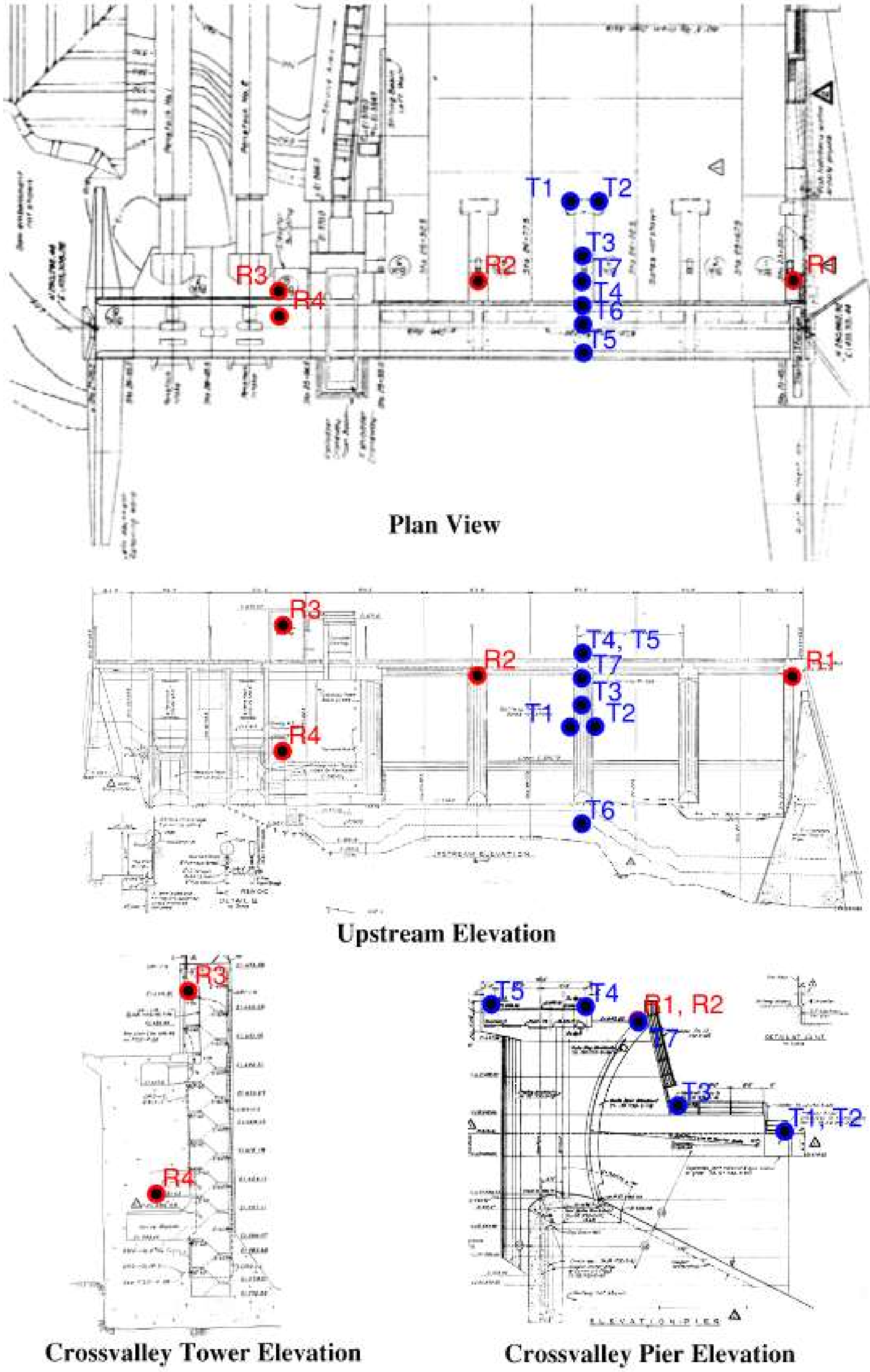

Figure 4. Test Setup 3 (TS-3) reference instruments (R1 through R4 in red) and temporary (T1 through T7 in blue) instrument locations. Top: plan view; middle: downstream elevation; bottom: cross-valley elevations. Adapted from USACE, 1964.

INSTRUMENTATION

Larzé vibration monitors were selected for the project based on their ease of deployment and instrument specifications. Each device is compact with dimensions of 120 x 90 x 80 mm and is designed to withstand varying weather conditions with an operating temperature range of -30ºC to 50ºC and water-resistant capabilities (Sensequake, 2023).

Data Acquisition and Recording

These vibration monitors have two types of internal vibration sensors: a triaxial velocimeter with a range of ±120 mm/s and bandwidth of 3 dB up to 1500 Hz—depending on the sampling frequency—and a triaxial accelerometer with a 3 dB bandwidth up to 1000 Hz (Sensequake, 2023). The velocimeters performed well in recording the low-amplitude vibrations observed during road closures, especially along the embankments. The accelerometers were able to record vibrations of up to 2 g and performed well for recording relatively high-amplitude vehicle-induced transient excitations.

The instruments were equipped with six independent and differential 24-bit channels that can sample between 16 Hz and 4000 Hz. The instruments were resynchronized between each test setup to allow for time synchronized recordings from locations without GPS or radio connectivity (e.g., the galleries of the dam) and maintained timing agreement within 1 microsecond between instruments following synchronization (Sensequake, 2023).

Data Storage and Battery

Each vibration monitor has 16 GB of built-in storage on a FAT32 file system which was found to be more than sufficient to store all test setup data without the need to delete or remove files. Power for these instruments is supplied by an internal lithium battery, which was found to last for approximately 10 hours on each charge at the recording frequencies used. The units needed to be recharged via Micro-USB each night during the testing deployment.

User Interface

The user controls on each instrument were limited to a single on-off power switch and an LED indicator which indicated the operational status. A dedicated smartphone application was used to control, synchronize, and initiate recording of the instruments. This system was found to be user-friendly in the field and satisfied the demands of the testing program.

DAM OPERATIONS

Operational and environmental requirements were balanced with considerations of this testing program. A consistent operational regime was preferable, i.e., with minimal changes to spillway release, power generation, and reservoir level, because the syncing of data from various test setups is premised on stationary input noise. Therefore, operational changes throughout the testing program were minimized as much as possible.

Pool elevation was maintained at an approximately constant level between 615.5 ft and 616.7 ft, typical springtime normal reservoir elevations, throughout the testing window of all four days of the testing program, as shown in Figure 5. To satisfy operational and environmental requirements, Bay 3 was opened to approximately 0.5 ft and consistently released approximately 500 cfs throughout the testing periods of all four days, as shown in Figure 6. It was anticipated that the associated stationary environmental noise (approximating Gaussian white noise), could provide broadband excitation to the structure.

Both powerhouse units were in service throughout all four days of the testing program and produced between approximately 6 MW and 9 MW each, as shown in Figure 7. Power generation generally increased each day, with the greatest power produced on 21 March 2024 and the least power produced on 18 March 2024. The effect of this slight change in power production over the course of the testing program was not expected to affect the analysis; however, the changes were observable in the amplitudes of ambient vibrations recorded from similar locations on different days.

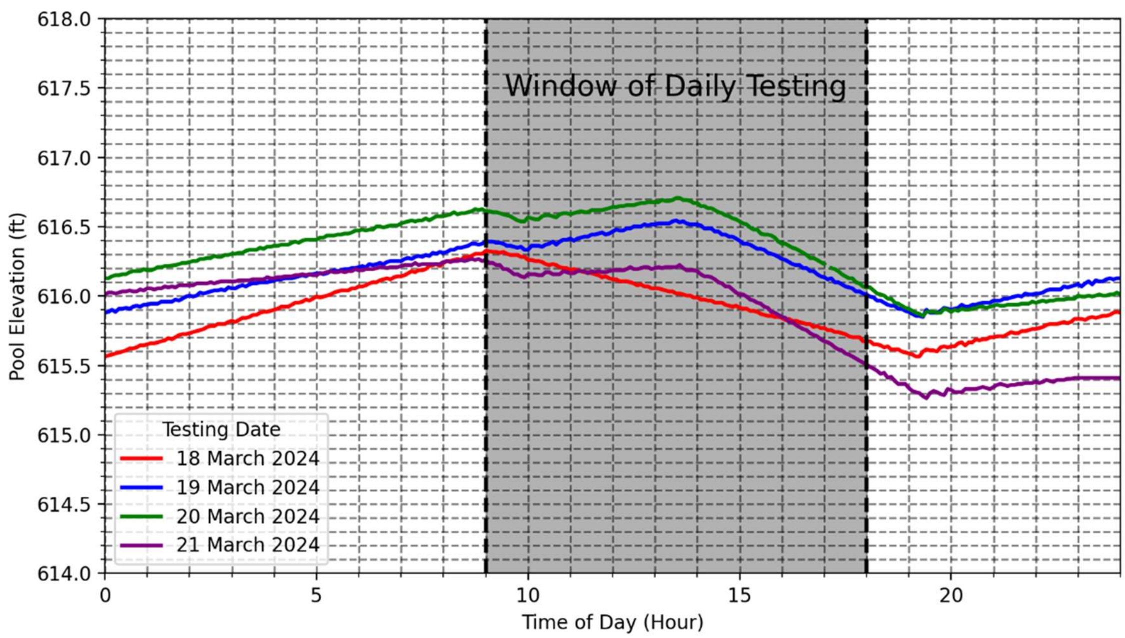

Figure 5. Reservoir pool elevation at Foster Dam during the four days of ambient vibration testing.

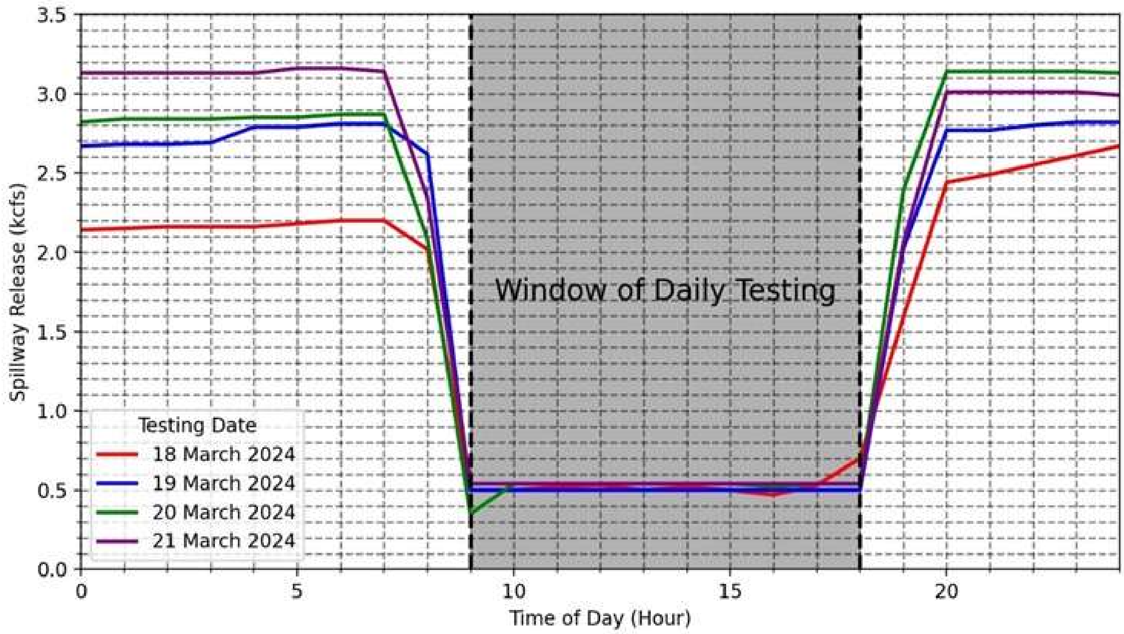

Figure 6. Spillway release at Foster Dam during the four days of ambient vibration testing.

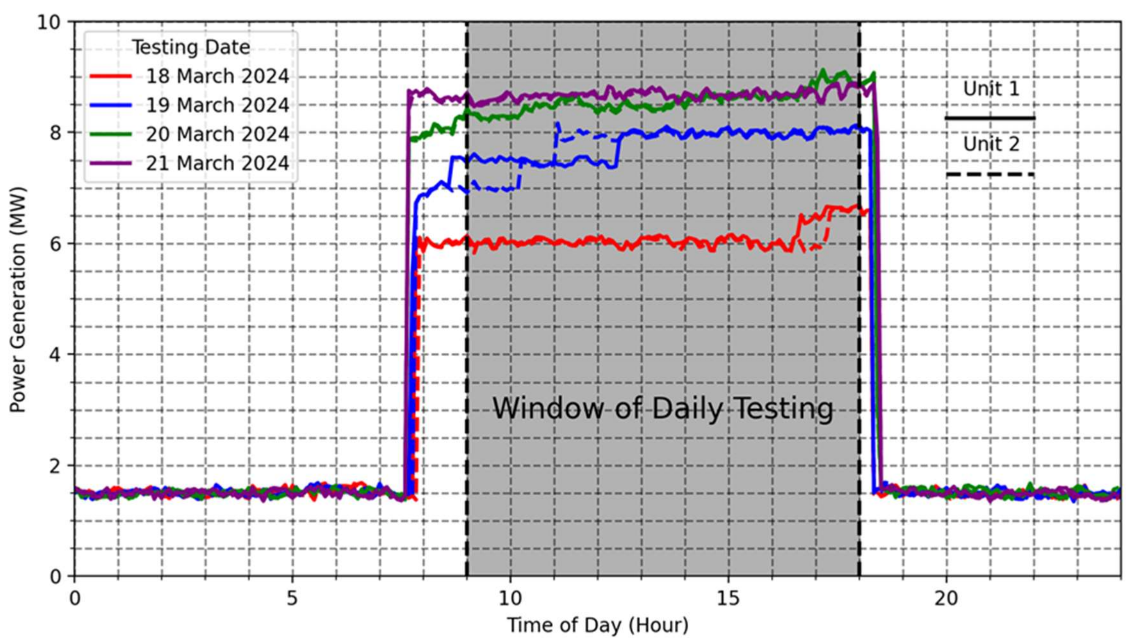

Figure 7. Power generation from Unit 1 and 2 of Foster Dam during the four days of ambient vibration testing.

MEANS AND METHODS

The following practices were implemented throughout the test program:

- Instruments were emplaced as free-standing instruments without bolted or mechanical anchorage to the structure.
- Locations within the structure were measured from the center upstream leveling leg of each instrument relative to local fixed structural reference points. The structural offsets for all instruments were calculated prior to the testing program and were marked on drawing key plans and on instrument placards.
- Instruments were numbered and labeled with unique numbers to facilitate consistent deployment of specific instruments at the reference locations and to facilitate data cleaning during post-processing should an instrument malfunction. Each instrument had the upstream direction (x-direction) clearly labeled.
- Locations on the dam were marked using dedicated placards to ensure correct placement and to allow for precise measurement of the instrument locations relative to local structural features. Test setup numbers were included on the placards placed next to each instrument to record the current test setup. Locations were numbered and the upstream orientation was labeled to prevent errors and to create a data trail for post-processing.
- A framing angle was used to orient all instruments to within 1 degree of upstream, measured with respect to the local dam axis at that portion of the dam.
- Instruments were leveled using a bubble level and the leveling legs were tightened with a nut.
- Weighted and transparent secondary enclosures were placed over all instruments during each recording to shield them from rain and wind gusts.
- Instrument locations along the right and left embankment were spaced at 155 ft. This spacing was selected because it allowed recording from sections with various heights and for uniform coverage along the entire length of each embankment with the seven temporary instruments. A larger spacing of 170 ft was used along the left embankment corner to avoid recording from the corner region.
- Instruments along the embankments were located along the center of the crest roadway using the centerline lane divider for reference. Measurements were made starting from the outside face of the embankment walls of the concrete portion of the dam with the distance from the concrete retaining wall along the crest measured using a surveyor’s wheel.
- Where required, moss and other loose debris was cleared using a trowel and horse wire brush to facilitate competent connection between the instrument and the dam structure.
- A picture was taken of each emplaced instrument for all test setups with the instrument number and orientation, location number and orientation, and test setup number clearly visible, as shown in Figure 8.

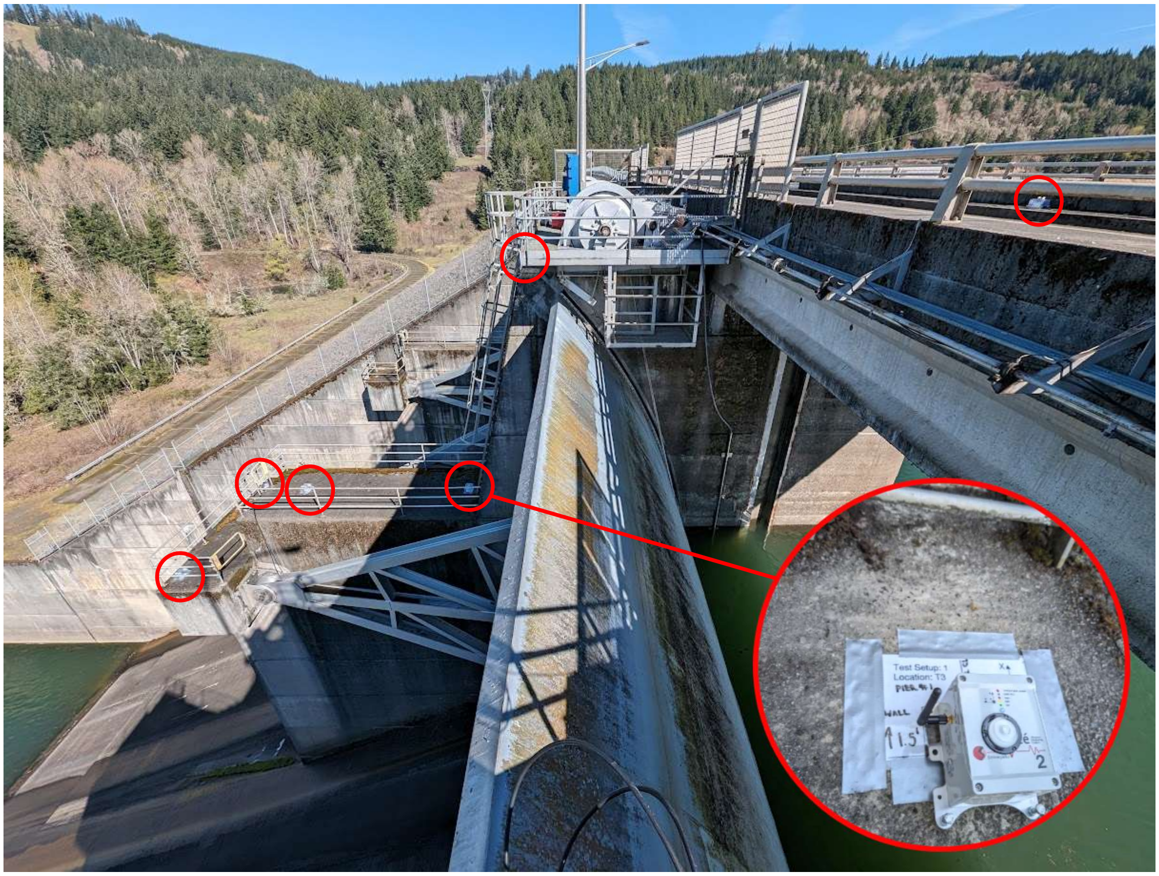

Figure 8. Photo of the Test Setup 2 (TS-2) with emplaced instruments. Inset photo of archetype instrument emplacement with bubble level, location number, sensor number, test setup number, and measurements to local structural reference points.

SUCCESSFUL STRATEGIES

The testing program made use of several successful strategies which improved the outcomes of the deployment, these included:

- Locations were selected which aligned along vertical, crossvalley, and instream gridlines which significantly simplified the development of subsequent models.
- Instruments were emplaced using offset distances from reference structural locations. These offsets were computed in the office prior to the deployment and were written directly on the instrument placards and on multiple drawing sets. This approach reduced both the time spent in the field and the potential for errors.
- It was found that preparation of placards in the office which were labeled with the test setup number, instrument location, and structural offsets helped speed up deployment in the field and allowed for thorough and accurate documentation of the instrument locations and placements throughout the testing program.

- The work plan sequence was well planned and resulted in an optimal progression through the different structural components in the dam. Test setups near the stairs were done first to minimize the travel times between instruments while the team dynamics were forming. The five near-identical pier test setups were done together on day two of the deployment to maximize efficiency of the team.
- It was found that 3 lb. weights were adequate to stabilize the vented enclosures which were placed on the instruments to shield them from rain and wind gusts.

LESSONS LEARNED

Several challenges were faced while in the field, and lessons were learned which could be used to refine the means and methods for future ambient testing programs, these include:

- The particular instruments used in the testing program required a period of syncing prior to each test setup. For the instruments we used, there was a slight delay between the sensors indicating that syncing was complete and the actual completion of background syncing processes. This resulted in occasional instrument malfunctions and required one test setup to be repeated. In the future, these malfunctions could be avoided by waiting an extra minute after the sensors indicate that syncing is complete to allow the background syncing processes to complete. It is understood that this issue has now been resolved via software update.
- It was found to be impractical and unnecessary to switch reference location placards between test setups, therefore a single reference instrument placard for each reference instrument indicating the instrument number and reference location will suffice for future testing programs.
- Approximately 4-8 instruments needed to be relocated slightly to avoid secondary structural components such as hatches and large joints. Accurate and thorough mapping of hatches and secondary components during initial field reconnaissance efforts could eliminate the need for field adjustments.
- It was anticipated that limited cell reception would necessitate the use of walkie-talkies while in the galleries and motor rooms of the dam; however, the use of walkie-talkies was found to be impractical and cumbersome due to their size. It is recommended that future deployments bring hip holsters or dedicated belts to attach the walkie-talkies to.
- A large and diverse set of field materials were variously used. It is recommended that future programs prepare multiple and redundant task-specific field backpacks for (i) placard placement including tape measure, tape, placards, markers, etc., (ii) instrument emplacement, including weights, enclosures, bubble levels, etc., and (iii) instrument retrieval (empty bags and wagon).
- A robust rope and durable bags for raising and lowering instruments and materials to pier landings is essential, along with at least two field personnel (one top and one bottom) to load, raise, and unload the bags.
- A low-cost hand-pulled wagon with off-road tires is recommended to transport the instruments large distances, e.g., through parking lots and along dam crests.

CONCLUSION

Ambient vibration data was recorded on Foster Dam to elucidate the dynamic behavior of structural components and to validate finite-element models of the dam. Vibration data was recorded over four days during close to normal operating conditions and without forced excitation of the structure. In total, 145 recordings were taken from 90 locations.

Eleven instruments (four reference instruments and seven temporary instruments) were deployed for thirteen 40-minute-long test setups. The 13 test setups included locations along the right and left embankment roadway, within the three galleries (right retaining wall, lower gallery, and upper gallery), and on various portions of all five spillway piers (trunnion anchor blocks, upper landing, and pier top).

The deployment benefitted from extensive in-office preparation and testing prior to arrival at site. In particular, the use of instrument location placards marked with offset dimensions from local structural reference points helped facilitate rapid yet accurate placement of many instruments. For future testing programs, key lessons include ensuring a sufficient sync period for instruments to avoid malfunctions and conducting thorough pre-test mapping of planned locations to reduce the need for field adjustments.

This paper is part one of a series of technical papers on ambient vibration data collection, component interactions (Dupuis et al, 2025), and LS-DYNA modeling efforts (planned for USSD 2026). Parts two and three will examine important component interactions affecting the seismic response of the dam and apply the estimated dynamic properties to validate an LS-DYNA model of Foster Dam, respectively.

ACKNOWLEDGEMENTS

The authors would like to thank the Risk Management Center of the U.S. Army Corps of Engineers for supporting this initiative and granting permission to publish this paper. The authors also thank Larry Nuss and Osmar Penner for serving as external reviewers and Alexandre Darche of Sensequake for his support during the deployment.

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