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Guided-Wave Inspection of California Department of Water Resources Tainter Gate Trunnion Rods

Inspection of Oroville Dam, Thermalito Bypass, and Pyramid Dam

Jason D. Ray, Richard D. Brown, and James A. Evans

September 2019



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Final Report

Approved for public release; distribution is unlimited.

Prepared for Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Project number 464475

Abstract

As part of the Oroville Dam reconstruction effort, The Sensor Integration Branch (SIB) at the Engineer Research and Development Center (ERDC) performed non-destructive testing (NDT) on the trunnion anchor rods at Oroville Dam, Oroville, California, Thermalito Bypass, Oroville-Thermalito Complex, and Pyramid Dam, near Castaic, Southern California, through the use of ultrasonic guided waves. The results of the testing on every rod will be discussed along with qualitative analysis in determining whether a rod is intact or compromised. Analysis is based upon the expected results from other rods at the sites and data gathered from the trunnion rod research test bed at ERDC.

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Preface

This study was conducted for the California Department of Water Resources, U.S. Army Corps of Engineers (USACE) Sacramento District under project number 464475.

The work was performed by the Sensor Integration Branch (SIB) of the Computational Science and Engineering Division (CSED), U.S. Army Engineer Research and Development Center (ERDC), Information Technology Lab (ITL). At the time of publication, Dr. Lacey S. Duckworth was the Acting Branch Chief, CEERD-IE-I, and Dr. Jerrell R. Ballard was Chief, CEERD-IE. Mr. Charles E. Wiggins, CEERD-HT, was the Technical Director, Navigation. The Deputy Director of ITL was Ms. Patti S. Duett and the Director was Dr. David A. Horner.

COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

Acronym	Meaning
CSED	Computational Science and Engineering Division
db	decibels
DoD	Department of Defense
ERDC	Engineer Research and Development Center
ITL	Information Technology Laboratory
NDT	Non-Destructive Testing
SIB	Sensor Integration Branch
USACE	U.S. Army Corps of Engineers
USB	Universal Serial Bus

1 Introduction

1.1 Background

Post-tensioned rods are used to anchor spillway gates and transfer the forces from the reservoir pool through the gates to the spillway structures. Large tensile loads are applied to these high-strength steel rods to compress the surrounding concrete and prevent it from experiencing excessive tensile forces, which are naturally problematic for concrete. The U. S. Army Corps of Engineers (USACE) Headquarters required the use of post-tensioned trunnion anchor rods in the design of spillway tainter gates in the 1960s and constructed several navigation, flood control, and hydroelectric projects during the 1960s and 1970s. These post-tensioned trunnion anchor rods were used extensively for support of tainter gates and are considered the standard for the USACE and other government and non-government agencies within the United States and worldwide. These rods are now experiencing ongoing failures. The USACE requires reliable non-destructive testing (NDT) methods that are rapid, robust, and capable of detecting and quantifying defects.

1.2 Objectives

Rapid methods to detect micro-cracks are required, this is because of the large number of rods that exist at some installations. Robustness is required to handle the significant variations in design, construction, and field conditions that are known to exist. Required defect detection and quantification provides tracking and monitoring data, this is important for planning and prioritizing remediation efforts or operational practices.

1.3 Approach

This research has resulted in the use of acoustical guided waves as a methodology to detect cracks that are somewhat orthogonal to the axis in the trunnion rods. This research has been demonstrated at the trunnion rod test bed located at the Engineer Research and Development Center (ERDC) facility located in Vicksburg, Mississippi.

1.4 Scope

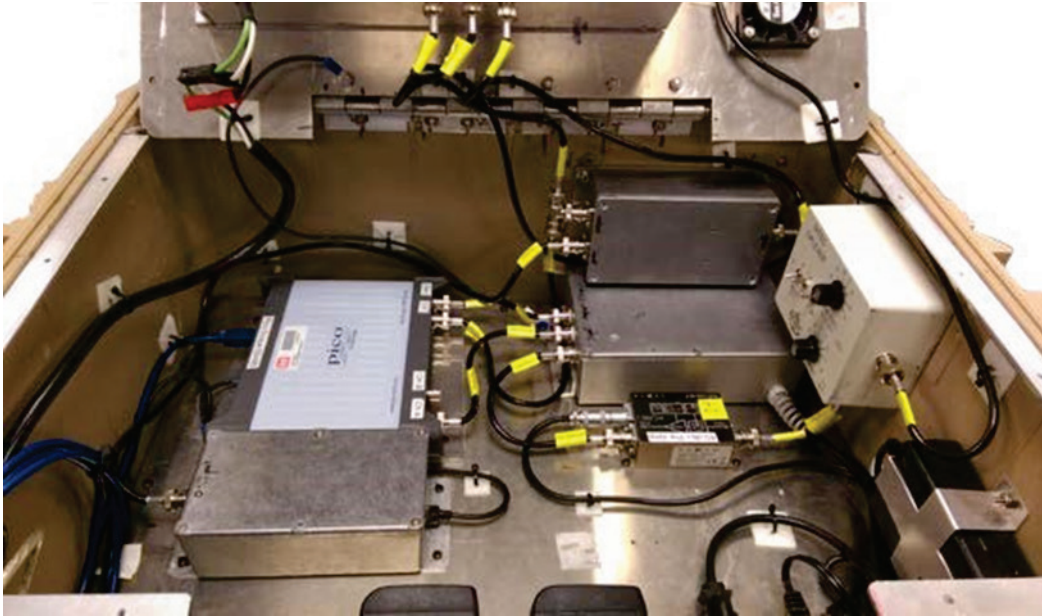
The SIB was tasked with performing the guided wave ultrasonic NDT at Oroville Dam, Oroville, California, Thermalito Bypass, Oroville-Thermalito Complex, and Pyramid Dam, near Castaic, Southern California. These three dams use post-tensioned trunnion anchor rods and normal ultrasonic testing does not propagate the length of these embedded members. The guided wave testing provides a snapshot of the rod health and can be periodically performed to assess whether the condition is changing over time. Two members of the SIB, Jason Ray and Richard Brown, performed the testing and this report dictates the results thereof.

1.5 The guided wave test system

The guided wave test system is based upon a laboratory grade amplifier system from RITEC Inc., the RITEC SNAP System. This system provides the best results, however, due to the amount of equipment required to perform testing a smaller field system was required in order to access the tendon ends.

The design of the smaller system is still based around an amplifier developed by RITEC Inc., the RITEC GA-2500A. Though it lacks features of the RITEC SNAP, the GA-2500A adequately amplifies the signal in order to excite the ultrasonic transducer on the tendon. All components required for signal generation, signal amplification, and data acquisition are packaged in a Pelican case model 1620 for protection while transporting. The output signal runs through a custom signal conditioning circuit before being amplified and sent to the transducer. The transducer is designed for pulse-echo ultrasonic testing, meaning that the same transducer is used to both send and receive the signal. The return signal is amplified before being recorded using a Universal Serial Bus (USB) oscilloscope. The internal parts of the guided wave test system are shown in Figure 1.

Figure 1. Guided-wave system internal parts (GA-2500A amplifier is not shown).



2 Pre-Test

2.1 Possible issues

2.1.1 Drilled tendons

Initial photos of the tendon ends showed the first possible issue (Figure 2). Each rod contains a drilled out end of varying depth and location on the rod face. The guided wave technology relies on a flat surface for the ultrasonic transducer to couple with. Any anomalies in the rod surface directly affects the resulting signal response.

Figure 2. Drilled tendon at Oroville Dam.



Experiments were performed at the ERDC trunnion rod test bed to validate the effects the drilled tendons create along with exploring possible ways to mitigate loss of signal. The results are discussed in section 2.2.

2.1.2 Rod curvature

Drawings of the trunnion bundles at the Oroville Dam, Oroville, California, Thermalito Bypass, Oroville-Thermalito Complex, and Pyramid Dam, near Castaic, Southern California, show that the original installation of the tendons required them to be installed in such a fashion, that while the exposed ends run parallel to each other, the dead end is curved to a higher and higher degree, proceeding up and down the rows of the bundles. Oroville Dam is shown in Figure 3 and the Thermalito Bypass is shown in Figure 4. Due to the smaller number of rods, it is assumed that greater curvature was not necessary at the Thermalito Bypass. Pyramid Dam is shown in Figure 5.

Figure 3. Rod curvature at Oroville Dam.

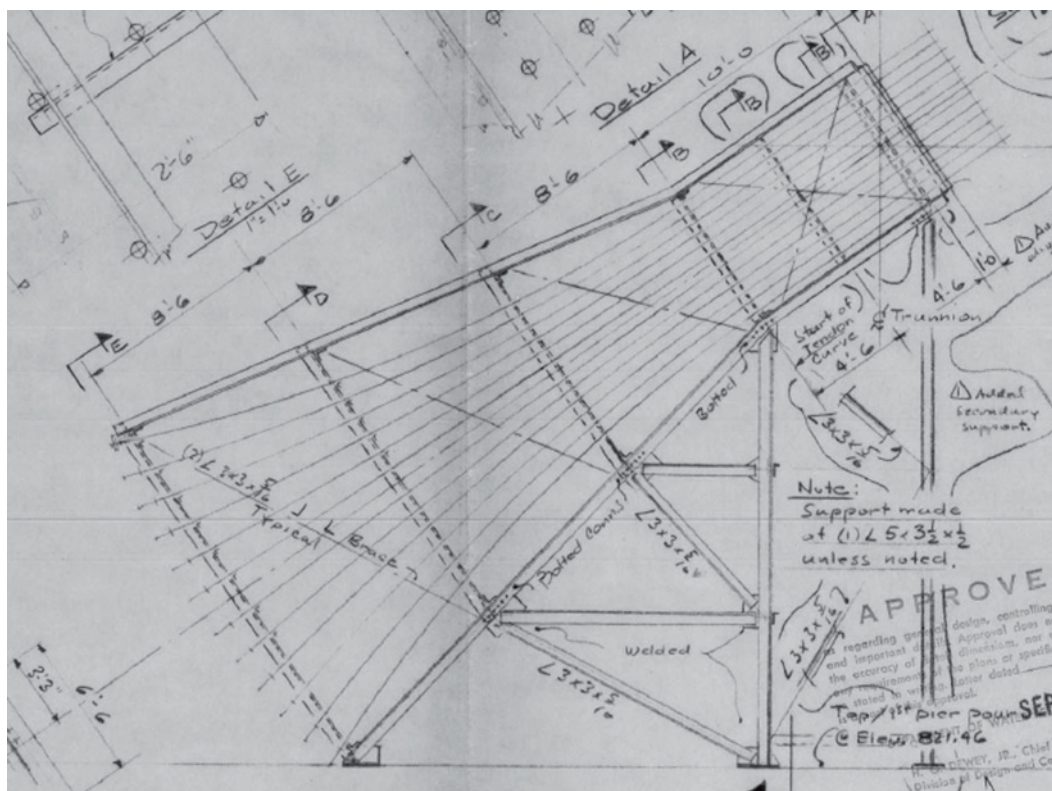


Figure 4. Rod curvature at Thermalito Bypass.

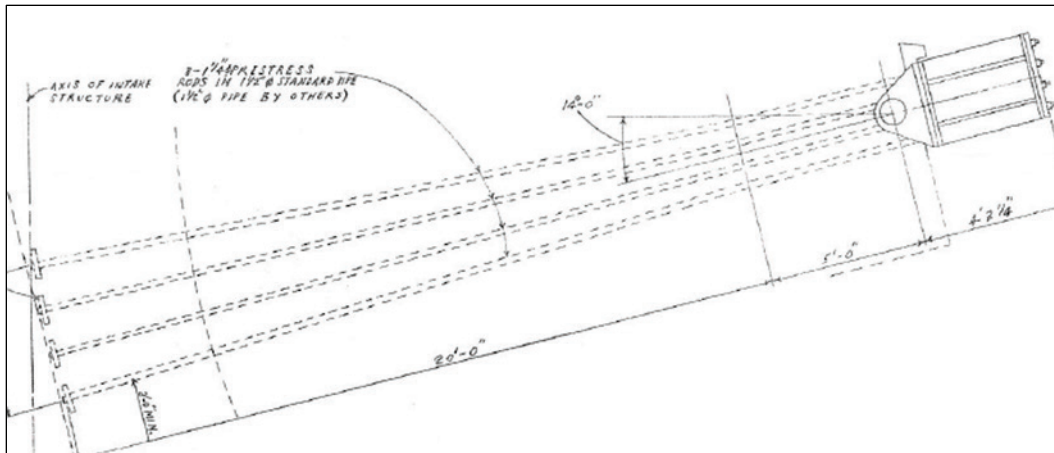
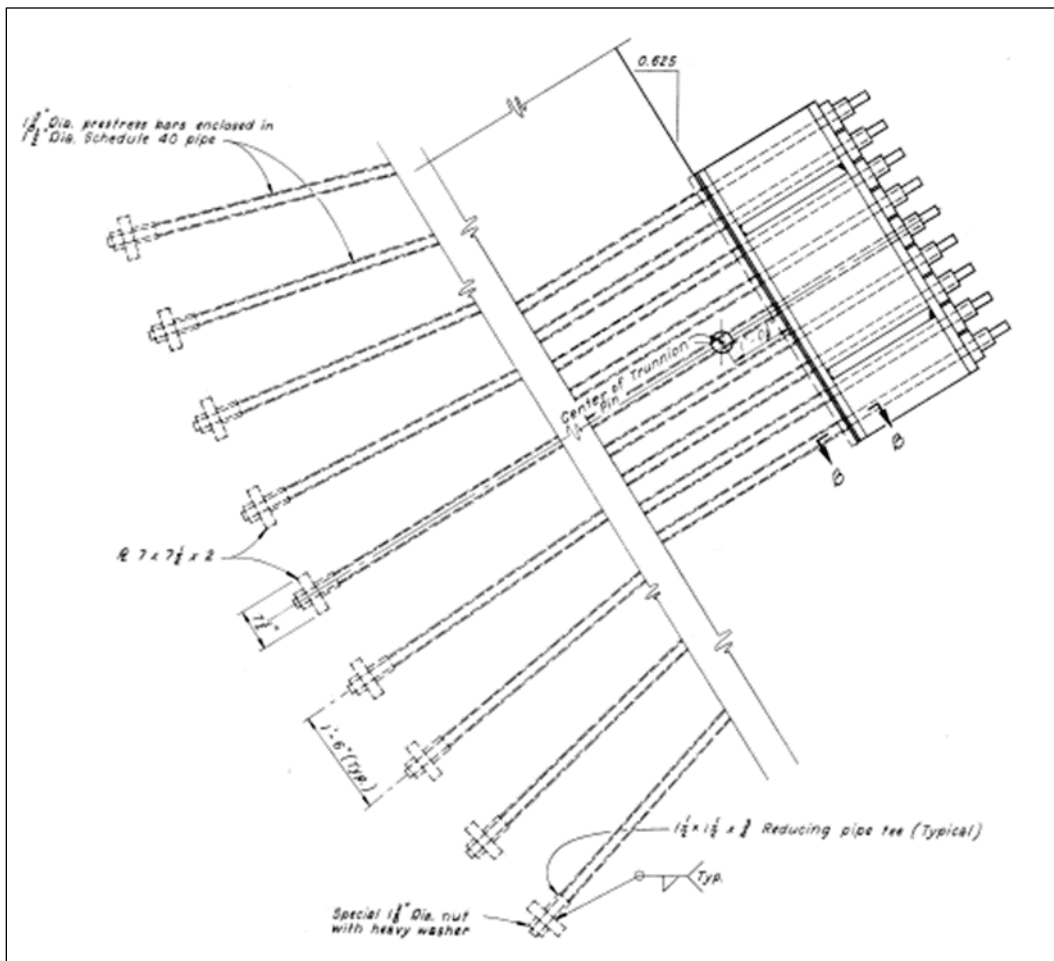


Figure 5. Rod curvature at Pyramid Dam.

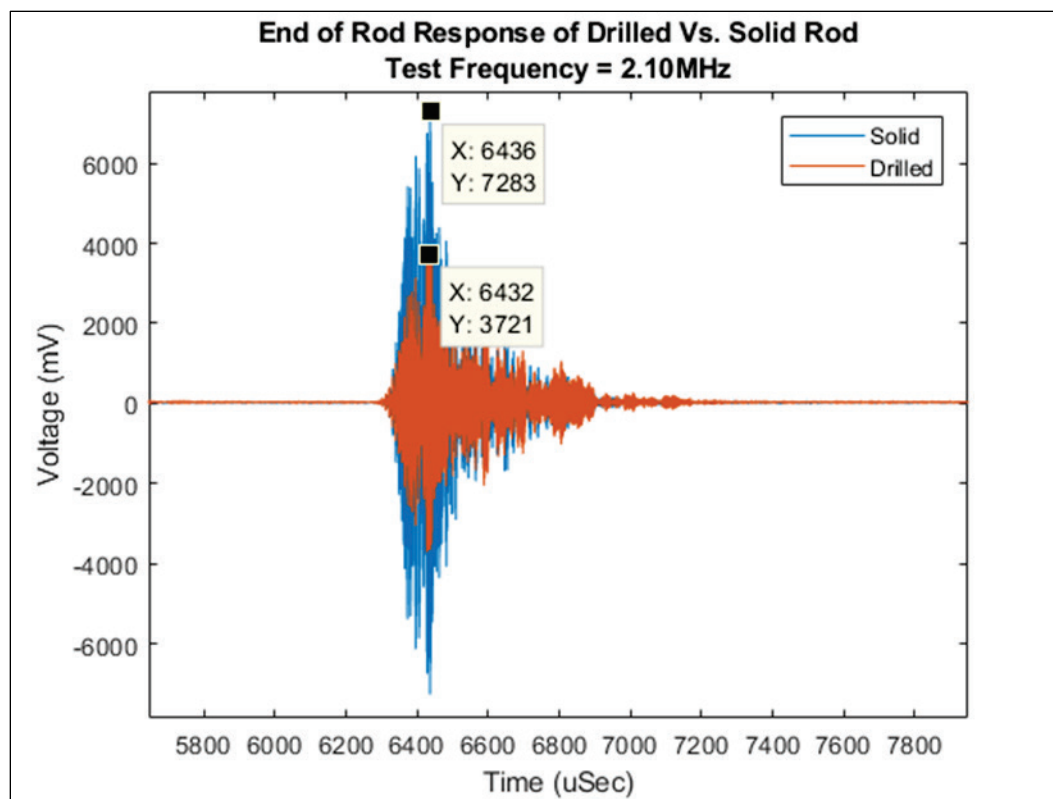


2.2 Pre-arrival validation

Through the use of the trunnion rod test bed at ERDC, the effects of having the end drilled on a 60 foot long, 1.25 in. diameter rod was compared to a solid specimen. The results of the first end of rod rebound at the test bed are shown in Figure 6.

An end of rod rebound is defined as the acoustic echo from the wave hitting the end of the rod and then returning to the transducer. Depending on the length, coupling end condition, rod diameter, and other parameters a return signal up to 180 feet is possible.

Figure 6. Drilled vs. solid tendon.



The drilled tendon end resulted in a decrease in end of rod response amplitude of 5.8 decibels (dB). This showed that while there is a decrease in how much initial energy is injected, enough energy transfers to propagate the rod length.

The ERDC has the capability of forming a coupling piece by casting metal to the end of the rod using an alloy called Field's Metal. Melting at a temperature of 62 °C, the casting is performed quickly and the metal can

be recast over and over. This option for overcoming the drilled end would not work due to the possibility of leaving behind residue.

Even though it was proven possible to still work within the confines of the Oroville Dam rod condition, several methods were tested to amplify the response. The first was the use of a plug to insert into the hole. The plug was made to fit using the same material as the rod. Coupling grease was applied inside the drilled hole in order to fill any imperfections from the drilling. This method provided a marginally better response, however, due to variability in the drilled tendons at Oroville Dam, this would not work, as inserts for every tendon could not be made. The second method was to attach a matching coupling rod end to extend the length of the rod slightly, thus, providing enough length for the guided wave modes to set up. This required tapping the drilled tendon end so that the coupling piece could be screwed on. The response with this method also did not provide enough of an increase in signal response to warrant trying to design for all possible cases at the dam. For these reasons it was decided to rely on injecting enough acoustical energy to simply overcome the loss in surface area.

3 Results

3.1 Oroville Dam

Across eight gates, Oroville Dam contains 384 total rods, 48 supporting each gate. The ERDC performed guided wave testing on each rod over the week of 23 July 2018. The following sections detail the conditions of the rods upon arrival, the effects caused by how they are embedded in the concrete, and the results obtained from the testing.

3.1.1 Condition

In addition to the drilled tendons as previously discussed, the smoothness of the rod end and how perpendicular the surface is with the length of the rod are major factors in how much energy is able to cross the air gap between the transducer and rod surface. Upon arrival, the rod ends were found to be in overall good shape. The ends were smooth and mostly perpendicular. Examples are shown in Figure 7.

Figure 7. Oroville Dam rod condition.

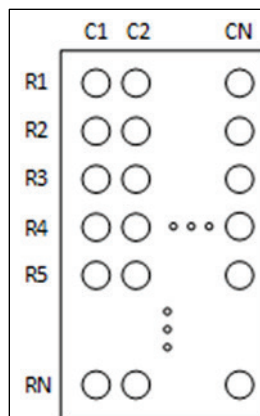


3.1.2 Results

Assigning each rod an individual name provides a way to reference it in the future. For the three dams tested, the same nomenclature is used. The rods are named based upon a matrix format with the origin being at the

top left, Row 1; Column 1, or R1 C1. Every bundle tested only contained two columns but the number of rows varied between sites. Oroville Dam contained twelve rows, Thermalito Bypass contained four rows, and Pyramid Dam contained nine rows. The naming convention is illustrated in Figure 8.

Figure 8. Rod naming convention.

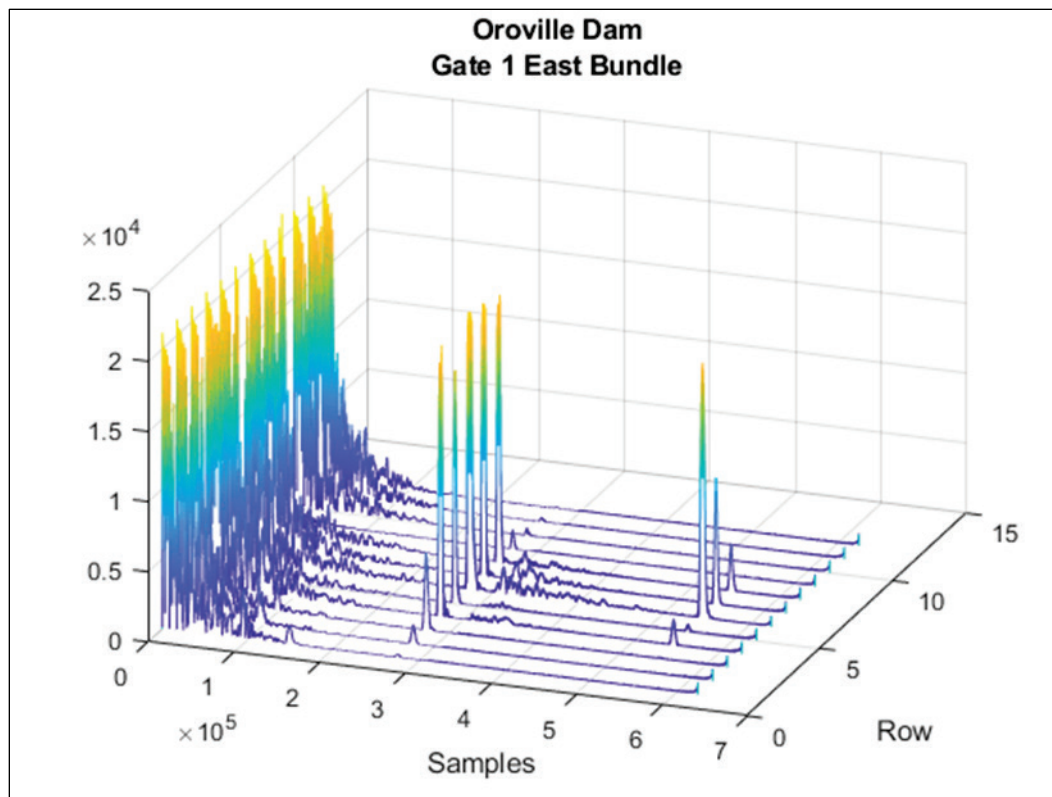


This describes the rods themselves, however each gate contains two bundles. For the sites tested, the bundles were oriented in a mostly east and west direction. The result is a rod name following this example: Oroville Dam, Gate 2; east Rod 1, Column 1. The results below detail east, west, and gate number along with the row and column number.

3.1.2.1 Effects of curvature

The rod curvature resulted in more issues than originally expected. As the bend of the rod increased (the upper and lower rows of rods), the signal attenuated at a faster rate. For example, the results of each row from a single column at Oroville Dam is show in Figure 9.

Figure 9. Oroville Dam rod curvature effects.



The right axis of Figure 9 represents the row number within the bundle. The middle most rods often result in a response that clipped the input of the oscilloscope requiring the overall gain to be reduced. The larger responses allow for multiple end of rod rebounds to occur, often resulting in three total. In every sample, at least one end of rod rebound was obtained, however, for the upper and lower limit rods, the response was very small.

3.1.2.2 Rod response

Rod condition is labeled in one of the following three categories: No Issue, Anomaly, and Possible Defect. The No Issue category represents a rod where based upon the majority of the responses obtained across the dam, these rods provide a clean signal between end of rod rebounds. An example of a No Issue response is shown in Figure 10.

Figure 10. Oroville Dam: Gate 4, west; Row 1, Column 1; no issue.

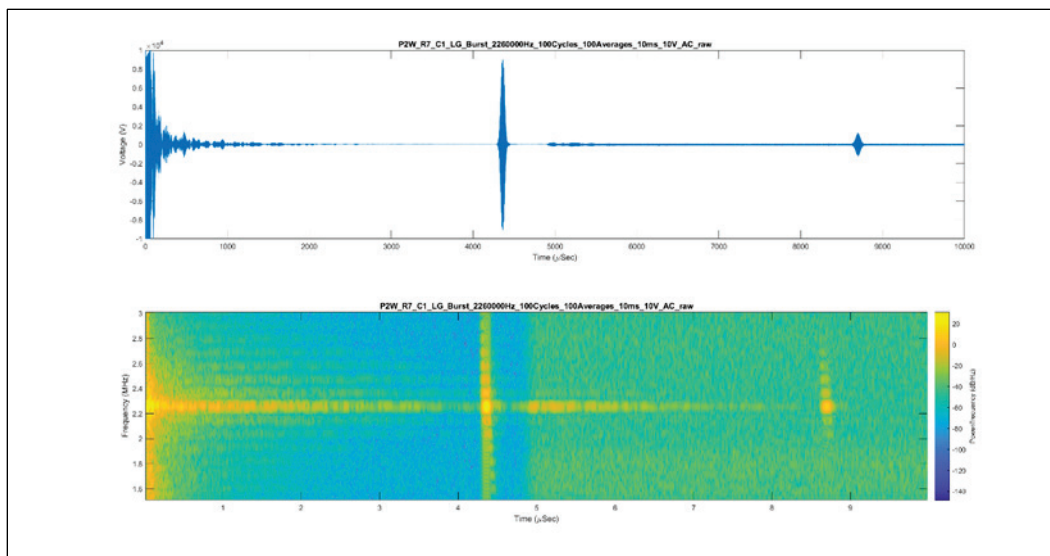


Figure 10 contains two plots that determine rod condition during post processing. The top plot is received when the testing is complete, the return amplitude of the signal expressed in volts on the y-axis and time on the x-axis. The second plot is a time-frequency representation of the same signal. One characteristic of the guided wave response is that the higher mode frequencies return slightly faster than the lower mode frequencies. This provides a fingerprint that surrounds the centralized testing frequency. Any response from an actual reflector would look like this, but more attenuated. The two echoes shown in Figure 10 are from end of rod rebounds.

The Anomaly category is mostly limited to the upper and lower most rods. In addition to the attenuated signal response, the reflectors were noticed before the end of rod response. These reflectors appear at roughly the same point in time for the rods labeled as anomaly. As detailed in 2.1.2, these rods were curved during installation. Due to the frequency of occurrence within the curved rods, it appears that the curvature is the cause for these anomalies. One possibility for this occurrence would be sleeve contact where the rod sleeve rests on internal guides as seen in Figure 11. According to the original drawings, the first of these guides appear at a rod length of 18'6" plus the exposed length of rod. The first anomaly reflector appears around 15' in the rod according to the received data.

Figure 11: Anchor guide distance.

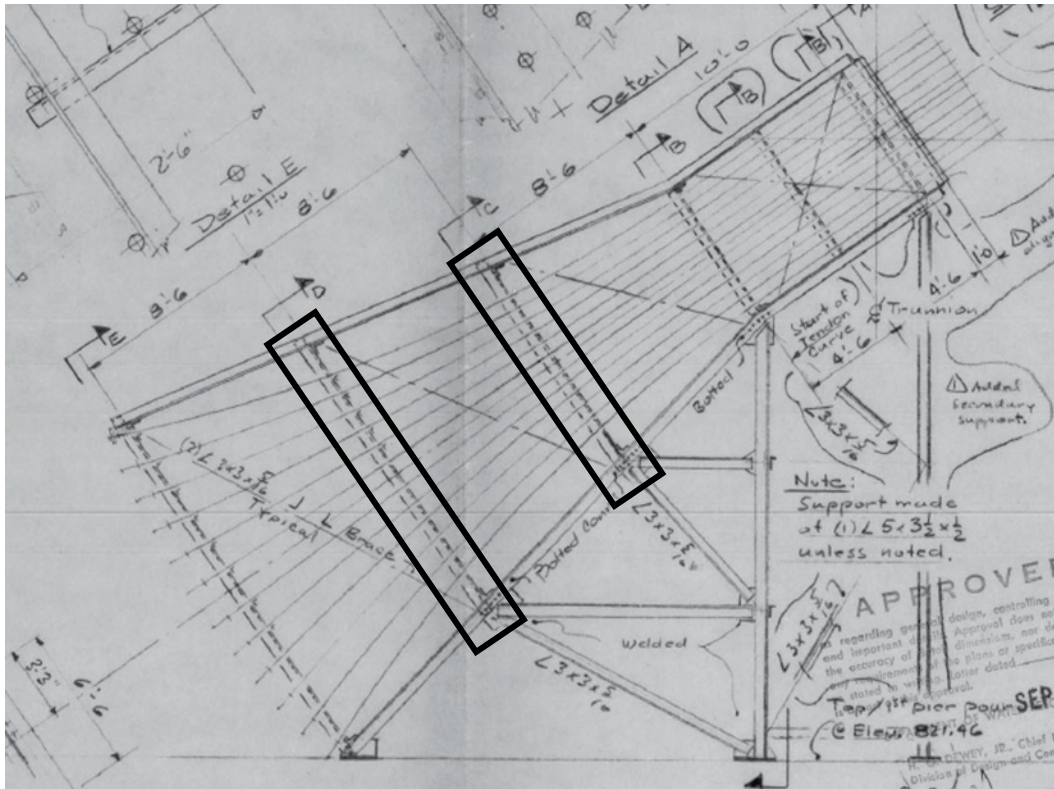


Figure 12. Oroville Dam: Gate 4, west; Row 1, Column 1; anomaly.

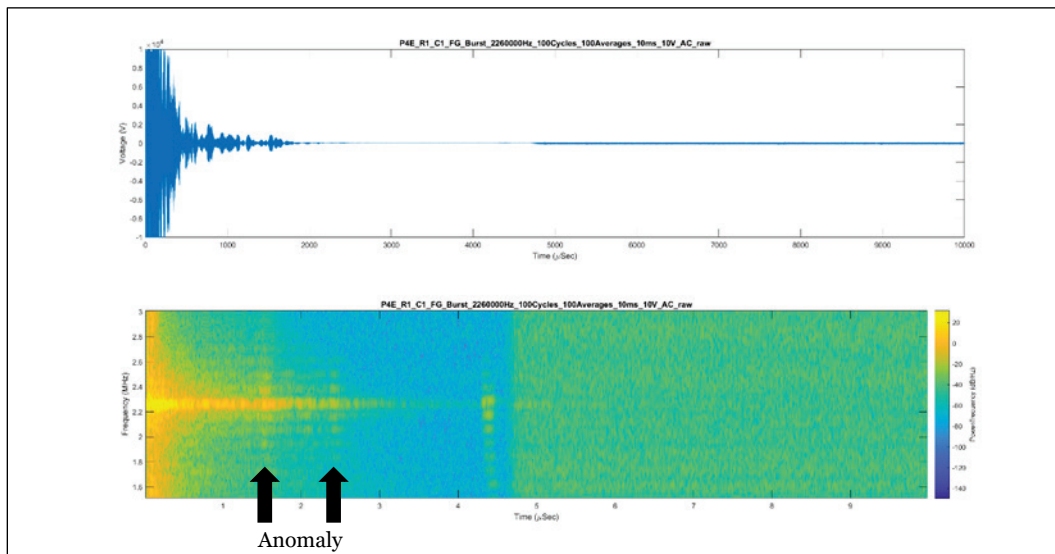
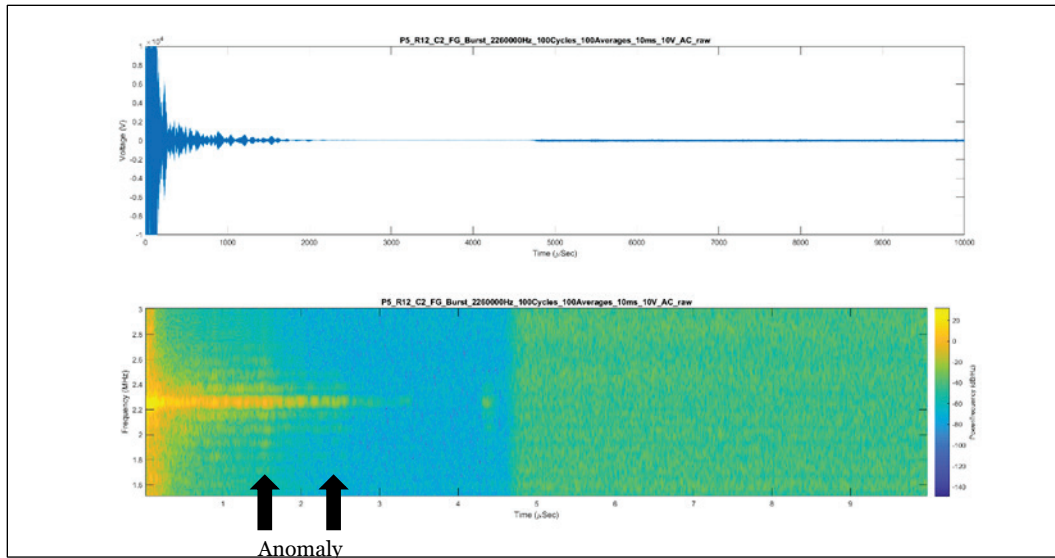


Figure 13. Oroville Dam: Gate 4, east; Row 12, Column 2; anomaly.



These two rods are a part of Gate 4 different bundles. Figure 12 is on the west bundle; Row 1, Column 1. Figure 13 is on the east bundle; Row 12, Column 2. The location of these anomalies is roughly the same for each case shown in the results section. Due to how frequent the anomaly appears, these rods are not labeled as damage.

Of the 384 rods tested, two rods are labeled as possible defects — Gate 4, west bundle; Row 2, Column 1, and Gate 7, west bundle; Row 2, Column 2. The responses of these two rods are shown in Figure 14 and Figure 15.

Figure 14. Oroville Dam: Gate 4, west; Row 2, Column 1; possible defect.

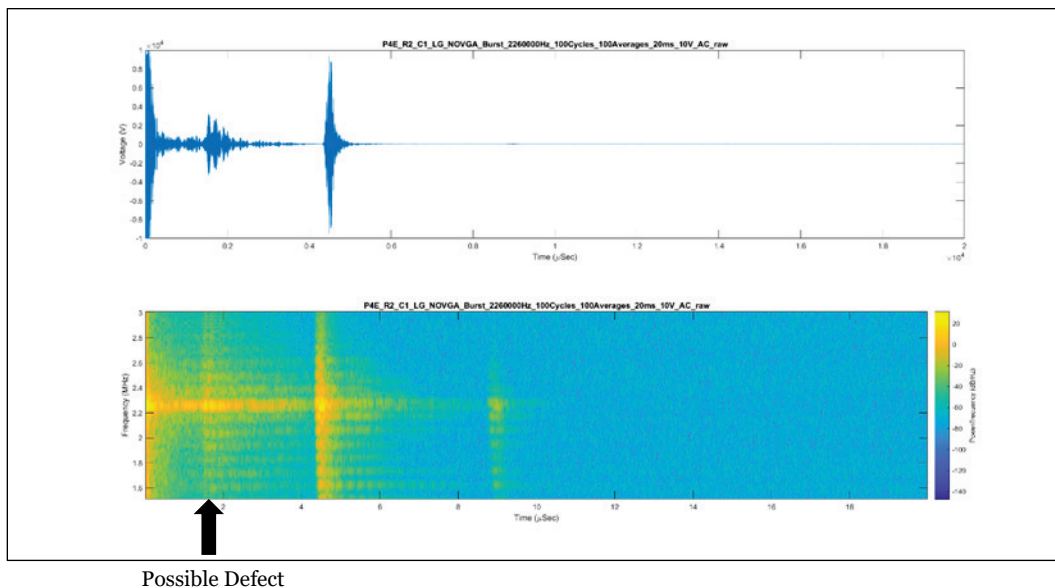
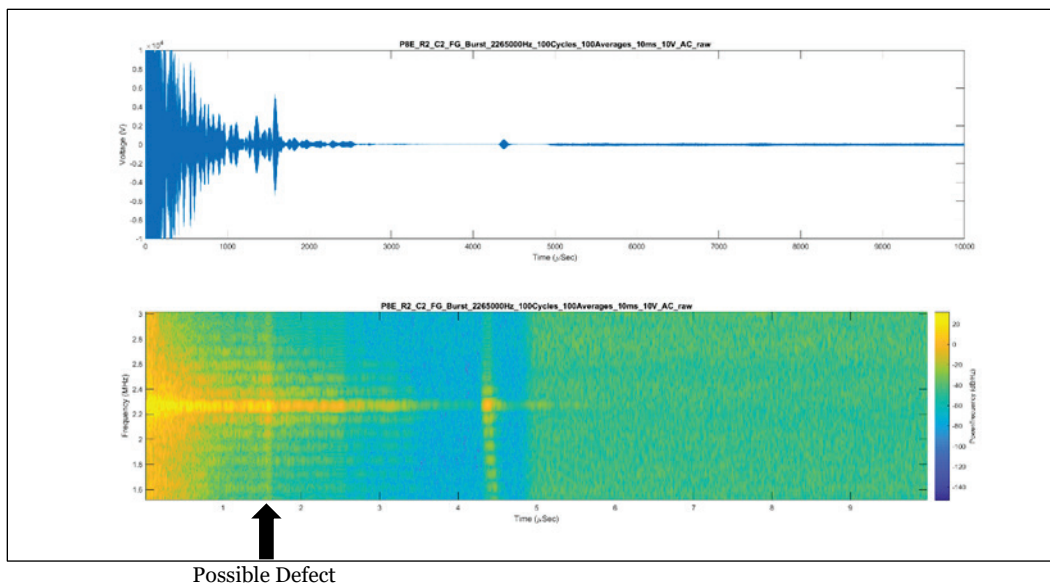


Figure 15. Oroville Dam: Gate 7, west; Row 2, Column 2; possible defect.



Of these two, Figure 14 shows the greatest possibility of being an actual defect. Both the time-voltage and time-frequency plots show a strong signature similar to that of the end of rod response. In Figure 15, the time-frequency signature looks similar to the anomalous rods though the time-voltage plot has a stronger response than other anomalous rods. For this reason it is being classified as a possible defect.

Figures 16–23 show the results of the 384 rods tested at Oroville Dam. Rods labeled as No Issue are white; Anomaly are yellow; Possible Defect are red. The gate order of the dam in Figure 16 is from the orientation of looking upstream.

Figure 16. Oroville Dam gate order.

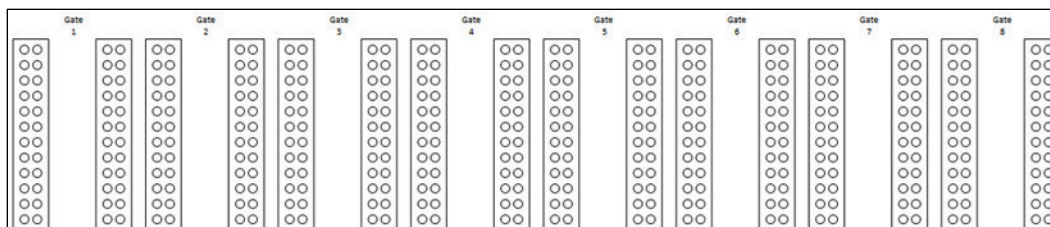


Figure 17. Oroville Dam, Gate 1 rods.

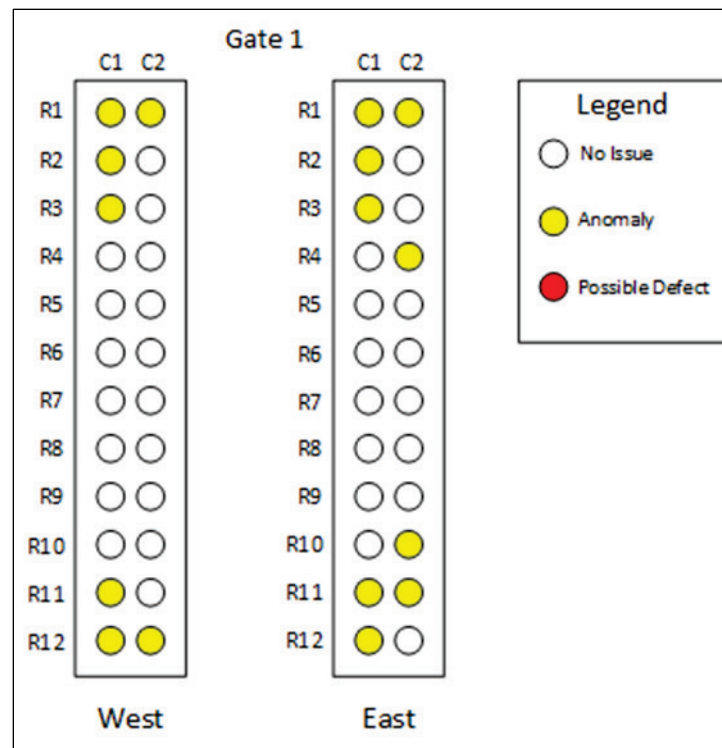


Figure 18. Oroville Dam, Gate 2 rods.

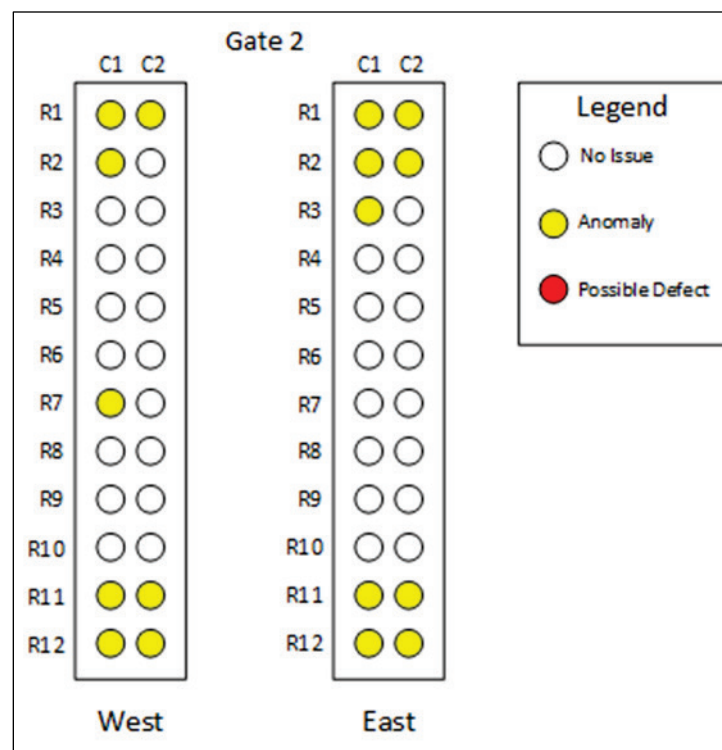


Figure 19. Oroville Dam, Gate 3 rods.

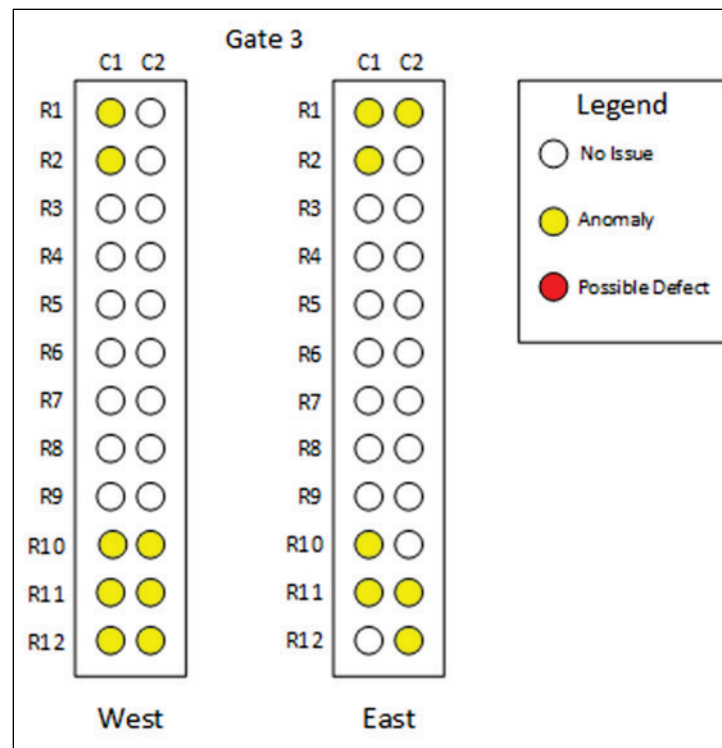


Figure 20. Oroville Dam, Gate 4 rods.

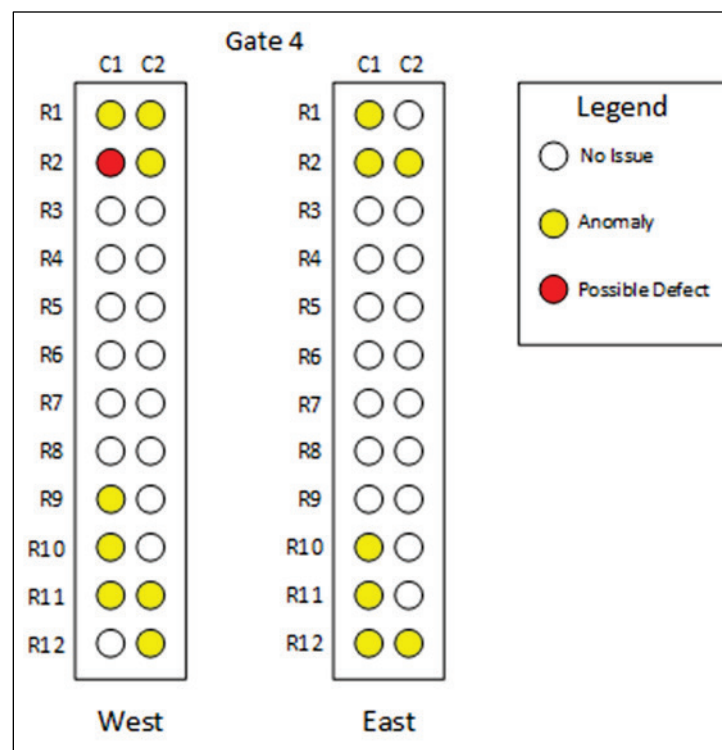


Figure 21. Oroville Dam, Gate 5 rods.

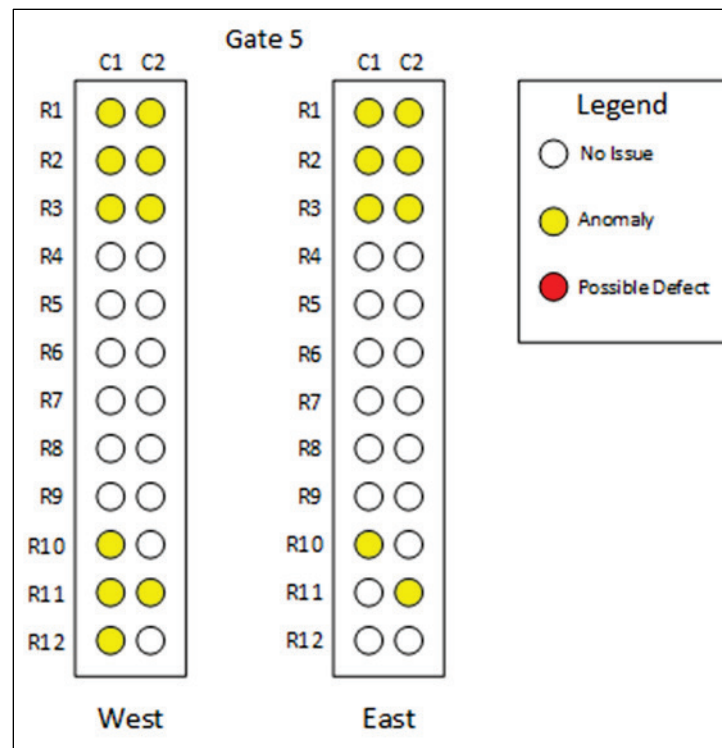


Figure 22. Oroville Dam, Gate 6 rods.

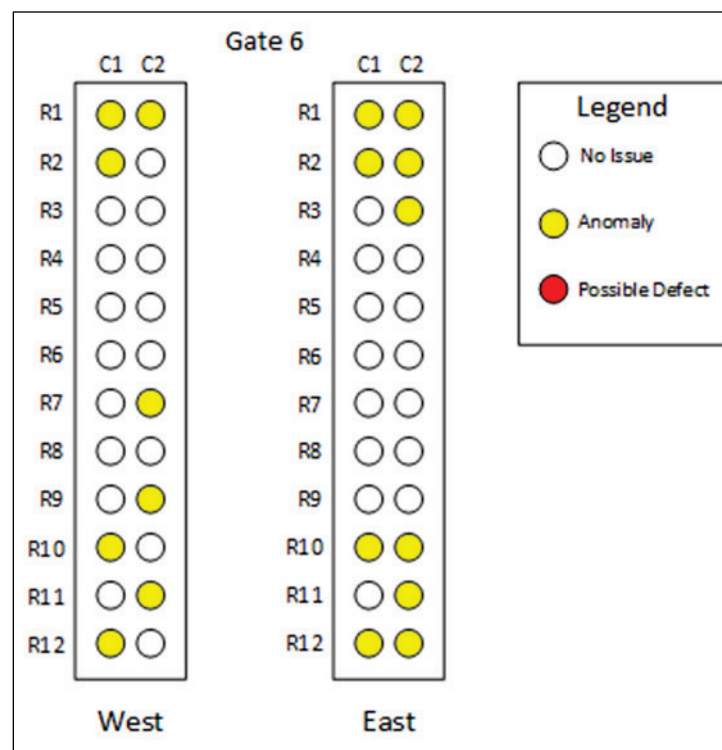


Figure 23. Oroville Dam, Gate 7 rods.

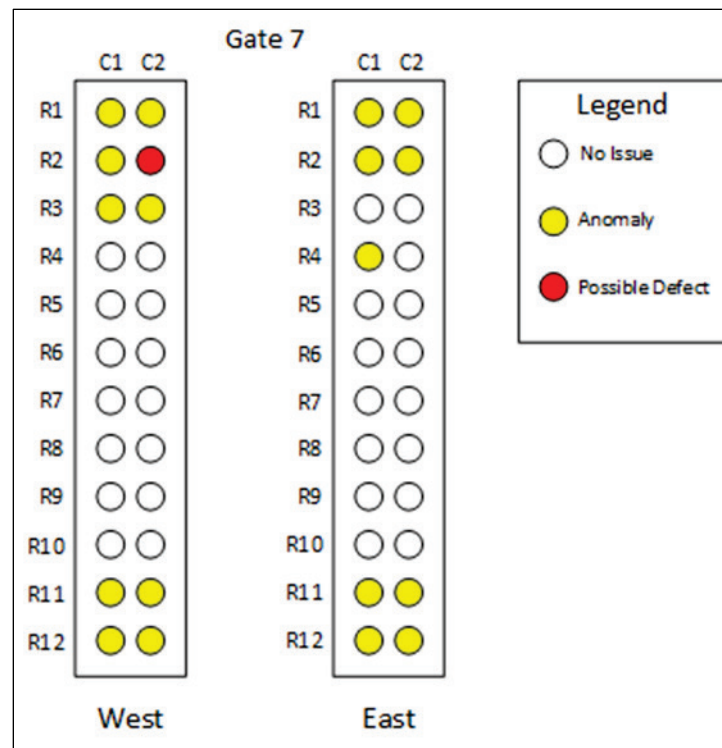
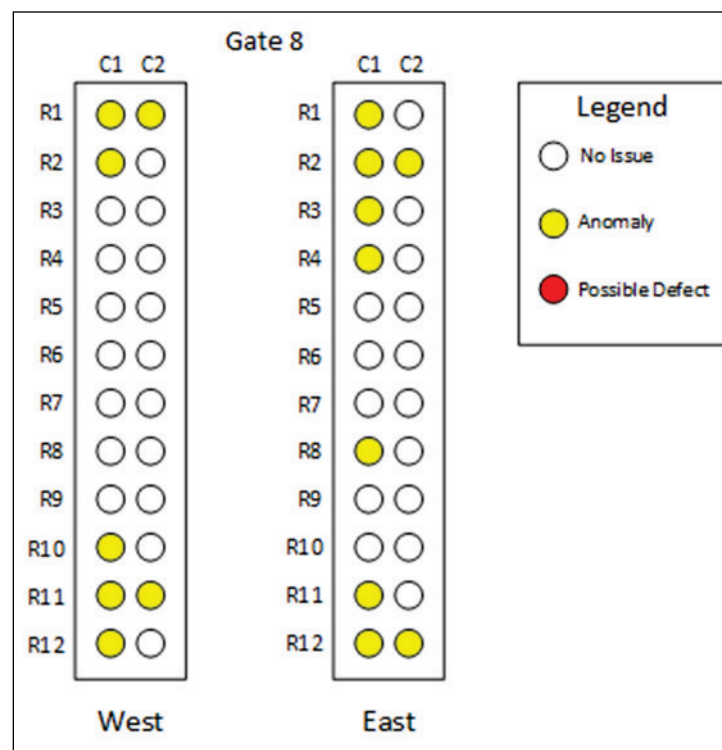


Figure 24. Oroville Dam, Gate 8 rods.



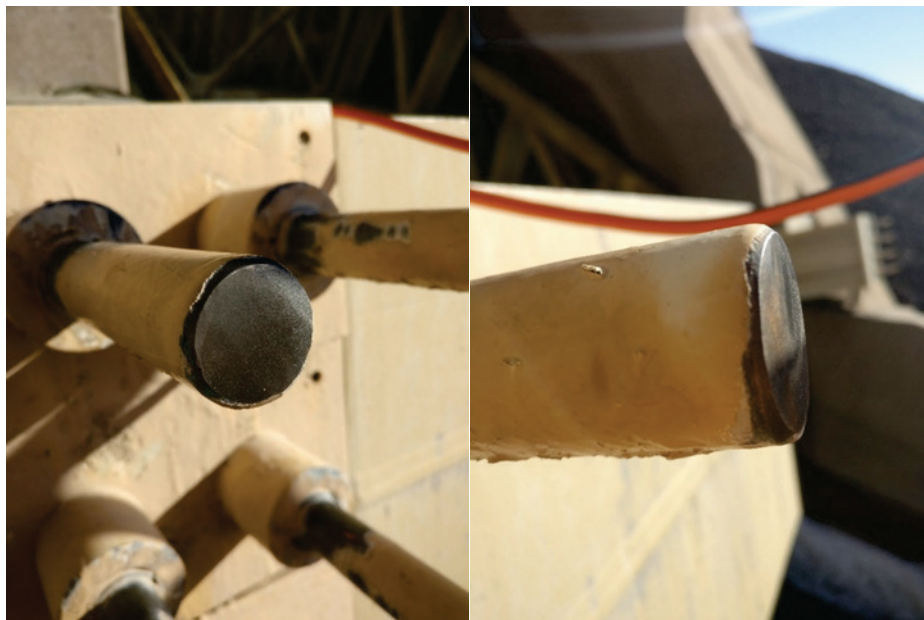
3.2 Thermalito bypass

Rods at Thermalito Bypass are shorter than Oroville Dam and do not contain the drilled end. However, the diameter of the rods are the same. The rod curvature does exist in the bundles, but due to less numbers of rods, the curvature is not as severe. The single gate contains 16 rods across two bundles. All 16 were tested.

3.2.1 Condition

Figure 25 shows the condition of the rods at the time of testing. Although the rod ends look smooth, there are irregularities in the surface which could lead to poor transducer contact. However the irregularities here are minor and the coupling grease fills in the imperfections to provide good surface contact with the transducer.

Figure 25. Thermalito bypass rod condition.



As with Oroville Dam, the more curved rods showed evidence of reflectors while the straighter rods came back with no evidence of issues. 16 rods were tested, Figure 26 shows the results of one of the rods showing No Issue. Figure 27 shows the results of one of the rods being labeled as an anomaly.

Figure 26. Thermalito Bypass: east; Row 2, Column 1; no issue.

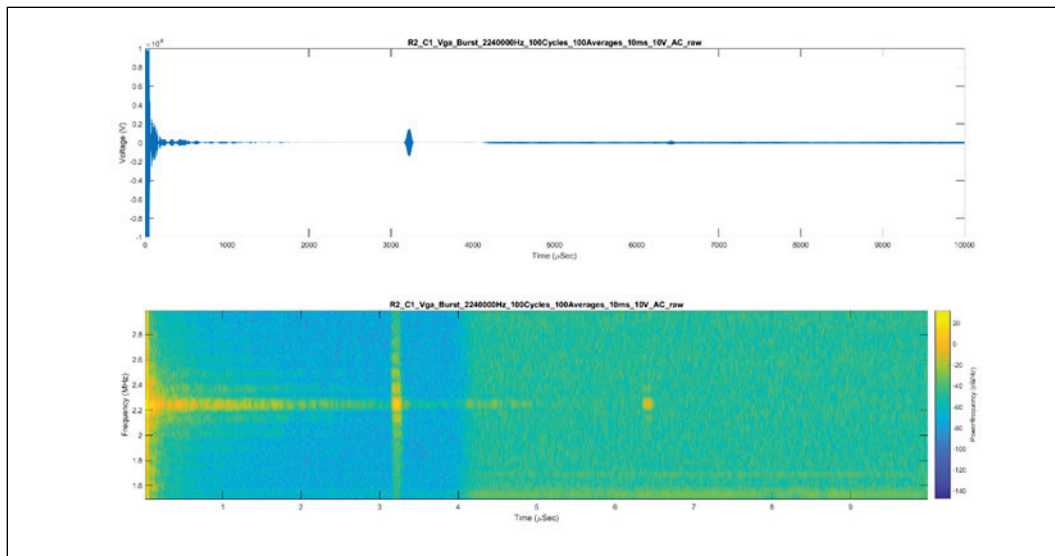


Figure 27. Thermalito Bypass: east; Row 4, Column 2; anomaly.

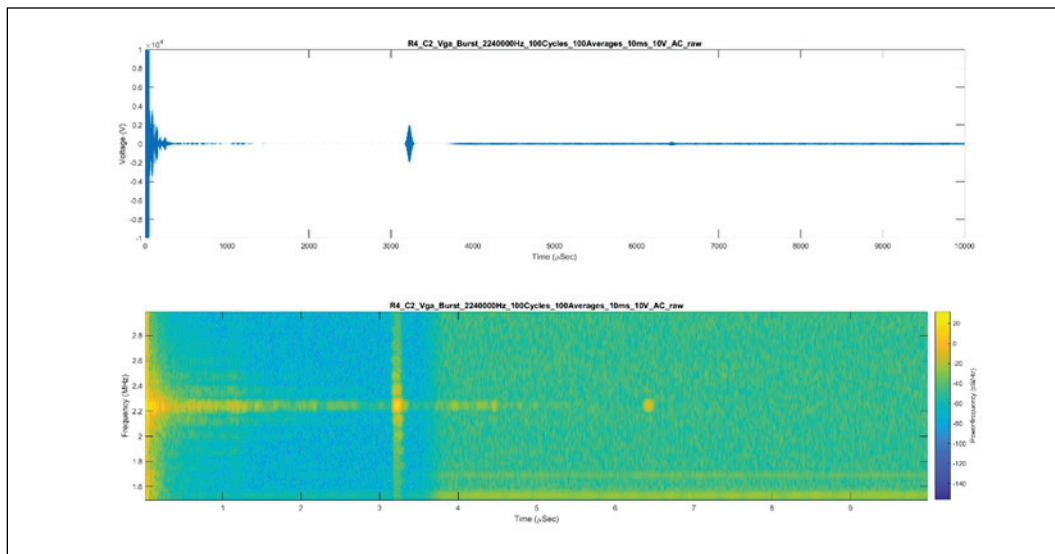
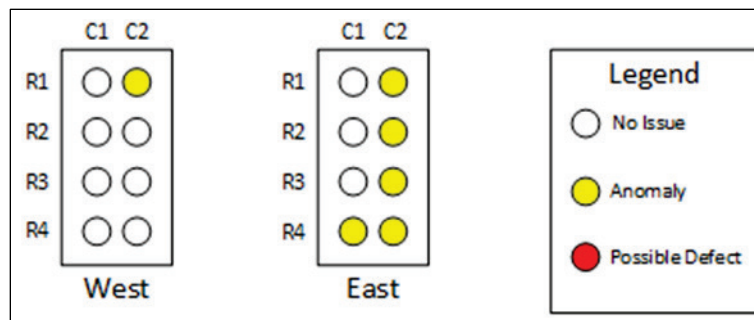


Figure 28 shows the results of the 16 rods tested at the Thermalito Bypass gate. Rods labeled as No Issue are white; Anomaly is yellow; Possible Defect is red.

Figure 28. Thermalito Bypass rods testing results.



3.3 Pyramid Dam

Testing at Pyramid Dam took place during the week of 15 October 2018. The single gate contains 36 rods across two bundles. The ERDC performed guided-wave testing across all 36 rods.

3.3.1 Condition

That rods at Pyramid Dam were both smooth and perpendicular to the length of the rod. No issues were seen with coupling. Figure 29 shows the condition.

Figure 29. Pyramid Dam rod condition.

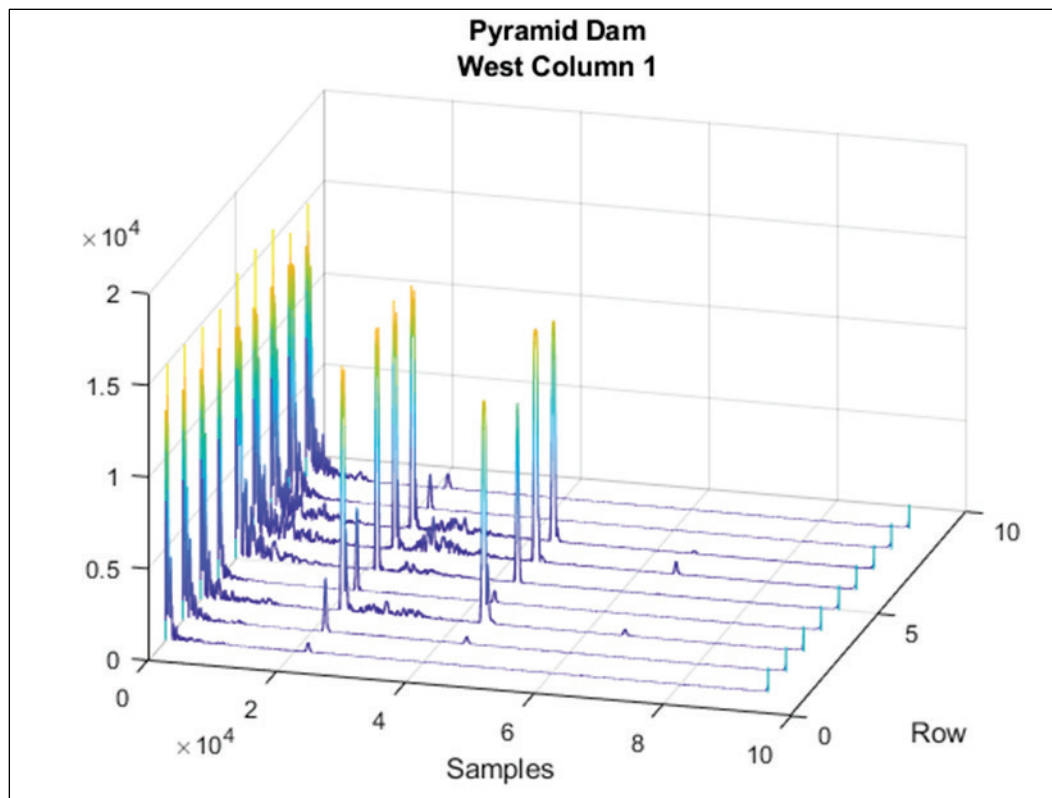


3.3.2 Results

3.3.2.1 Effects of curvature

Like Oroville Dam and Thermalito Bypass, Pyramid Dam contains rods that are curved. The rods of a single column in a bundle were plotted together to show the effects the curvature has on the signal. The results are shown in Figure 30.

Figure 30. Pyramid Dam rod curvature effects.



3.3.2.2 Rod response

Figure 31 is an example of a rod showing No Issues. Further evidence supporting the theory that rod curvature causes anomalies in the data; the rods at Pyramid Dam exhibited reflectors on the rods that bend upward and downward within the dam. This effect is seen in Figure 32.

Figure 31. Pyramid Dam: east; Row 5, Column 1; no issue.

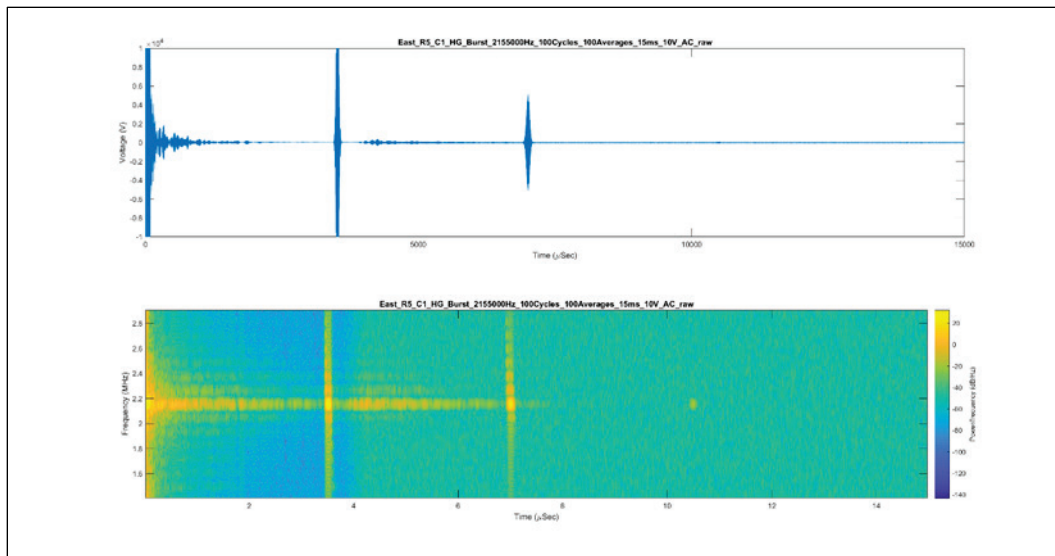


Figure 32. Pyramid Dam: east; Row 2, Column 1; anomaly.

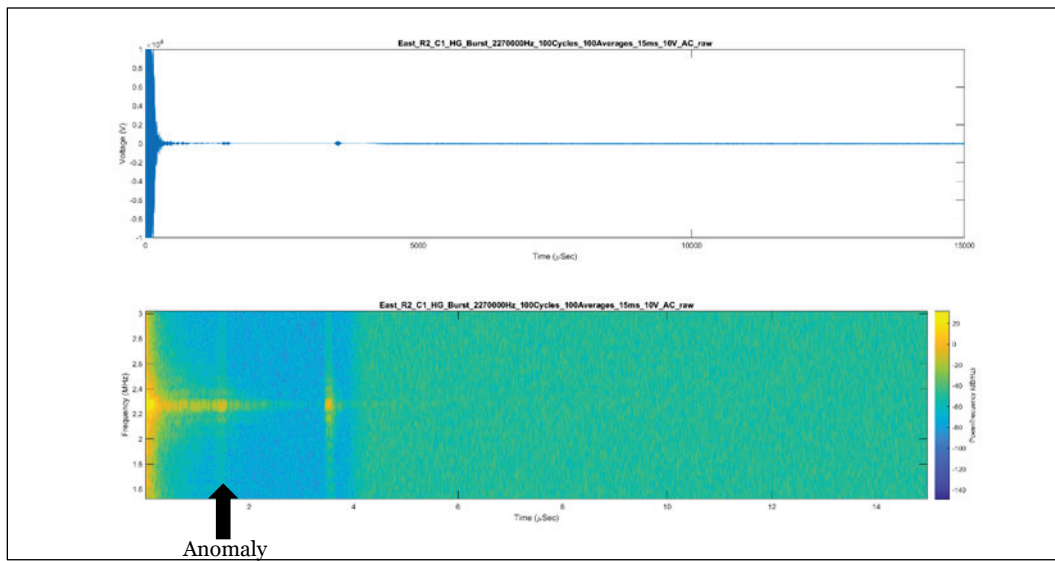
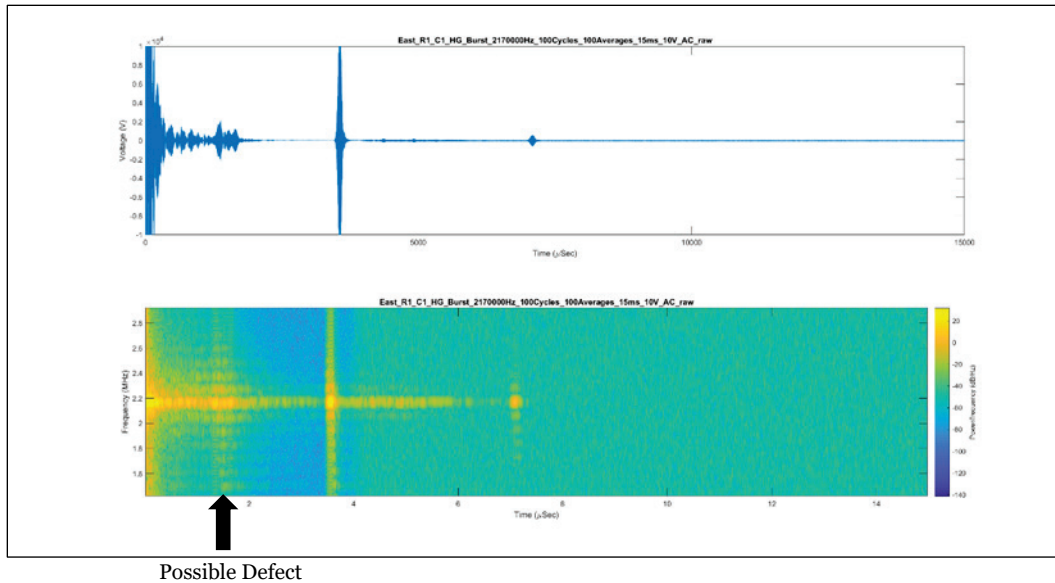


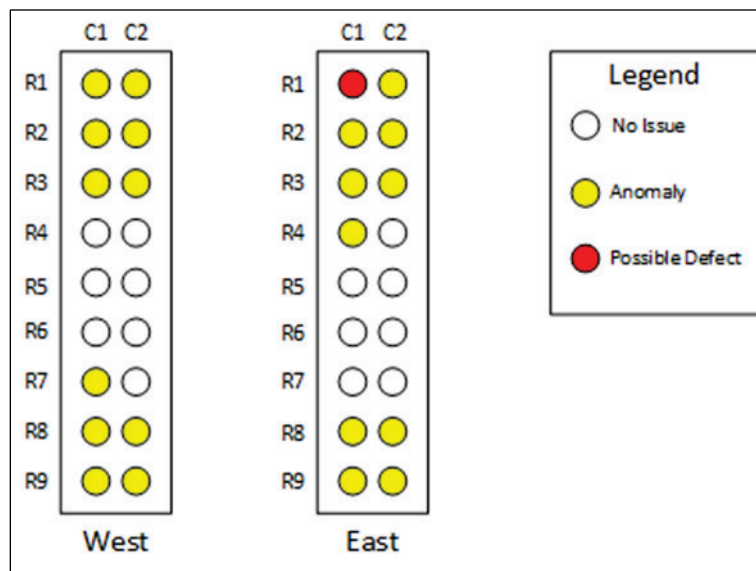
Figure 33. Pyramid Dam: east; Row 1, Column 1; possible defect.



Very similar to the Oroville rod response of Figure 14, Figure 33 shows a possible defect on rod east bundle; Row 1, Column 1. Even though the response time of this anomaly is similar to the other curved rods, the amplitude is much greater than the others.

Figure 34 shows the results of the 36 rods tested at the Pyramid Dam. Rods labeled as No Issue are white; Anomaly is yellow; Possible Defect is red.

Figure 34. Pyramid Dam rods testing results.



4 Conclusion and Recommendations

Between July and October 2018, the SIB from the ERDC performed guided wave ultrasonic inspections of the trunnion anchor rods at Oroville Dam, Thermalito Bypass, and Pyramid Dam. The inspection provides a look at the health of the embedded trunnion anchor rods using a custom built test system. Three categories of health condition provided were the following: No Issue, Anomaly, and Possible Defect. Based upon expected results, the anomaly category appears to be concentrated with the rods at the higher and lower extremes of the bundles, this is due to the curvature in the design. These returns would typically indicate a defect, however, due to the vast number of these upper and lower bounds returning the same anomalies, it was concluded that it is not due to corrosion or micro-cracking. Three rods were found to be in the Possible Defect category. Still limited to the upper and lower regions of the bundles, these three rods returned reflectors outside the expected results for the anomalous data. For this reason they are labeled as possible defects, though the cause could be due to rod curvature.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) September 2019		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Guided-Wave Inspection of California Department of Water Resources Tainter Gate Trunnion Rods: Inspection of Oroville Dam, Thermalito Bypass, and Pyramid Dam				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT	
6. AUTHOR(S) Jason D. Ray, Richard D. Brown, and James A. Evans				5d. PROJECT NUMBER 464475	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Information Technology Laboratory U.S. Army Engineer Research and Development Center 3909 Halls Ferry Rd. Vicksburg, MS 39180				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/ITL SR-19-16	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Headquarters, U.S. Army Corps of Engineers Washington, DC 20314-1000				10. SPONSOR/MONITOR'S ACRONYM(S) ERDC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT As part of the Oroville Dam reconstruction effort, The Sensor Integration Branch (SIB) at the Engineer Research and Development Center (ERDC) performed non-destructive testing (NDT) on the trunnion anchor rods at Oroville Dam, Oroville, California, Thermalito Bypass, Oroville-Thermalito Complex, and Pyramid Dam, near Castaic, Southern California, through the use of ultrasonic guided waves. The results of the testing on every rod will be discussed along with qualitative analysis in determining whether a rod is intact or compromised. Analysis is based upon the expected results from other rods at the sites and data gathered from the trunnion rod research test bed at ERDC.					
15. SUBJECT TERMS Hydraulic structures—California, Hydraulic gates--Nondestructive testing, Oroville Dam (Calif.), Pyramid Dam (Calif.), Thermalito Bypass (Calif.)					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 35	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)