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# 2021 Guided Wave Inspection of California Department of Water Resources Tainter Gate Post-Tensioned Trunnion Anchor Rods

Oroville Dam

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*Information Technology Laboratory*
*U.S. Army Engineer Research and Development Center*
*3909 Halls Ferry Rd.*
*Vicksburg, MS 39180-6199*

Final Special Report



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# Abstract

The Engineering and Test Branch within the Division of Operations and Maintenance of the California Department of Water Resources (DWR) and U.S. Army Corps of Engineers (USACE), Sacramento District, tasked the Sensor Integration Branch (SIB) at the Engineer Research and Development Center (ERDC) to perform nondestructive testing (NDT) on the trunnion anchor rods at Oroville Dam through the use of ultrasonic guided waves. This is the fourth year of this NDT. The results of the testing are presented 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 site, knowledge of rod response at other sites, data gathered from the trunnion rod research test bed at ERDC, and comparison to the previous year's effort.

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# Preface

This study was conducted for the California Department of Water Resources and U.S. Army Corps of Engineers (USACE) Sacramento District under MIPR W62N6M13089302.

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, Ms. Amie J. Burroughs was the Branch Chief, and Dr. Jeffrey L. Hensley was Division Chief. The Deputy Director of ERDC-ITL was Dr. Jacqueline S. Pettway, and the Director was Dr. David A. Horner.

COL Christian Patterson was Commander of ERDC, and Dr. David W. Pittman was Director.

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# 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 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 USACE and other government and non-government agencies within the United States and worldwide. USACE requires reliable nondestructive testing (NDT) methods that are rapid, robust, and capable of detecting and quantifying defects.

## 1.2 Objectives

Rapid methods to detect microcracks are needed because of the large number of rods that exist at some installations. Robust equipment is required to handle the existing significant variations in design, construction, and field conditions. Reliable defect detection and quantification provides tracking and monitoring data, which are important for planning and prioritizing remediation efforts or operational practices.

## 1.3 Approach

It has been demonstrated at the trunnion rod test bed located at the ERDC facility in Vicksburg, Mississippi, that acoustical guided waves serve as a methodology to detect cracks that are somewhat orthogonal to the axis in trunnion rods (Evans and Haskins 2015). Additionally, it has been shown in a laboratory setting that the guided wave methodology provides information about the remaining cross-sectional area of solid tendons. Cross-sectional area loss research is still ongoing, so this report does not contain information about the remaining cross-sectional area on tendons considered Possible Defect.

## 1.4 Scope

The Sensor Integration Branch (SIB) was tasked with performing repeat guided wave ultrasonic NDT at Oroville Dam Flood Control Outlet (FCO) for fiscal year 2021. This dam uses post-tensioned trunnion anchor rods, and normal ultrasonic testing does not propagate the length of these embedded members. Guided wave testing provides a snapshot of rod health and can be periodically performed to assess whether the condition is changing over time. Two members of SIB performed the testing, and this report provides the results.

## 1.5 The guided wave test system

The guided wave system includes a RITEC GA-2500A high power amplifier and custom signal conditioning circuitry for performing level shifting, minor amplification, and gate signal generation for the GA-2500A before sending the excitation signal to the ultrasonic 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 on a Universal Serial Bus (USB) oscilloscope.

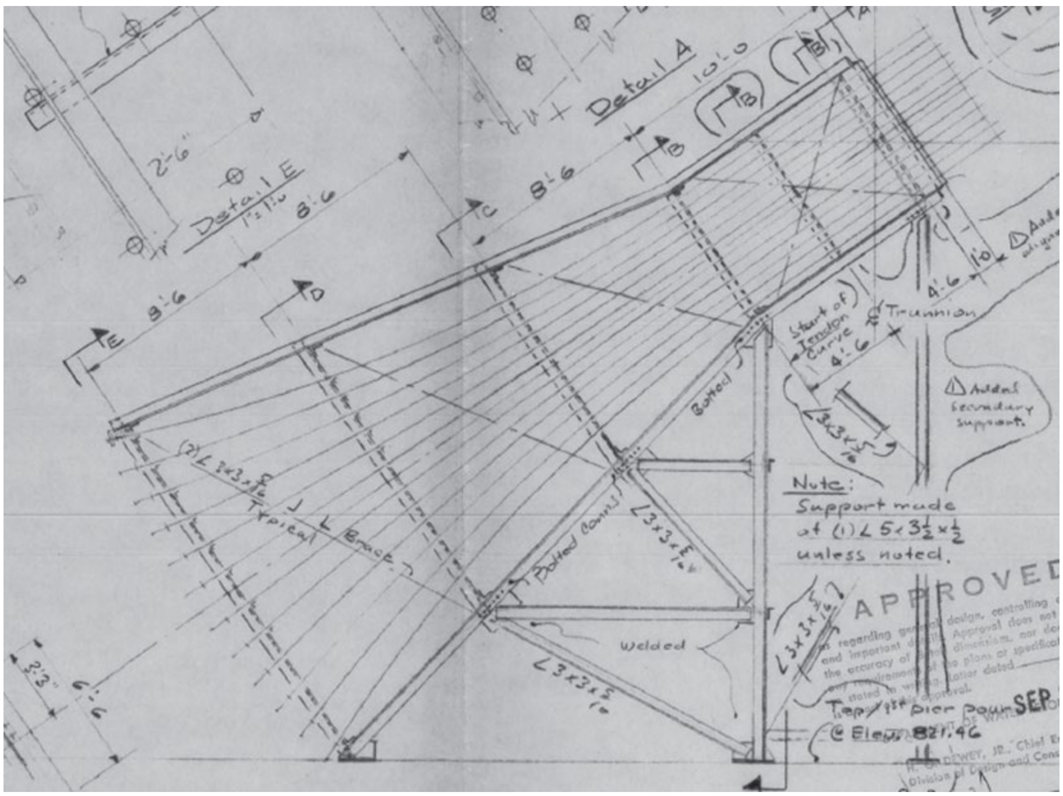
Previous years of traveling with the guided wave test system showed a need to repackage the equipment into a form factor that could survive the occasionally harsh conditions of package carriers. The repackaged equipment contains no new hardware from previous years but provides a safe way to ship the delicate electronics across the country. The equipment is suspended within a Pelican-Hardigg rack mount case with eight points of shock isolation (see Figure 1). This packaging, while increasing the total footprint of the system, increases the overall probability of a successful mission.

Figure 1. Current guided wave system.

# 2 Pretest

Drawings of the trunnion bundles at the Oroville Dam show that the original installation of the tendons required the exposed ends to run parallel to each other. The dead end is curved to an increasingly higher degree, proceeding up and down the rows of the bundles. The drawing for the installation at Oroville Dam is shown in Figure 2.

Figure 2. Rod curvature at Oroville Dam.




Previous years of testing at Oroville Dam have documented the effects of rod curvature on the guided wave results. Overall, rod curvature reduces the amplitude of the return as the angle of curvature increases, in addition to creating anomalous reflectors along the return signal. Studies are underway at ERDC to get a better understanding of why the curvature affects the signal.

# 3 Results

## 3.1 Condition

The conditions of the tendon ends remain unchanged from the previous year (Figure 3). Through sufficient greasing, use of cover boxes, and overhead coverage, it is not expected that the tendon ends will change from year to year. All tendon ends have previously been ground flat and polished.

Figure 3. Transducer attached to tendon end.


## 3.2 2021 results compared to 2020

ERDC's testing of the Oroville Dam in 2021 is the third sequential year of guided wave testing on the 384 tendons. A database of testing parameters has been developed from these years of evaluation. This repository provides a means to determine the optimal hardware settings to accurately portray a snapshot of the rod. Before this year's test, the database was queried for the optimal test parameters by iterating through all the tested parameters and choosing ones that gave the greatest end of rod reflection. The main parameter searched for is the tested frequency since it is what determines which guided wave modes are excited. Certain frequencies, determined by the specimen's geometry, propagate further and provide a larger amplitude response on reflectors.

Figure 4 through Figure 11 provide an overview of the results on a rod-by-rod basis, giving a rating of No Issue, Anomaly, Possible Defect, or Not Tested. Rods given the Not Tested rating were not possible to test due to the cut of the rod being too short to attach the transducer. An additional category was added this year, Variance from Previous Year, which is explained following the figures.

Images are provided in a separate collection with this report to show the raw data used to make these determinations for each rod. Examples of each qualification category are provided in the following sections with a complete overview of each rod that qualified as Possible Defect. The data shown for each example come in two forms: a time-voltage plot (colloquially known as an A-Scan in ultrasonic testing) and a time-frequency plot known as the short-time Fourier transform (STFT). The STFT takes short segments of the signal and applies the discrete Fourier transform (DFT), which gives information on the frequency content present in the signal. These segmented portions of the signal are concatenated together to give a complete picture of the frequency content along the entire time-series return. One of the key characteristics of guided waves is that the frequency packet is dispersive in nature, which means that as the signal propagates the length of the specimen under test, the individual frequencies that compose the packet travel at different speeds. This effect causes the higher-frequency content to travel faster than the lower-frequency content. By observing the data in both spectrums, more conclusions can be drawn about any reflectors.

Figure 4. Gate 1—2021 results compared to 2020 results.

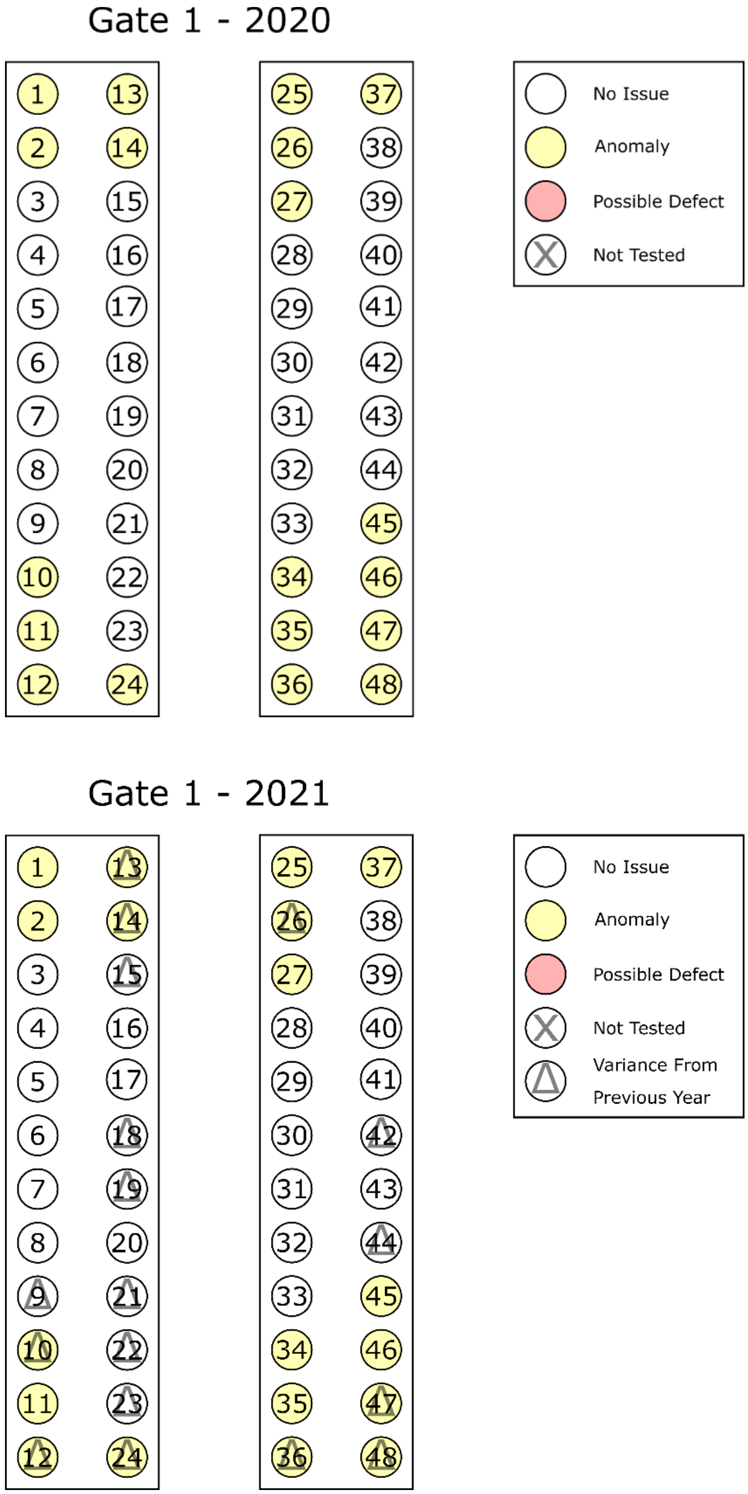


Figure 5. Gate 2—2021 results compared to 2020 results.

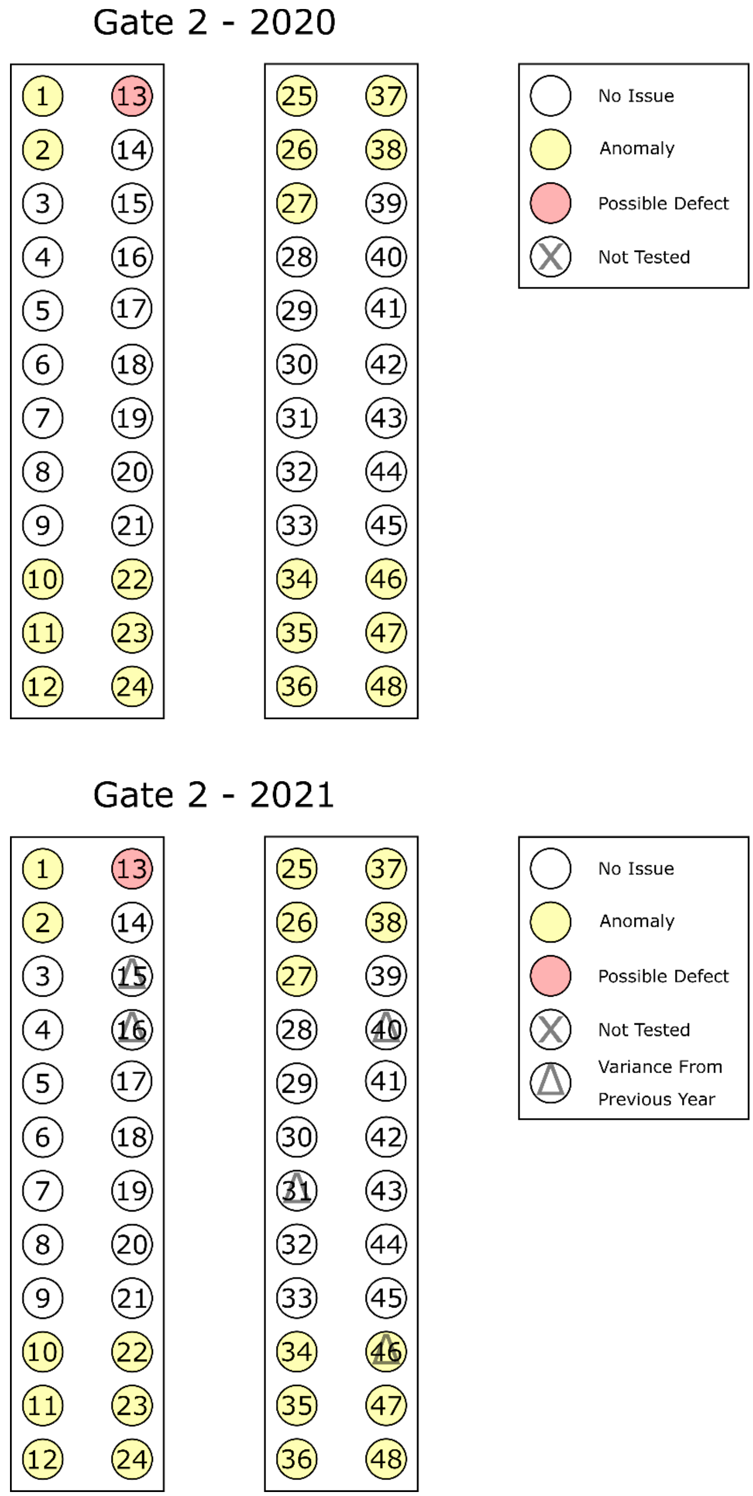


Figure 6. Gate 3—2021 results compared to 2020 results.

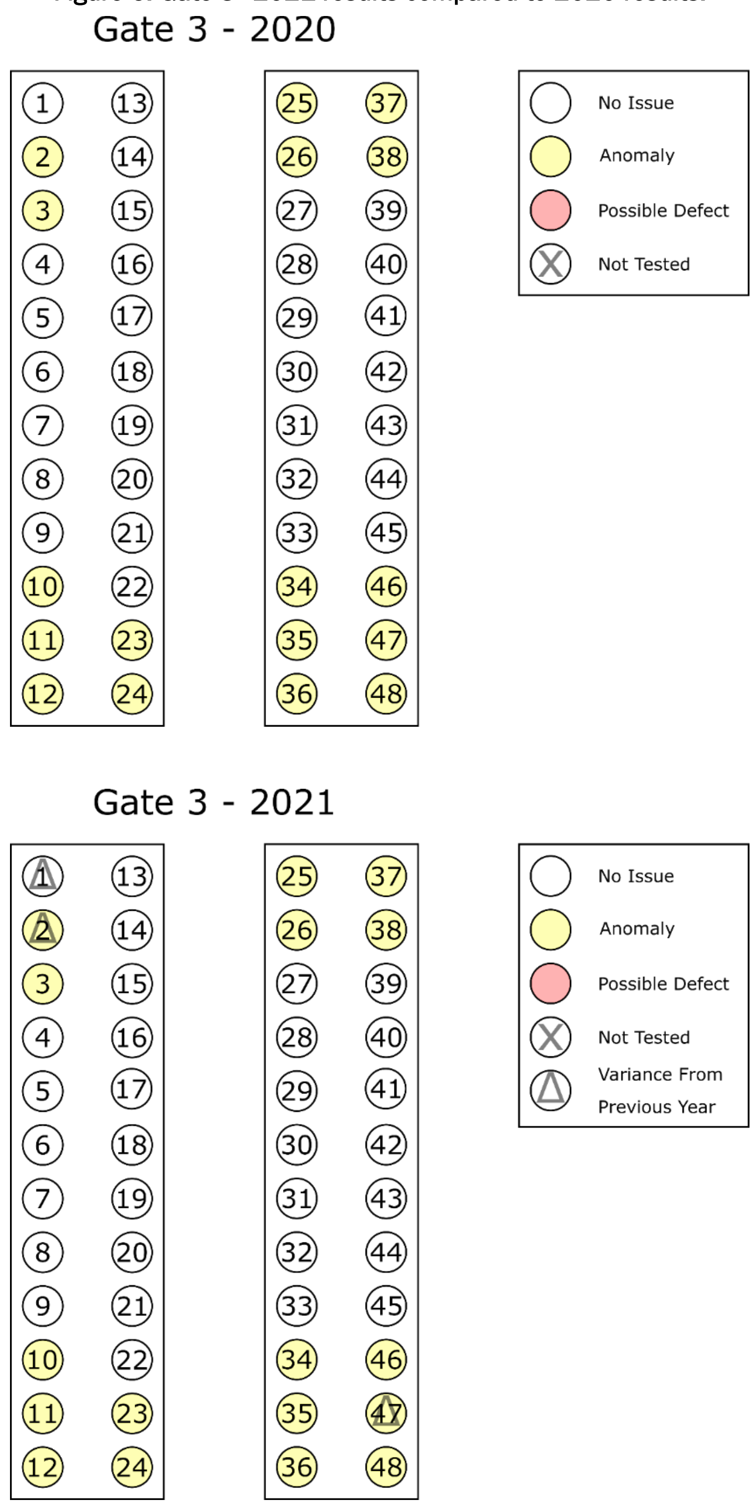


Figure 7. Gate 4—2021 results compared to 2020 results.

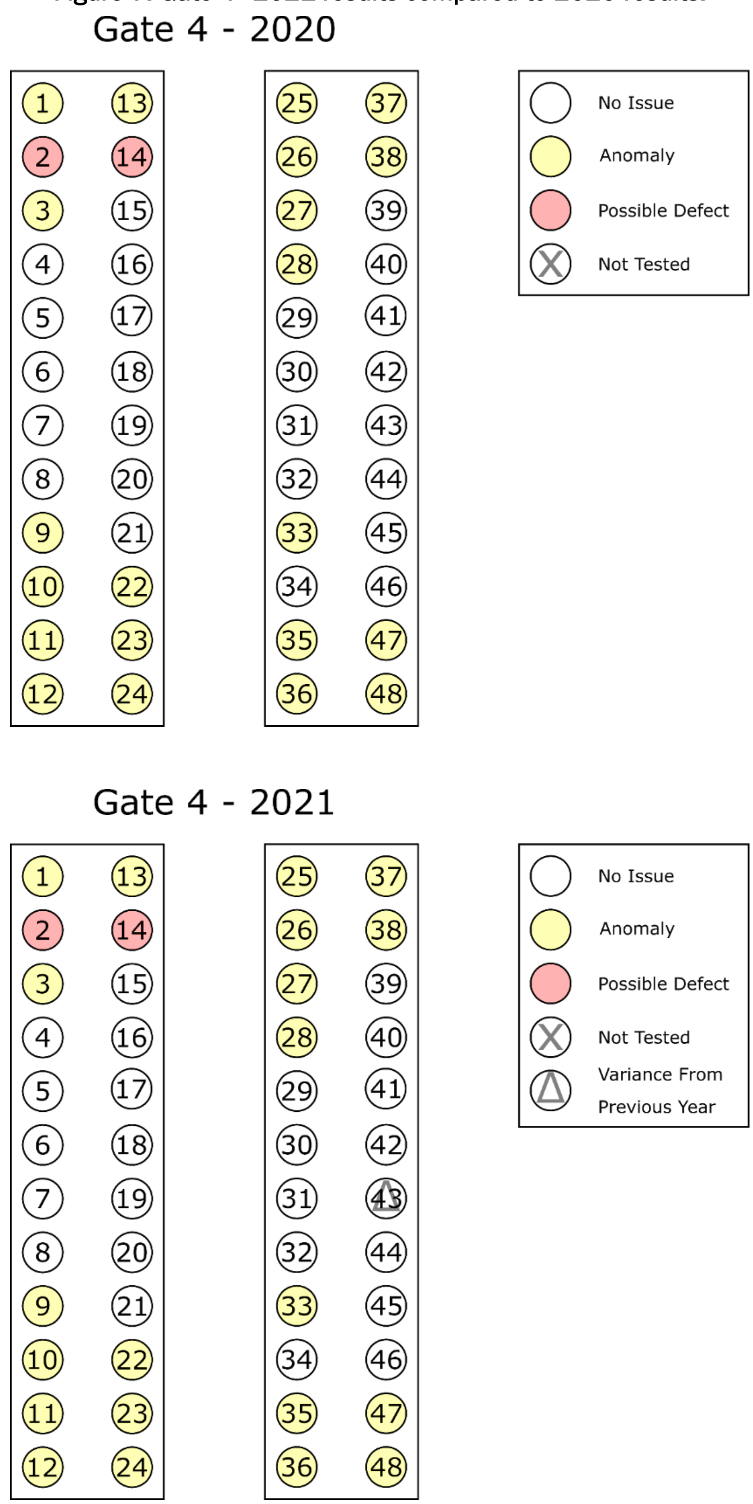


Figure 8. Gate 5—2021 results compared to 2020 results.

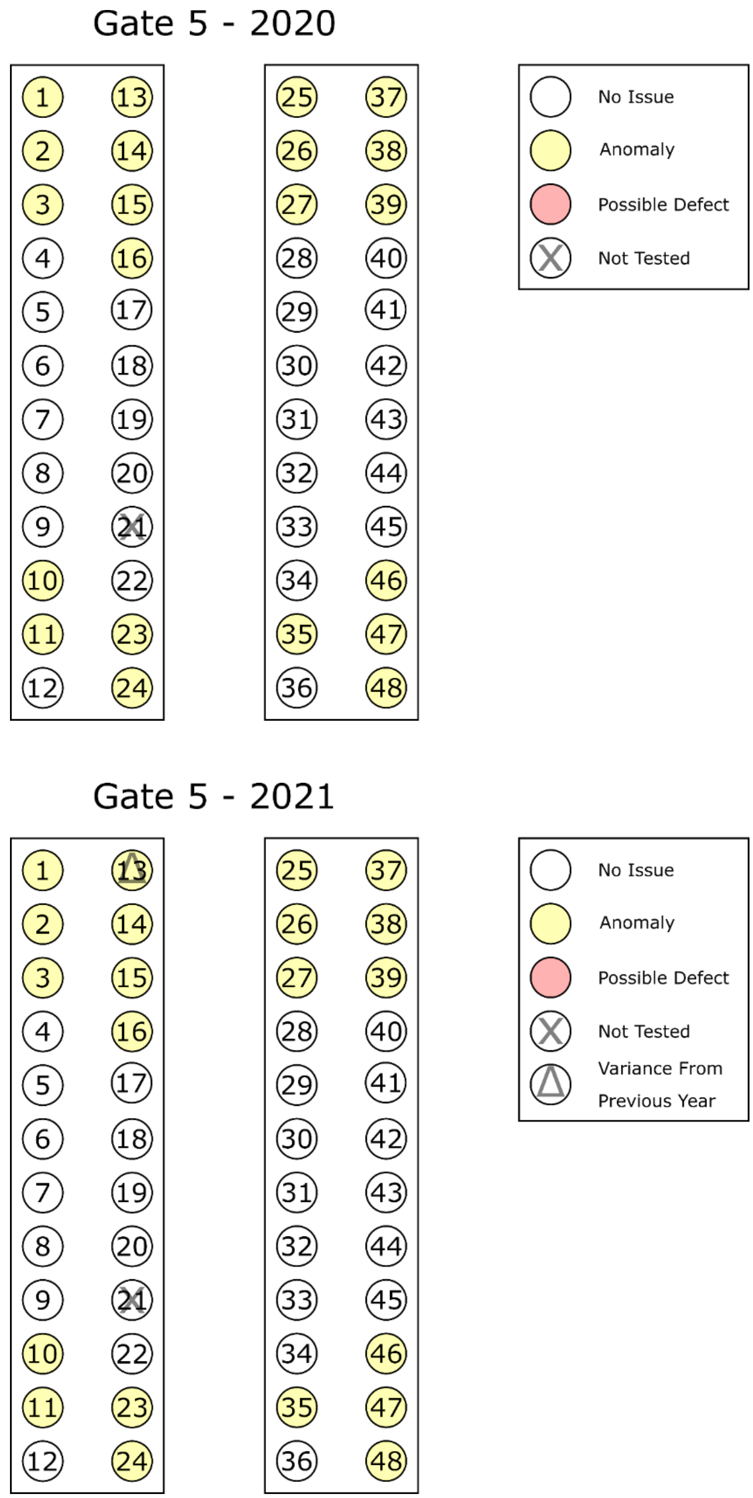


Figure 9. Gate 6—2021 results compared to 2020 results.

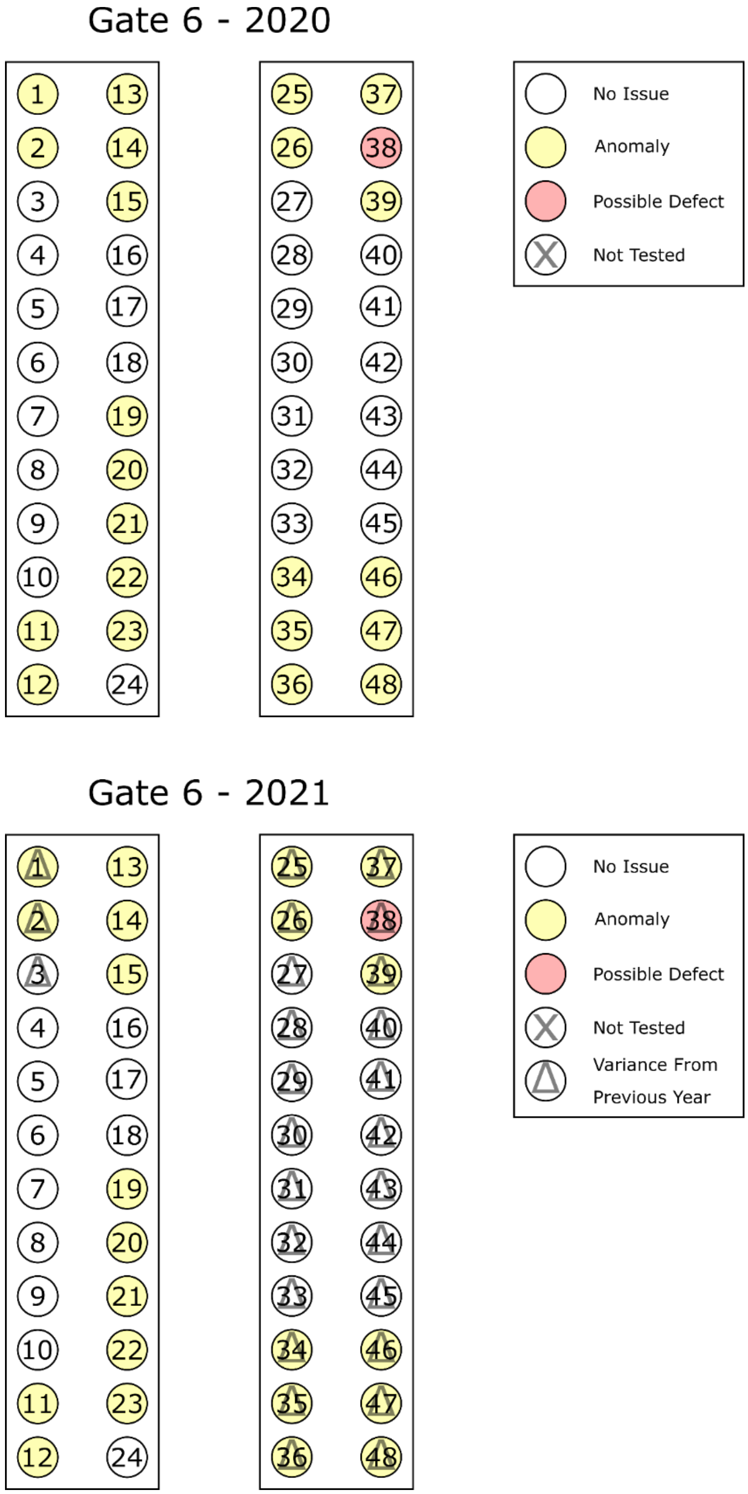


Figure 10. Gate 7—2021 results compared to 2020 results.

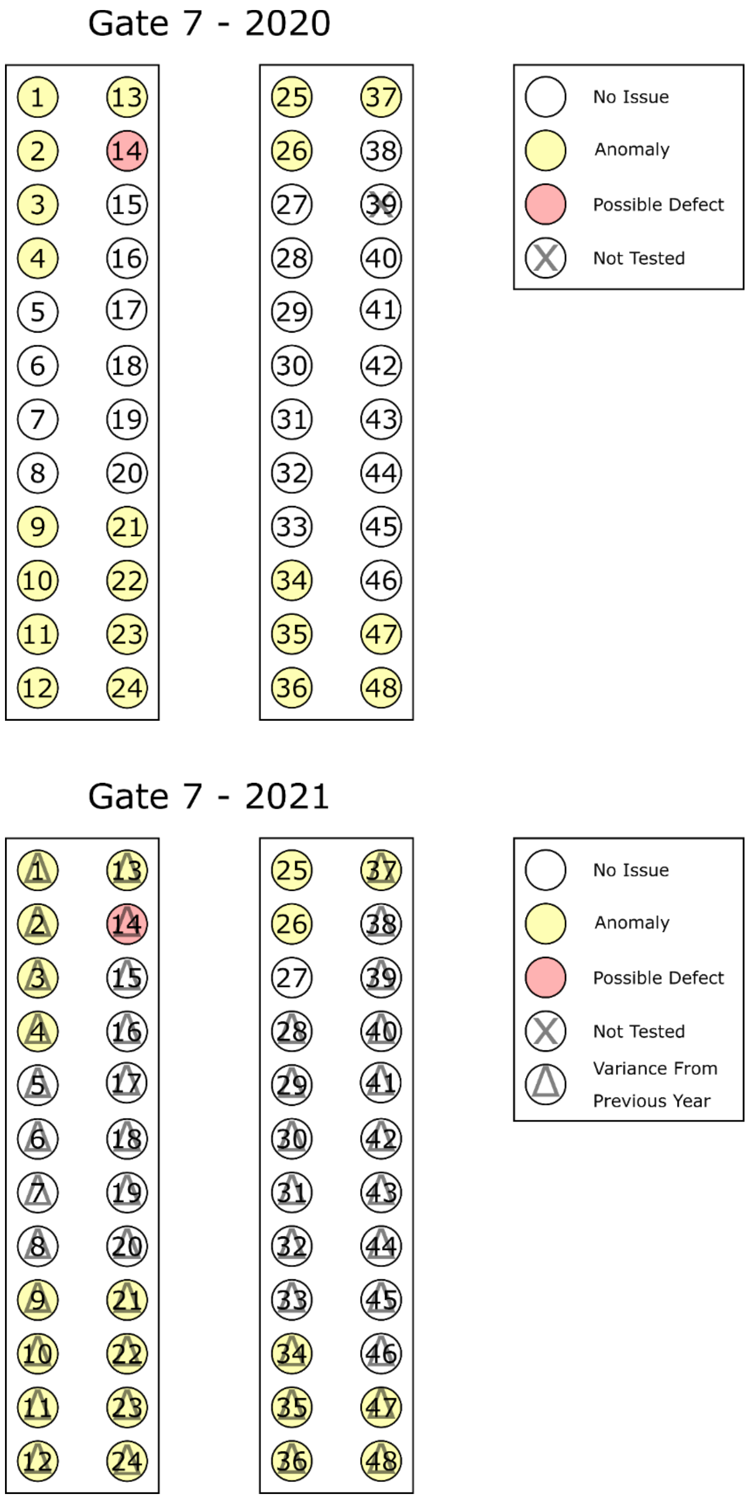
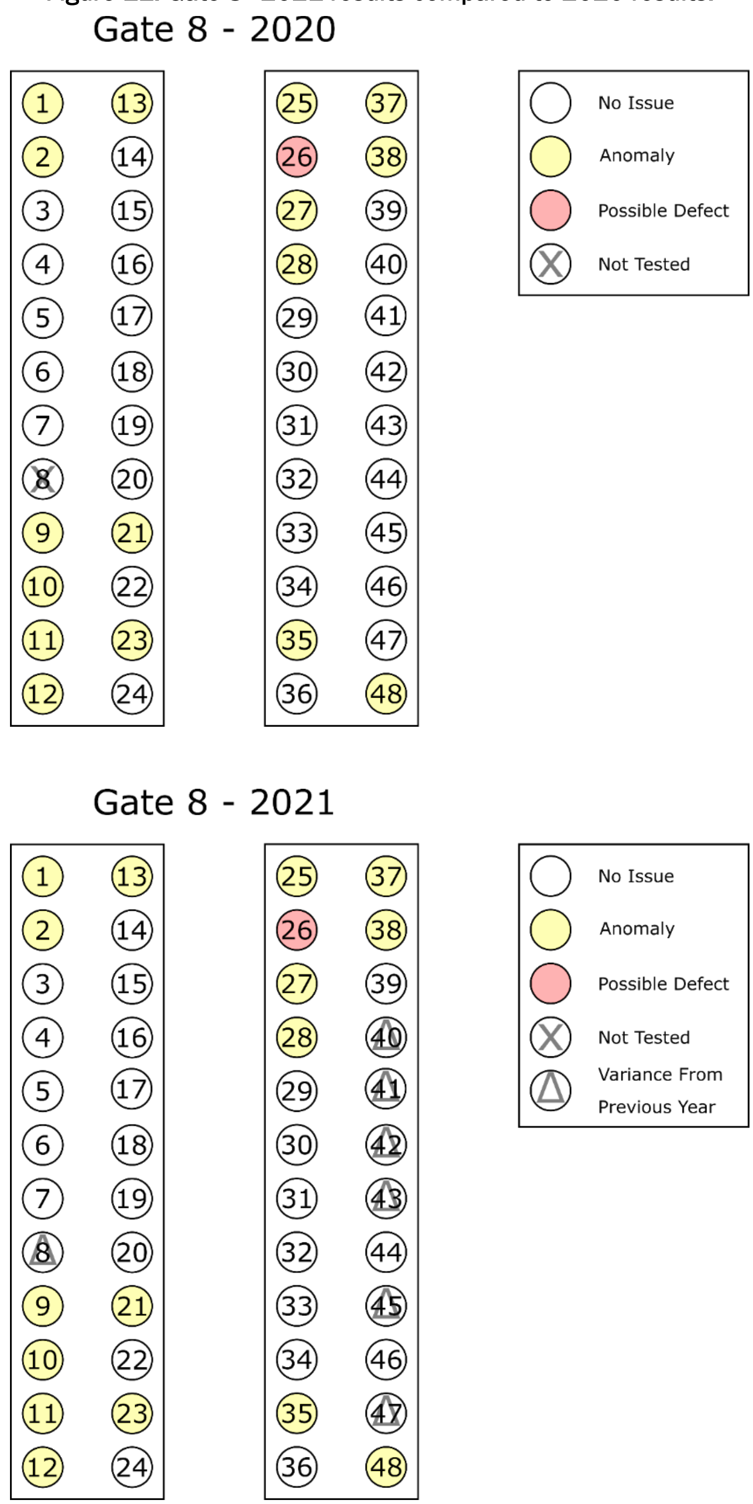


Figure 11. Gate 8—2021 results compared to 2020 results.

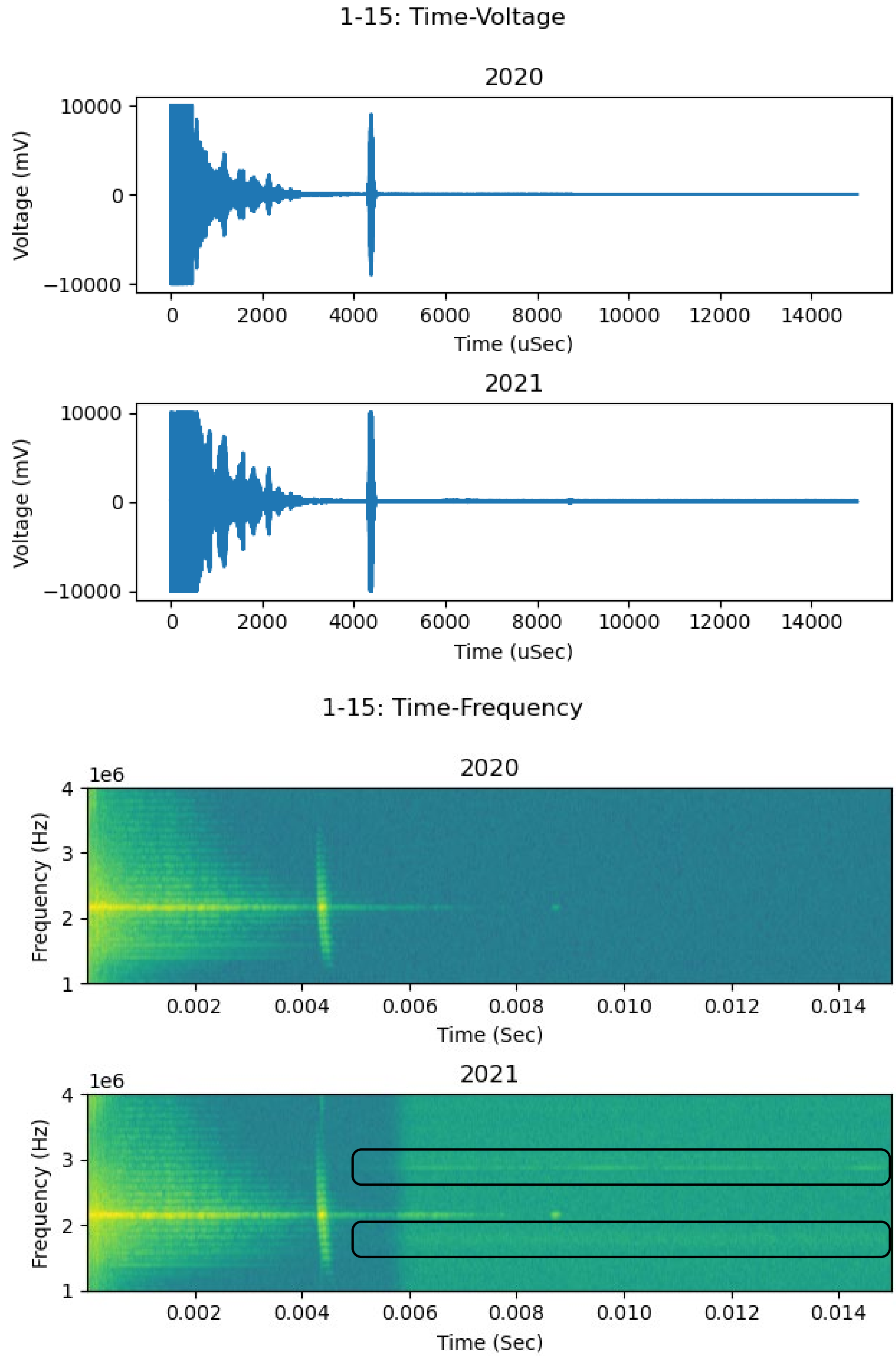


### 3.2.1 Results labeled as Variance from Previous Year

This year a fourth category was added to the possible options of rod condition, Variance from Previous Year. The purpose of this category is to identify changes from year to year that are not indicative of an actual issue. While system settings such as gain and frequency are persistent, there are variables that are not maintainable. For instance, while the transducers used each year are the same make and model, the outputs vary. The overall signature of the response remains the same, but there can be changes in amplitude. It has also been observed that temperature has an effect on how well a previous couplant transferred the acoustic energy into the tendon. This testing year, a new couplant was used to counteract the effects of temperature on the results.

The main indication of rods in this category is the presence of what appears to be electrical noise coupled to the response. This effect is not seen in the time-series data but is pronounced in the time-frequency data. An example of this is shown in Figure 12. All results marked Variance from Previous Year contained similar noise.

Figure 12. Example of a Variance from Previous Year result.



### 3.2.2 Results labeled as No Issue

The results labeled as No Issue mainly consist of anchors that are more centralized within the bundles. In making decisions on what category an anchor falls in, the area between the start of the test and the first rebound is primarily investigated. Any reflectors present in the tendon will appear in this area. Reflectors close to the testing end can be lost in the noise of the return signal due to the amount of energy required to propagate the full distance. Figure 13 shows an example of a No Issue result and illustrates the region of interest in the black rectangular area.

### 3.2.3 Results labeled as Anomaly

Across the eight piers at the Oroville Complex, it has been shown over the previous two testing years that the upper and lower rods within the bundles contain reflectors in the vast majority of the collection. While not thought to be defects, something related to the rod bending in the design specifications causes both these reflectors to appear and greatly attenuate the return signal related to the end of the rod. Figure 14 shows an example of an Anomaly result and illustrates what gave it this label.

### 3.2.4 Results labeled as Possible Defect

As the signature of the reflections on each rod has not changed since the 2020 inspection, the rods that were previously labeled as Possible Defect remain labeled as Possible Defect. Each instance of this labeling is shown in Figure 15 through Figure 18.

### 3.2.5 Rods 4-2 and 4-14

Rods 4-2 and 4-14 continue to show behavior outside what is expected for the Oroville Dam. Not only does the amplitude of the reflections exceed the same positions on the other gates, but the amplitude also exceeds that of most rods at the complex. This larger amplitude response has been confirmed by other contractors on site.

The results of these two rods are shown in Figure 19 and Figure 20. The gain on the transmitting amplifier had to be reduced well beyond what was used on tendons in proximity and in the same position on other piers.

Figure 13. Example of a No Issue result.

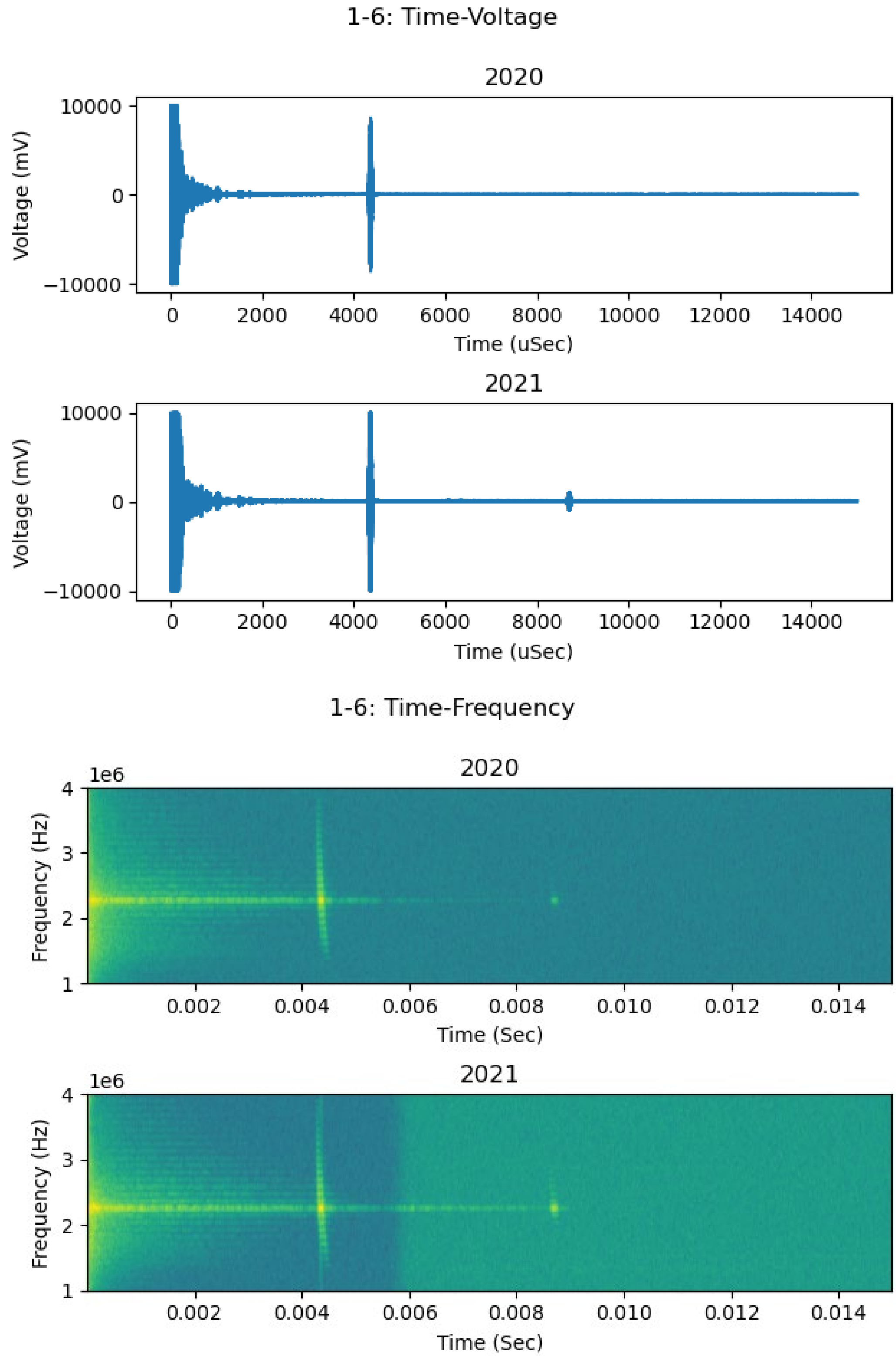


Figure 14. Example of an Anomaly result.

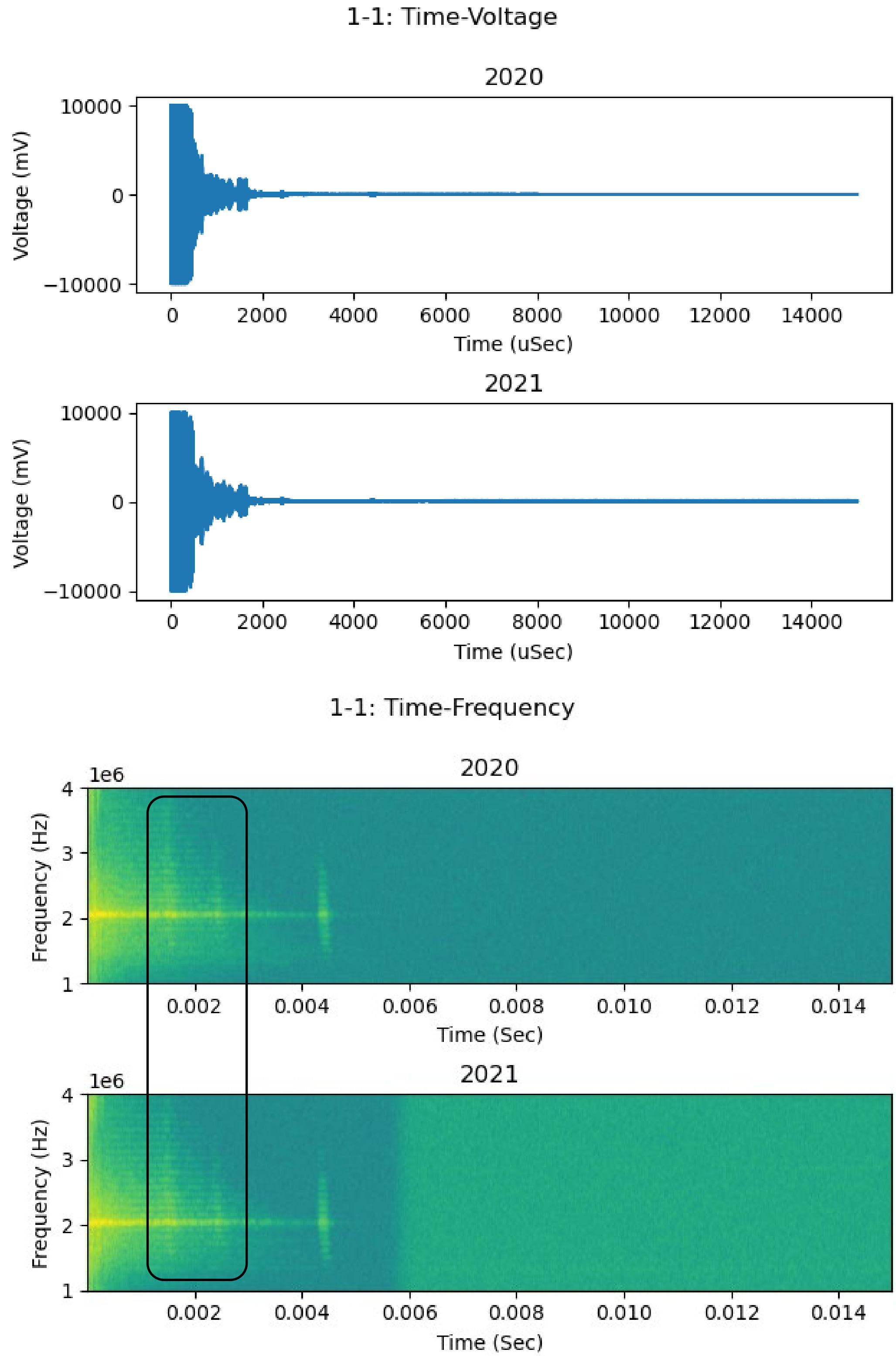


Figure 15. Possible Defect rod 2-13.

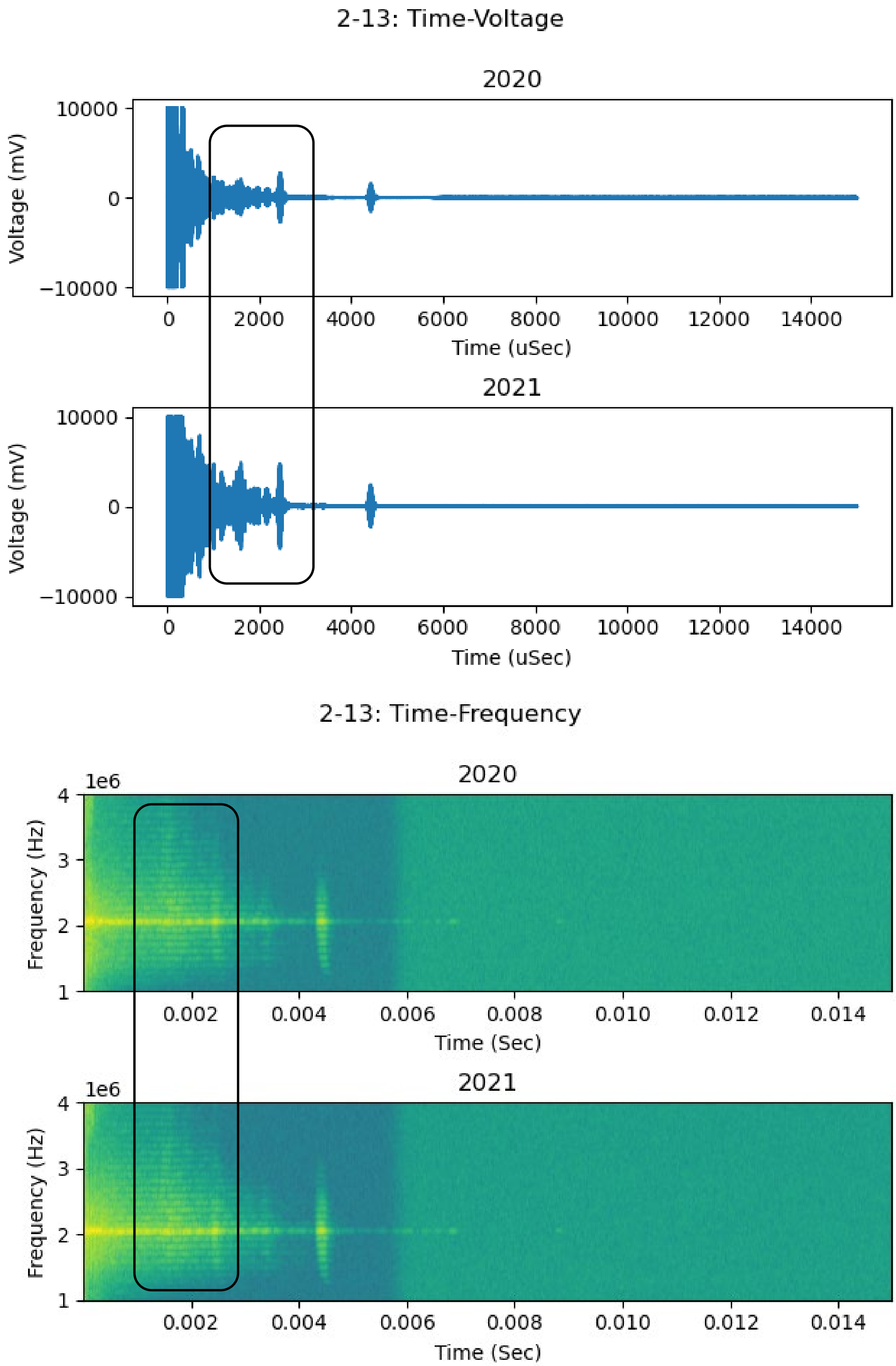


Figure 16. Possible Defect rod 6-38.

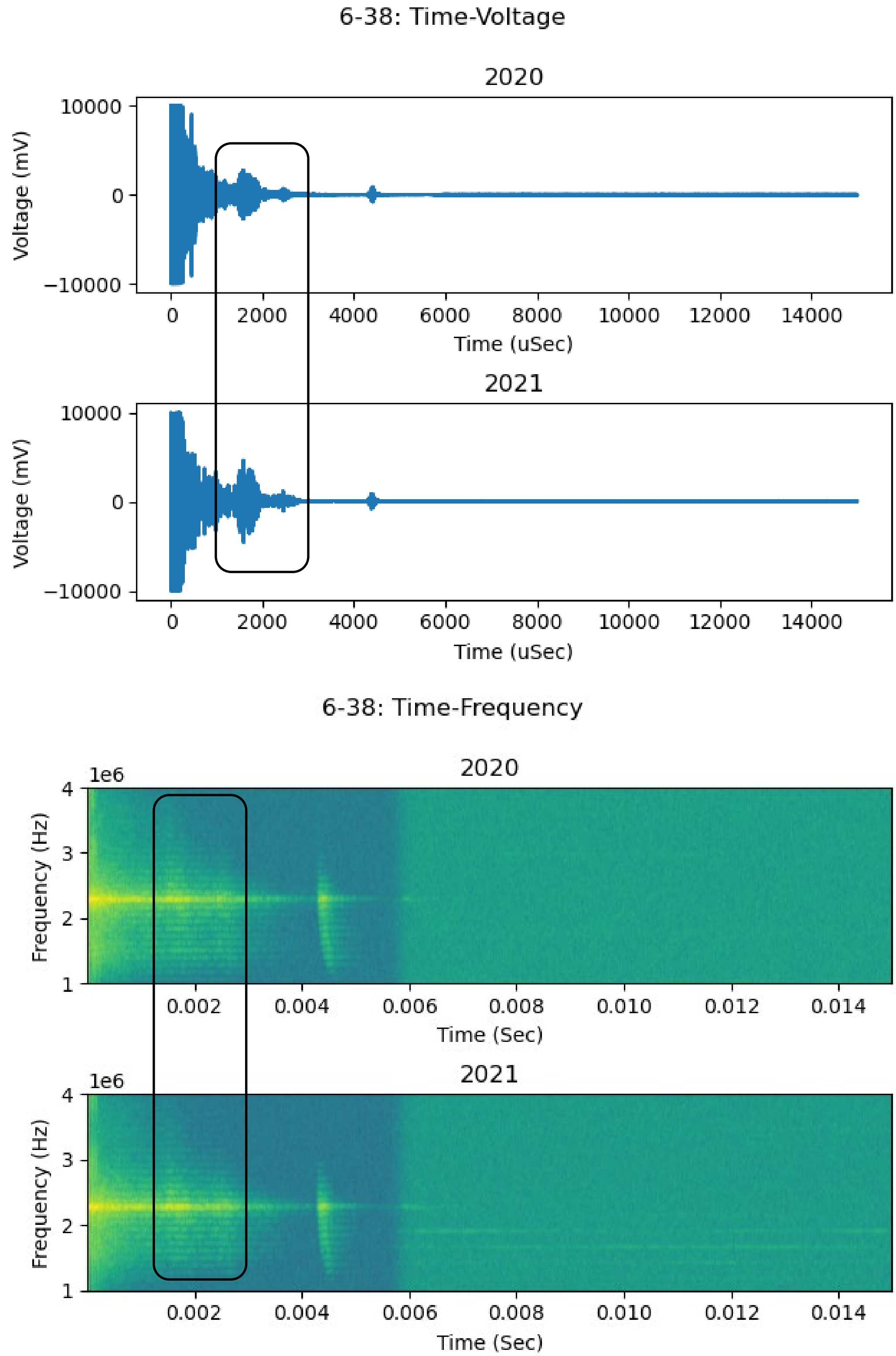


Figure 17. Possible Defect rod 7-14.

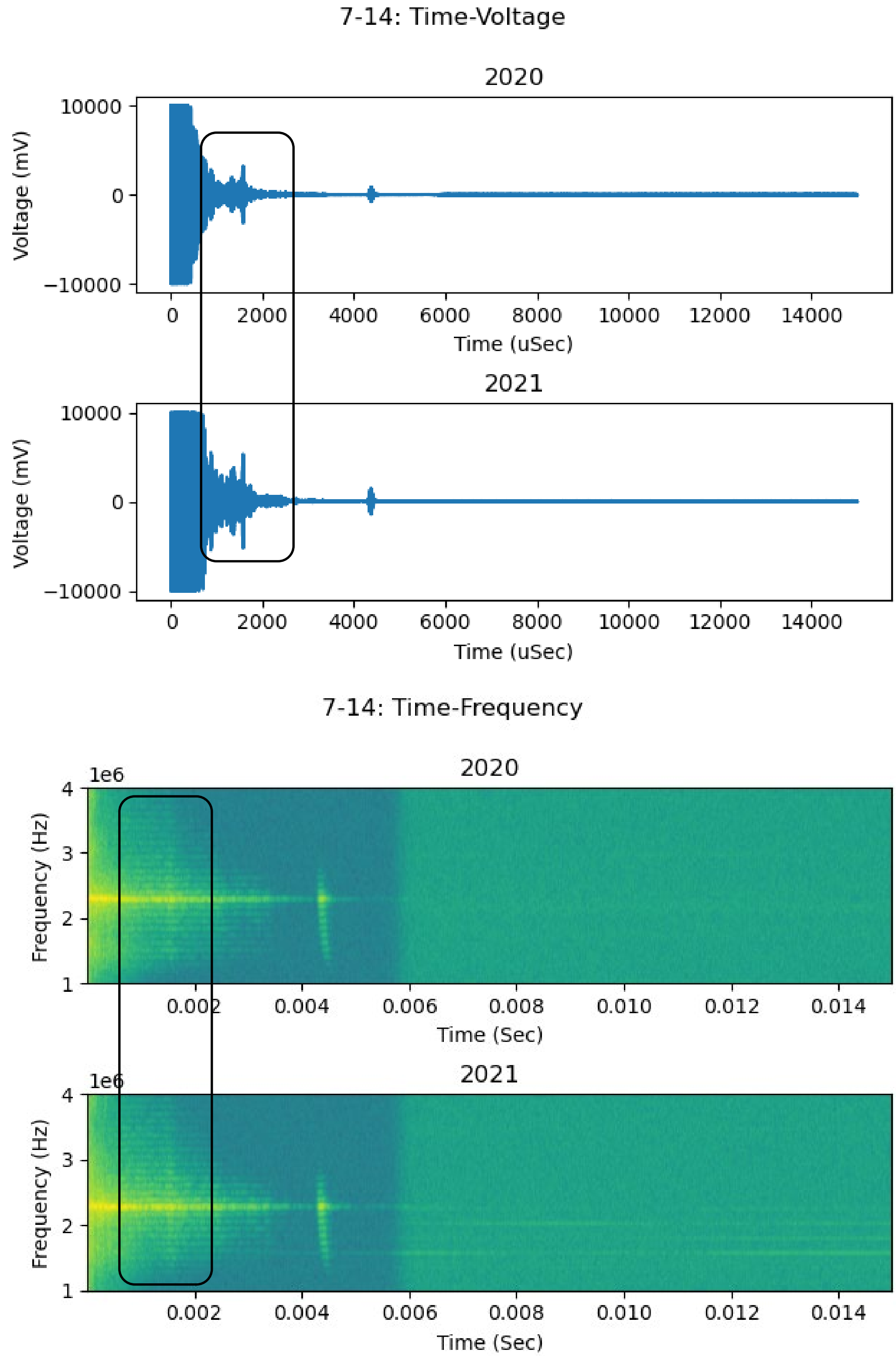


Figure 18. Possible Defect rod 8-26.

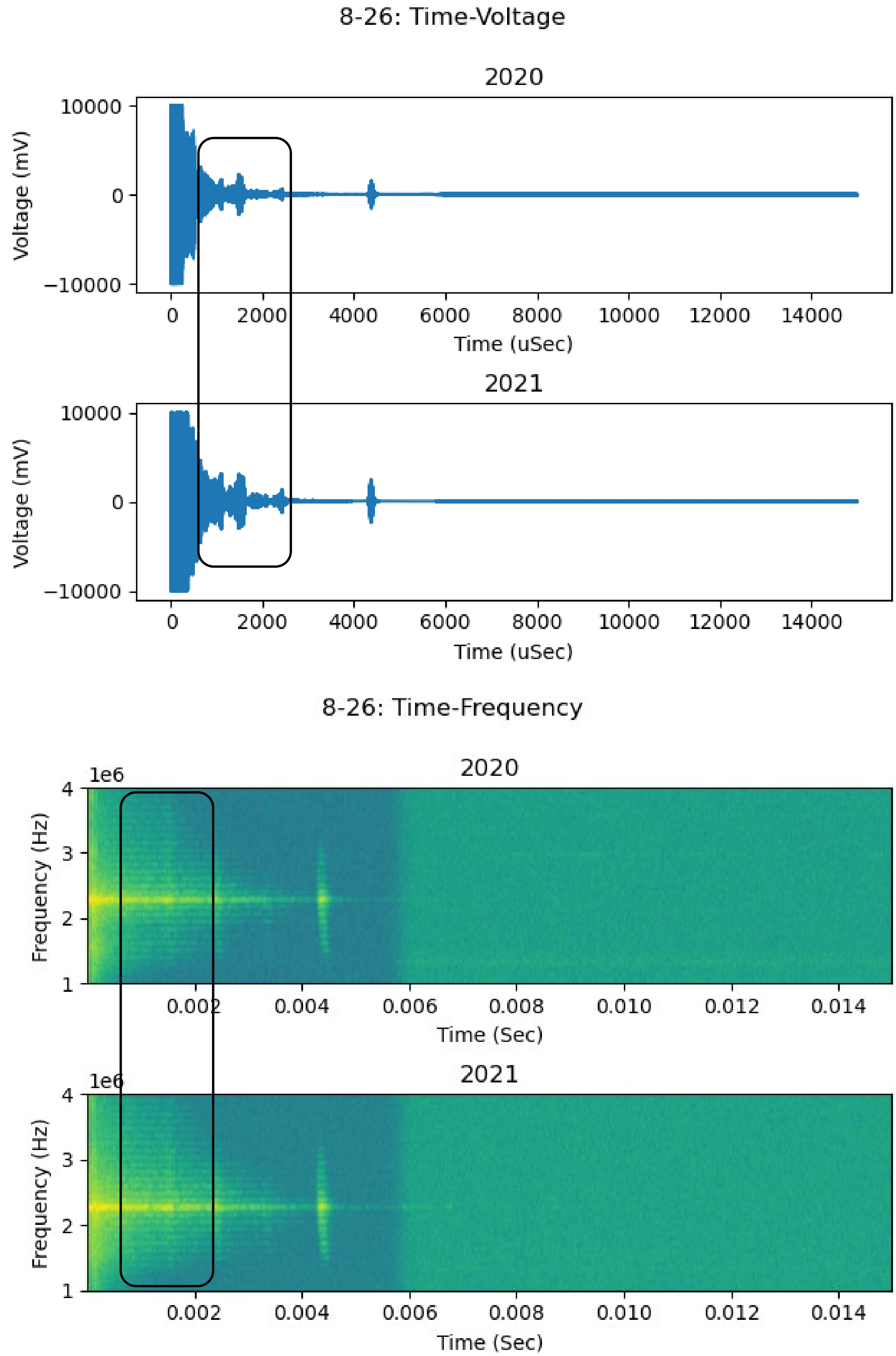


Figure 19. Rod 4-2.

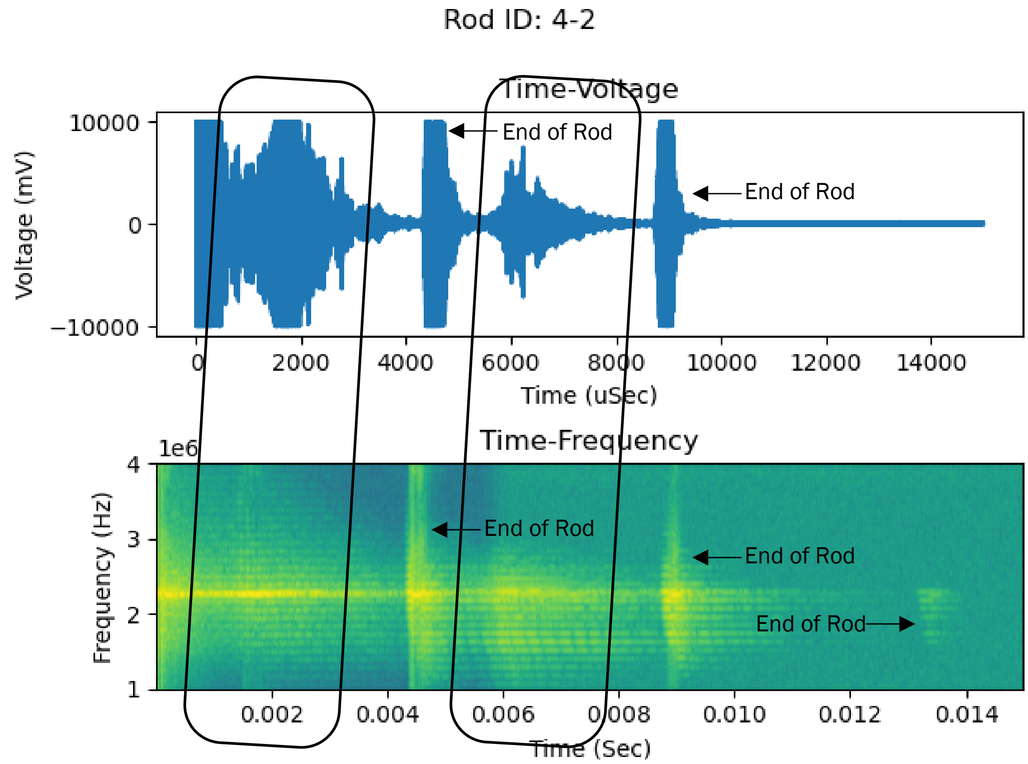
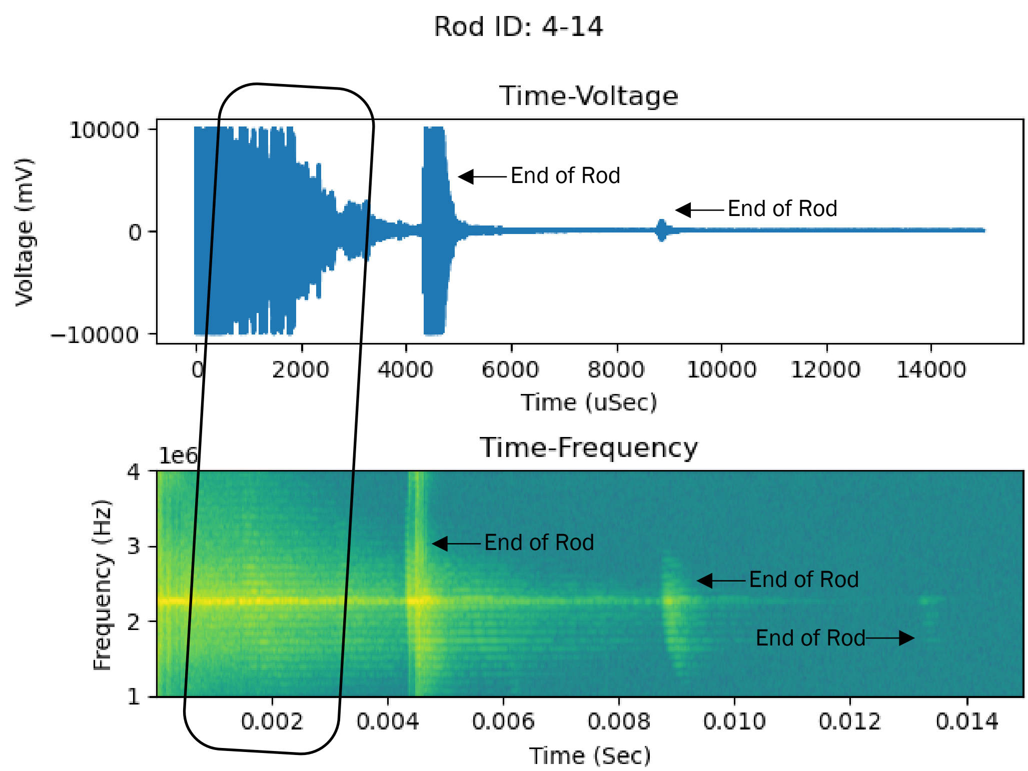



Figure 20. Rod 4-14.



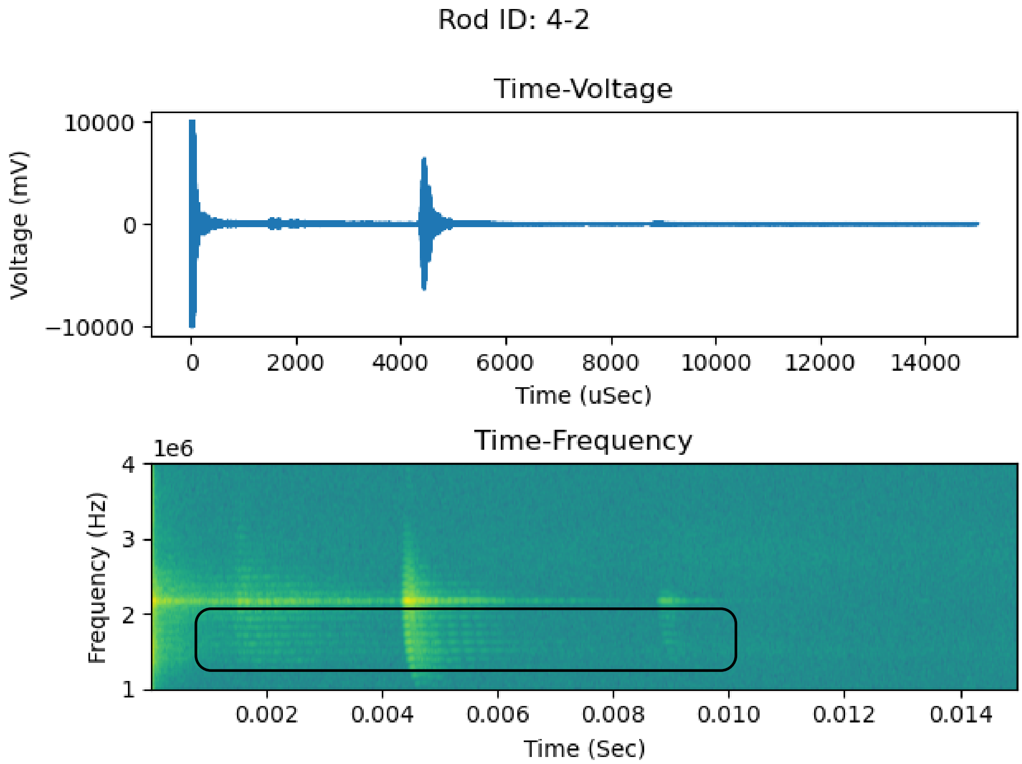
The black rectangle that spans the two plots in each figure shows what looks to be a Possible Defect. If a defect is present in a tendon, the expected result in the amplitude of the end of rod reflection is that it is reduced compared to if the tendon was undamaged. In the case of these two tendons, the amplitude of the end of the rod is very large and even exceeds that of many tendons that are more centralized in the bundles. From a blind-testing perspective, these two tendons appear to not have the same progressive bend as the tendons on the other gates in the same location.

At this time, there are no conclusions to draw as to why these two tendons exhibit this behavior. A true defect in the tendon would provide a reflection between the first and second end-of-rod reflection. The time-series and STFT representation of the tendons do not show this. The acoustic behavior in these tendons is similar to the tendons labeled Anomaly, though the amplitude of the reflections is greater.

Another observation made on these two rods is how the frequency content on the end-of-rod reflection spreads further in time than other tendons. The area outlined in Figure 21 shows this spreading of frequency when plotted as an STFT. This figure captures rod 4-2 tested at a different frequency: 2.169 MHz. This capture was chosen because the end-of-rod reflection did not clip the analog-to-digital converter (ADC).

Unexpected information like this helps to identify tendons that were either installed differently, have a defect, or some other unknown.

Figure 21. Rod 4-2 frequency spreading.



# 4 Conclusion and Recommendations

Based on the results obtained this year in comparison to the results obtained in 2019 and 2020, it appears that the overall condition of the rods remains unchanged. There appears to be electrical noise coupled to the signals on some rods—these rods are labeled as Variance from Previous Year—but this does not indicate a change in rod condition. For the rods now labeled as Possible Defect, aside from rods 4-2 and 4-14, the signature looks similar to those labeled as Anomaly, but the overall amplitude of the reflectors is higher. With other groups reporting similar responses from rods 4-2 and 4-14, the recommendation is to continue observing these anchorages along with comparing the results obtained from this report and the reports of the other contractors.

# Reference

Evans, J. A., and R. W. Haskins. 2015. *Detection of Microcracks in Trunnion Rods Using Ultrasonic Guided Waves*. ERDC/ITL TR-15-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

# Acronyms and Abbreviations

| | |
|---|---|
| ADC | Analog to Digital Converter |
| CSED | Computational Science and Engineering Division |
| DoD | Department of Defense |
| DWR | Department of Water Resources |
| ERDC | Engineer Research and Development Center |
| DFT | Discrete Fourier transform |
| ITL | Information Technology Laboratory |
| NDT | Nondestructive testing |
| SIB | Sensor Integration Branch |
| STFT | Short-time Fourier transform |
| USACE | U.S. Army Corps of Engineers |
| USB | Universal Serial Bus |

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The Engineering and Test Branch within the Division of Operations and Maintenance of the California Department of Water Resources (DWR) and U.S. Army Corps of Engineers (USACE), Sacramento District, tasked the Sensor Integration Branch (SIB) at the Engineer Research and Development Center (ERDC) to perform nondestructive testing (NDT) on the trunnion anchor rods at Oroville Dam through the use of ultrasonic guided waves. This is the fourth year of this NDT. The results of the testing are presented 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 site, knowledge of rod response at other sites, data gathered from the trunnion rod research test bed at ERDC, and comparison to the previous year's effort.

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