Appendix I
Seismic Analysis

December 2019

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1. INTRODUCTION

This Appendix reviews data from permanent seismograph stations and portable monitoring stations in proximity to Vale S.A.'s ("Vale") Córrego do Feijão Mine Dam I ("Dam I") in Brumadinho, Brazil. The objective in gathering these data was to understand the characteristics of recorded ground vibrations proximate to Dam I at or around the time of the failure of the dam on January 25, 2019. This Appendix presents: (i) the sources of data reviewed, (ii) analyses and interpretations of the data, and (iii) conclusions.

2. SOURCES OF DATA

2.1 Permanent Seismograph Stations

The data reviewed were recorded at four permanent seismograph stations: (i) Feijão ("FJAO"), (ii) Água Limpa ("AGLP"), (iii) Bom Sucesso ("BSCB"), and (iv) Diamantina ("DIAM"). FJAO and AGLP are stations in the Vale seismograph network ("VL"); BSCB and DIAM are stations in the Brazilian seismograph network ("BL"). The locations of the Córrego do Feijão mine ("CFJ Mine"), Dam I, and each seismograph station are presented in Table 1. The distance from each seismograph station to the approximate center of: (i) Dam I, and (ii) the CFJ Mine also is shown in Table 1.

Table 1: Locations of CFJ Mine, Dam I, and Permanent Seismograph Stations

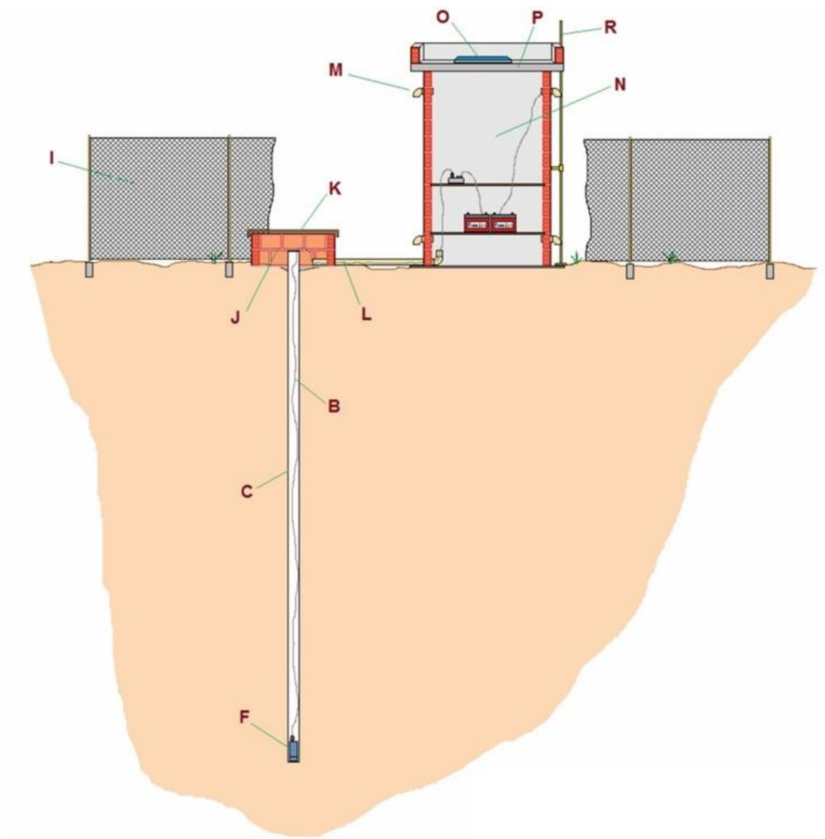
Feature	Coordinates		Calculated Distance to Dam I (m)	Calculated Distance to CFJ Mine (m)
	Northing (m)	Easting (m)		
CFJ Mine[1]	7,776,519.4	591,123.6	1,662	-
Dam I[2]	7,775,080.0	591,955.0	-	1,662
FJAO[3]	7,777,215.3	590,951.6	2,359	717
AGLP[3]	7,794,390.1	685,476.6	95,494	96,030
BSCB[4]	7,678,011.3	524,579.5	118,160	118,878
DIAM[4]	7,976,637.9	641,121.0	207,468	206,270

The review focused on analyzing and interpreting data from FJAO because of its proximity to the CFJ Mine and Dam I. The other three stations are at least 40 times further away from Dam I. For

[1] Approximate center of the excavation (Figure 2).
[2] Approximate center of the dam (Figure 2).
[3] VALE Seismological Network (June 18, 2018) ("Vale Seismological Network Documents").
[4] Rede Sismográfica Brasileira. (2019). Map of seismograph stations in Brazil. Retrieved from http://www.rsbr.gov.br/

this reason, vibrations recorded at FJAO are more representative of those likely to have been experienced at Dam I.

The general configuration of the permanent seismograph stations in the VL seismic network is shown in Figure 1. A nanometrics Meridian Compact digital, broadband seismometer is installed at FJAO in a post-hole at a depth of approximately six meters (m) below the ground surface. The triaxial seismometer measures particle velocity in three orthogonal directions (H1, H2, and Z).[5]



Item	Name
A	Sensor tube cap
B	Sensor cable
C	Sensor tube
D	Cement
E	Crushed glass
F	Sensor
G	Steel cap
H	Acrylic or glass wool
I	Fence
J	Junction box
K	Metal cap
L	Conduit
M	Ventilation
N	Compartment
O	Solar panel
P	Compartment ceiling
Q	Compartment door
R	Pole
S	Shelves
T	Cement floor

Figure 1: General Configuration of VL Permanent Seismograph Stations[6]

2.2 Portable Monitoring Stations

In addition to permanent seismograph stations, three portable monitoring stations—designated as PV7, PV16, and PV17—were installed near Dam I. The locations of the CFJ Mine, Dam I, and the portable monitoring stations are presented in Table 2. The distance from each portable monitoring station to the approximate center of (i) Dam I and (ii) the CFJ Mine is also shown in

5 Vale Seismological Network Documents; FJAO Metadata Data File; Meridian compact posthole. Retrieved from https://www.nanometrics.ca/products/seismometers/meridian-compact-posthole

6 Vale Seismological Network Documents. Note that not all lettered items are included in the figure's diagram.

Table 2. Figure 2 shows the location of the FJAO seismograph station and the three portable monitoring stations relative to Dam I and the CFJ Mine.

Table 2: Locations of CFJ Mine, Dam I, and Portable Monitoring Stations

Feature	Coordinates		Calculated Distance to Dam I (m)	Calculated Distance to CFJ Mine (m)
	Northing (m)	Easting (m)		
CFJ Mine[7]	7,776,519.4	591,123.6	1,662	-
Dam I[8]	7,775,080.0	591,955.0	-	1,662
PV7[9]	7,773,211.0	591,754.0	1,880	3,368
PV16[9]	7,775,093.0	591,524.0	431	1,482
PV17[9]	7,774,969.0	592,066.0	157	1,814

The portable monitoring stations have three sensors mounted in orthogonal directions (transverse, longitudinal, and vertical) to record ground vibrations and a microphone to record air-borne noise. Unlike the permanent seismograph stations that record continuously, the portable monitoring stations are set to trigger (i.e., begin recording) once the velocity of ground vibrations exceeds 5×10^{-4} meters per second (m/s).[10]

7 Approximate center of the excavation (Figure 2).
8 Approximate center of the dam (Figure 2).
9 Seismographic Monitoring Technical Report, Córrego do Feijão Mine Region (Vale 2019) ("Vale Seismographic Monitoring Report").
10 Vale Seismographic Monitoring Report.

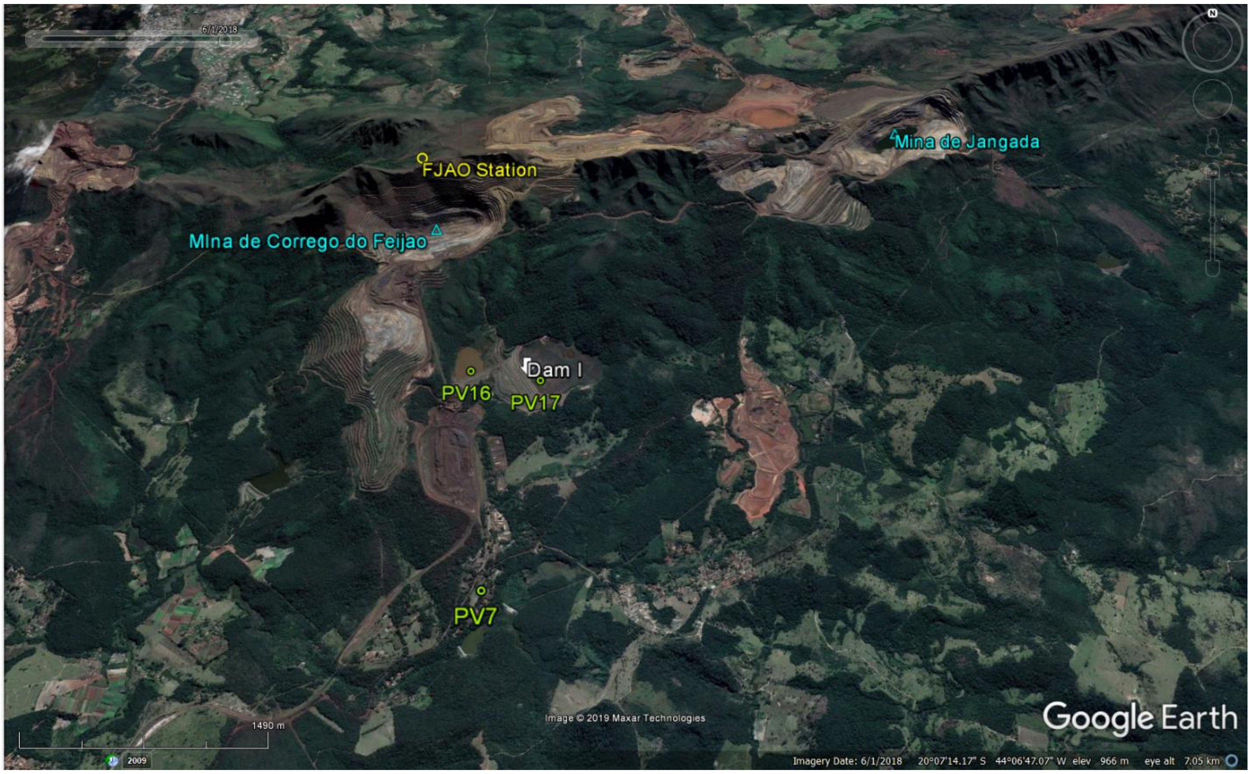


Figure 2: Locations of Dam I, CFJ Mine, FJAO Seismograph Station, and Portable Monitoring Stations[11]

2.3 Time of Failure of Dam I

For comparison with the seismograph data, this Appendix relies on video analysis to identify the time of the failure of Dam I. The first visible indication of failure occurs at 12:28:21:90 local time on January 25, 2019 (Appendix D). As described in Appendix D, the time of initiation of the failure used herein has been subtracted by one second to account for the time difference between the time stamp of the video camera and Coordinated Universal Time (UTC), adjusted to local time (UTC -2).[12]

11 Google Earth. (n.d.). Retrieved June 1, 2018. Text added by authors.

12 According to a report issued by the University of São Paulo, the time at the FJAO seismograph station is synchronized via the Global Positioning System (GPS) and is accurate within approximately one microsecond. Seismographic Network of the Iron Quadrangle: Seismological Monitoring, Center of Seismology, University of São Paulo (February 2019) (“USP Seismographic Network for the Iron Quadrangle Report”).

3. ANALYSIS AND INTERPRETATION OF DATA

3.1 Permanent Seismograph Stations

Data from the FJAO seismograph station was provided in miniSEED file format. Additional metadata was provided to define the sensor characteristics, such as sensitivity. The raw sensor output was converted to ground velocity prior to interpretation by: (i) detrending each time series, (ii) using the instrument sensitivity to calculate the ground velocity in m/s, and (iii) applying a high-pass filter with a corner frequency of 1 hertz (Hz) to remove low-frequency noise.

Figure 3 shows the recorded data at the FJAO seismograph station on January 25, 2019, between 10:00 and 14:00 local time. The time of the visible initiation of the Dam I failure (12:28:21:90) also is depicted for reference. The three seismograms present the measured particle velocity as a function of time in the H1, H2, and Z directions. The seismograph data were adjusted to local time (UTC -2) to facilitate comparisons with the time of the Dam I failure. There are two events recorded at FJAO that occur near the time of the failure: (i) a small-velocity event (“Event 1”) and (ii) a larger-velocity event that occurs subsequently (“Event 2”). No other events are apparent during this four-hour time period.

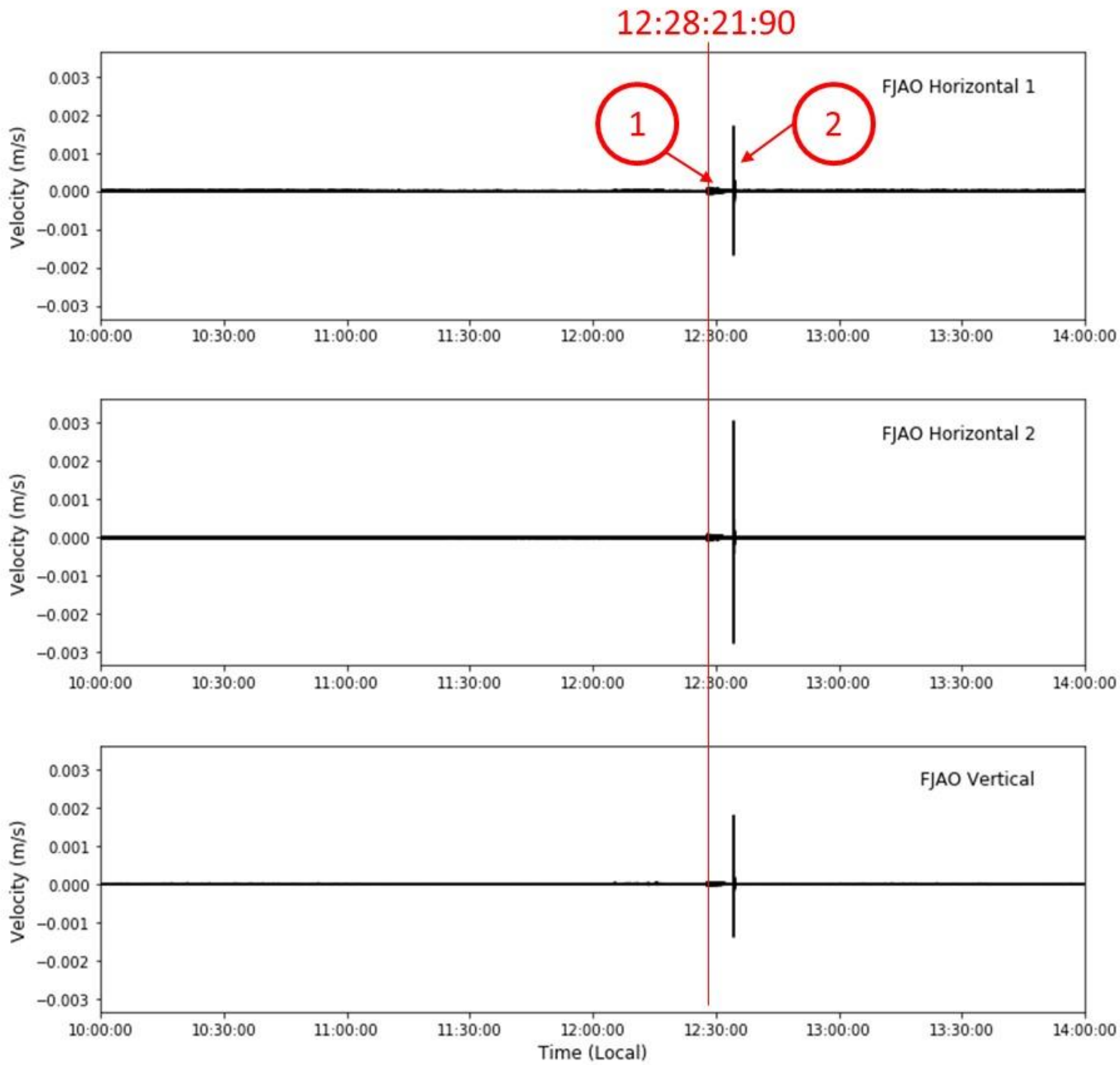


Figure 3: FJAO Seismograph Data for 10:00 to 14:00 Local Time on January 25, 2019

Figure 4 depicts the seismograms plotted on an expanded time scale from 12:27:00 to 12:35:00 local time. Event 1 appears to initiate prior to the first visible indication of the initiation of the Dam I failure as established by the video analysis, and Event 2 occurs approximately six minutes after the initiation of the failure.

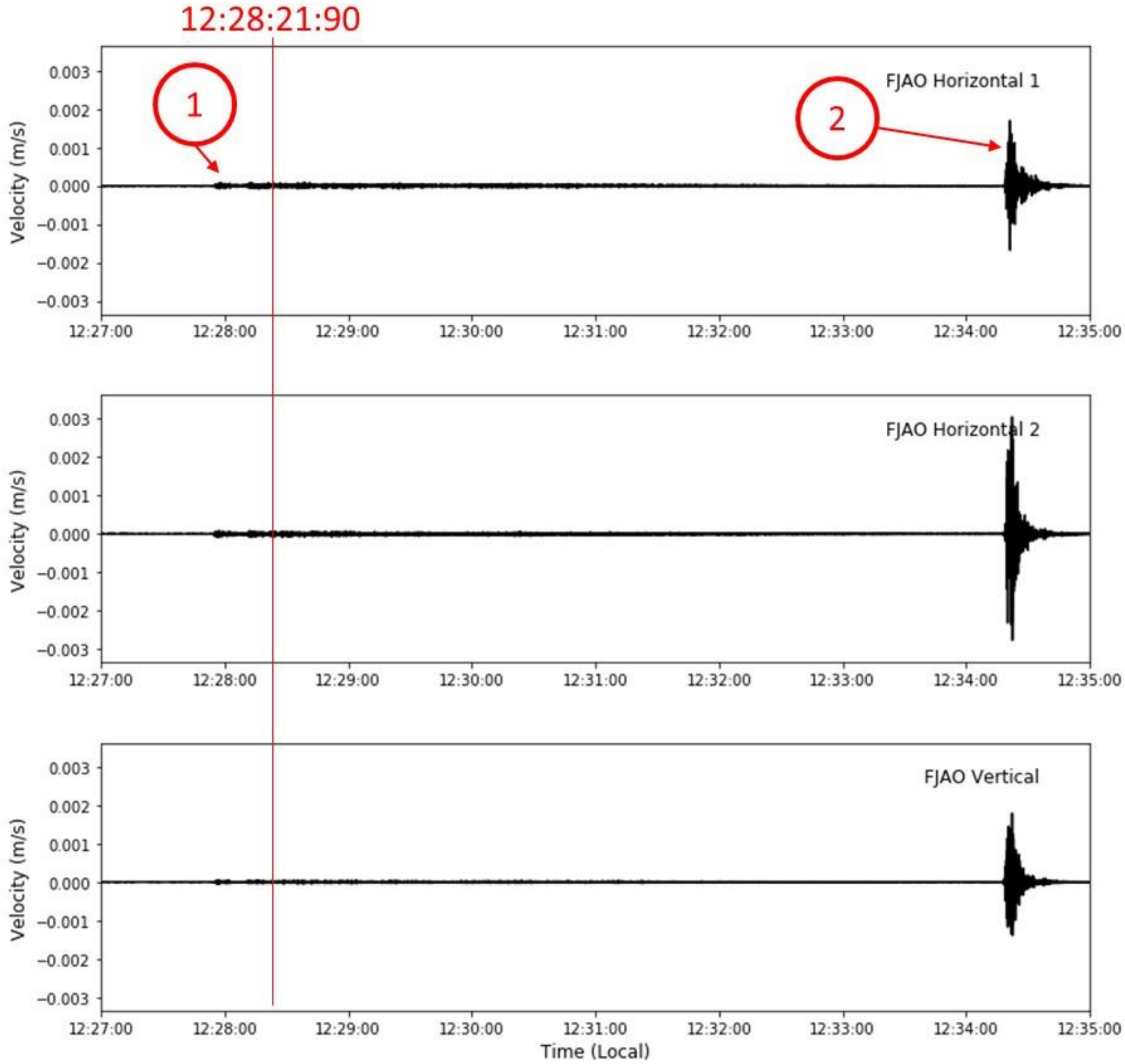


Figure 4: FJAO Seismograph Data for 12:27 to 12:35 Local Time on January 25, 2019

Figures 5 and 6 are expanded plots of Events 1 and 2, respectively, to enable additional details to be seen for each event. Event 1 initiated at approximately 12:27:54 local time with a duration of approximately six minutes, and the peak velocity (recorded on H2) is approximately 9×10^{-5} m/s. Event 1 appears to consist of two subevents – an initial subevent at 12:27:54 that had a duration of approximately 16 seconds, followed by a second, continuous event at approximately 12:28:10 local time. Event 2 initiated at approximately 12:34:17 local time with a shorter duration of approximately 10 to 20 seconds and a larger velocity (recorded on H2) of approximately 3×10^{-3} m/s.

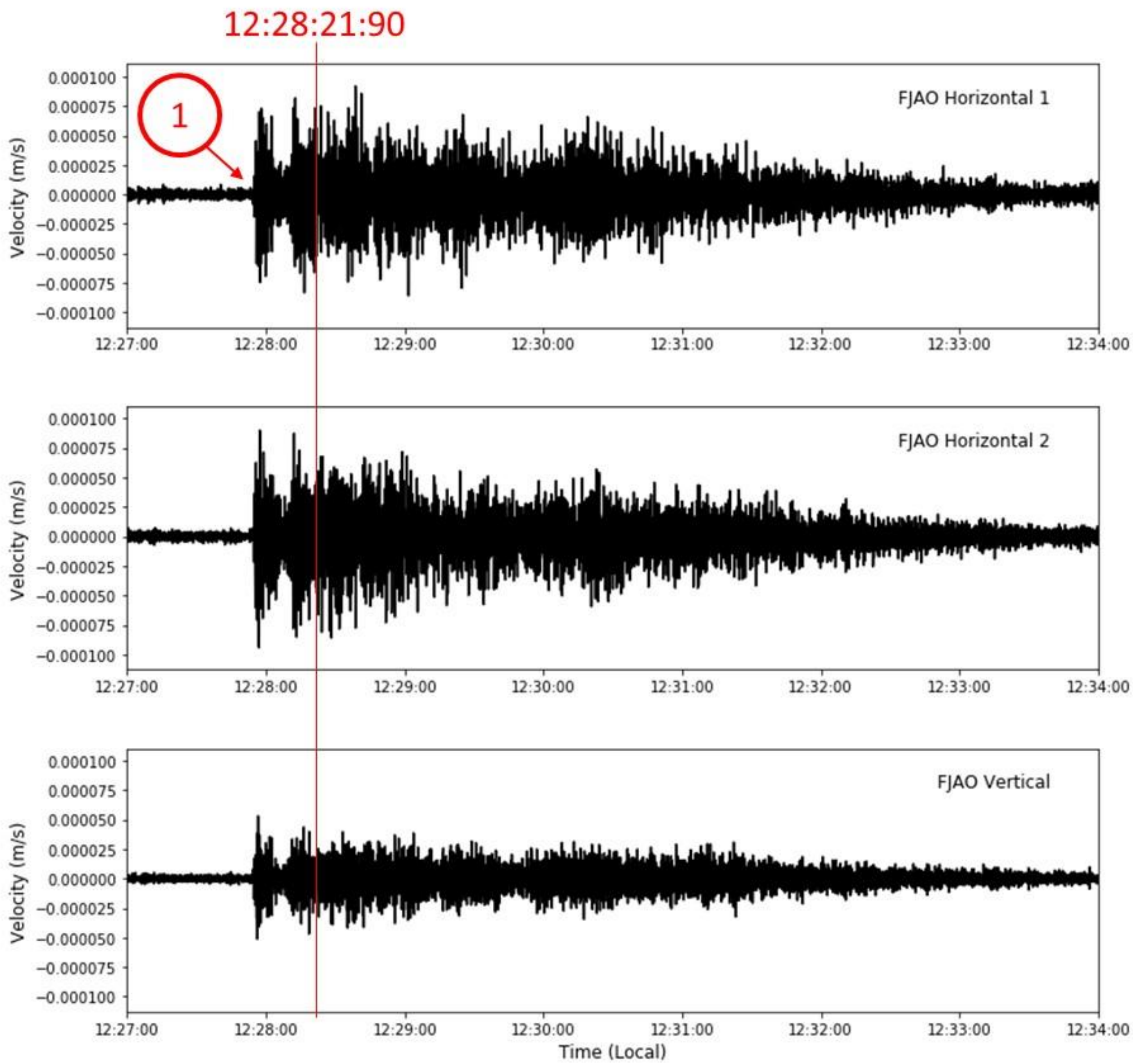


Figure 5: FJAO Seismograph Data for Event 1 on January 25, 2019

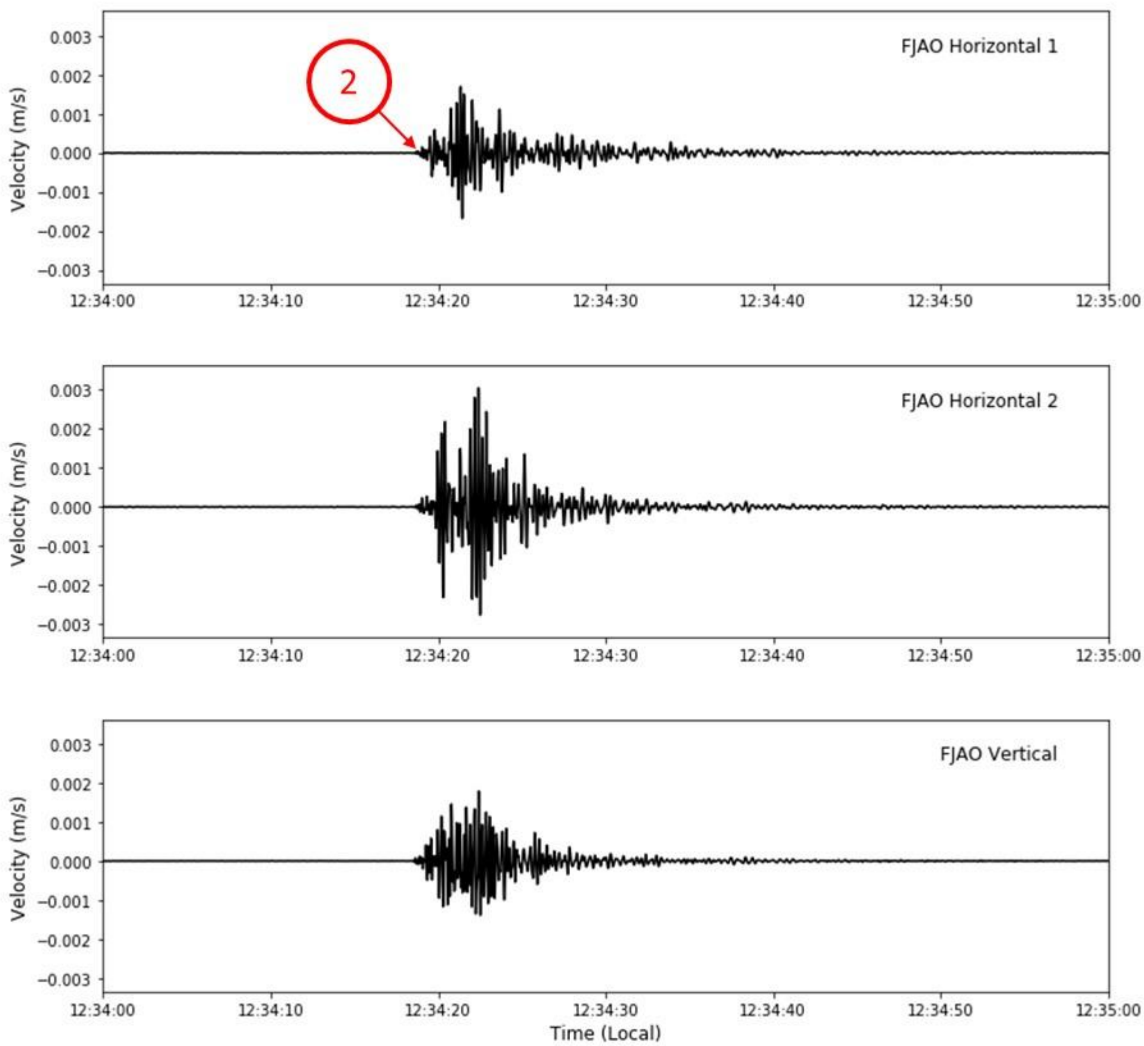


Figure 6: FJAO Seismograph Data for Event 2 on January 25, 2019

Neither event displays the characteristics of a natural earthquake in terms of duration, frequency content, or other waveform properties, which is supported by reports from the University of São Paulo.[13] Furthermore, in a report issued following the failure, the University of Brasilia found no earthquake activity occurred on January 25, 2019 within 100 kilometers (km) of Dam I.[14]

13 Revised Bulletin from the Station Records of Vale's Seismographic Network, Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo (January 28, 2019) ("USP Bulletin on Vale's Seismographic Network"); USP Seismographic Network for the Iron Quadrangle Report.

14 Seismic Bulletin: Seismic Activity in the Brumadinho Region for the Last Six Months, Institute of Geoscience/Seismological Observatory, University of Brasília (January 29, 2019).

The peak velocity for Event 1 was significantly less than the minimum safe levels of ground vibration required to reduce the potential for threshold damage in residential structures, which range from approximately 1.5×10^{-2} m/s to 5×10^{-2} m/s.[15] As further set out in a report from the University of São Paulo, the calculated response spectra for Event 1 are less than those calculated for various events recorded at FJAO on or before January 25, 2019, including natural earthquakes.[16] Accordingly, it appears that Dam I was subjected to seismic excitation greater than Event 1 on various occasions prior to the failure.

3.1.1 Evaluation of Potential Blasting Events

To evaluate whether Events 1 and 2 may be associated with blasting events at CFJ, the characteristics of Events 1 and 2 were compared with data recorded at FJAO on four prior dates: January 7, 2019, January 10, 2019, January 14, 2019, and January 22, 2019. These four dates were selected because firing plans indicate that blasts occurred at CFJ on these days at the times shown in Table 3. Firing plans ("planos de fogo") are records maintained by Vale that document the time and location of a blast, the number and configuration of holes for explosives, and the mass of explosives used.

Table 3: Blasts at CFJ from January 7 to 22, 2019, as Documented on Available Firing Plans[17]

Date	Time	Location	Number of Holes	Mass of Explosives (kg)
January 7, 2019	14:50	1170 ZE	150	10,915
January 10, 2019	11:25	1170 ZE	81	8,510
January 14, 2019	11:25	1010 ZN	110	2,240+
January 22, 2019	13:10	1050 ZS	70	4,910

Figures 7 through 10 show the seismograms recorded at FJAO on the four prior dates at times that approximately correspond to the time recorded in the firing plans. The seismograms have durations of 10 to 20 seconds and peak velocities that range from approximately 6×10^{-4} m/s to 3×10^{-3} m/s. Differences in the observed peak velocities correspond reasonably well to the varying mass of explosives used for each blast.

15 U.S. Bureau of Mines. (1980). Structure response and damage produced by ground vibration from surface mine blasting (Report of Investigation (RI) 8507). Washington, DC: U.S. Government Printing Office.

16 USP Seismographic Network for the Iron Quadrangle Report.

17 Vale Córrego do Feijáo Firing Plan for January 7, 2019; Vale Córrego do Feijáo Firing Plan for January 10, 2019; Vale Córrego do Feijáo Firing Plan for January 14, 2019; Vale Córrego do Feijáo Firing Plan for January 22, 2019.

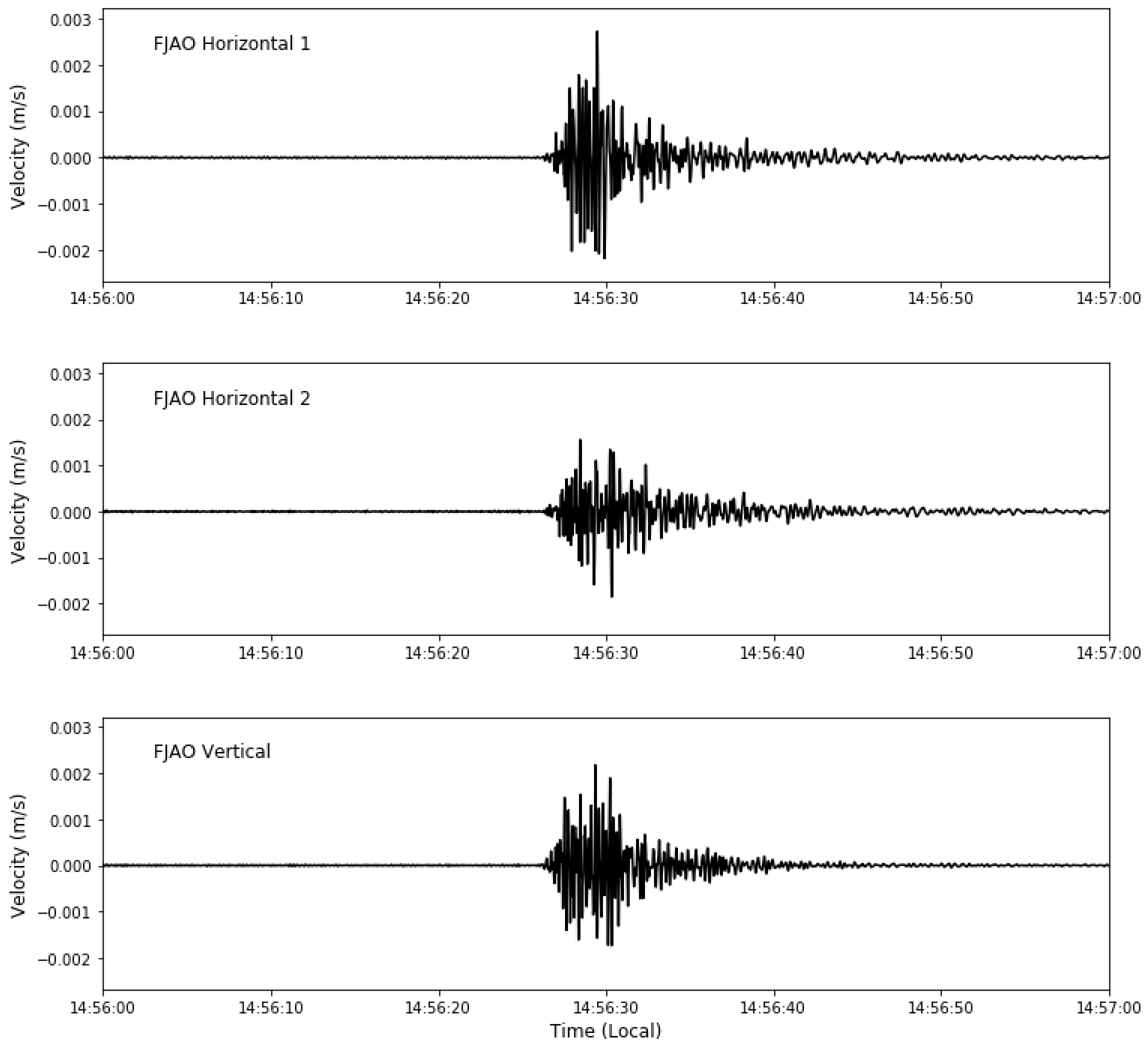


Figure 7: FJAO Seismograph Data from 14:56 to 14:57 Local Time on January 7, 2019

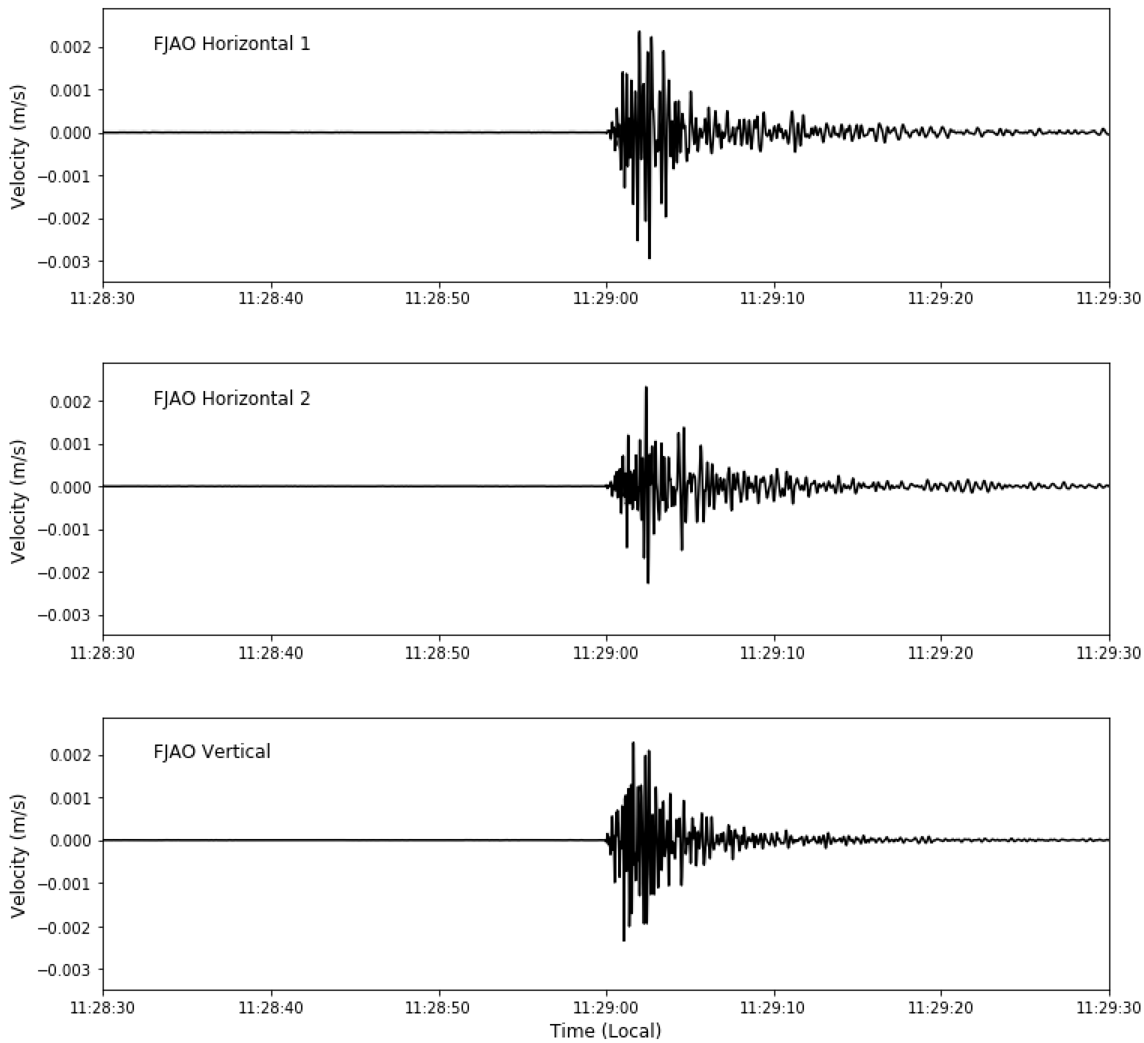


Figure 8: FJAO Seismograph Data from 11:28:30 to 11:29:30 Local Time on January 10, 2019

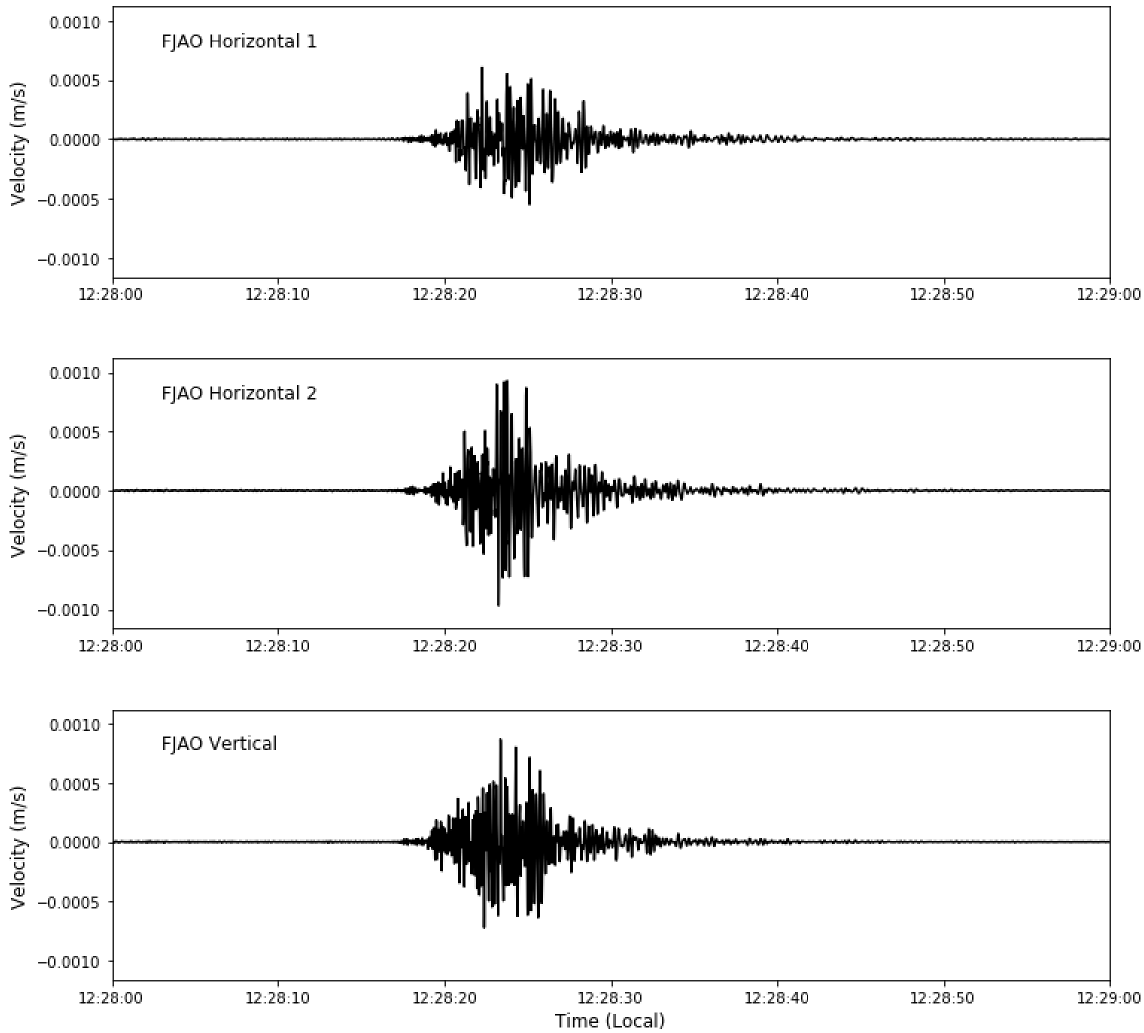


Figure 9: FJAO Seismograph Data from 12:28 to 12:29 Local Time on January 14, 2019

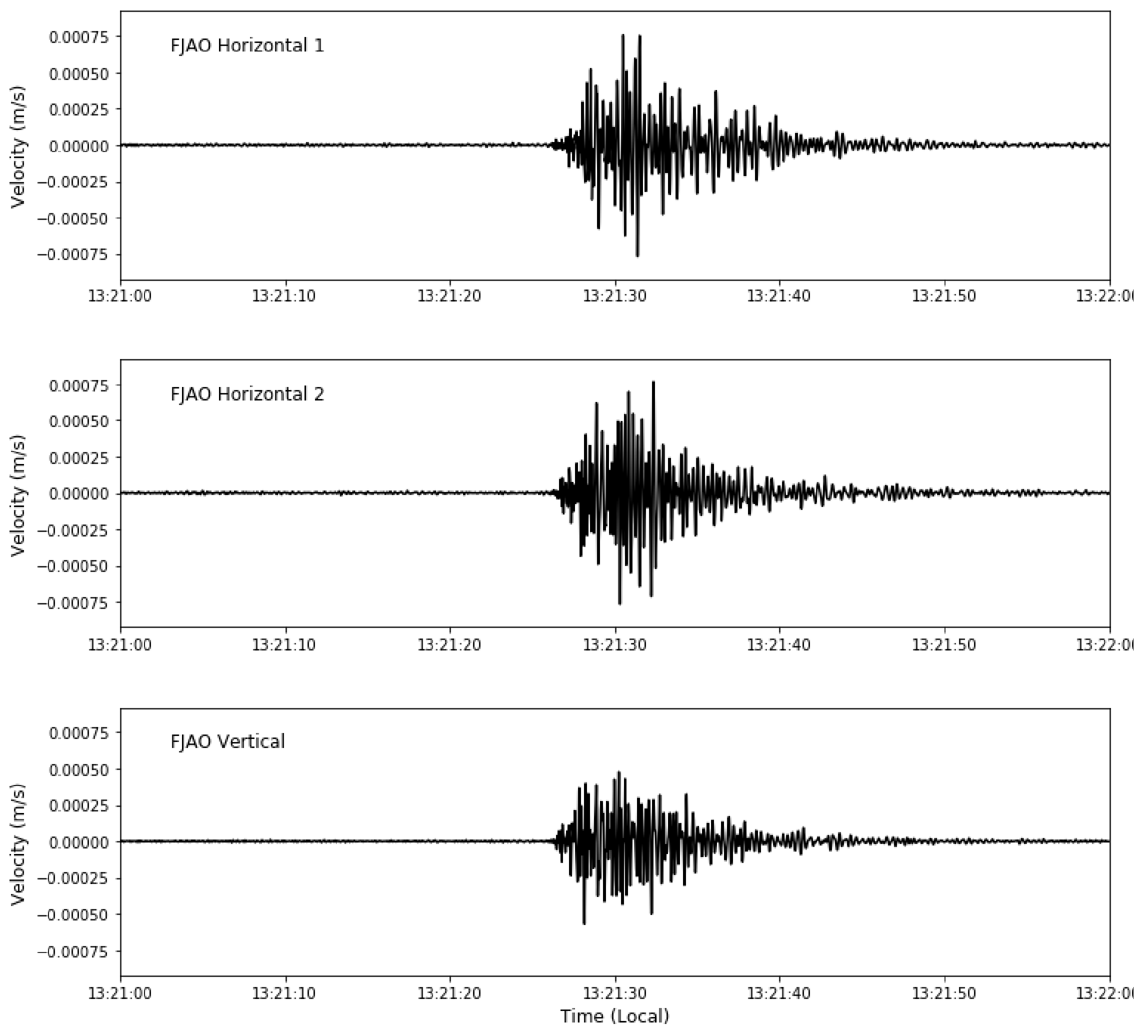


Figure 10: FJAO Seismograph Data from 13:21 to 13:22 Local Time on January 22, 2019

A comparison of Event 1 (Figure 5) with the seismograms in Figures 7 through 10 reveals that Event 1 had a much lower peak velocity (9×10^{-5} m/s) than the recorded blasts from the four prior dates. Based on this comparison, it can be concluded that Event 1 was not a blast. In addition, it appears that Dam I was subjected to various seismic events of a higher peak velocity than Event 1 in the form of the blasts, as shown above, on various occasions prior to January 25, 2019.

Qualitatively, Event 2 (Figure 6) had a very similar duration (10 to 20 seconds) and peak velocity (3×10^{-3} m/s) to the blasts recorded on the four prior dates (Figures 7 through 10), and therefore, Event 2 is likely the result of a blast. To confirm this interpretation, Event 2 was compared with the blasts on the four prior dates quantitatively by calculating the cross-correlation function between each pair of seismograms. Figure 11 presents a matrix of plots showing the results. Along the diagonal of the matrix are the cross-correlation functions of each seismogram with itself; thus, the maximum correlation is 1.0. The off-diagonal plots show cross-correlation functions between different days. The well-defined peak in each of the off-diagonal plots indicates that the two seismograms are correlated, confirming the interpretation that Event 2 is the result of a blast.

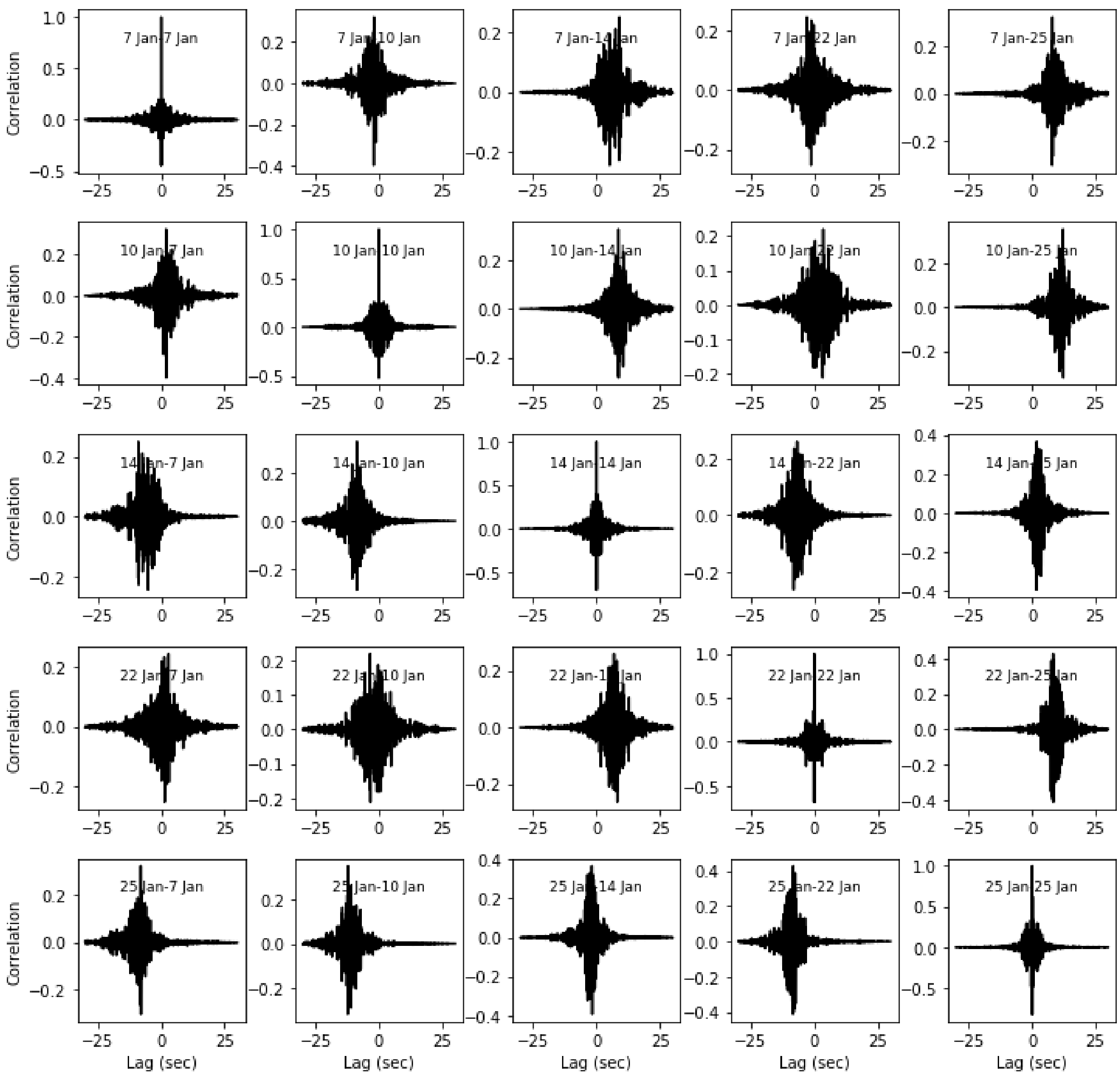


Figure 11: Cross-Correlation Functions

The firing plans for January 25, 2019, indicate that blasts occurred at 12:00 and 13:33 local time, but no significant ground vibrations were recorded at FJAO at either time.[18] As shown in Figure 6, Event 2 occurred at 12:34:17 local time.

18 Vale Córrego do Feijáo Firing Plans for January 25, 2019.

3.1.2 Potential Effect of Pre-Failure Blasting at CFJ

In order to consider the potential effect of the blasting occurring at CFJ mine on Dam I, peak cyclic shear strain associated with each of the blast events recorded at FJAO on the five dates referenced above (including Event 2 on January 25, 2019) were calculated using the following formula:

$$\text{Cyclic shear strain} = \text{Resultant peak particle velocity} / \text{Shear wave velocity}$$

For each blast event the resultant peak particle velocity was calculated by conservatively assuming that the peak particle velocity for each individual component (H1, H2, and Z) occurred at the same time. The shear wave velocity was conservatively assumed to be 100 m/s based on available shear wave velocity profiles for tailings at Dam I (see Appendix E). The corresponding values of cyclic shear strain for each of the blasting events range from approximately 1×10^{-3} to 5×10^{-3} percent. These values are roughly an order of magnitude less than the (minimum) threshold shear strain of 3×10^{-2} percent for soils suggested by Dobry and Abdoun (2015).[19]

Table 4: Peak Particle Velocity Associated with Blasting Events

		Peak Particle Velocity (m/s)				
Date	Local Time	H1	H2	Z	Resultant	Cyclic Shear Strain (%)
7-Jan-19	14:56:26	2.73E-03	1.85E-03	2.18E-03	3.95E-03	3.95E-03
10-Jan-19	11:29:00	2.94E-03	2.31E-03	2.34E-03	4.41E-03	4.41E-03
14-Jan-19	12:28:18	6.06E-04	9.70E-04	8.65E-04	1.43E-03	1.43E-03
22-Jan-19	13:21:26	7.69E-04	7.68E-04	5.72E-04	1.23E-03	1.23E-03
25-Jan-19	12:34:17	1.69E-03	3.05E-03	1.79E-03	3.92E-03	3.92E-03

3.1.3 Comparison with Data Recorded during DHP 15 Installation

On June 11, 2018, DHP 15 was installed near the toe of Dam I. Between approximately 8:20 and 12:00 local time, a borehole was advanced using a tricone bit. Beginning at 13:00 local time, casing was installed in the borehole. Sometime between approximately 14:00 and 16:30 local time, a discharge of water and fines was observed approximately 15 m from and 7 m higher than

[19] Dobry, R., & Abdoun, T. (2015). Cyclic shear strain needed for liquefaction triggering and assessment of overburden pressure factor K_σ. *Journal of Geotechnical and Geoenvironmental Engineering, 141*(11).

where DHP 15 was being installed. As soon as the discharge was noticed, drilling activities were stopped.[20] Small but rapid deformations in the dam were detected by the ground-based radar between 13:53 and 15:16 local time as recorded by the computer to which the radar was connected, as discussed in Appendix D.

The data recorded at FJAO on June 11, 2018 was reviewed to compare measured ground vibrations on the day of the DHP 15 installation with those recorded on January 25, 2019. The only event observed between 8:00 and 16:00 local time that exceeded ambient noise levels occurred at approximately 13:46 local time. Figure 12 shows the data recorded at FJAO between 13:00 and 16:00 local time. The event that occurs at approximately 13:46 local time has a peak velocity of approximately 7×10^{-5} m/s. Figure 13 shows an expanded view of the event that indicates the duration was approximately 25 seconds.

The event on June 11, 2018 was compared with Event 1 on January 25, 2019 to evaluate whether there are similarities between the seismograph records of the two events. The event on June 11, 2018 had a similar peak velocity to Event 1 on January 25, 2019. The duration was much shorter compared to the total duration of Event 1. However, as shown in Figure 14, the duration of the event on June 11, 2018 was similar to the duration of the initial subevent associated with Event 1. Both events were small in velocity and significantly smaller than blasting events that occurred at the dam on prior occasions.

[20] See Appendix A for more details on the DHP 15 incident.

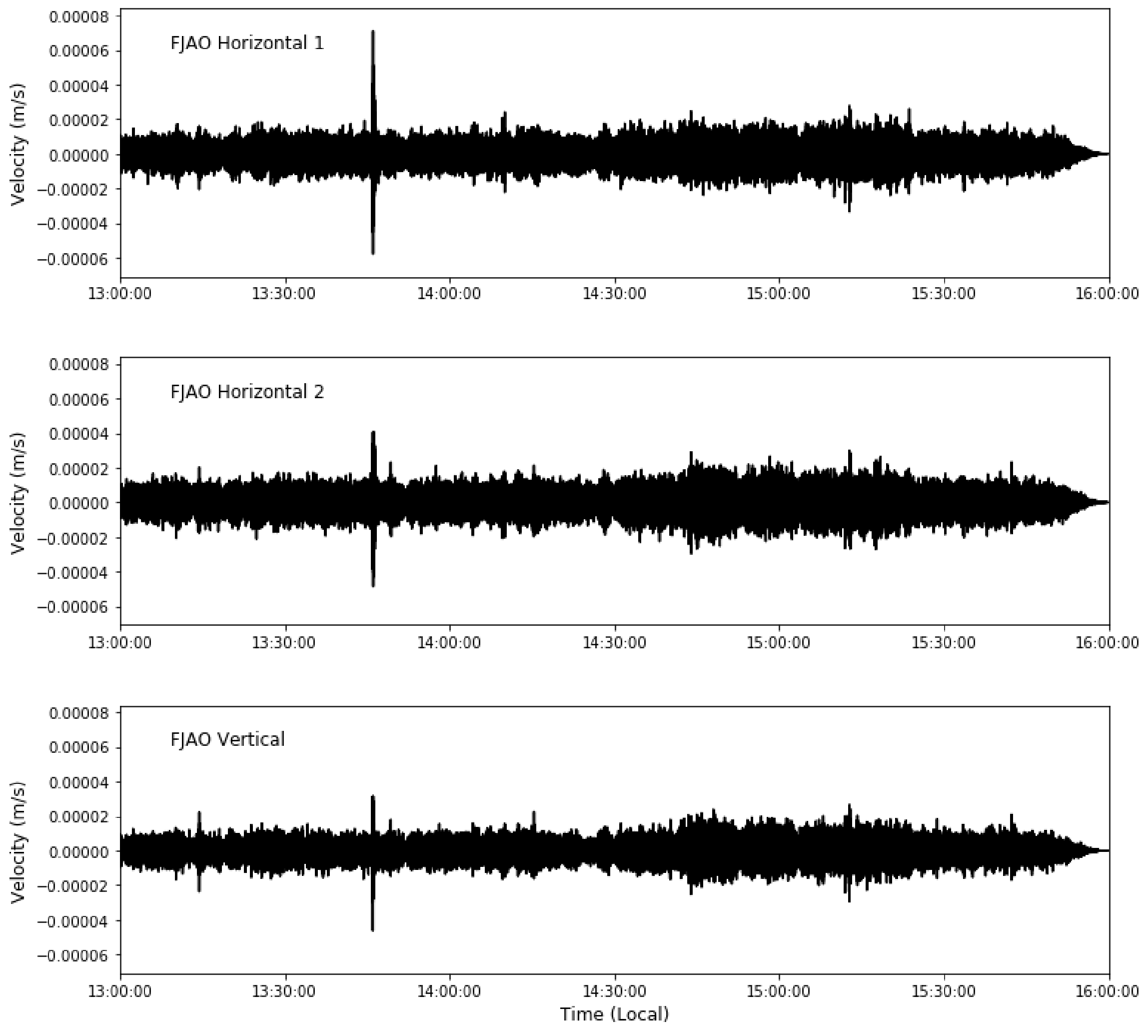


Figure 12: FJAO Seismograph Data from 13:00 to 16:00 Local Time on June 11, 2018

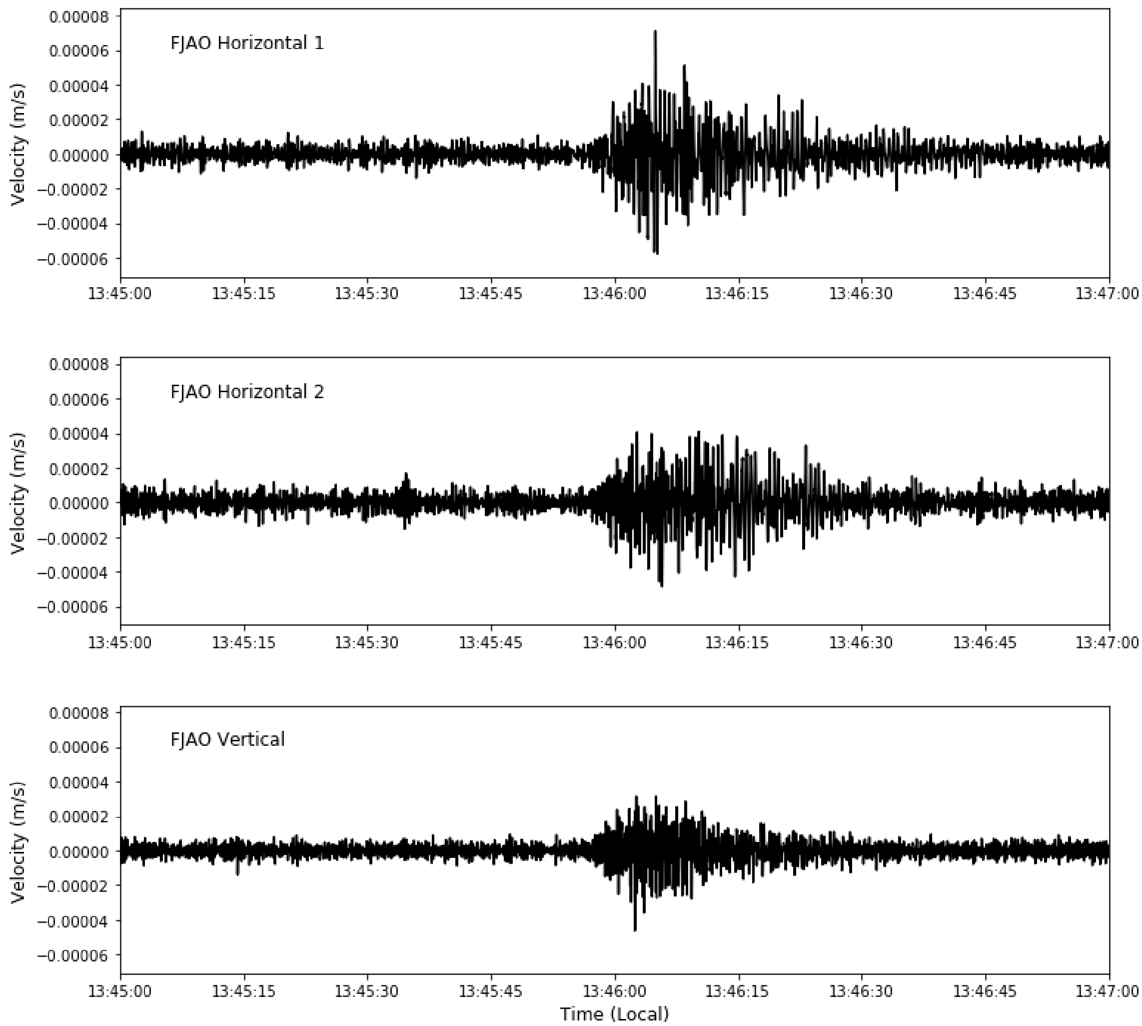


Figure 13: FJAO Seismograph Data from 13:45 to 13:47 Local Time on June 11, 2018

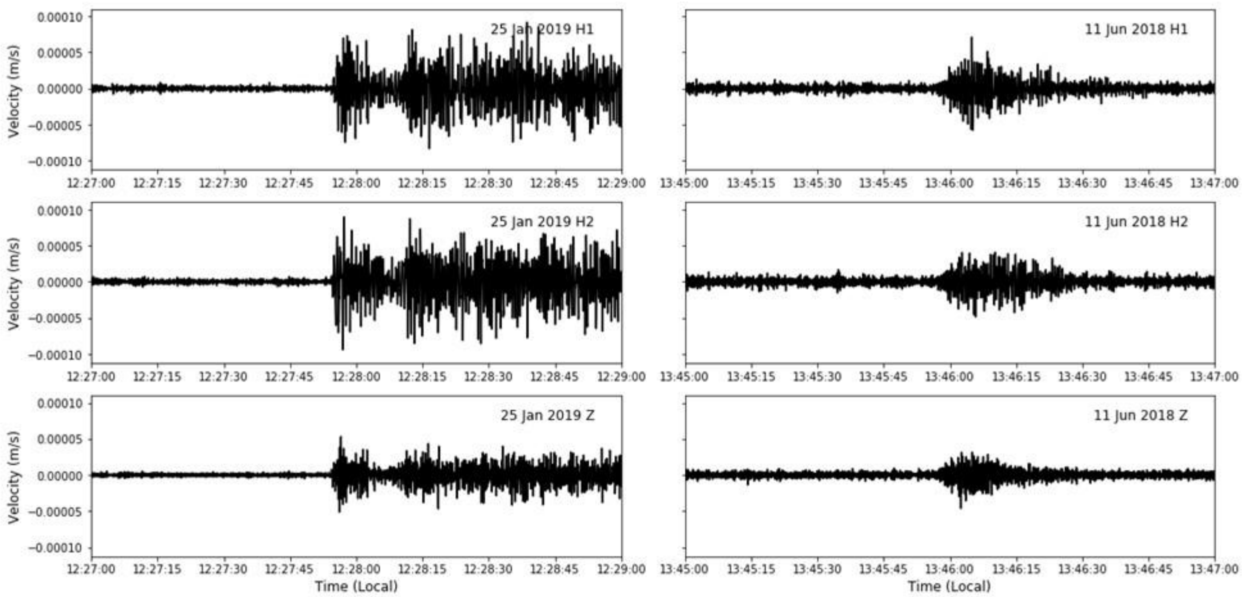


Figure 14: Comparison of Event 1 on January 25, 2019 with event on June 11, 2018

3.2 Portable Monitoring Stations

According to documentation, ground vibrations at the three portable monitoring stations did not exceed their trigger level of 5×10^{-4} m/s on January 25, 2019, and thus, no data was recorded.[21] The observation that ground vibrations did not exceed 5×10^{-4} m/s is consistent with the review of the data:

- PV7 is located in Comunidade de Feijão at a distance of 3,368 m from CFJ. Peak velocity has been shown to be proportional to $D^{-1.54}$ where D is distance from a blast.[22] Thus, the estimated peak velocity at PV7 due to Event 2 is approximately 3×10^{-4} m/s, which is less than the trigger level of the instrument.

- PV16 is at the crest of Dam VI at CFJ, 1,482 m from the center of the excavation. Although the estimated peak velocity at this distance exceeds the trigger level of the instrument, the instrument is located on the crest of Dam VI, which may have reduced the peak velocity.

- PV17 was at the crest of Dam I and likely was destroyed during the failure.

[21] Vale Seismographic Monitoring Report.
[22] Dowding, C.H. (1985). *Blast vibration monitoring and control*. Englewood Cliffs, NJ: Prentice-Hall.

4. CONCLUSIONS

The following conclusions were reached based on the review, analysis, and interpretation of the seismograph data for the permanent FJAO station on January 25, 2019, and for four prior dates, and documentation on three portable monitoring stations at or near CFJ:

- The ground vibrations recorded at FJAO on January 25, 2019 do not have the characteristics of a natural earthquake, which is confirmed by evaluations by the University of São Paulo and University of Brasilia.

- Low-velocity ground vibrations (Event 1) were observed at FJAO approximately 28 seconds before the failure of Dam I was observed. Event 1 does not present the characteristics of a blast based on comparisons with known blasting events on four prior dates in January 2019. The peak velocity of Event 1 (9×10^{-5} m/s) was very small. For comparison, safe levels of ground vibration for residential structures generally ranged from approximately 1.5×10^{-2} m/s to 5×10^{-2} m/s.

- Event 2 on January 25, 2019 is consistent with a blast based on a comparison with the known blasting events on four prior dates. Event 2 occurred approximately six minutes *after* the initiation of the failure was observed and had a peak velocity of 3×10^{-3} m/s.

- Peak cyclic shear strain range associated with blasting events at the CFJ mining pit range from approximately 1×10^{-3} to 5×10^{-3} percent, which are roughly an order of magnitude less than the (minimum) threshold shear strain of 3×10^{-2} percent.

- An event was observed on June 11, 2018 during the drilling incident at DHP 15 that had a similar velocity to the peak velocity of Event 1 on January 25, 2019. The June 11 event also had a similar duration to the initial subevent taking place within Event 1.