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Seismograph Comparison Study
DRAFT REPORT

Project: Supergraph II Comparison Study at the BART Transbay Tube During Underwater Pier Blasting for Caltrans
Submitted to: Jeff Taylor, Sauls Seismic, Inc.
Date: January 29, 2016

Background

This report summarizes a side-by-side study of three different seismograph systems used to record vibrations measured on a subway tunnel wall during an underwater blast of a bridge pier. Monitoring of background train and the blast vibrations in the BART Transbay Tube between San Francisco and Oakland, CA, took place on November 14, 2015. The Transbay Tube is a reinforced concrete submerged tunnel under the San Francisco Bay that is buried in engineered fill within the Bay mud. The Tube carries BART commuter trains on two tracks oriented eastbound and westbound.

Figure 1 shows a plan view of the instrumentation location relative to the blast of Pier E3 approximately 3000 ft away. Table 1 provides a summary of operating parameters for each instrument. The comparative study was conducted to determine relative peak amplitudes of motions and frequencies as a function of sample rate and geophone low-end resolution. Seismographs included a Nomis Supergraph II set to record at 16,384 Hz, a White MiniSeis III set at 4096 Hz, and two MiniSeis II, set at 2048 Hz. The MiniSeis II units employed geophones of two different low-end resolutions. A PCB Piezotronics accelerometer, model 356A34, was mounted on the tunnel wall to obtain direct acceleration that was of interest to the BART engineers. A SoMat eDAQ-Lite data acquisition system was used to capture acceleration time histories at a sample rate of 100,000 Hz.

Figure 2 shows the mounting of the geophones and accelerometer on two brackets affixed to the north wall of the central gallery between the two tracks. Brackets were epoxied to the concrete. The Supergraph II and MiniSeis III geophones were mounted on the west bracket (Figure 2, right). The two MiniSeis II geophones and the accelerometer were mounted on the east bracket (left in Figure 2). Details of the accelerometer mounting is shown in Figure 3.

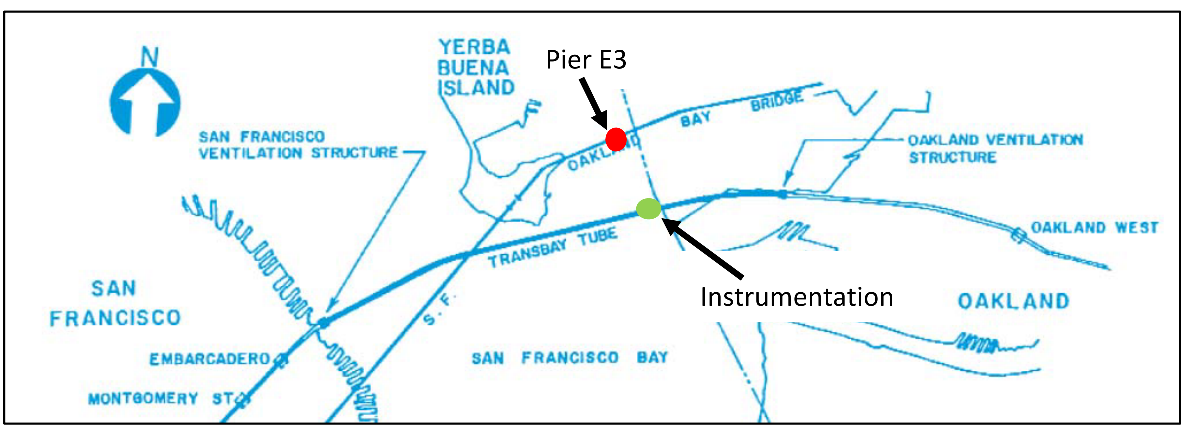


Figure 1 Plan view of the pier blast and instrumentation in the BART Tube

Table 1 Operating parameters for different monitoring systems

Serial No.	Manufacturer	Model	Amplitude Units	Low-end Resolution	Upper Range	Sample Rate (Hz)
5159	White	MiniSeis II - 32X	in/s	0.0003	0.16	2,048
2407	White	MiniSeis II - 8X	in/s	0.0012	0.6	2,048
7211	White	MiniSeis III	in/s	0.0009	10.0	4,096
20049	Nomis	Supergraph II	in/s	0.0003	10.0	16,384
113189	PCB Piezotronics & HBM	356A34 accelerometer & SoMat eDAQ Lite	g's	0.00003 noise: ~0.003	500	100,000

Figure 2 Gallery wall instrumentation showing velocity seismographs 5159 and 2407 and accelerometer (left) and seismograph serial numbers 7211 and 20049 (right)

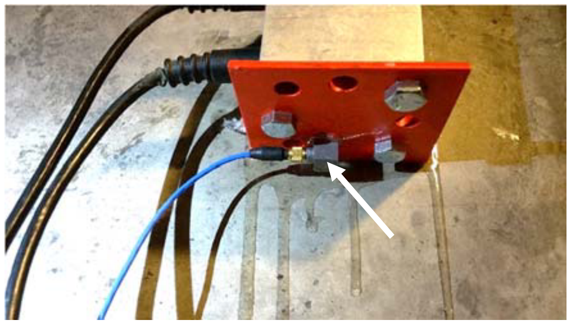


Figure 3 Accelerometer mounted below bracket

Background monitoring was conducted before and after the blast on November 14, 2015 to collect vibration measurements during the passing of several commuter trains travelling at various speeds between San Francisco and Oakland. The blast represented the demolition of Pier E3, measuring 132 ft by 40 ft, that supported the old San Francisco-Oakland Bay Bridge (SFOBB). The blast was designed with 590 individual explosive charges, a maximum of 35 lb per delay, and 5.3 sec total blast duration. A double-ring bubble curtain was used approximately 35 ft away from the pier to mitigate close-in water overpressures during the blast. A sequence of photographs taken during the demolition is provided in the Appendix.

Prior to and after the blast, systems were deemed operable and were used to record vibrations from several passing trains starting at 6:02 am. The blast occurred at 7:16 am and triggered all four seismograph systems. However, the accelerometer system did not trigger due to the very low frequency of the blast motions on the tunnel wall (less than 4.1 Hz). This indicated wall accelerations were less than 0.1 g's.

Monitoring Results

Comparison of Blast Results

Table 2 provides a summary of blast measurements from each of the 4 seismograph monitoring systems. Displacements and accelerations were computed using the seismograph software.

The transverse components were used for analysis as this represented the out-of-plane motions in the tunnel wall that represented the highest component. The highest wall velocity recorded during the blast was 0.061 in/s recorded with the Nomis Supergraph II employing the highest sample rate of 16,384 Hz. The high sampling rate resulted in a peak frequency of 115.3 Hz that was far higher than frequencies recorded at lower sample rates. Sample rates of 4098 and less used with the other systems produced lower peaks at peak frequencies less than 4.1 Hz.

Table 2 Summary of seismograph blast vibrations

Serial No.	Manufacturer	Model	Sample Rate	Peak Particle Velocity	Peak Frequency	FFT Frequency	Acceleration	Displacement
			(Hz)	(in/s)	(Hz)	(Hz)	(g's)	(in)
5159	White	MiniSeis II - 32X	2,048	0.044	4.1	4.13	0.040	0.00180
2407	White	MiniSeis II - 8X	2,048	0.044	4.1	4.13	0.064	0.00166
7211	White	MiniSeis III	4,096	0.053	1.8	1.26	0.063	0.00322
20049	Nomis	Supergraph II	16,384	0.061	115.3	2.62	0.114	0.00471

Table 3 Summary of seismograph train vibrations for the event at 6:50 am

Serial No.	Manufacturer	Model	Sample Rate	Peak Particle Velocity	Peak Frequency	FFT Frequency	Acceleration	Displacement
			(Hz)	(in/s)	(Hz)	(Hz)	(g's)	(in)
5159	White	MiniSeis II - 32X	2,048	0.065	204.8	247.1	0.218	0.00004
2407	White	MiniSeis II - 8X	2,048	0.024	256.0	247.1	0.073	0.00002
7211	White	MiniSeis III	4,096	0.029	204.8	200.2	0.119	np
20049	Nomis	Supergraph II	16,384	0.094	199.8	204.3	0.307	0.0001

Comparison of a Single Train Event

Table 3 provides a summary of the train measurements at 6:50 am just prior to the blast. The highest background velocity was recorded with the Supergraph II. The peak was 0.0944 in/s at 200 Hz peak frequency.

Figure 4 is a plot of peak velocity versus frequency for all background train measurements. It is interesting to note that the Supergraph velocity peaks provided a consistent peak frequency centering around 200 $\pm$ 17.5 Hz as compared with the MinSeis III (214 $\pm$ 168.3 Hz), MiniSeis II - 8x (208.6 $\pm$ 45.6 Hz) and MiniSeis II -32 x (244.5 $\pm$ 25.9 Hz). The lowest standard deviation among all peaks for the Supergraph provides a high level of confidence in the measurements.

Time Histories Comparison

A series of time history plots were prepared to visually show the effects of sample rate on peak amplitudes and, to some extent, the frequencies.

Blast Wave forms

Figure 5 shows the transverse component of time histories for the blast as recorded by the seismograph systems. The total time duration of all blast holes detonations was 5.3 sec. This is evident in the first half of the plot in Figure 4 with the high frequency content that ceased around the 5 sec mark. The tube and wall continued to move with a predominant low frequency response long

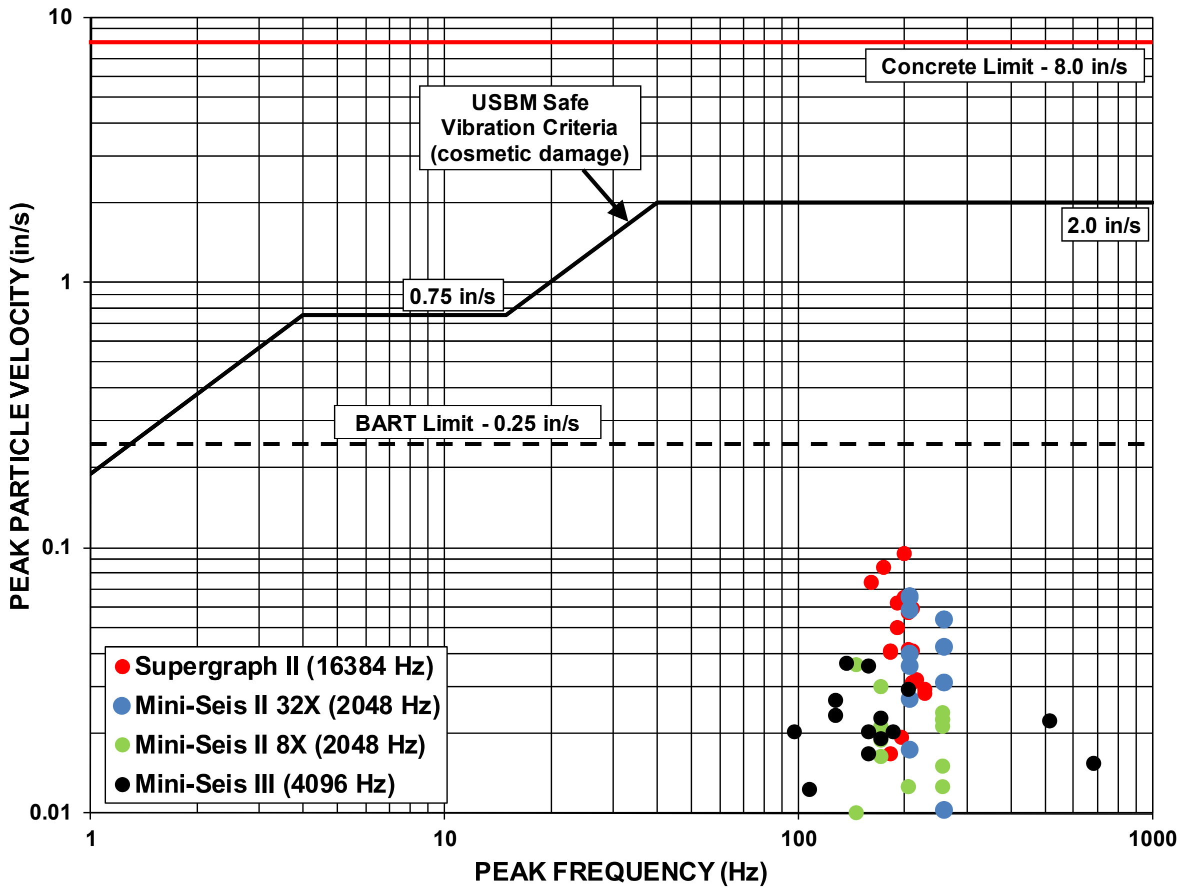


Figure 4 Peak velocity versus frequency comparison of different seismograph systems showing all recorded trains

after the blast excitation ended. The record length of the two MiniSeis systems was a maximum of 6 sec while the MiniSeis III and Supergraph continued to record for 12 sec.

It is important to note that the peak velocity recorded by each of the 4 systems occurred at different times during the entire wave form duration. The highest recorded amplitude for the Supergraph occurred early in the time history during blast hole detonations that were dominated by high frequency motions. It is in this early time where the Supergraph showed the largest difference in amplitudes among other systems. This indicates that the slower sample rates and possibly the frequency response of the other systems were inadequate to capture the true peaks of this beginning high frequency motion. This section is expanded for closer inspection in Figures 6 through 8.

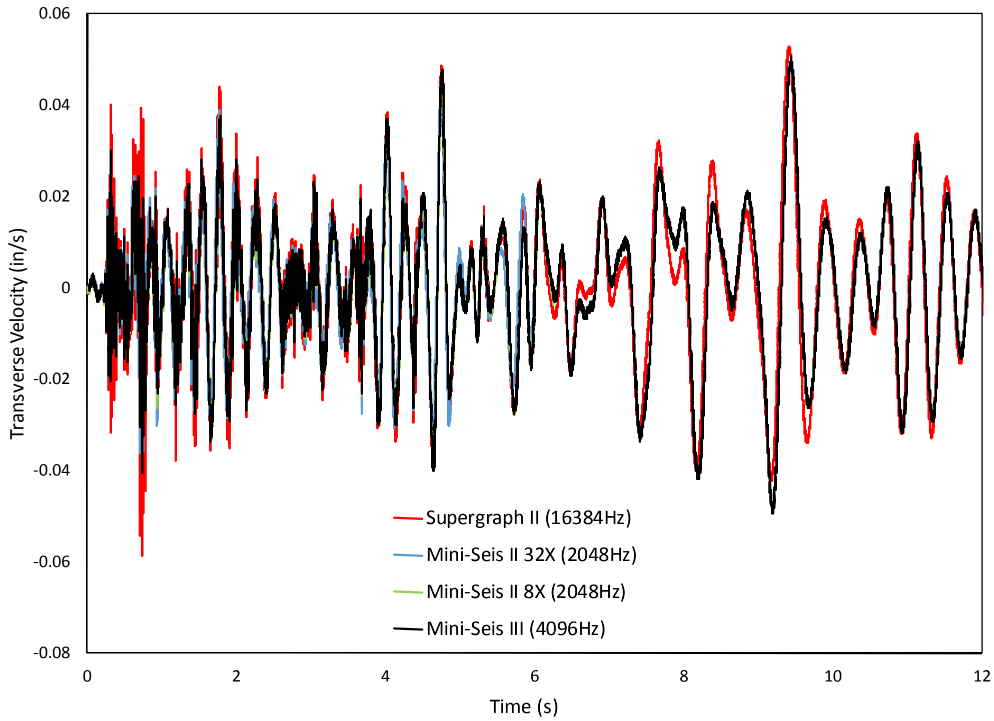


Figure 5 Comparison of entire blast time histories

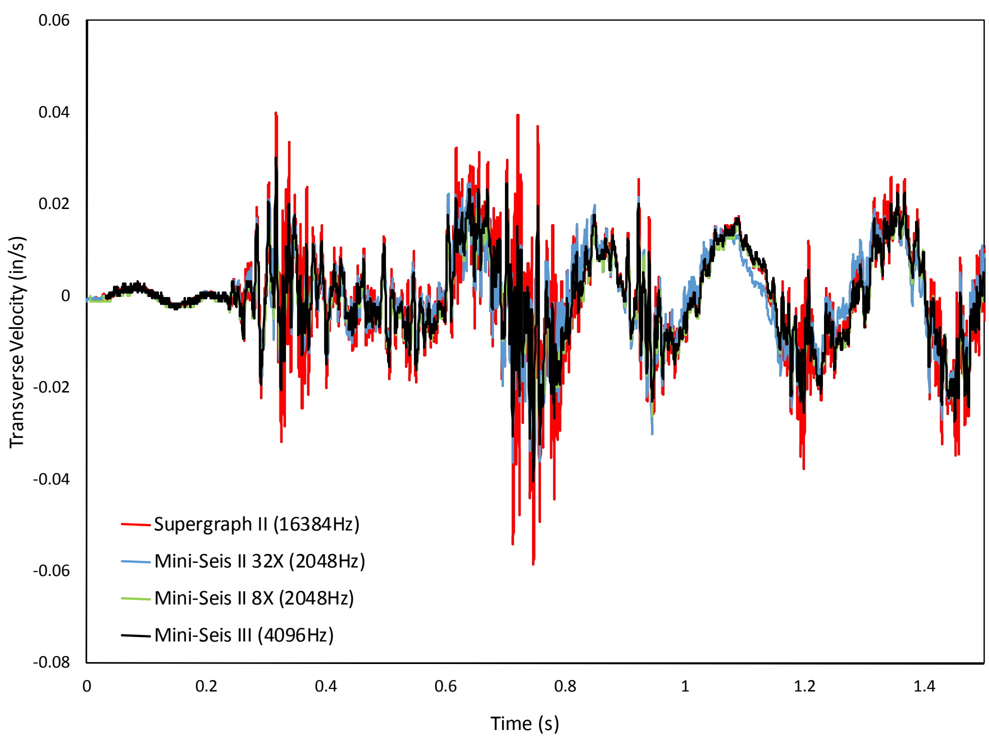


Figure 6 High-frequency section of the time history showing Supergraph higher amplitudes

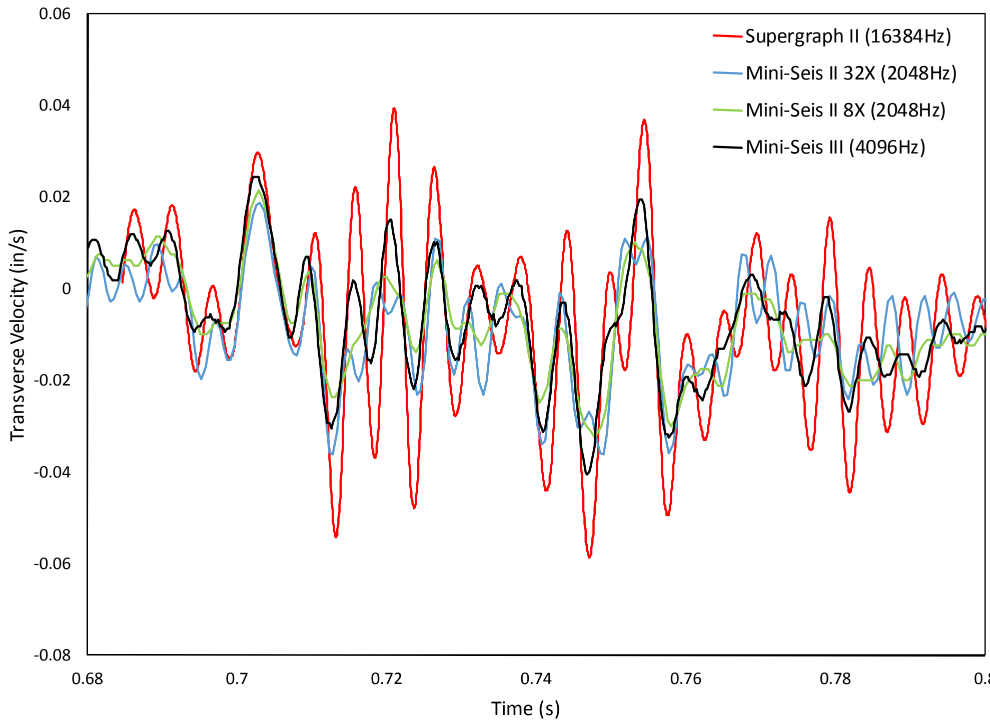


Figure 7 Very early time histories comparisons

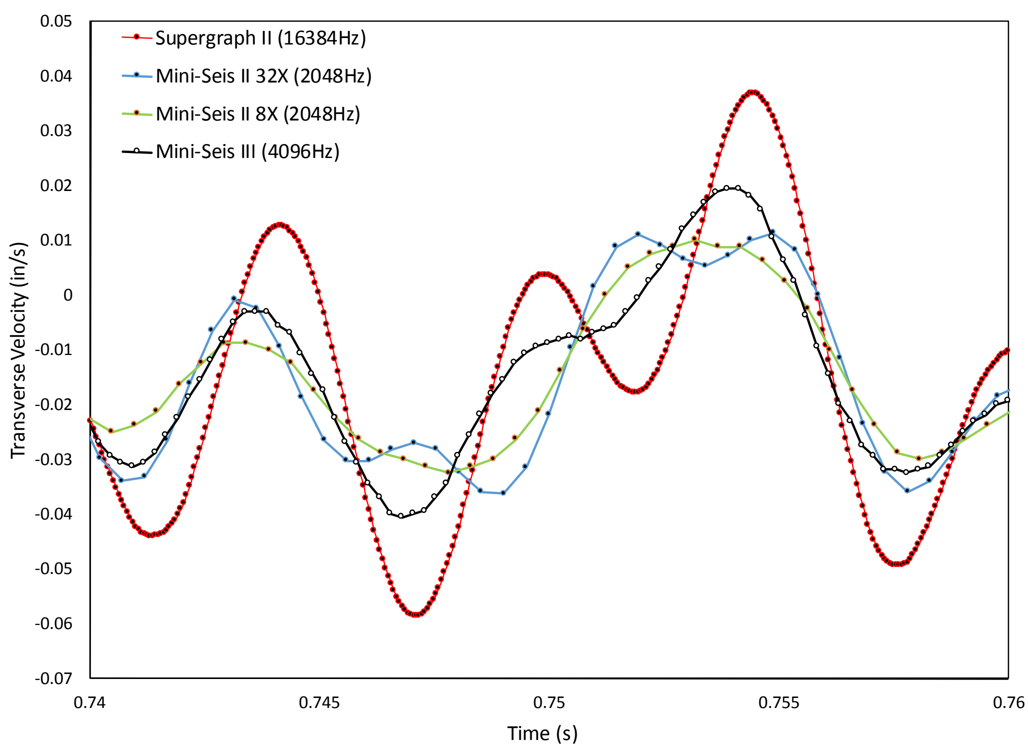


Figure 8 Narrow time window showing individual sampled data points

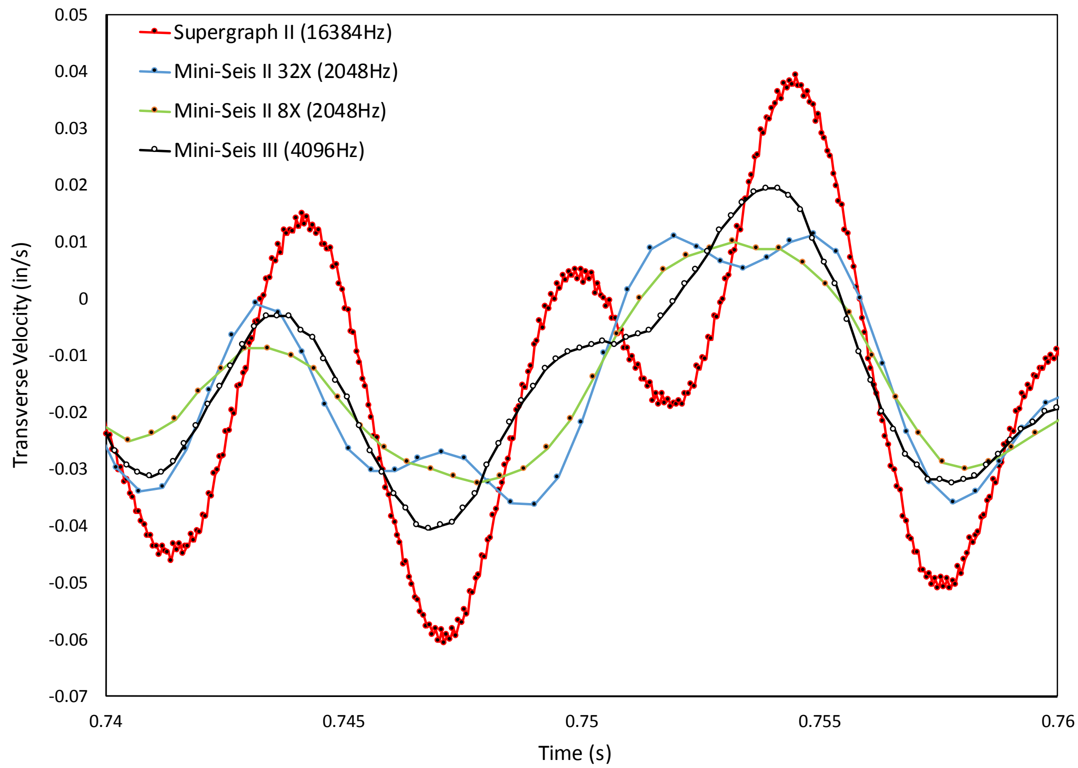


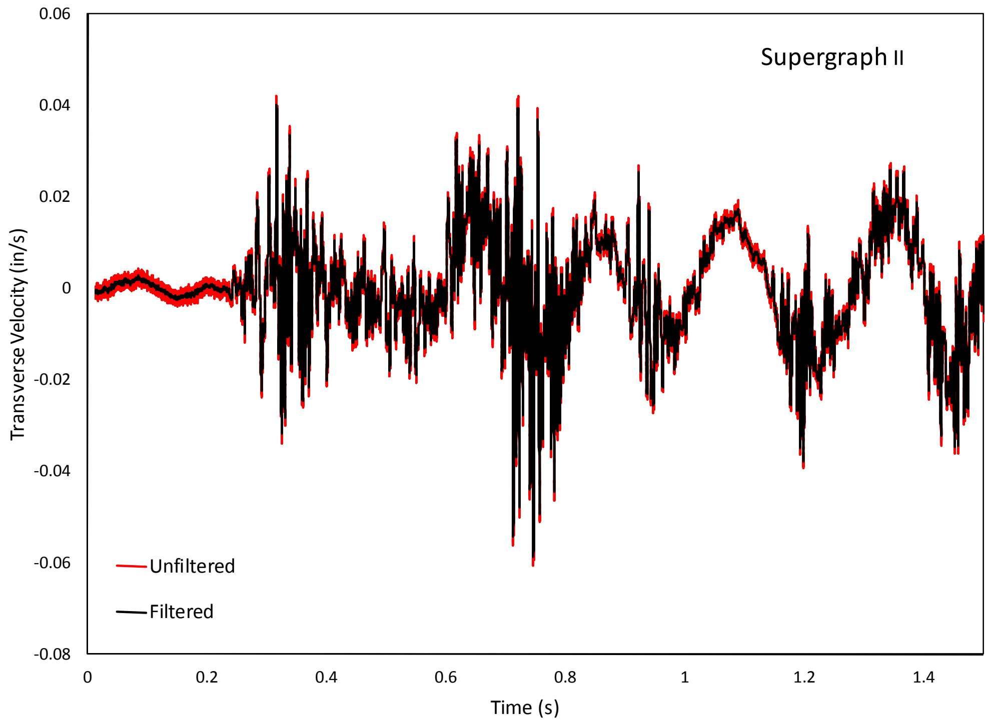
Figure 9 Same high-frequency section, with unfiltered Supergraph II data

In all of the previous figures, data recorded using the Supergraph II were filtered using a 1,000 Hz low pass Butterworth filter to remove system noise. Figure 9 shows unfiltered data for the same section given in Figure 8. Figure 10 shows a comparison of filtered and unfiltered blast time histories at two different time scales.

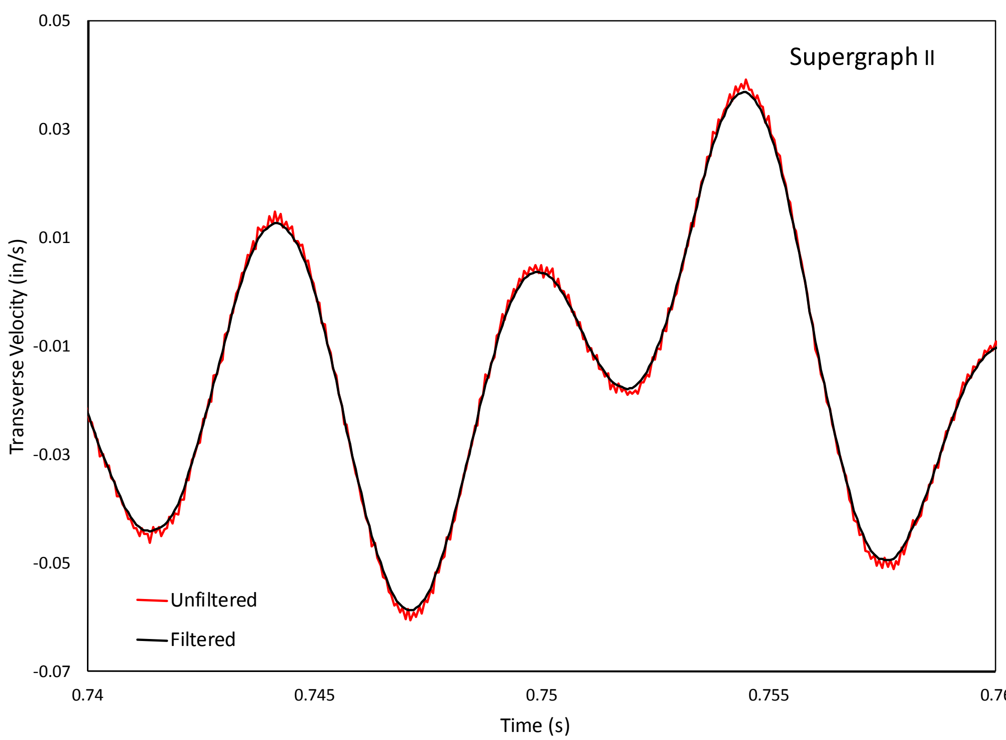
The peak velocity amplitude as recorded using 2048 Hz occurred later in the time histories where low frequency tube response just begins near the end of the detonations. This section is plotted in Figure 11. The recorded amplitudes do not differ as much in this section because the true peak is not missed by the lower sample rate seismographs in comparison with the higher rate Supergraph. Hence, the 2048 Hz sample rate may be sufficient to measure the peak amplitude of the tube response.

Example Train Time Histories

Velocity wave forms of the passing train are shown in the Figures 12 through 15 with decreasing time windows for peak comparisons. Figure 15, shows individual data points, highlighting the differences in sample rate and recorded peak amplitudes. Data from the Supergraph II was not filtered for this analysis of train vibrations.



(a)



(b)

Figure 10 Comparison of filtered and unfiltered blast data at two different time scales

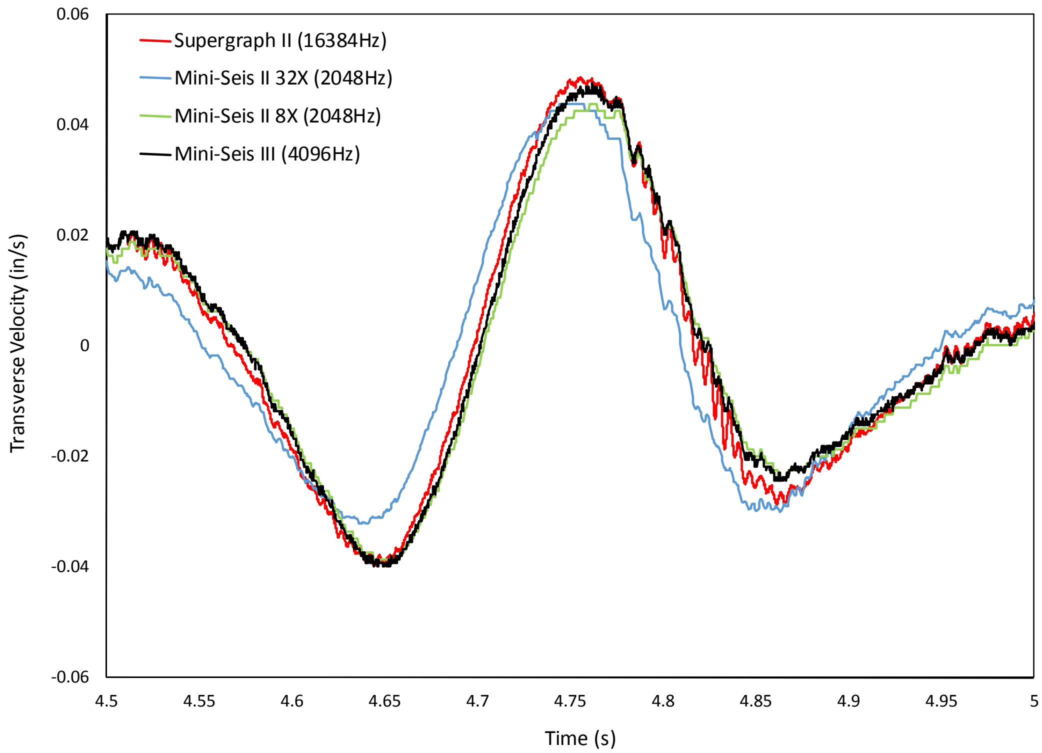


Figure 11 Low frequency section of the detonations

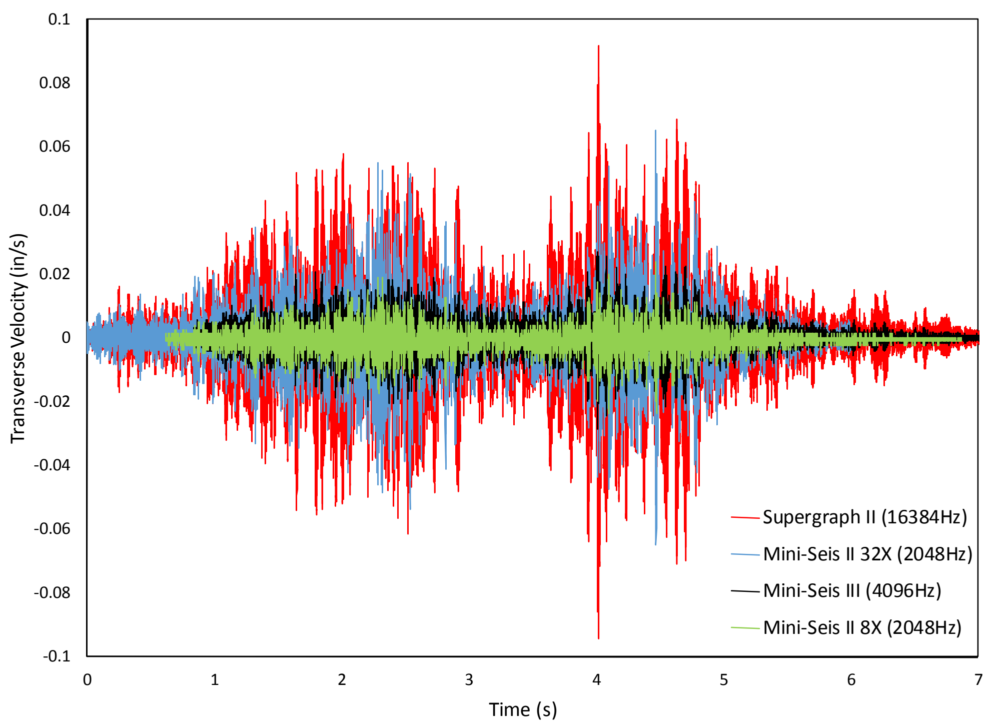


Figure 12 Tunnel wall vibrations during the passing of the BART train

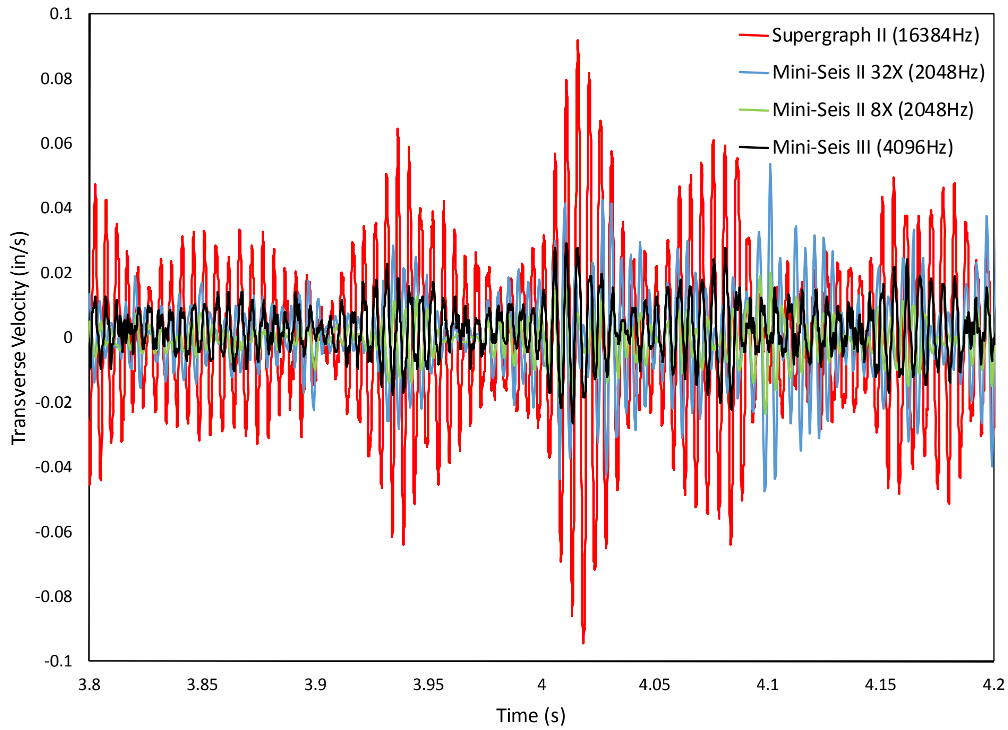


Figure 13 Close in view of Figure 12

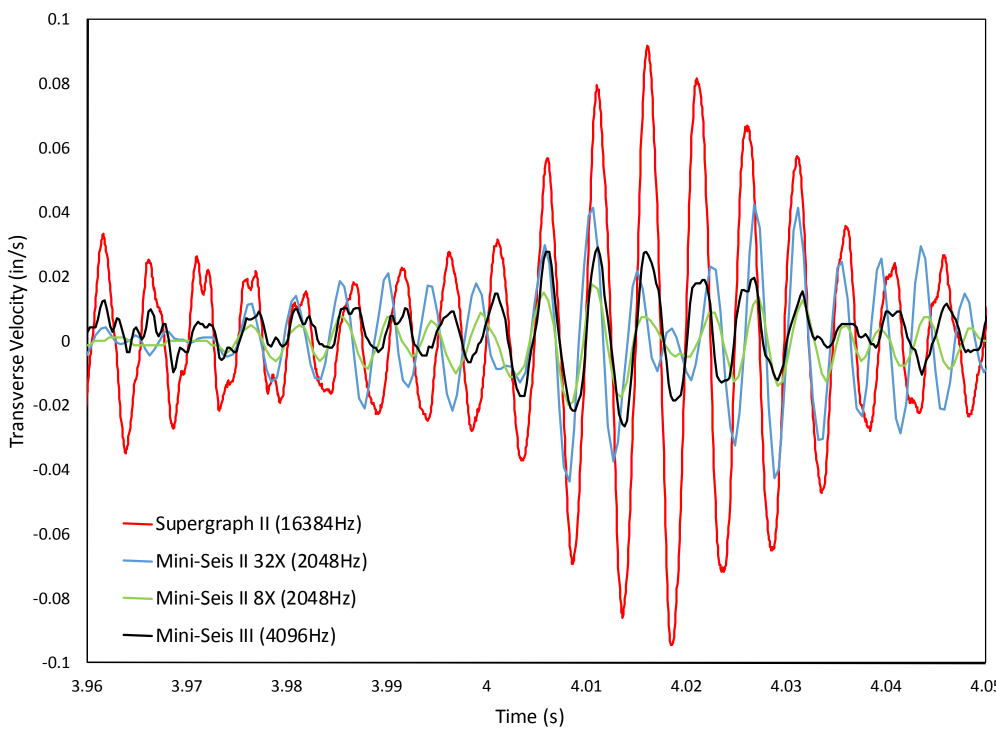


Figure 14 Closer view of Figure 13

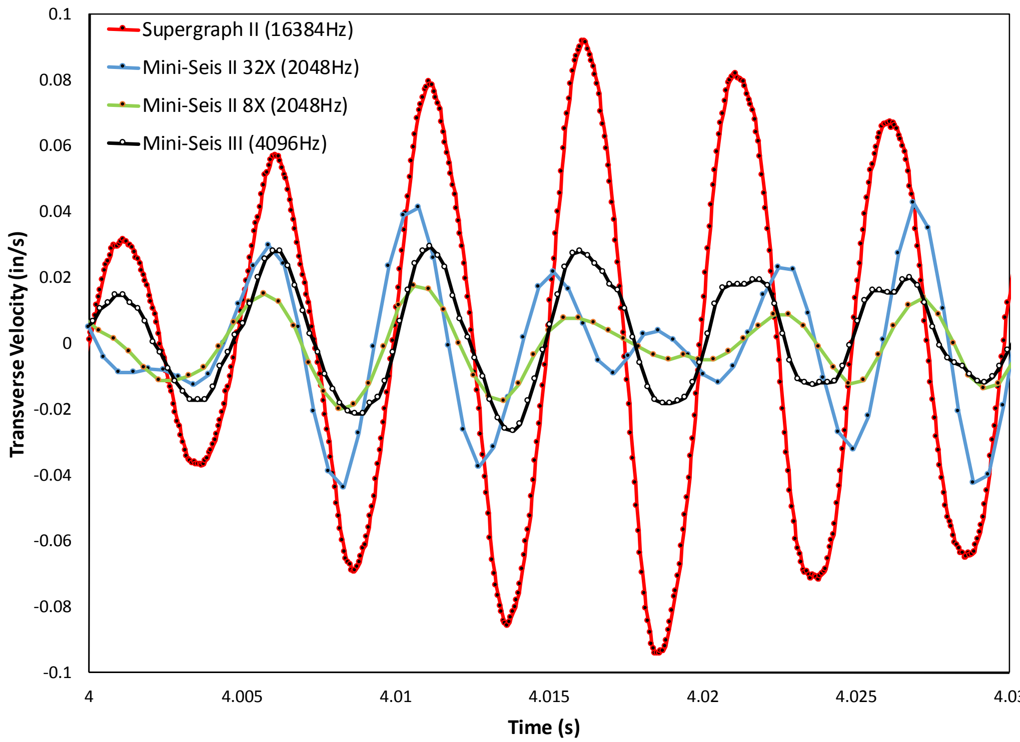


Figure 15 Close in view of train event showing recorded measurements

Measurements recorded with the Supergraph II provided far higher peak velocities for this and nearly all other train events. As such, it is clear that the consistent train-induced frequency near 200 Hz requires a high sample rate to provide accurate peaks.

APPENDIX