Marshall Mega Site, Calhoun County, MI

Vibration Monitoring and Analysis

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FINAL REPORT

March 4, 2022

WJE No. 2021.6124

PREPARED FOR:

Burns & McDonnell
9400 Ward Parkway, Kansas City, MO 64114

PREPARED BY:

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INTRODUCTION

At the request of Burns & McDonnell (BM) on behalf of the Michigan Economic Development Corporation (MEDC), Wiss, Janney, Elstner Associates, Inc. (WJE) observed and analyzed ground vibrations and response characteristics at the Marshall Mega Site (site) near Marshall in Calhoun County, Michigan. This report summarizes our observations and findings.

BACKGROUND

WJE was engaged by BM to install a system to monitor ground vibrations at a large tract planned for future commercial development near Marshall, Michigan. The anticipated source of ground vibrations that were the subject of our investigation was freight and passenger train activity on a nearby railway mainline. The tract is approximately 1,540 acres in total, consisting of three primary areas, and is located about a mile west of the intersection of Interstate 69 and Michigan State Highway 96. The tract and the mainline are shown in Figure 1.

During the development of our monitoring program, we were provided the following information by BM and MEDC:

- Approximately 50 trains per week pass the tract on the railway
- A minimum one-week monitoring period was an acceptable duration to observe ground vibrations

The purpose of the vibration monitoring system was to observe ground vibrations at various locations within the tract and understand the correlation, if any, to nearby train or vehicular activities. No information was provided regarding the number, size(s), or location(s) of buildings planned to be constructed on the tract. As a result, the vibration monitoring program was intended to provide coverage of the entire tract, as described below, rather than coverage for specific locations within the tract. Also, no limits or criteria regarding the vibration amplitude or frequency related to the future use of such buildings were provided.

INVESTIGATION

Monitoring Plan

An instrumentation program was developed to measure and record ground vibrations on site. Referencing Figure 1, our preliminary monitoring plan, which was reviewed and approved by MEDC, included vibration monitoring in Area 2, but not in Area 1 or Area 3. MEDC indicated that no development was planned for Area 3, and we did not propose monitoring Area 1 because it was much smaller and further from the railway than Area 2.

Due to the size of Area 2, and instrumentation considerations as described below, vibration monitoring was performed in three phases (West, Central, and East) as shown in Figure 2. Monitoring took place in each phase for a minimum of one week, with the specific dates indicated below.

- Central Phase: November 24, 2021 – December 6, 2021
- East Phase: December 7, 2021 – December 13, 2021
- West Phase: December 13, 2021 – December 26, 2021

The sequencing of the monitoring in each phase was influenced by soil boring operations on the site in December 2021. The soil boring schedule had been established prior to the development of our monitoring plan, as follows:

- West Phase: November 29, 2021 – December 3, 2021
- Central Phase: December 13, 2021 – December 17, 2021
- East Phase: December 20, 2021 – December 23, 2021

When possible, vibration monitoring was performed when no soil boring work was scheduled on site. If soil boring work was scheduled on site, vibration monitoring was performed in a different phase than the soil boring work. Due to the schedule constraints established by MEDC, it was not possible to perform all vibration monitoring at times when no soil boring work was being performed on site.

Due to multiple issues observed with the monitoring results after the initial installation of the Central phase, several of the sensor locations were adjusted from those shown on the preliminary monitoring plan (Figure 2). The final monitoring plan is shown in Figure 3. The observed issues and the differences between the preliminary and final monitoring plans are described below.

Instrumentation and Data Collection

In each phase, three vibration monitoring systems were installed, as shown in Figure 3. The three systems in the west phase were labeled W1, W2, and W3, in the central phase C1, C2, and C3, and in the east phase E1, E2, and E3. Each vibration monitoring system consisted of four triaxial PCB Piezotronics Model 356B18 accelerometers, IEPE (ICP), connected to a National Instrument NI cRIO, modular data acquisition system (DAQ) with three NI-9234 4-channel C-series modules. Each DAQ was powered by a bank of deep-cycle batteries, which were periodically recharged by solar panels. The DAQs were enclosed by a NEMA-rated weather-resistant housing. A typical DAQ housing and solar panel setup is shown in Figure 4.

Each DAQ was running a proprietary vibration monitoring program developed in the NI LabVIEW programming language by WJE specifically for this type of project. Each DAQ was connected to a cellular modem, allowing for remote connection, data management, and real time data viewing by WJE personnel. The program scanned all channels at a rate of 5,120 samples per second, continually evaluating the measured vibration amplitudes each 0.1-second in a first-in-first-out (FIFO) buffer to display a continuously updated 1-second waveform. Every second, the program stored the maximum acceleration and velocity parameters and rms velocity measured during that period to an ASCII comma-separated-variable (CSV) log file. A separate CSV log file was saved for each day of monitoring. If the vibration amplitude on any sensor exceeded a programmed trigger threshold, a 1-second waveform file containing that occurrence was stored. The trigger threshold was typically set at 0.005 inches per second (in/s) to 0.01 in/s peak particle velocity (PPV).

Each accelerometer was mounted to a steel plate, which was secured in place by three ground anchors as shown in Figure 5. Each accelerometer assembly was covered by a weather-resistant housing (Figure 6) with colored marking flags installed nearby (Figure 7). One of the four accelerometers in each vibration monitoring system was typically located within a few feet of the DAQ (labeled as Sensor 4 in Figure 3), and the other three accelerometers (labeled as Sensors 1, 2, and 3 in Figure 3) were located at various distances away from the DAQ.

Train Activity on Railway Mainline

It is our understanding that the train activity on the railway mainline located adjacent to the site consists of both commuter and freight trains. In an effort to correlate observed vibration results with train activity, we reviewed published Amtrak schedules and researched available information related to freight train activity.

Based on information provided on the Amtrak.com website, the routes from Pontiac, Michigan to Battle Creek, Michigan and from Battle Creek to Pontiac use the railway mainline adjacent to the site. The arrival and departure times at the Battle Creek Amtrak station published on Amtrak.com are shown in Table 1. The published arrival and departure times are the same for every day of the week.

Battle Creek is west of the site, and the Amtrak station in Battle Creek is located about 8 miles, measured along the railway, from the west end of the site. There is about 4 miles of railway from the west end to the east end of the site. Based on this information, estimated time windows for Amtrak train activity near the site are shown in Table 1. These estimates are based on an assumed 20-minute window centered on the arrival time minus 15 minutes or the departure time plus 15 minutes. During the initial system installation on November 24, 2021, WJE observed an eastbound Amtrak train passing the site at 5:27 pm CST. This train passage event fell within the assumed 20-minute window.

In addition, we determined that the Norfolk Southern Railway operates on the mainline adjacent to the site. However, we have been unable to locate schedules for the freight train activity. The Michigan Department of Transportation indicated that freight train schedules have generally not been publicly available since 2001 for security reasons.

VIBRATION MONITORING RESULTS

Maximum peak particle velocity (PPV) and root mean squared (RMS) amplitudes of vibrations due to train activity recorded by the three West Phase systems on December 14, 2021, for each 1-second interval, along with the associated frequency, are provided in the north-south, east-west, and vertical directions in Tables 2, 3, and 4.

Representative velocity and acceleration waveforms are provided in Figures 9 through 22 for several vibration events produced by train activity. Two events correspond to the Central Phase, one event corresponds to the East Phase, and four events correspond to the West Phase. The event durations range from 2 to 9 seconds, and the time interval of the data is about 0.0002 seconds (5,120 samples per second).

DISCUSSION AND CONCLUSIONS

Site Considerations

The installation of the instrumentation at the beginning of the first phase (Central) took approximately two days. Subsequent site visits to move the instrumentation to the next phase required one to two days for each move. WJE was typically on site to install, move, or deinstall the instrumentation, but providing a full-time site presence during each monitoring phase was not included in our proposed monitoring program.

Due to multiple issues observed with the monitoring results after the installation of the Central phase, WJE made a second site visit during this phase to attempt to diagnose and address the observed issues. At several locations, cabling connecting accelerometers to the DAQ was found to have been damaged (Figure 8), likely by wildlife on the site. This had the effect of adding significant noise to the vibration data. We also observed continuous noise in other sensor channels for which the cabling was not damaged, which likely was the result of electromagnetic interference (EMI) at the site or moisture infiltration at the cable connections. The EMI-related noise was characterized as a steady-state noise at 60 cycles per second (60 Hz). The noise typically masked any underlying vibration data from train activity. In addition, because the noise amplitudes typically exceeded the trigger threshold to record a 1-second waveform as described above, numerous waveforms were stored which provided no useful information. On many days, the noise-related waveforms caused the local storage to be filled, preventing the storage of other waveforms potentially related to train activity.

One of the actions taken to attempt to address the issue of EMI was to shorten the sensor cables and adjust the sensor locations from those shown on the preliminary monitoring plan. During the second site visit for the Central Phase, and during the installation for the East and West Phases, the position of each sensor was adjusted on site while the associated vibration signal was monitored remotely by WJE personnel. This additional step was intended to maximize the length of each sensor cable, to improve the monitoring coverage, while establishing a sensor location where the effect of EMI did not appear to be significant. In the preliminary monitoring plan, Sensors 1, 2, and 3 were planned to be located about 1000 to 1200 feet away from the DAQ. In the Central Phase, which was the first phase of the three, the sensors were initially installed at the planned locations. However, during our second Central Phase site visit and for the East and West Phases, the sensors were located at various distances from the DAQ as shown in Figure 3. In many cases, the sensors were located much closer to the DAQ than the originally planned distance.

These steps reduced the impact of noise related to EMI, instrumentation damage, and moisture infiltration but did not prevent it. EMI can vary daily and in some cases noise in the vibration data appeared after we established the sensor locations and left the site. Damage to sensor cables, likely due to wildlife, occurred in all three phases, and providing enhanced protection for the cabling would have required placing them in conduit. The cable connections were wrapped with moisture-resistant tape, however moisture continued to migrate into the connections in some instances. As a result, even with the additional steps taken, triggered waveforms related to train activity may have only been recorded and stored for a part of the 24-hour period on any given day.

Observed Ground Vibrations for a Typical Day

PPV and RMS vibration amplitudes related to train activity were provided in Tables 2, 3, and 4 for a day during the West Phase monitoring period. The maximum PPV recorded on this day was 0.063 inches per second at Sensor 1 in System 3. This day was selected because it appeared to be typical for other days during the West Phase monitoring, and because triggered waveforms were recorded for the majority of the 24-hour period. In addition, the vibration amplitudes for the West Phase appeared to be greater than for the East or Central Phases. In some cases, vibration amplitudes that were greater than those shown in Tables 2, 3, and 4 were recorded. However, they were excluded from the tables because they appeared to be the result of localized activity, instrumentation issues and/or EMI, not train activity.

Our opinion regarding the source of the vibrations being train activity is primarily based on our review of the stored waveforms, including the durations of the vibration events and the frequencies associated with the predominant amplitudes. In addition, the time the events occurred was compared to schedules of train activity, where available. Vibration event durations related to train activity are typically several seconds, depending on the length and speed of the train. Recorded vibration events likely related to other sources, such as an animal contacting a sensor or cable, typically have much shorter durations. In addition, the predominant frequencies for ground vibrations from trains can vary from 10 Hertz (Hz) to 100 Hz or more, depending in part on the weight and speed of the train and the soil characteristics at the site. Based on our review of the recorded data, train activity appears to typically produce predominant vibration amplitudes between 20 and 30 Hz. In some cases, waveforms related to vibration amplitudes shown in Tables 2, 3, and 4 were not available for reasons described above. However, the associated frequencies corresponded to typical ground vibration frequencies, suggesting that the events are the result of train activity.

Typical Observed Acceleration and Velocity Waveforms

Typical acceleration and velocity waveforms for seven vibration events produced by train activity are shown in Figures 9 through 22. The majority were recorded in the West Phase because more events occurred in that phase which exceeded the trigger threshold and were related to train activity. Most of the triggered events in the East and Central Phases were related to instrumentation issues or EMI. As indicated above, the vibration amplitudes for the West Phase appeared to be greater than for the East or Central Phases.

The waveforms varied in duration from two to nine seconds, which is typical for events produced by train activity as described above. The overall PPV and RMS vibration amplitudes for the seven vibration events are shown in Table 5. Also shown are the 1/3-octave RMS vibration amplitudes, which are less than the overall RMS amplitudes.

Typical Vibration Criteria

A set of commonly referenced vibration criteria are shown in Table 6, which provide a guide for designers of vibration-sensitive manufacturing facilities and equipment. The vibration criteria are velocity spectra in 1/3-octave bands, and therefore can be compared to the observed 1/3-octave RMS vibration amplitudes in Table 5.

The vibration criteria in Table 6 can also be compared to the observed overall RMS vibration amplitudes in Tables 2, 3, and 4, in the sense that the 1/3-octave RMS amplitudes would be less than the overall RMS amplitudes.

Table 1. Estimated Amtrak Train Activity near Site

Route	Arrival / Departure at Battle Creek[1]	Estimated Train Activity near Site
Pontiac to Battle Creek	8:44am	8:19am – 8:39am[2]
Pontiac to Battle Creek	12:45pm	12:20pm – 12:40pm[2]
Pontiac to Battle Creek	8:29pm	8:04am – 8:24am[2]
Battle Creek to Pontiac	11:25am	11:30am – 11:50am[3]
Battle Creek to Pontiac	5:11pm	5:16pm – 5:36pm[3]
Battle Creek to Pontiac	9:33pm	9:38pm – 9:58pm[3]

Notes:

1. *Arrival or departure time at Battle Creek, Michigan station published on Amtrak.com*
2. *Estimated Activity near Site assumes 20-minute window centered on the arrival time minus 15 minutes*
3. *Estimated Activity near Site assumes 20-minute window centered on the departure time plus 15 minutes*

Table 2. Typical Daily Vibration Velocity Summary during Monitoring Period - West Phase System 1 (W1)

	North-South			East-West			Vertical		
System	PPV (in/s)	Freq (Hz)	RMS (in/sec)	PPV (in/sec)	Freq (Hz)	RMS (in/sec)	PPV (in/sec)	Freq (Hz)	RMS (in/sec)
Sensor 1	0.0065	128.0	0.0008	0.0065	14.6	0.0022	0.0052	34.1	0.0006
Sensor 2	0.0089	7.9	0.0035	0.0082	69.2	0.0016	0.0048	5.8	0.0019
Sensor 3	-	-	-	0.0619	80.0	0.0144	0.0302	7.4	0.0088
Sensor 4	0.0160	11.8	0.0057	-	-	-	0.0164	6.5	0.0065

Table 3. Typical Daily Vibration Velocity Summary during Monitoring Period - West Phase System 2 (W2)

	North-South			East-West			Vertical		
System	**PPV (in/sec)**	**Freq (Hz)**	**RMS (in/sec)**	**PPV (in/sec)**	**Freq (Hz)**	**RMS (in/sec)**	**PPV (in/sec)**	**Freq (Hz)**	**RMS (in/sec)**
Sensor 1	0.0142	11.5	0.0037	0.0141	11.7	0.0035	0.0136	11.5	0.0034
Sensor 2	0.0070	45.7	0.0013	0.0131	7.3	0.0048	0.0309	8.1	0.0082
Sensor 3	0.0092	111.0	0.0012	0.0113	94.8	0.0017	0.0056	5.9	0.0019
Sensor 4	0.0093	18.2	0.0027	0.0063	11.1	0.0023	0.0071	15.7	0.0022

Table 4. Typical Daily Vibration Velocity Summary during Monitoring Period - West Phase System 3 (W3)

	North-South			East-West			Vertical		
System	**PPV (in/sec)**	**Freq (Hz)**	**RMS (in/sec)**	**PPV (in/sec)**	**Freq (Hz)**	**RMS (in/sec)**	**PPV (in/sec)**	**Freq (Hz)**	**RMS (in/sec)**
Sensor 1	0.0634	7.1	0.0231	-	-	-	0.0601	7.1	0.0226
Sensor 2	0.0209	15.1	0.0059	0.0251	8.6	0.0092	0.0121	15.9	0.0037
Sensor 3	0.0112	23.5	0.0015	0.0109	23.5	0.0015	0.0107	23.7	0.0015
Sensor 4	0.0090	21.9	0.0014	0.0152	69.2	0.0026	0.0048	116	0.0005

Table 5. Vibration Velocity Summary for Train Passage Event Waveforms

		North-South				East-West				Vertical			
		Overall		1/3-Octave		Overall		1/3-Octave		Overall		1/3-Octave	
Date & Time	Sensor	PPV (in/sec)	RMS (in/sec)	RMS (in/sec)	Freq (Hz)	PPV (in/sec)	RMS (in/sec)	RMS (in/sec)	Freq (Hz)	PPV (in/sec)	RMS (in/sec)	RMS (in/sec)	Freq (Hz)
December 2, 2021, at 02:36:29[1]	C1-4	0.00179	0.00047	0.00014	2.0	0.00638	0.00159	0.00075	2.5	0.00147	0.00045	0.00020	3.2
December 2, 2021, at 00:11:21[2]	C2-4	0.00054	0.00015	0.00005	160.0	0.00068	0.00017	0.00008	5.0	0.00031	0.00011	0.00005	5.0
December 8, 2021, at 11:00:16[3]	E2-4	0.00029	0.00008	0.00004	8.0	0.00030	0.00010	0.00005	10.0	0.00041	0.00010	0.00004	400.0
December 16, 2021, at 00:01:02[4]	W3-2	0.00436	0.00095	0.00040	6.3	0.01756	0.00301	0.00116	8.0	0.00885	0.00172	0.00077	5.0
December 16, 2021, at 00:01:02[5]	W3-3	0.00322	0.00050	0.00025	100.0	0.00319	0.00048	0.00019	100.0	0.00112	0.00033	0.00015	8.0
December 16, 2021, at 00:01:02[6]	W3-4	0.00129	0.00020	0.00009	63.0	0.00248	0.00054	0.00029	6.3	0.00149	0.00032	0.00017	6.3
December 14, 2021, at 09:25:13[7]	W3-4	0.00279	0.00083	0.00050	10.0	0.00346	0.00092	0.00046	12.5	0.00235	0.00057	0.00029	12.5

Notes:

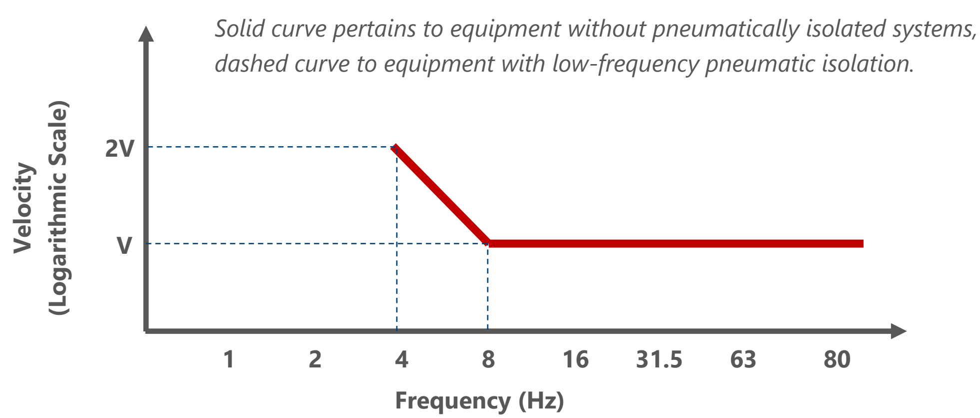
1. *Corresponds to events shown in Figures 9 and 10.*
2. *Corresponds to events shown in Figures 11 and 12.*
3. *Corresponds to events shown in Figures 13 and 14.*
4. *Corresponds to events shown in Figures 15 and 16.*
5. *Corresponds to events shown in Figures 17 and 18.*
6. *Corresponds to events shown in Figures 19 and 20.*
7. *Corresponds to events shown in Figures 21 and 22.*

Table 6. Vibration Criteria

Vibration Curve Criterion	RMS Vibrational Velocity[1] (in/sec)	Description of Use
Workshop (ISO)	0.0320	Distinctly perceptible vibration. Appropriate to workshops and non-sensitive areas.
Office (ISO)	0.0160	Perceptible vibration. Appropriate to offices and non-sensitive areas.
Residential Day (ISO)	0.0080	Barely perceptible vibration. Usually adequate for computer equipment, hospital recovery rooms, semiconductor probe test equipment and microscopes less than 40X.
Operating Theater (ISO)	0.0040	Vibration not perceptible. Suitable in most instances for surgical suites, microscopes to 100X.
VC-A	0.0020	Adequate in most instances for optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, etc.
VC-B	0.0010	Appropriate for inspection and lithography (including steppers) to 3 µm line widths.
VC-C	0.0005	Appropriate standard for optical microscopes to 1,000X, inspection and lithography inspection equipment (including moderately sensitive electron microscopes) to 1 µm detail size, TFT-LCD stepper/scanner processes.
VC-D	0.00025	Adequate in most instances for electron microscopes (TEMs and SEMs) and E-Beam systems.
VC-E	0.000125	Adequate in most instances for long path, laser-based, small target systems, E-Beam lithography systems working at nanometer scales, and other systems requiring extraordinary dynamic stability.

Notes:

1. *Value of V in figure below.*



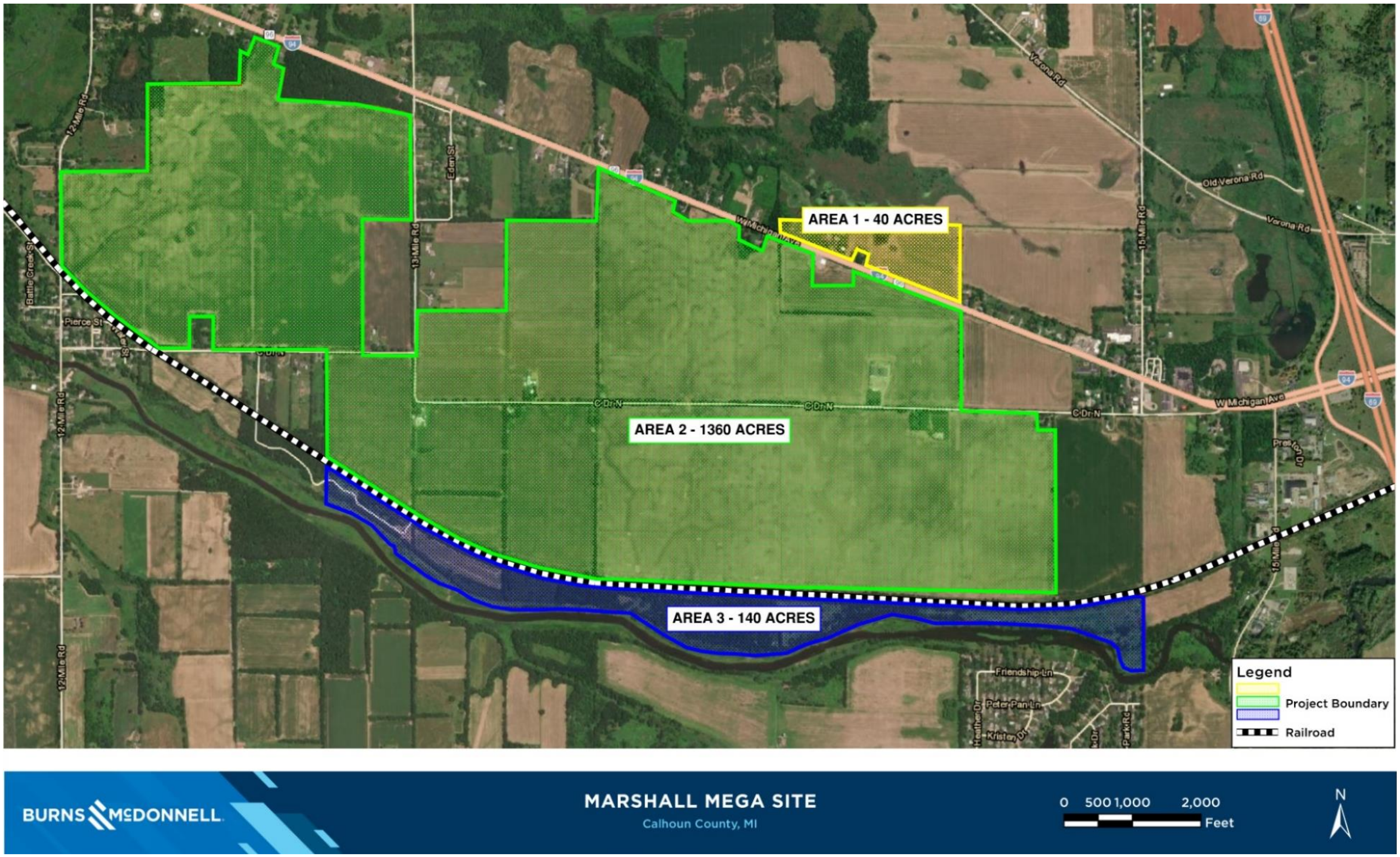


Figure 1. Overall site plan.

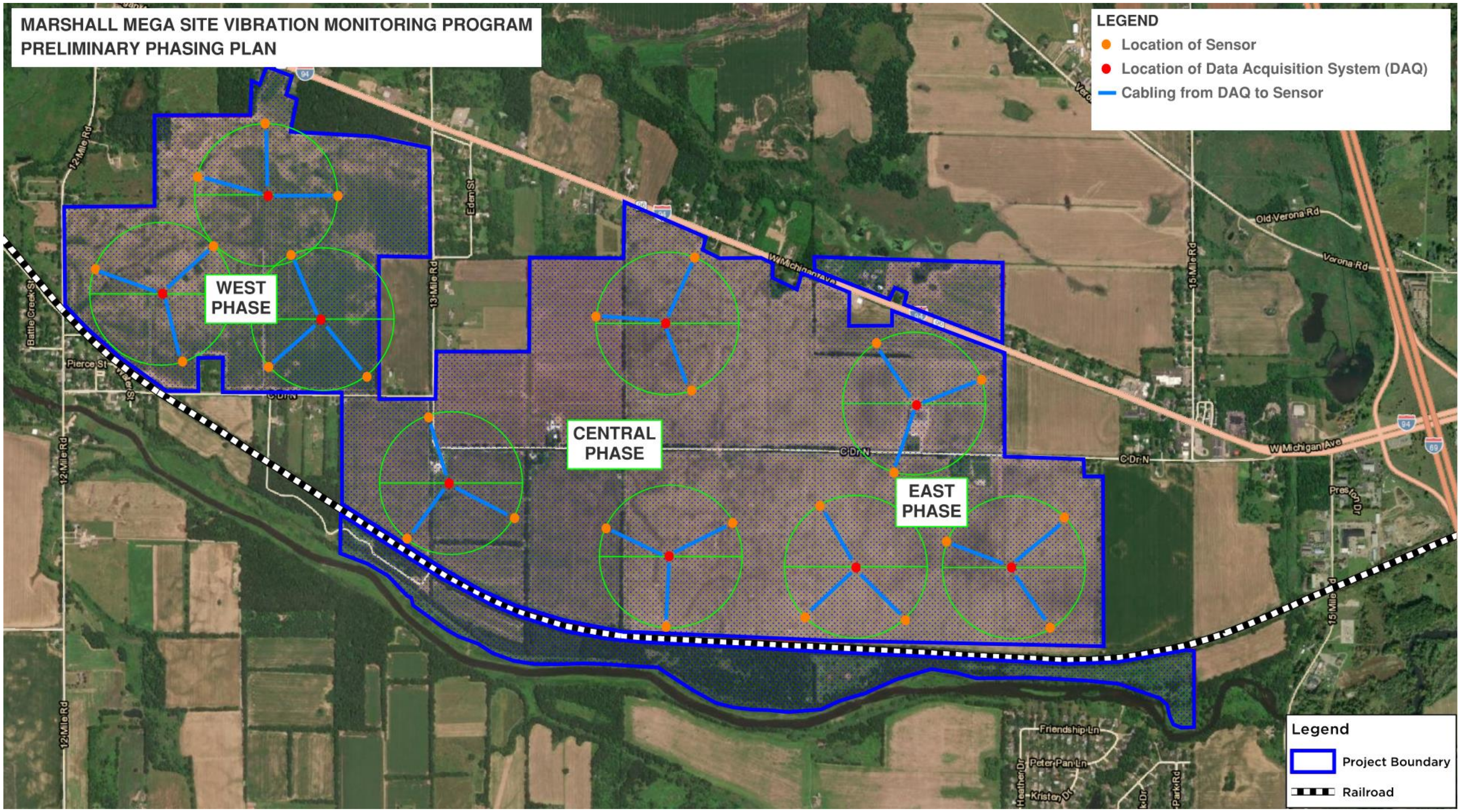


Figure 2. Preliminary monitoring and phasing plan.

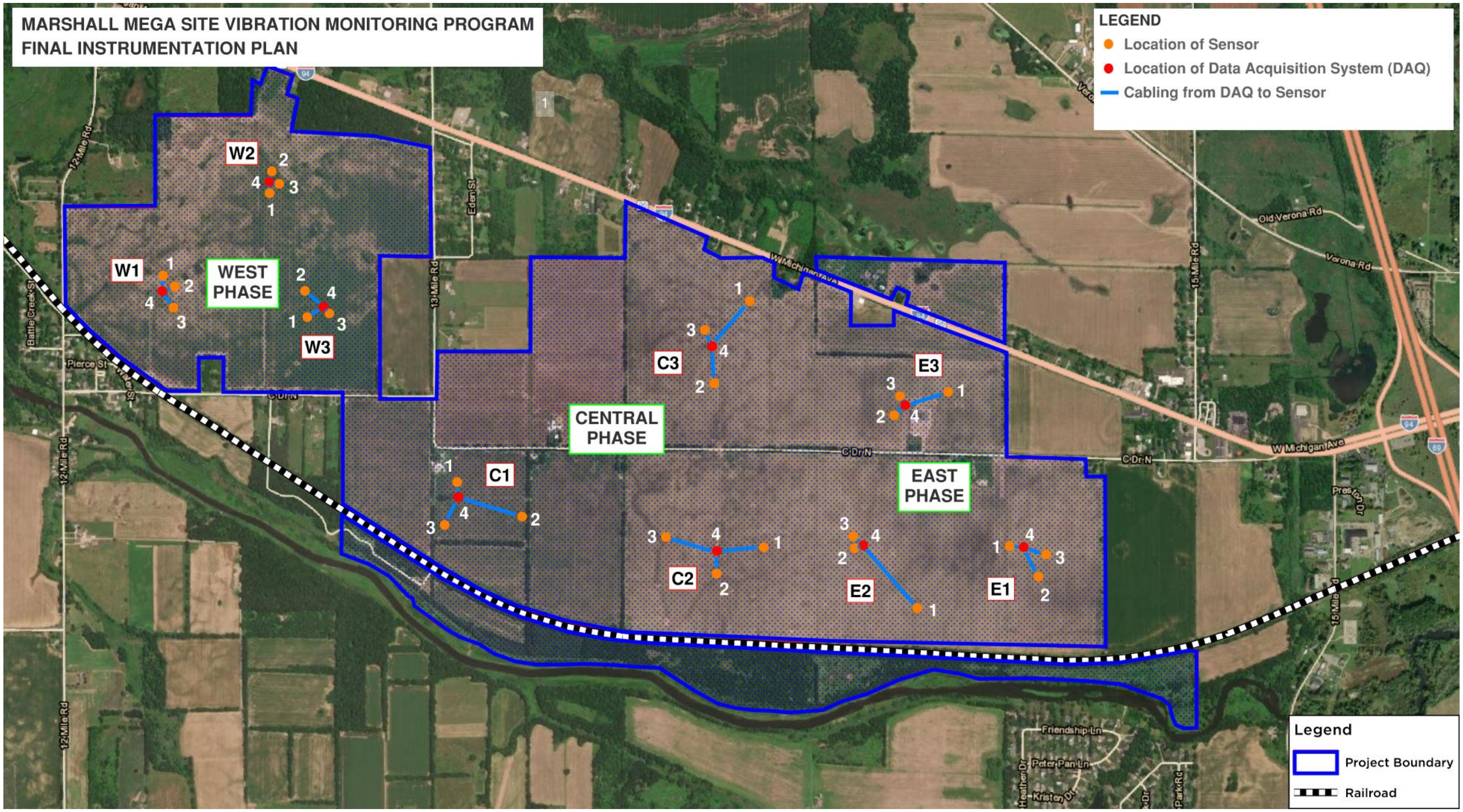


Figure 3. Final monitoring and phasing plan.

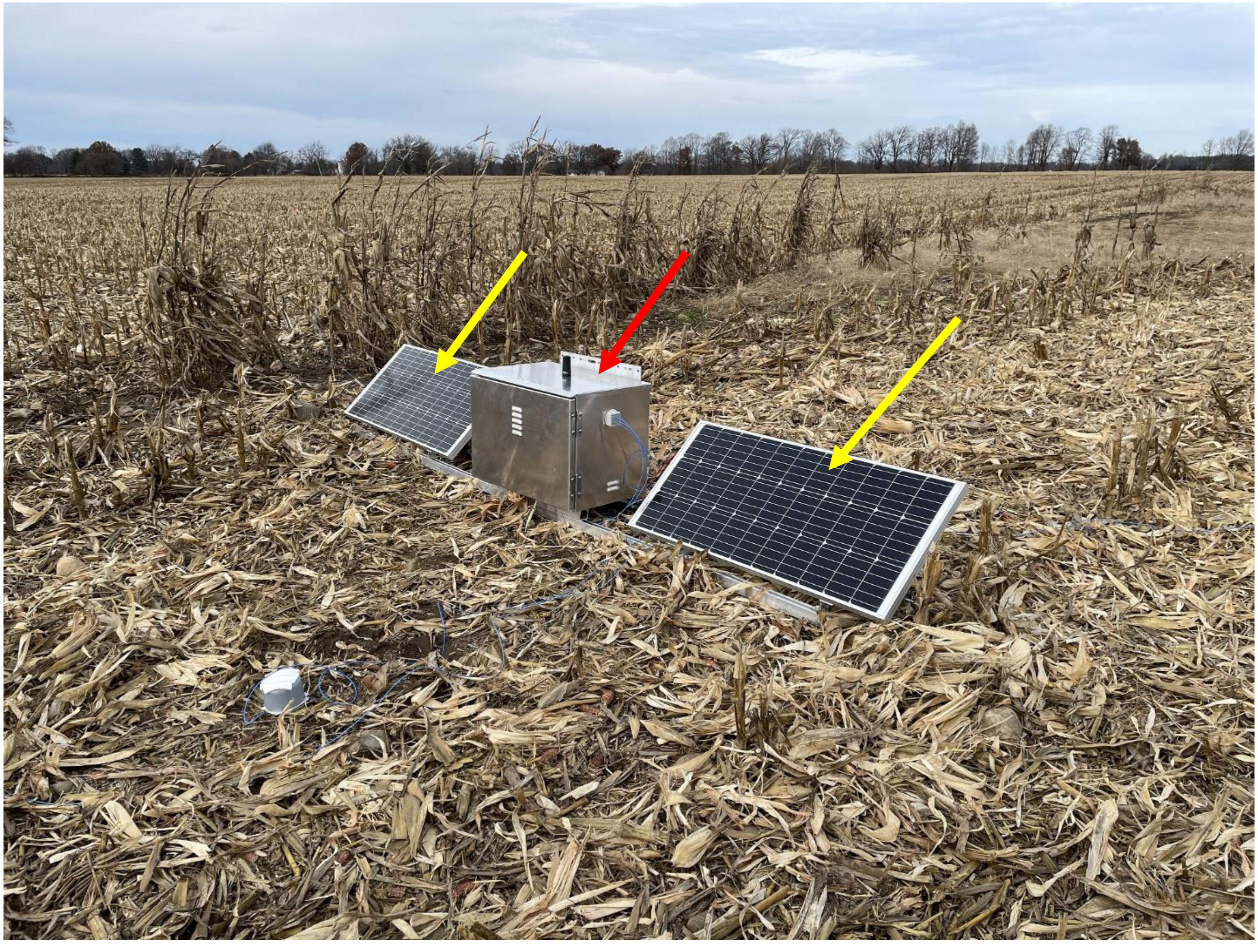


Figure 4. Typical data acquisition system housing (red arrow) with solar panels (yellow arrows).

Figure 5. Typical accelerometer installation without cover. Sensor indicated by red arrow.

Figure 6. Typical accelerometer installation with cover (red arrow).

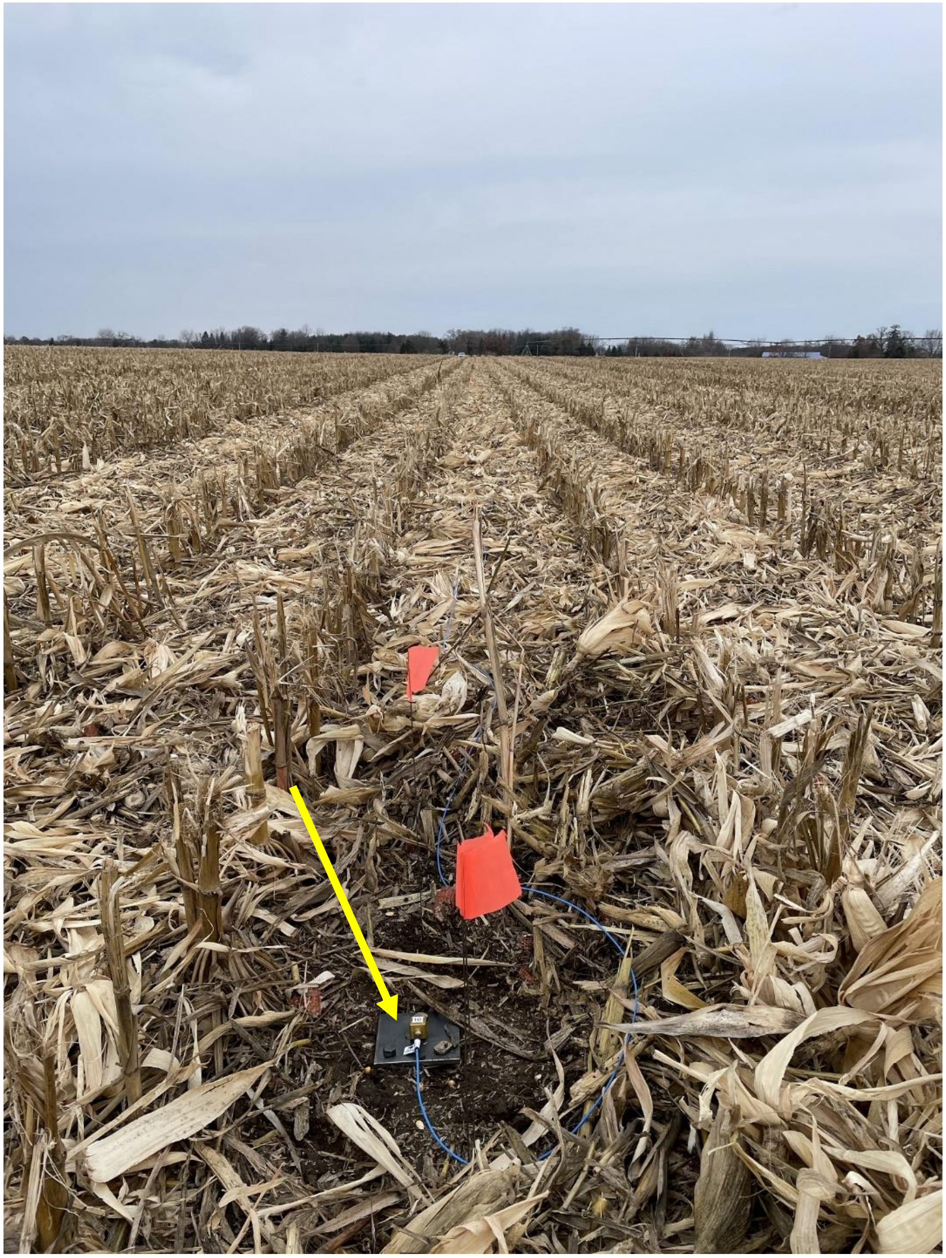


Figure 7. Typical accelerometer (yellow arrow) installation with marker flags.


Figure 8. Cabling damaged on site (yellow arrow).

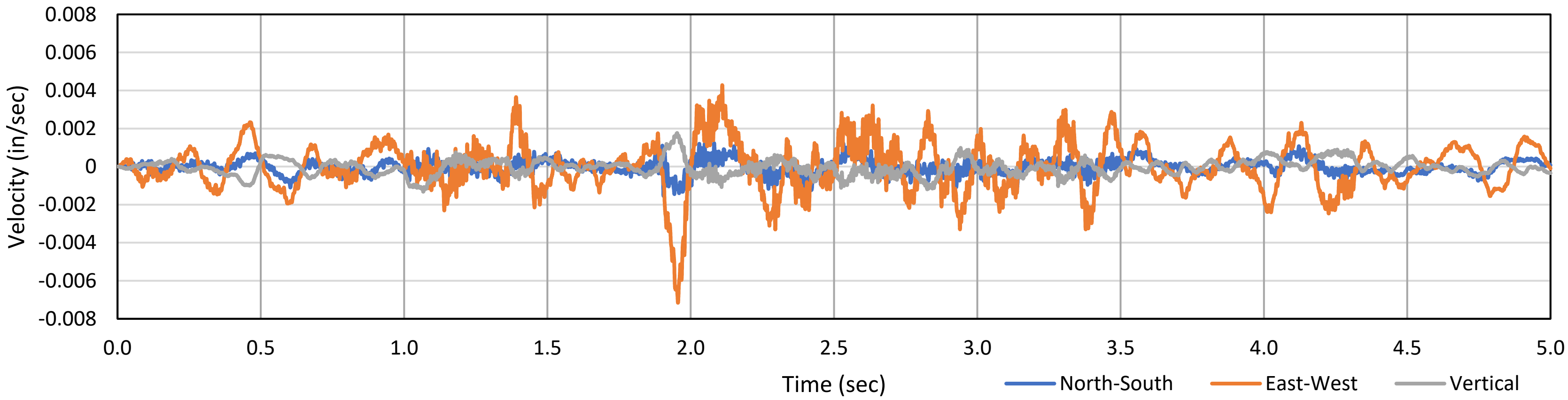


Figure 9. Train Passage Event – Particle Velocity vs. Time – Central Phase, System 1, Sensor 4 (C1-4) – December 2, 2021, at 02:36:29.

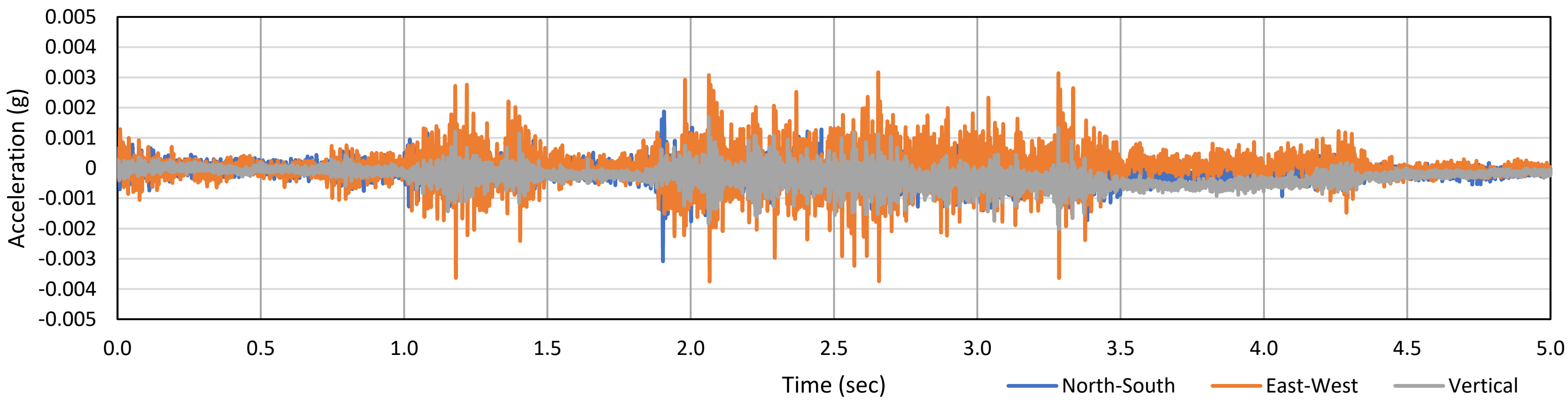


Figure 10. Train Passage Event – Acceleration vs. Time – Central Phase, System 1, Sensor 4 (C1-4) – December 2, 2021, at 02:36:29.

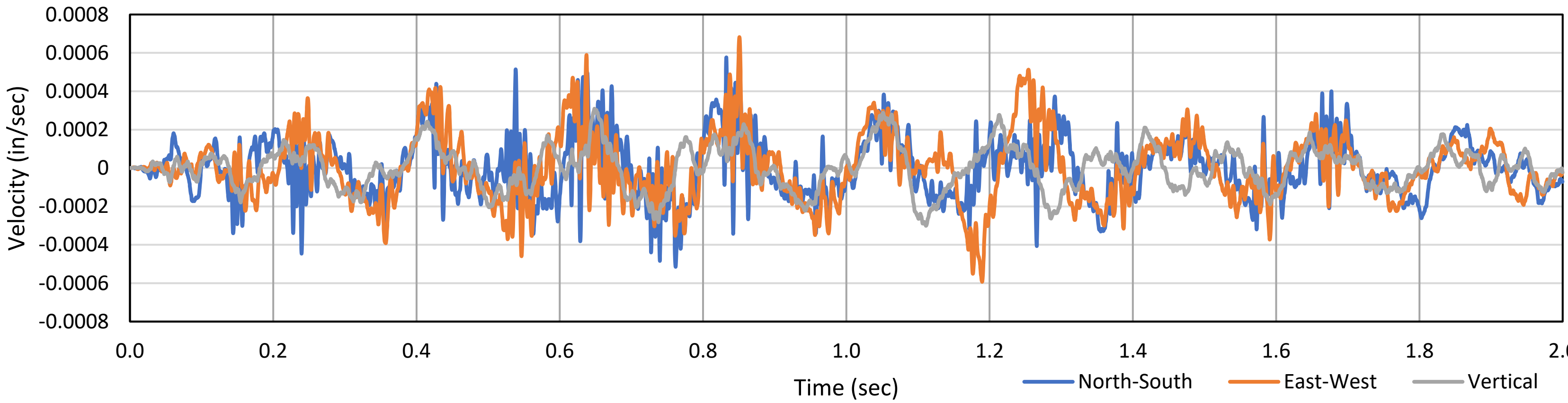


Figure 11. Train Passage Event – Particle Velocity vs. Time – Central Phase, System 2, Sensor 4 (C2-4) – December 2, 2021, at 00:11:21.

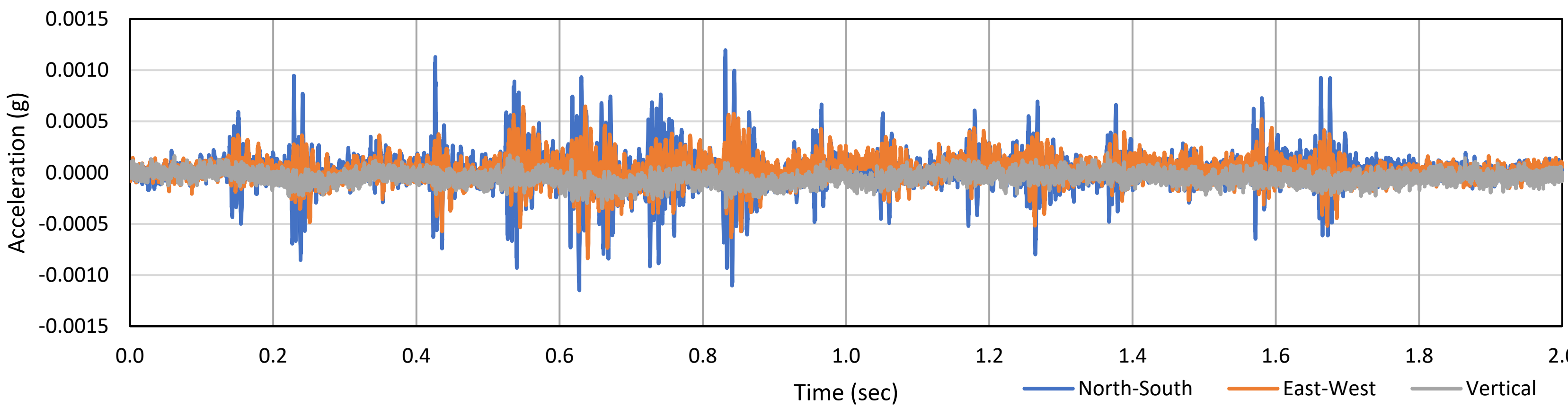


Figure 12. Train Passage Event – Acceleration vs. Time – Central Phase, System 2, Sensor 4 (C2-4) – December 2, 2021, at 00:11:21.

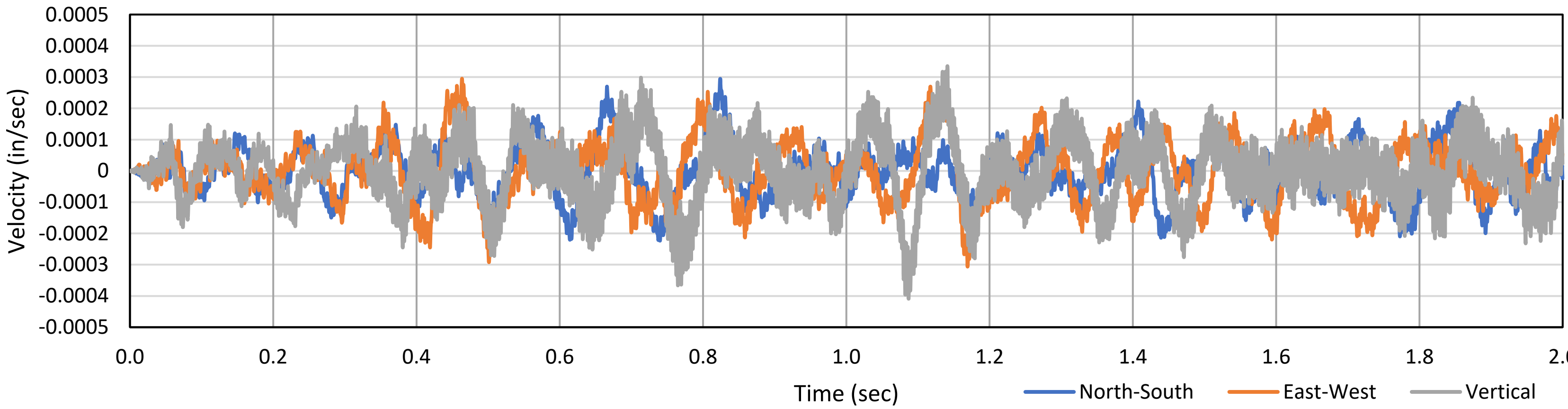


Figure 13. Train Passage Event – Particle Velocity vs. Time – East Phase, System 2, Sensor 4 (E2-4) – December 8, 2021, at 11:00:16.

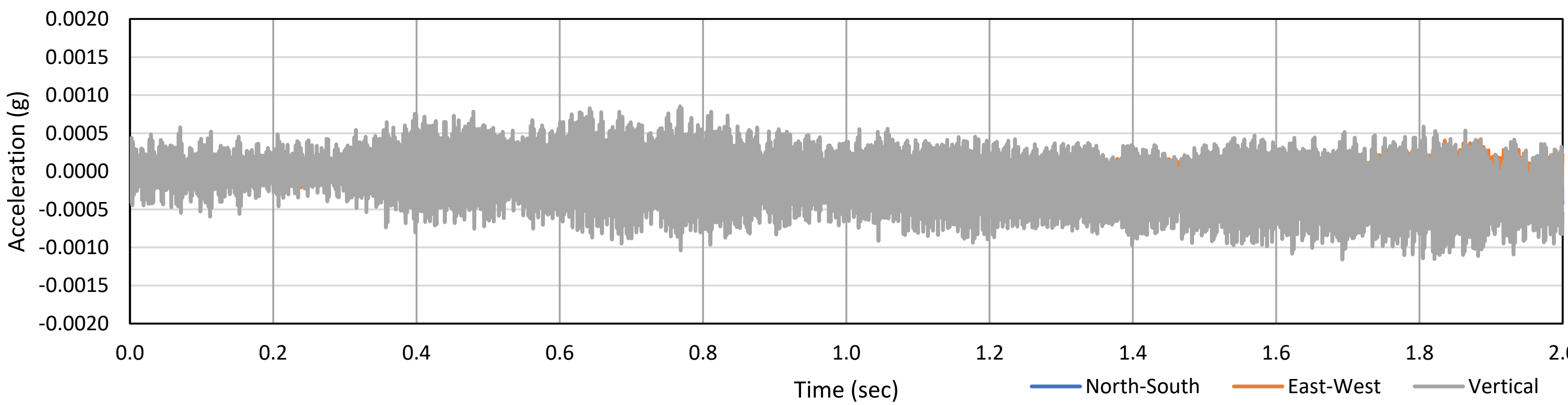


Figure 14. Train Passage Event – Acceleration vs. Time – East Phase, System 2, Sensor 4 (E2-4) – December 8, 2021, at 11:00:16.

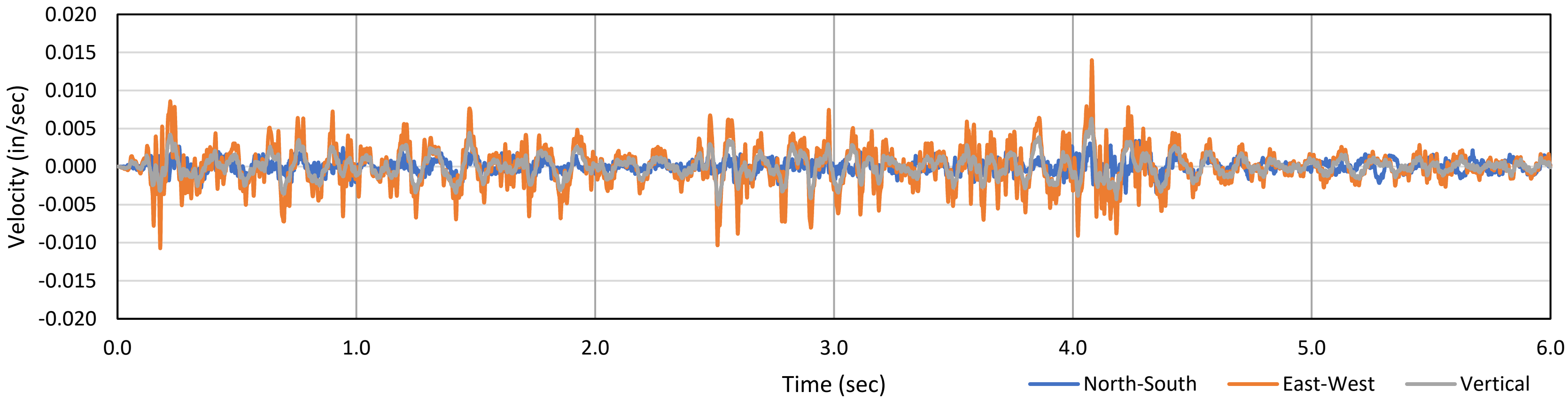


Figure 15. Train Passage Event – Particle Velocity vs. Time – West Phase, System 3, Sensor 2 (W3-2) – December 16, 2021, at 00:01:02.

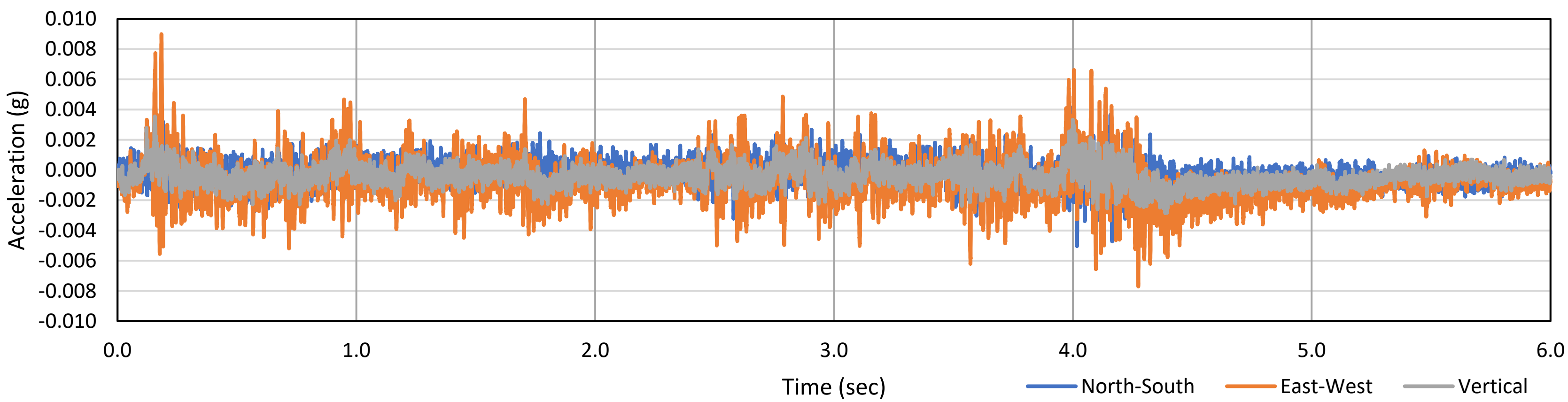


Figure 16. Train Passage Event – Acceleration vs. Time – West Phase, System 3, Sensor 2 (W3-2) – December 16, 2021, at 00:01:02.

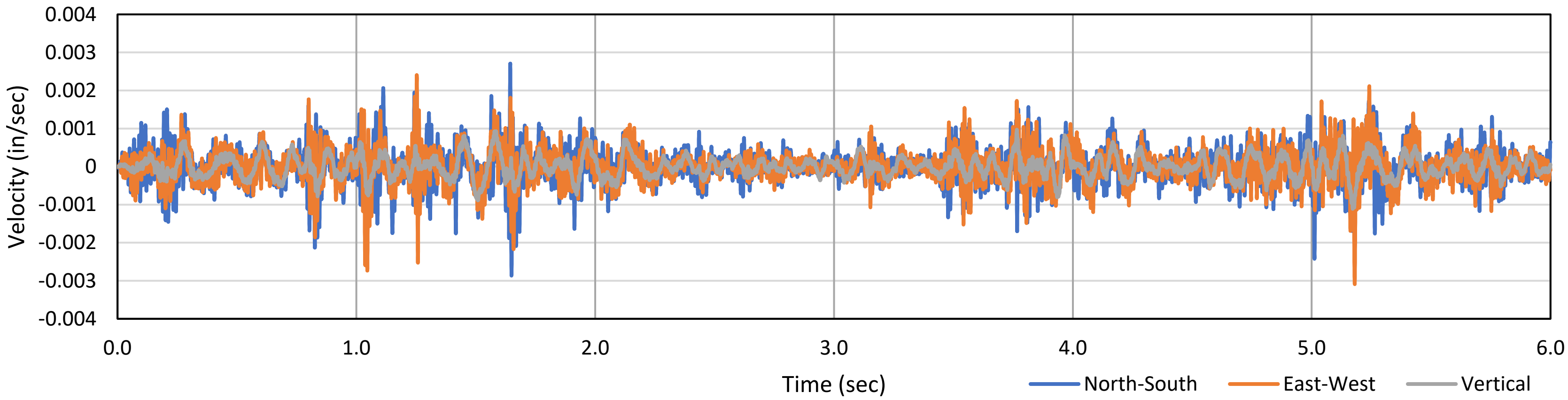


Figure 17. Train Passage Event – Particle Velocity vs. Time – West Phase, System 3, Sensor 3 (W3-3) – December 16, 2021, at 00:01:02.

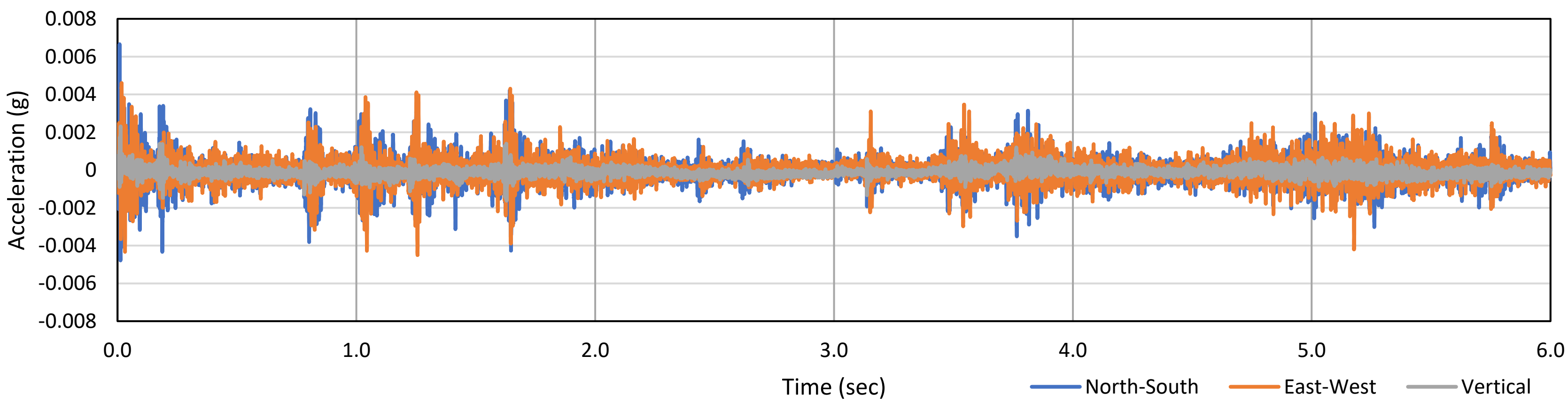


Figure 18. Train Passage Event – Acceleration vs. Time – West Phase, System 3, Sensor 3 (W3-3) – December 16, 2021, at 00:01:02.

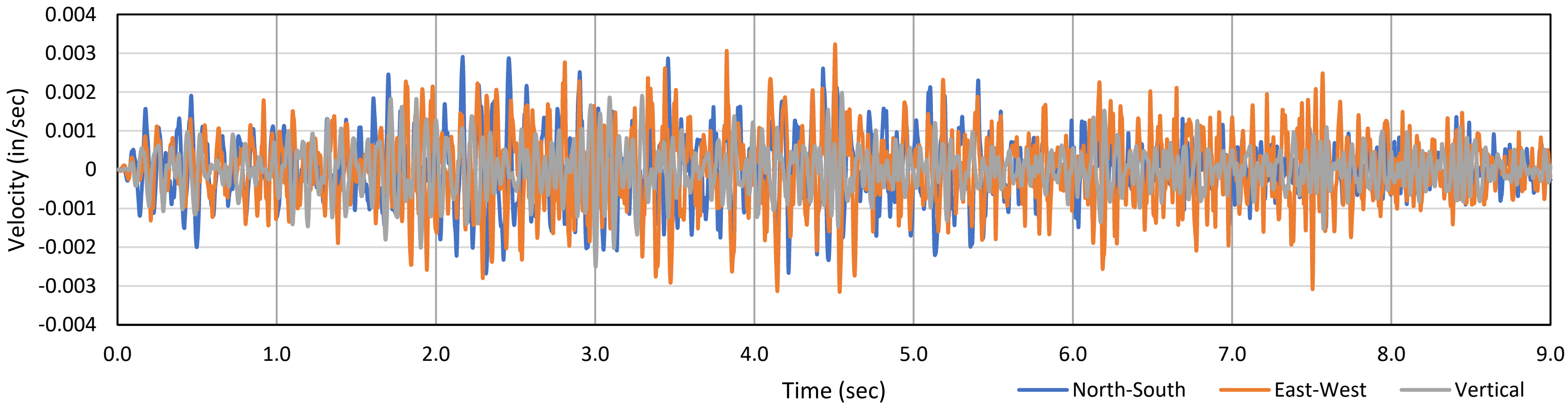


Figure 19. Train Passage Event – Particle Velocity vs. Time – West Phase, System 3, Sensor 4 (W3-4) – December 14, 2021, at 09:25:13.

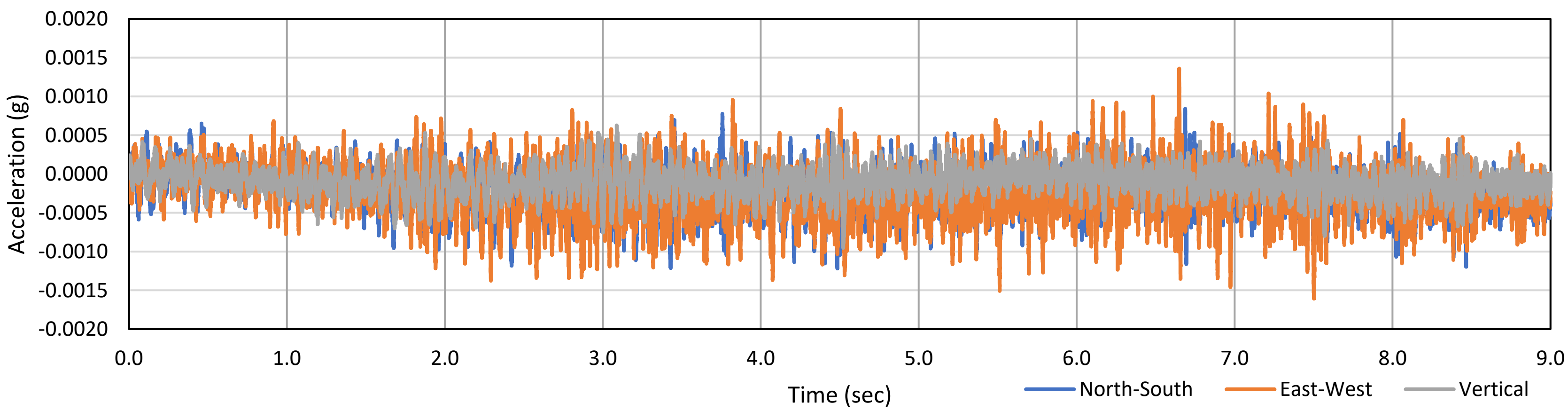


Figure 20. Train Passage Event – Acceleration vs. Time – West Phase, System 3, Sensor 4 (W3-4) – December 14, 2021, at 09:25:13.

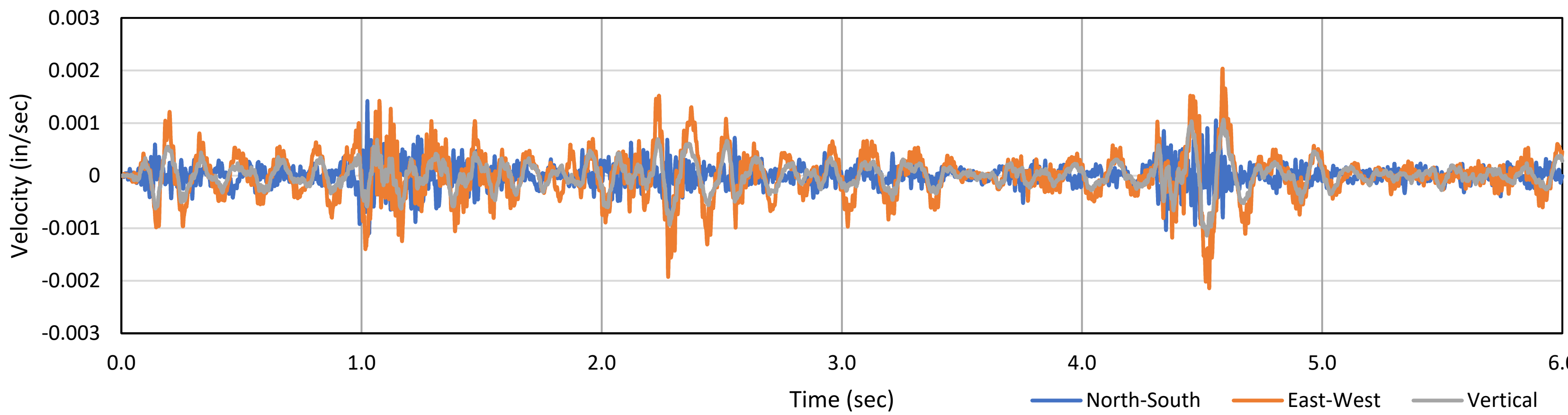


Figure 21. Train Passage Event – Particle Velocity vs. Time – West Phase, System 3, Sensor 4 (W3-4) – December 16, 2021, at 00:01:02.

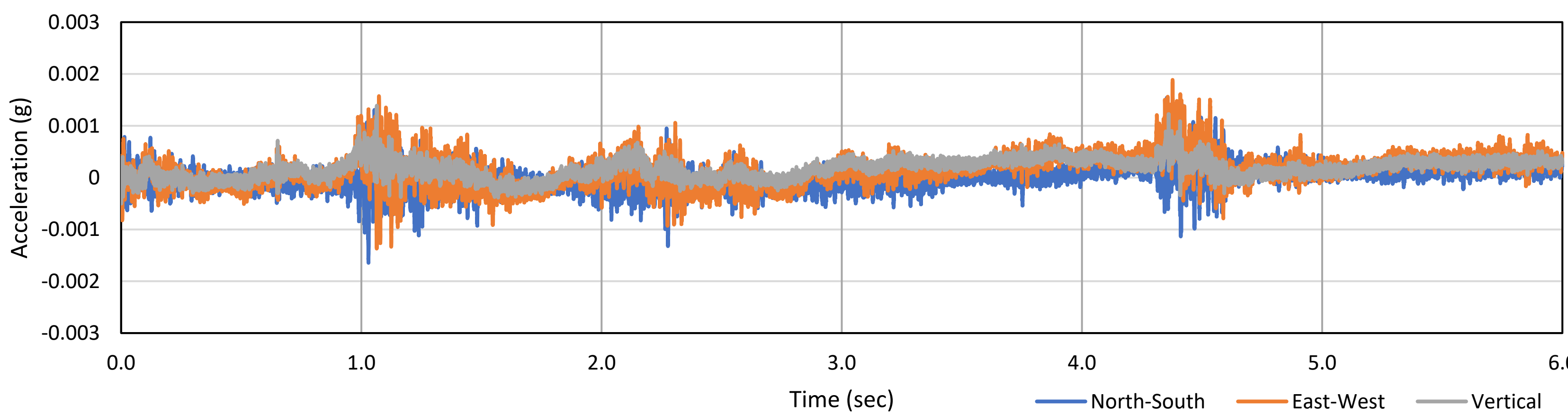


Figure 22. Train Passage Event – Acceleration vs. Time – West Phase, System 3, Sensor 4 (W3-4) – December 16, 2021, at 00:01:02.