PNNL- 27666

Pacific Northwest NATIONAL LABORATORY

The Dalles Dam Fish Ladder Auxiliary Water System Vibration Monitoring

Final Report

December 2018

ZD Deng
X Zang
JM Martinez
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
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BATTELLE
for the
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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

The U.S. Army Corps of Engineers modified the Fish Ladder Auxiliary Water System at The Dalles Dam in October 2017. To mitigate impacts from potential delays to migrating salmonids associated with the planned construction work, vibration in the East Fish Ladder support columns in the vicinity of the excavation area was monitored and recorded during construction activities. Three locations on the inner wall of the fish ladder were selected for vibration monitoring. Each of the three vibration monitoring systems included an array of tri-axial accelerometers, a solar power system, and a data acquisition unit. Before the construction activities began, baseline vibration measurements were continuously monitored from October 5 to October 16. During construction, vibration was monitored from October 16 to October 31. The recorded acceleration data were processed by taking the root mean square of the acceleration magnitude in the 5-10 Hz band of each 1-second period. The results then were evaluated relative to the 0.01 m/s^2 threshold level that was selected from scientific literature as the level that could elicit avoidance behavior in salmonids. Knudsen et al. (1992) has shown that two-second stimuli of 0.01 m/s^2 particle acceleration could elicit avoidance response from juvenile Atlantic salmon. This study used 1-second duration of exceedance as a trigger for north ladder attraction spill to minimize potential delay impacts associated with the construction activities. Daily reports of vibration monitoring during construction were generated and over-limit events that would trigger a spill were reported. In total, five construction days exceeded the acceleration threshold, with the 3, 1, 8, 9, and 14 events on each day, respectively.

Acknowledgments

The authors are thankful to all who contributed to this study, including Jon Rerecich, Ricardo Walker, Brad Eppard, and Scott Fielding of U.S. Army Corps of Engineers (USACE) Portland District, USACE personnel at The Dalles Dam, and many staff members at Pacific Northwest National Laboratory.

Acronyms and Abbreviations

Hz	Hertz
m	meter
mm	millimeter
mm/s^2	millimeter per second square
m/s^2	meter per second squared
mV/g	microvolt per gravitational acceleration
RMS	root mean square
USACE	U.S. Army Corps of Engineers
V	volt
μPa	micro-pascal

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1.0 Background

The U.S. Army Corps of Engineers (USACE) planned to modify the Fish Ladder Auxiliary Water System at The Dalles Dam in October 2017. To mitigate impacts from potential delays to migrating salmonids associated with the planned construction, vibration in the East Fish Ladder support columns in the vicinity of the excavation area (Figure 1.1) were monitored and recorded during construction activities. Daily reports were generated during the October 16–31, 2017, construction period. When vibration exceeded a set threshold, dam operators conducted a forced spill to allow salmonids that may have been deterred by the vibrations to navigate through the ladder.

Figure 1.1. Construction Site at The Dalles Dam Fish Ladder. The excavation area is marked with the black line numbered from 3 to 5.

The behavior of salmon in response to underwater sounds is still largely unknown. Salmon have relatively poor hearing with a sharp cut-off frequency of 380 Hz. Typically, salmon are sensitive to particle motion (i.e., bulk motion of water resulting from pressure wave propagation) rather than sound pressure (Hawkins and Johnstone 1978; Redford et al. 2012). It has been suggested that fishes, including salmonids, may use infrasound (sound waves at a frequency below 20 Hz) to detect moving objects in their surroundings. It has also been suggested that salmon may use the ambient infrasound in the ocean, produced by waves, tides, and other large-scale motion, for orientation during migration. Among the different measures of particle motion, particle acceleration is believed to be the most relevant measure, as it is closest to the way that fish auditory systems function (Au and Hastings 2008; Mooney et al. 2010).

Data on the behavioral responses of fishes such as salmon to sound exposure are very limited, apart from experiments done on the responses of salmon to short bursts of infrasound. Knudsen et al. (1992) studied juvenile Atlantic salmon in a pool and concluded that the particle acceleration at 5 to 10 Hz should be at least 0.01 m/s^2 to elicit an avoidance response. In a subsequent study, Knudsen and his team reported that a particle acceleration of 0.01 m/s^2 deterred downstream migrating Atlantic salmon smolts in a river (Knudsen et al. 1994). The same behavioral experiment was performed with juvenile spring Chinook salmon and rainbow trout in a tank. In that test, avoidance behavior was observed and did not habituate even after 20 trials (Knudsen et al. 1997). More recently, Sand et al. (2008) suggested that near-field particle motion generated by the moving hulls of ships are mainly in the infrasonic range, and infrasound is particularly potent in evoking directional avoidance responses to ships. Higher frequencies did not result in any behavioral changes, even at 150 Hz, which is the most sensitive frequency for salmon.

Thus, to mitigate the impact of construction activities to migrating salmon, it was necessary to measure particle motion rather than sound pressure in this project. Based on published information on the behavioral response of salmon to particle motion, the 0.01 m/s^2 particle acceleration in the 5 to 10 Hz band was selected as the threshold to be used in this vibration monitoring project. Using three sets of autonomous acceleration recording systems, we continuously monitored the vibration at three locations that are close to the proposed construction area. To establish a baseline for vibration, the monitoring started one week before construction began. During the construction, acceleration data were processed every day, and a daily report was submitted to USACE the next day for decision-making purposes.

2.0 Field Deployment

On October 5, 2017, we deployed three identical measurement systems at three deployment sites (Figures 2.1, 2.2, and 2.3). Each system included a data acquisition system and sensors. To measure the particle motion in terms of acceleration in three orthogonal directions (x-, y-, and z-directions), three high-sensitivity (approximately 1000 mV/g) accelerometers (PCB Piezotronics model 393A03) were rigidly mounted in perpendicular directions (Figure 2.4). Cables for the three accelerometers were bundled and routed to a weatherproof enclosure. A solar power system (i.e., solar panel, charge controller, and two 12-V batteries) were located near each deployment site, with the solar panel mounted on a standalone structure that allowed the panel to face the southern sky. The PCB Piezotronics model 393A03 accelerometers used were designed to measure ultra-low-amplitude, low-frequency vibrations. They have a frequency range of 0.5 Hz to 2 kilohertz (Appendix A) and a broadband resolution of 0.0001 m/s^2. All accelerometers were calibrated in the laboratory prior to field deployment (Appendix B). Monitoring commenced on October 5 and ran continuously until October 16 to develop baseline vibration levels. Monitoring of construction vibration levels started on October 16 and ended on October 31.

Figure 2.1. Deployment Location #1. The site is located at the entrance of the fish ladder, on the side where the construction will occur. Accelerometers were attached to the inner wall of the fish ladder above the water level.

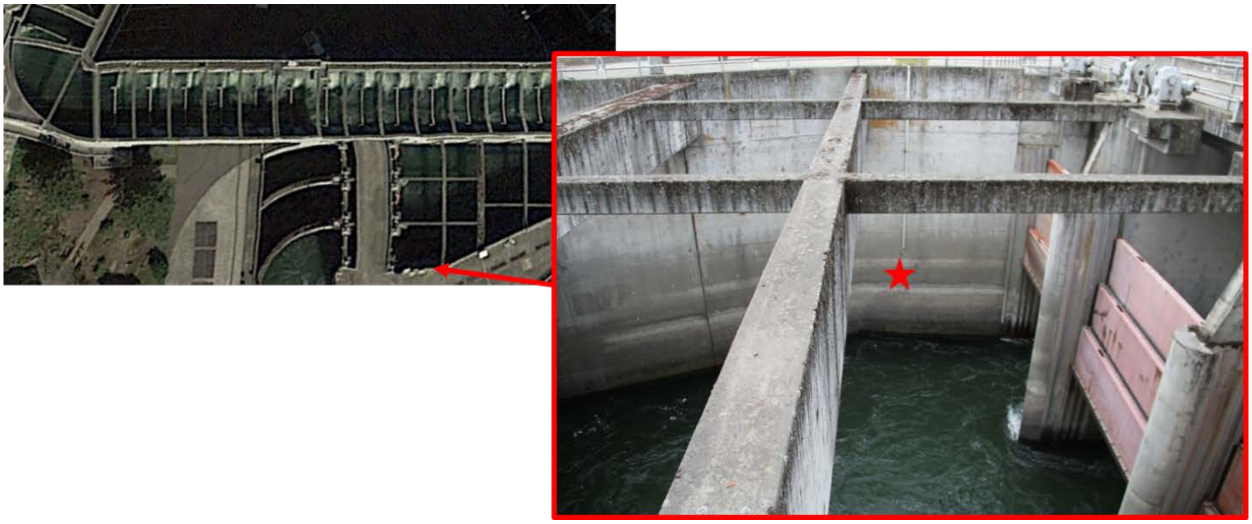

Figure 2.2. Deployment Location #2. The site is located on the opposite side of Location 1 at the entrance of the fish ladder. Accelerometers were attached to the inner wall of the fish ladder above the water level.

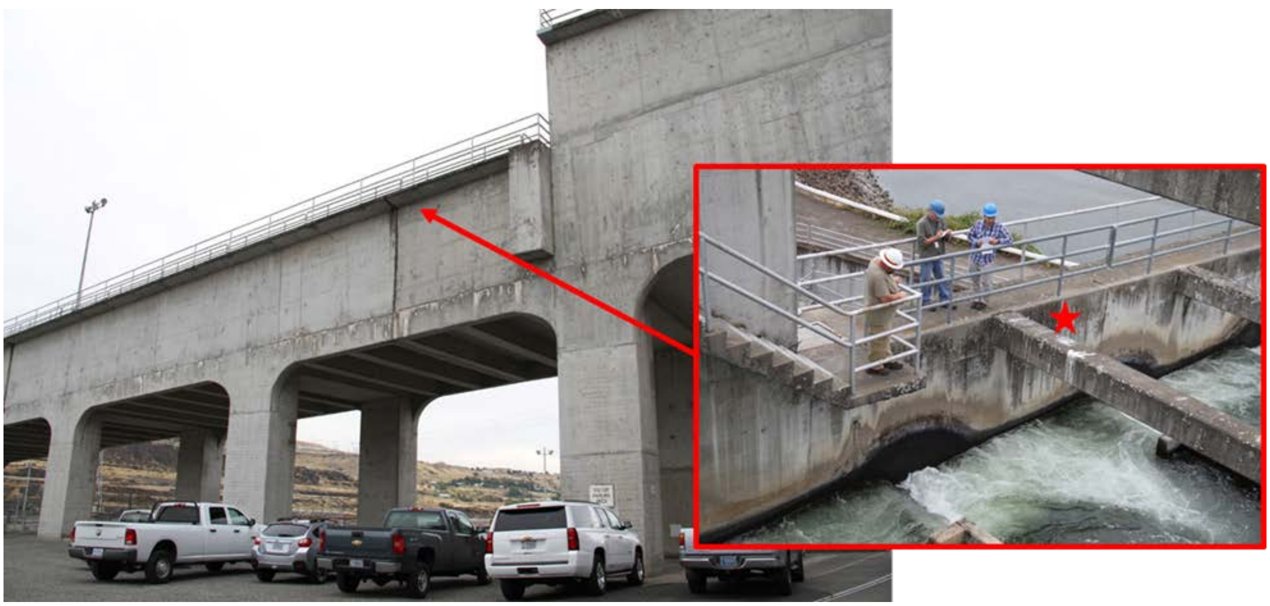

Figure 2.3. Deployment Location #3. The site is located at the upper side of the fish ladder. Accelerometers were attached to the inner wall of the fish ladder above the water level.

Figure 2.4. Photograph PCB Piezotronics Model 393A03 Single-Axis Accelerometer. Accelerometers were installed in a tri-axial array at each of the measurement sites.

3.0 Data Analysis

3.1 Acceleration Threshold Selection

Salmon are believed to be more sensitive to particle motion than sound pressure. Table 3.1 provides summaries of publications that discuss the avoidance response of juvenile salmon to infrasound, which is sound with a frequency less than 20 Hz).

Table 3.1. Publications that Discuss the Avoidance Response of Juvenile Salmon to Infrasound

Researcher	Fish Species	Test Frequency	Study Location	Results
Knudsen et al. 1992	Juvenile Atlantic salmon	5, 10, 60, and 150 Hz	In a tube	The thresholds for awareness reactions were much lower at 5 to 10 Hz than at 150 Hz.
		10 and 150 Hz	In a pool	1. 10 Hz sound evoked avoidance response for fish within 2 m of the sound source. 2. The avoidance response threshold to 10 Hz sound was 10 to 15 decibels above the spontaneous awareness reaction threshold. 3. At 5 to 10 Hz the particle acceleration should be at least 0.01 m/s^2 to elicit an avoidance response. 4. The 150-Hz sound failed to evoke avoidance response.
Knudsen et al. 1994	Juvenile Atlantic salmon	10 and 150 Hz	In a small river	Avoidance response to 10-Hz sounds was seen up to 3 m from the source, where sound intensity was about 0.01 m/s^2.
Knudsen et al. 1997	Juvenile spring Chinook salmon and rainbow trout	10 Hz	In a tank	Initial tests always resulted in a strong flight response, but after three to four tests the fish more typically simply swam away as far as possible from the source. The avoidance response did not habituate even after 20 trials.
Mueller et al. (Pacific Northwest National Laboratory) 1998	30-70 mm rainbow trout and Chinook salmon	7-14 Hz, 150, 180, and 200 Hz	In a tank	1. Juvenile salmonids, as small as 30 mm long, have infrasound detection capability when the particle motion exceeds 10^{-2} m/s^2 at a frequency of 7 to 10 Hz. 2. A startle response in wild Chinook salmon was observed when exposed to high-intensity (162 decibels re 1 µPa), 150-Hz pure tone sound. 3. No observable effects were noted on hatchery Chinook salmon or rainbow trout fry when exposed to 150, 180, or 200 Hz high-intensity sound. 4. Even for the maximum range at which acceleration measurement was made (4.2 m), the local flow acceleration exceeded the minimum required for fish reactance (10^{-2} m/s^2).
Mueller et al. (Pacific Northwest National Laboratory) 1999	Juvenile Chinook salmon, brook trout and rainbow trout	10 Hz	In a tank	1. Wild Chinook salmon are much more likely to respond to 10-Hz infrasound than hatchery reared fish. 2. Rainbow trout fry showed no observable avoidance responses to infrasound, although a startle response was observed with 16% of the first five test exposures. 3. Test groups of eastern brook trout displayed the least behavior responses to the infrasound.

Knudsen et al. (1992) studied juvenile Atlantic salmon in a pool and concluded that particle acceleration at frequencies from 5 to 10 Hz should be at least 0.01 m/s^2 to elicit an avoidance response. In a subsequent study (Knudsen et al. 1994), they reported that a particle acceleration of 0.01 m/s^2 deterred downstream migrating Atlantic salmon smolts in a river. Therefore, in this study an acceleration value of 0.01 m/s^2 in the 5 to 10 Hz frequency band was selected as the threshold of Root Mean Square (RMS) acceleration magnitude. Acceleration magnitudes calculated in each 1-second time period were evaluated against this threshold.

3.2 Data Analysis Method

The RMS particle acceleration in the 5 to 10 Hz frequency band was calculated using the following steps:

1. Convert raw acceleration data from each axis (a_x, a_y, a_z) to physical units according to the sensitivity of each individual accelerometer (Appendix B)
2. Calculate the acceleration magnitude using Equation 1

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{1}$$

3. Filter the particle acceleration magnitude (calculated in step 2) with a 5 to 10 Hz bandpass filter
4. Calculate the RMS of the filtered acceleration magnitude in each 1-second time period.

Figure 3.1 shows how the data analysis was performed for the tri-axial acceleration data. Panels 1, 2, and 3 are the x, y, and z components of particle accelerations after converting raw data to the physical unit of m/s^2 according to the sensitivity of each individual accelerometer (Appendix B). Panel 4 shows the acceleration magnitude calculated with Eq. (1). Panel 5 is the filtered acceleration magnitude in the 5 to 10 Hz band. It should be noted that the acceleration magnitude in the 5 to 10 Hz band exceeded the 0.01 m/s^2 threshold at about 43 seconds. A review of the raw audio file revealed that the over-threshold acceleration occurred during loud construction activities.

The selection of the time duration for the RMS calculation is important. Knudsen et al. (1992) found that a 2-second stimulus could evoke an avoidance response of juvenile Atlantic salmon to 0.01 m/s^2 particle accelerations at 5 to 10 Hz. To err on the conservative side in our study, we calculated the metrics for every 1-second of acceleration data. Each over-threshold occurrence was considered to be a spill trigger for the dam management.

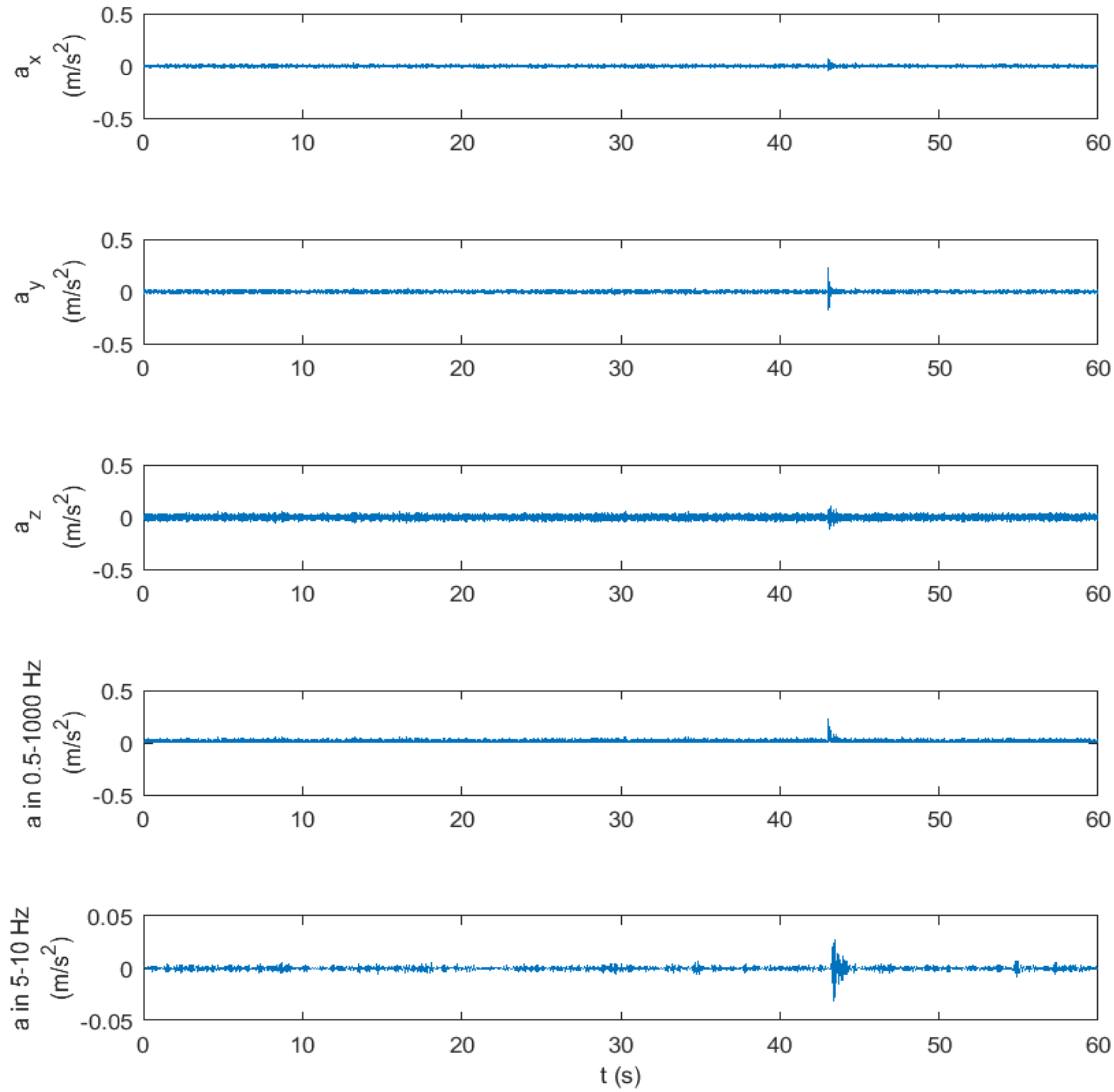

Figure 3.1. Demonstration of the Data Analysis Method with a 1-Minute-Long Data File Recorded at Location 3 from 19:44:30 to 19:45:30 on October 16, 2017.

4.0 Results

4.1 Baseline Monitoring (October 5–16, 2017)

The baseline accelerations at the three locations were monitored from October 5 to October 16, 2017 (see Table 4.1 and Figure 4.1). The mean baseline (denoted by the magenta dash line) is highest at Location 3 and lowest at Location 1. Baseline accelerations at Location 2 have higher standard deviations than those at Locations 1 and 3. In addition, a 1-second spike exceeded the threshold at about 13:00 on October 12. This event was not related to any construction activities.

Table 4.1. Mean and Standard Deviation of Baseline RMS Accelerations at the Three Study Locations

	Location 1	Location 2	Location 3
RMS acceleration mean (m/s^2)	0.0001	0.0007	0.0013
RMS acceleration standard deviation (m/s^2)	0.0001	0.0005	0.0004

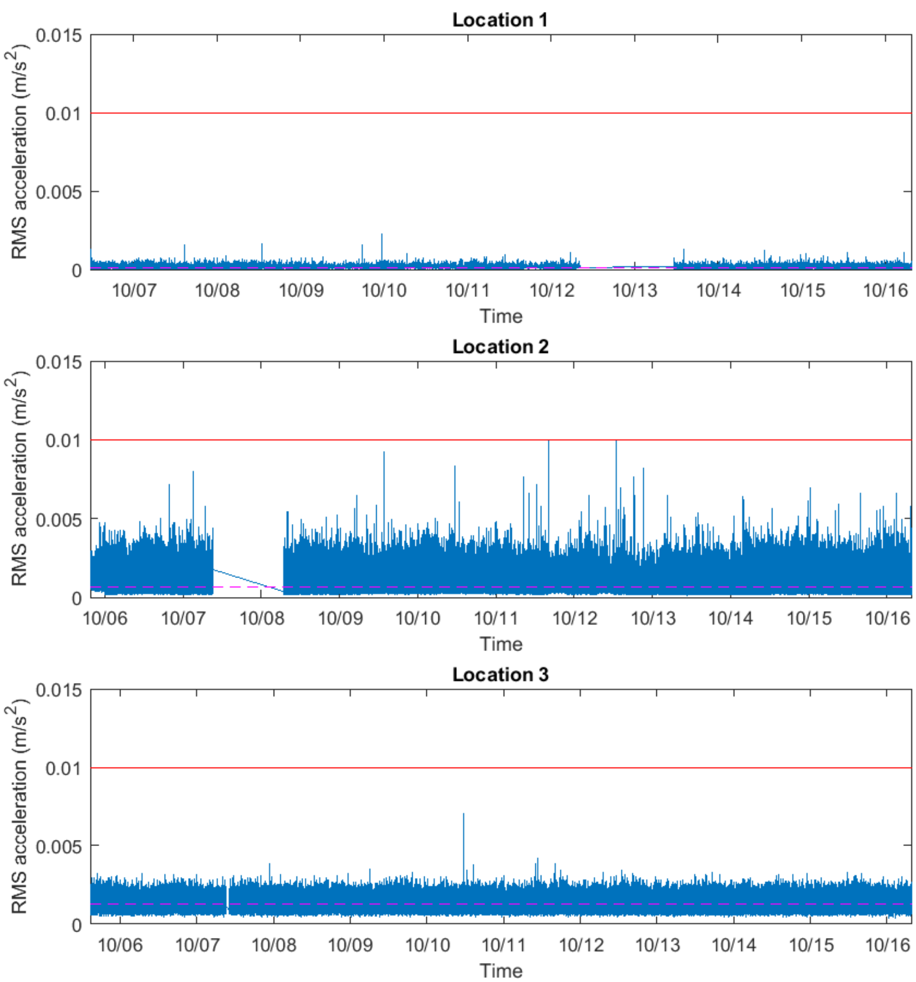

Figure 4.1. RMS Particle Accelerations at Locations 1, 2 and 3 from October 5, 2017, to October16, 2017 (before construction began). The magenta dash line represents the mean baseline RMS particle acceleration at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

4.2 Construction Monitoring (October 16–31, 2017)

The acceleration at the three locations were monitored during the construction period from October 16 to October 31, 2017. Daily reports of the acceleration monitoring were submitted to USACE to inform decisions regarding forced spills. All over-limit events were carefully examined by checking the associated raw data file and comparing data with construction pictures taken by the security camera. This was done to ensure that the event was related to construction activities. Over-limit durations that were not related to construction activities were denoted separately. An example of a daily report (October 16–17) is presented in Table 4.2 and Figure 4.2. Reports of the other dates are provided in Appendix C.

Table 4.2. Duration (seconds) of Over-Threshold Events and Trigger Levels at the Three Study Locations. Table included in the daily report for October 16–17.

	Location 1	Location 2	Location 3
Over threshold	0	0	3[a]

[a] Over-limit events occurred at 19:45:13, on October 16, 2017, 23:08:32 on October 16, 2017, and 03:32:32 on October 17, 2017.

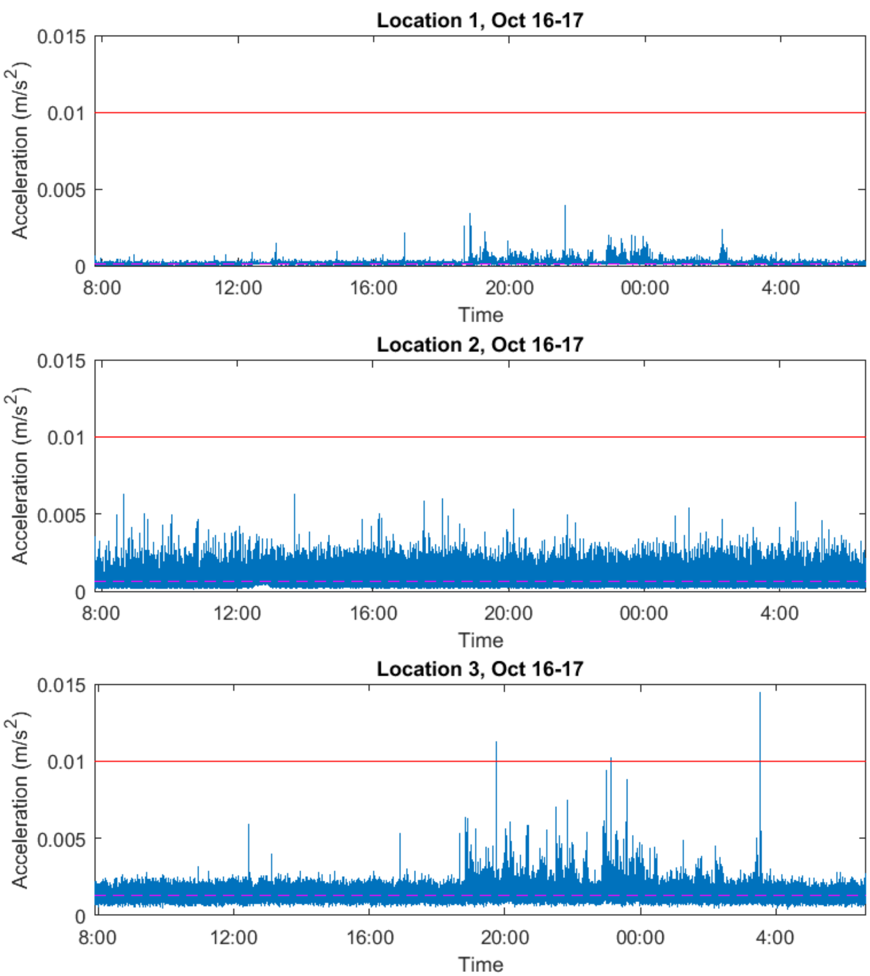

Figure 4.2. RMS Particle Accelerations at Location 1, 2 and 3 on October 16–17, 2017. The magenta dash line represents the mean baseline RMS particle acceleration at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

During construction that occurred from October 16–31, 2017, there were 5 days during which over-threshold events of at least a 1-second duration occurred at one or more locations (Table 4.3). These over-threshold events occurred at Location 3. The only other over-threshold event that was observed was at Location 1 during October 25–26. Following the daily report, water was spilled on four days at 15,000 cubic feet per second (Table 4.4) as north ladder attraction spill to minimize potential delay impacts associated with construction activity.

Table 4.3. Number of 1-Second Durations during which the RMS Acceleration Exceeded the 0.01 m/s^2 Threshold at Each of the Measurement Locations

Date	Location 1	Location 2	Location 3
October 16–17, 2017	0	0	3
October 17–18, 2017	0	0	0
October 18–19, 2017	0	0	1
October 19–20, 2017	0	0	8
October 20–21, 2017	0	0	0
October 21–22, 2017	0	0	9
October 22–23, 2017	0	0	0
October 23–24, 2017	0	0	0
October 24–25, 2017	0	0	0
October 25–26, 2017	2	0	12
October 26–27, 2017	0	0	0
October 27–28, 2017	0	0	0
October 28–29, 2017	0	0	0
October 29–30, 2017	0	0	0
October 30–31, 2017	0	0	0

Table 4.4. Water Spill Operations During The Construction Period October 16-31, 2017*

Date	Hours	Spill (cubic feet per second)
October 19, 2017	6:00-19:00	15,000
October 21, 2017	6:00-19:00	15,000
October 22, 2017	6:00-19:00	15,000
October 25, 2017	15:00-20:00	15,000

* Data Courtesy of U.S. Army Corps of Engineers, DART Hourly Water Quality Measurements
www.cbr.washington.edu/dart/query/wqm_hourly

5.0 Summary

Vibration in the East Fish Ladder support columns at The Dalles Dam was monitored during construction activities to mitigate impacts from potential delays to migrating salmonids. Three locations on the inner wall of the fish ladder were selected for deployment of acceleration measurement systems, each of which included an array of tri-axial accelerometers, a solar power system, and a data acquisition unit. Before construction began, baseline vibration measurements were monitored continuously from October 5 to 16. During construction, vibration was monitored from October 16 to 31. The recorded acceleration data were processed by calculating the RMS of the acceleration magnitude in a 5 to 10 Hz band of each 1-second period. The results then were evaluated relative to the 0.01 m/s^2 threshold level that was selected from published literature as the level that could elicit avoidance behavior in salmonids. Over-limit events were examined by checking the raw data file and comparing that information with the pictures taken by the security camera to determine if the events were related to construction activities. Daily reports of vibration monitoring during construction were generated, and over-limit events that would trigger a spill were reported. In total, the acceleration threshold was exceeded on five construction days.

6.0 References

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Appendix A

Typical Frequency Response of Accelerometers

Appendix A

Typical Frequency Response of Accelerometers

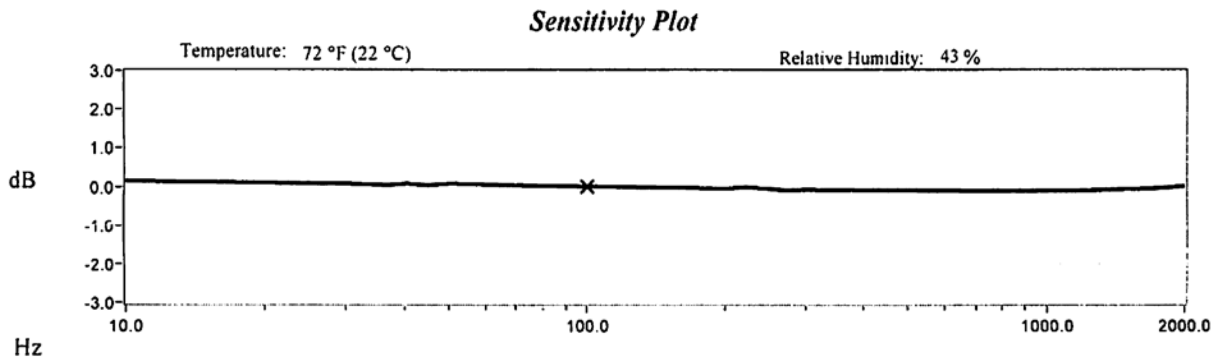

Figure A.1. Sensitivity Plot of ICP Accelerometer Model 393A03, Serial Number 43375.

Appendix B

Calibration of Accelerometers

Appendix B

Calibration of Accelerometers

Accelerometer Set 1	Accelerometer S/N	Noise floor (OBS + Accelerometer)	Sensitivity (calibrated)	Sensitivity (manufacturer)
Channel 1	00043376	8.40 mm/s^2	996.1 mV/g	1020 mV/g
Channel 2	00043477	7.35 mm/s^2	968.3 mV/g	998 mV/g
Channel 3	00043378	9.21 mm/s^2	963.2 mV/g	977 mV/g
Accelerometer Set 2	Accelerometer S/N	Noise floor (OBS + Accelerometer)	Sensitivity (calibrated)	Sensitivity (manufacturer)
Channel 1	00043377	7.75 mm/s^2	975.1 mV/g	1004 mV/g
Channel 2	00043574	8.72 mm/s^2	963.6 mV/g	1000 mV/g
Channel 3	00043573	7.82 mm/s^2	939.9 mV/g	976 mV/g
Accelerometer Set 3	Accelerometer S/N	Noise floor (OBS + Accelerometer)	Sensitivity (calibrated)	Sensitivity (manufacturer)
Channel 1	00043375	6.38 mm/s^2	994.1 mV/g	1015 mV/g
Channel 2	00043571	6.43 mm/s^2	975.6 mV/g	1003 mV/g
Channel 3	00043475	6.42 mm/s^2	1000 mV/g	1020 mV/g

Appendix C

Additional Daily Reports of Construction Monitoring

Appendix C

Additional Daily Reports of Construction Monitoring

C.1 Daily Report (10/17/2017–10/18/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0[a]	0
[a] There is a one-second over threshold at location 2 that occurred at 17:10:43, 10/17/2017. This was outside of the construction activity.			

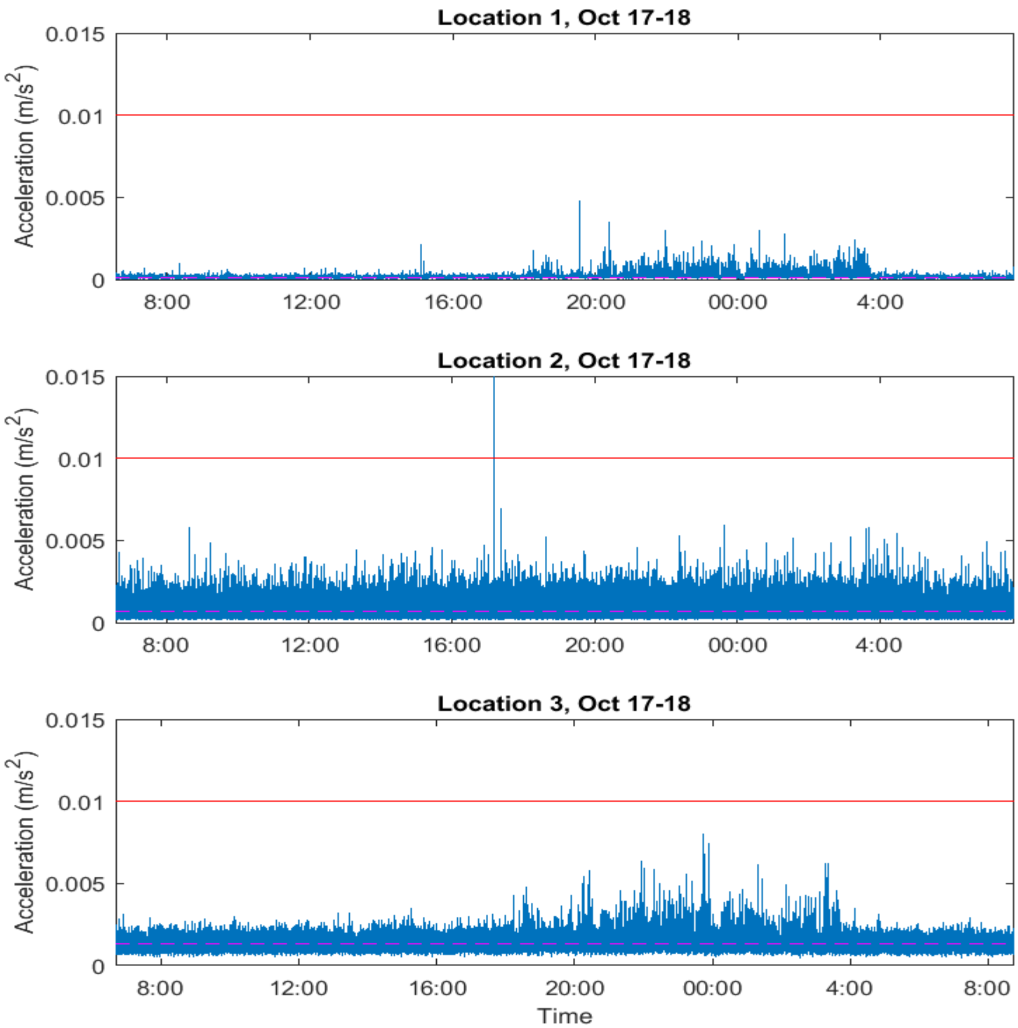

Figure C.1. RMS particle accelerations at Locations 1, 2, and 3 on October 17-18, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.2 Daily Report (10/18/2017–10/19/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	1[a]
[a] The over-limit duration occurred at 19:21:38, 18-Oct-2017.			

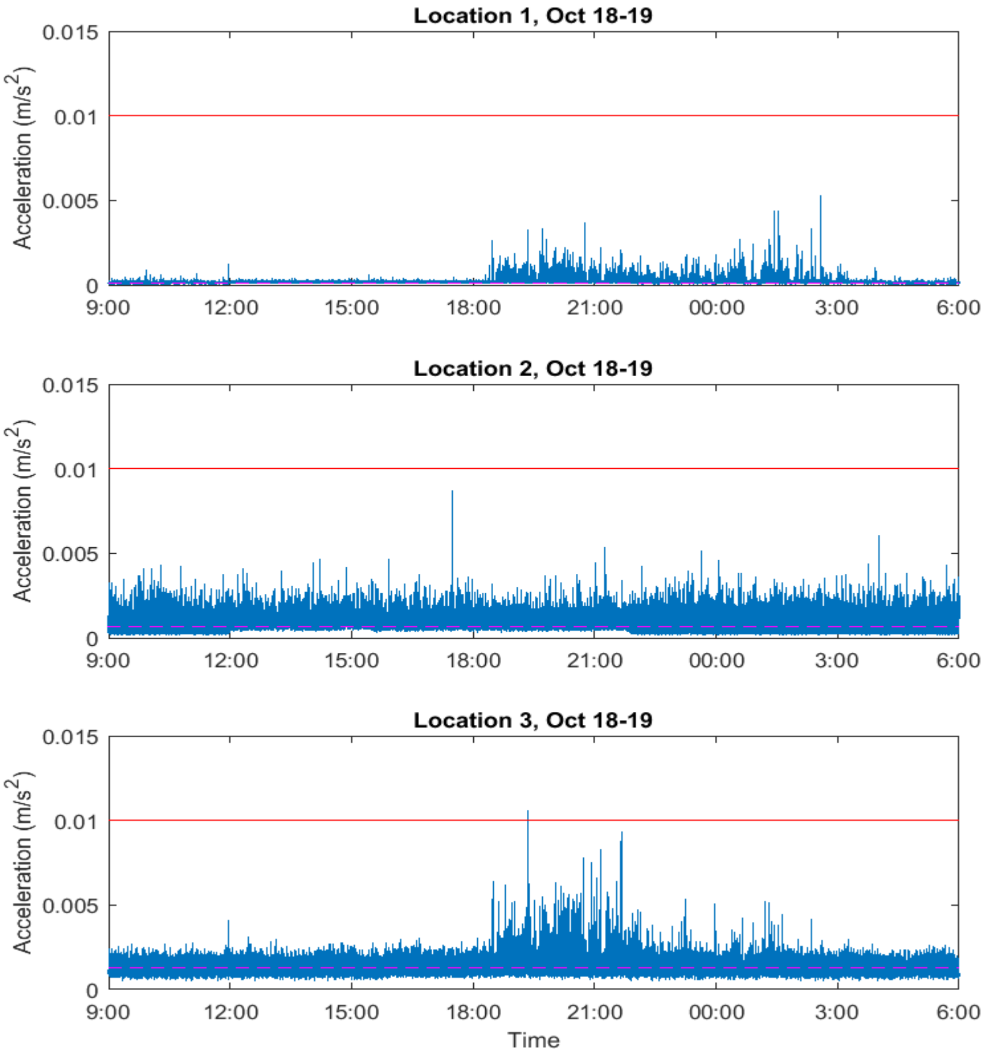

Figure C.2. RMS particle accelerations at Locations 1, 2, and 3 on October 18-19, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.3 Daily Report (10/19/2017 – 10/20/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM)

	Location 1	Location 2	Location 3
Over threshold	0	0	8[a]

[a] The over-limit duration occurred at:
20-Oct-2017 00:19:31
20-Oct-2017 00:19:43
20-Oct-2017 00:19:44
20-Oct-2017 00:19:45
20-Oct-2017 00:19:46
20-Oct-2017 00:19:47
20-Oct-2017 00:20:49
20-Oct-2017 00:20:50

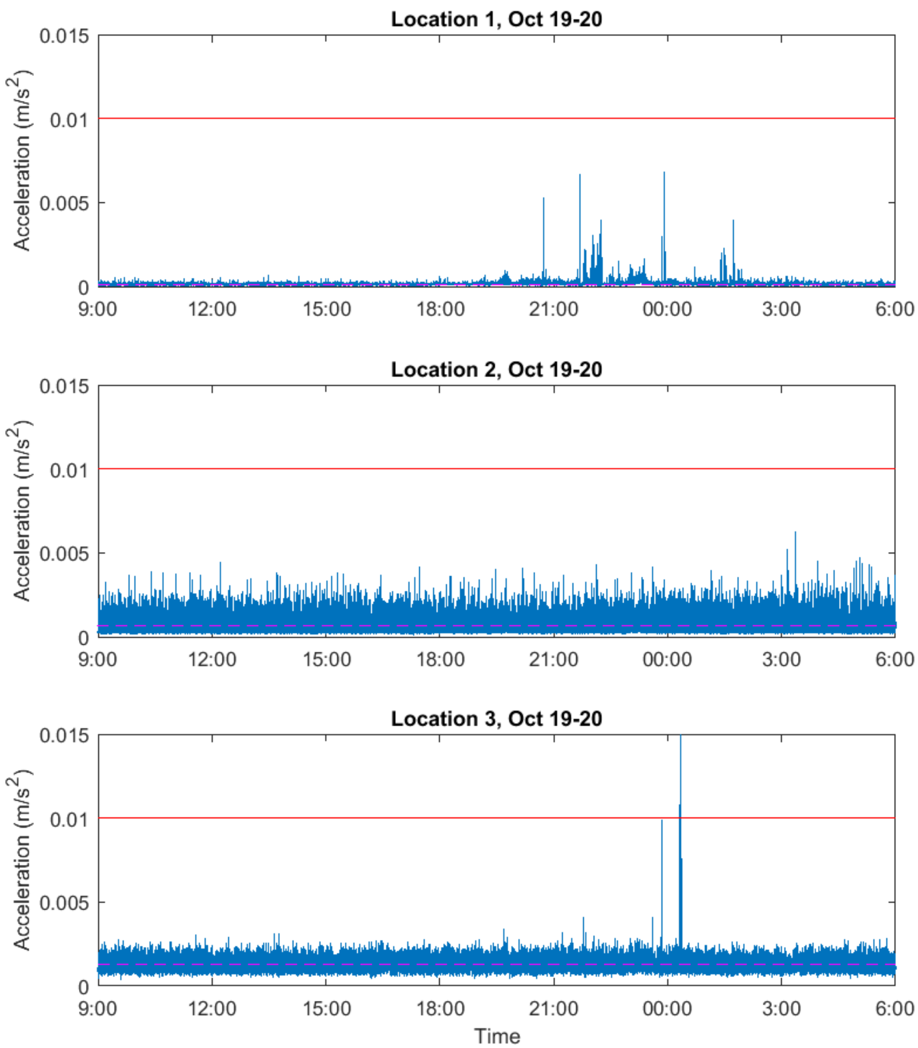

Figure C.3. RMS particle accelerations at Locations 1, 2, and 3 on October 19-20, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.4 Daily Report (10/20/2017–10/21/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	0

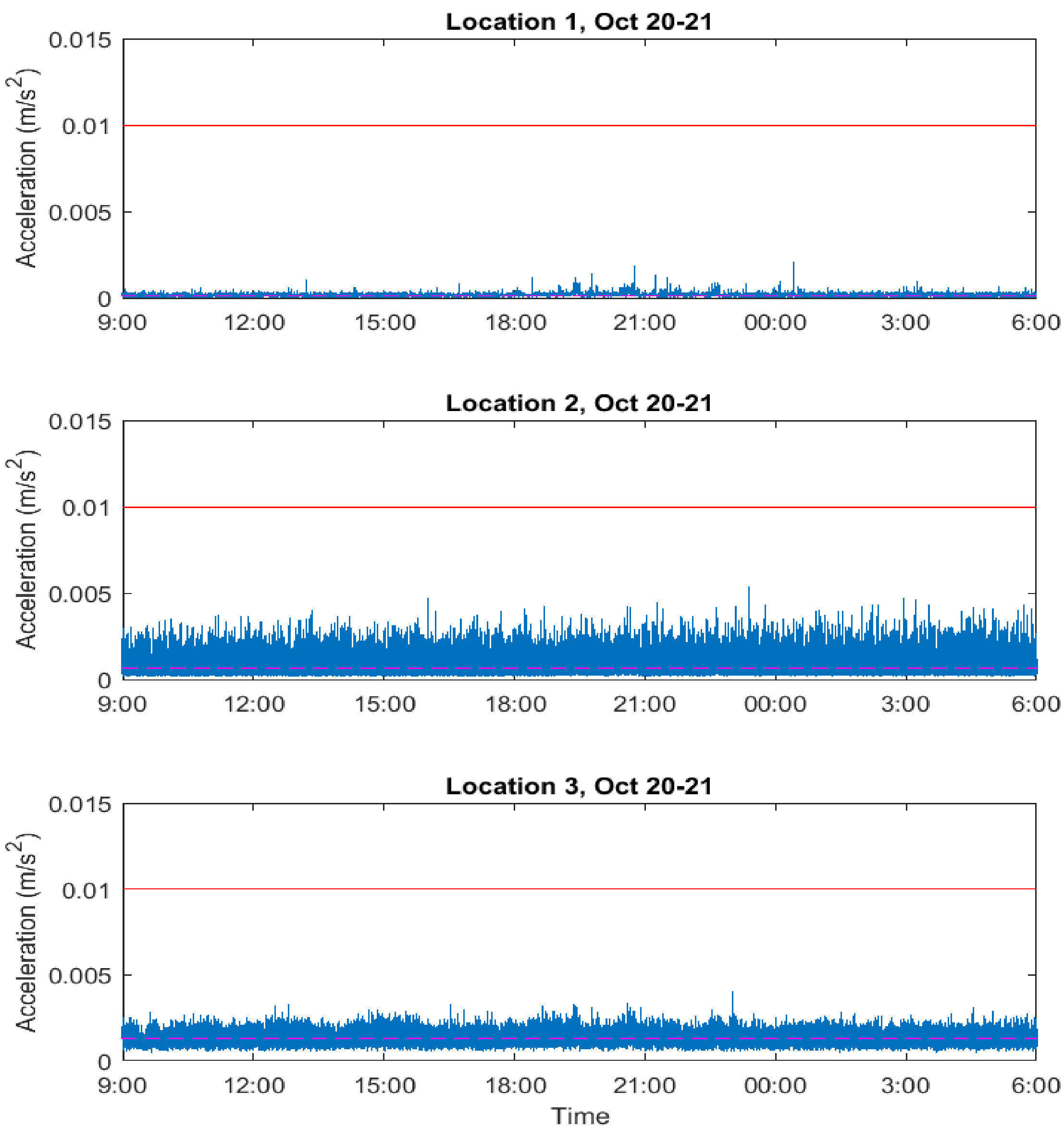

Figure C.4. RMS particle accelerations at Locations 1, 2, and 3 on October 20-21, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.5 Daily Report (10/21/20–10/22/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	9[a]

[a] The over-limit duration occurred at:
21-Oct-2017 17:50:42
21-Oct-2017 17:50:43
21-Oct-2017 17:50:44
21-Oct-2017 17:53:28
21-Oct-2017 17:53:29
21-Oct-2017 17:53:30
21-Oct-2017 17:53:31
21-Oct-2017 17:54:29
21-Oct-2017 17:54:30

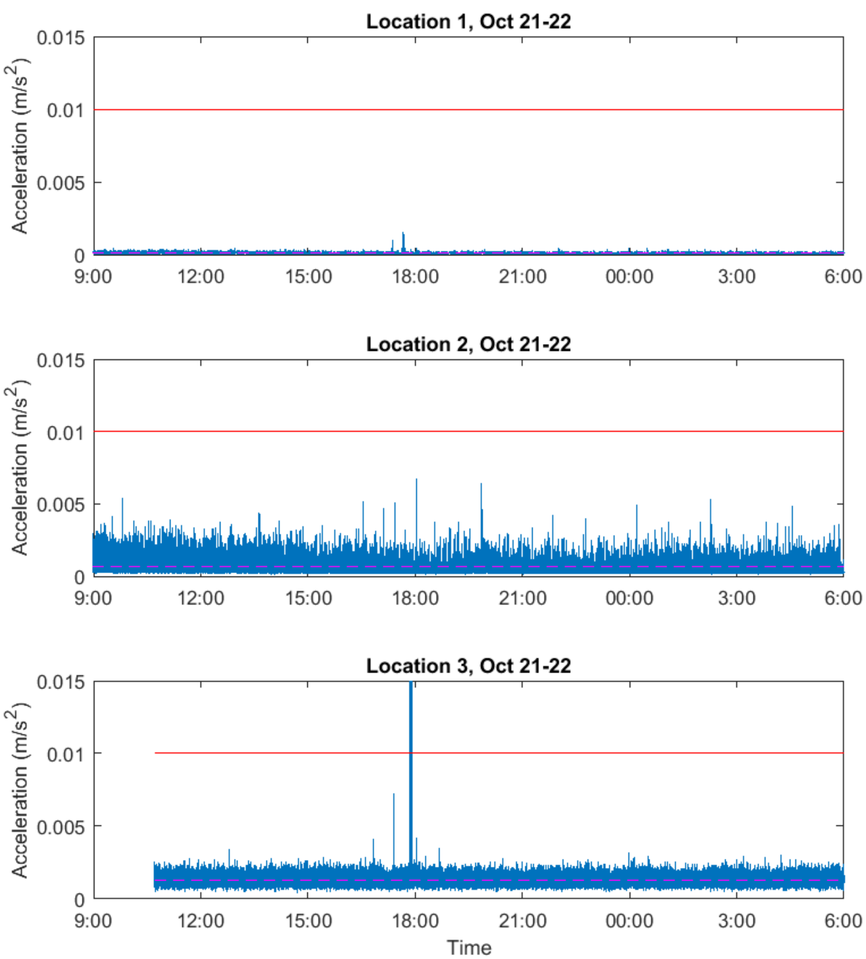

Figure C.5. RMS particle accelerations at Locations 1, 2, and 3 on October 21-22, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.6 Daily Report (10/22/2017–10/23/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	0

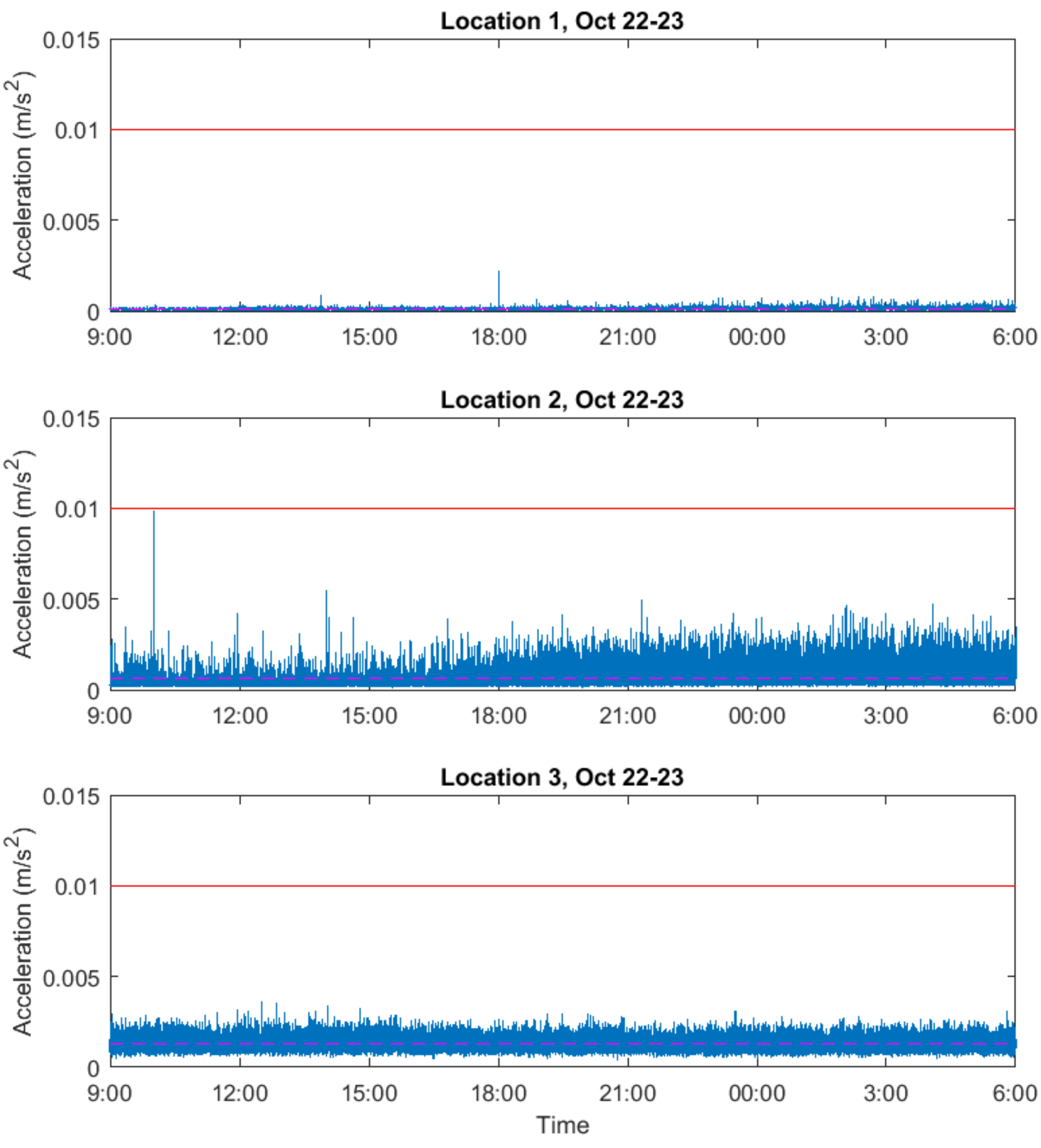

Figure C.6. RMS particle accelerations at Locations 1, 2, and 3 on October 22-23, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.7 Daily Report (10/23/2017 – 10/24/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	0

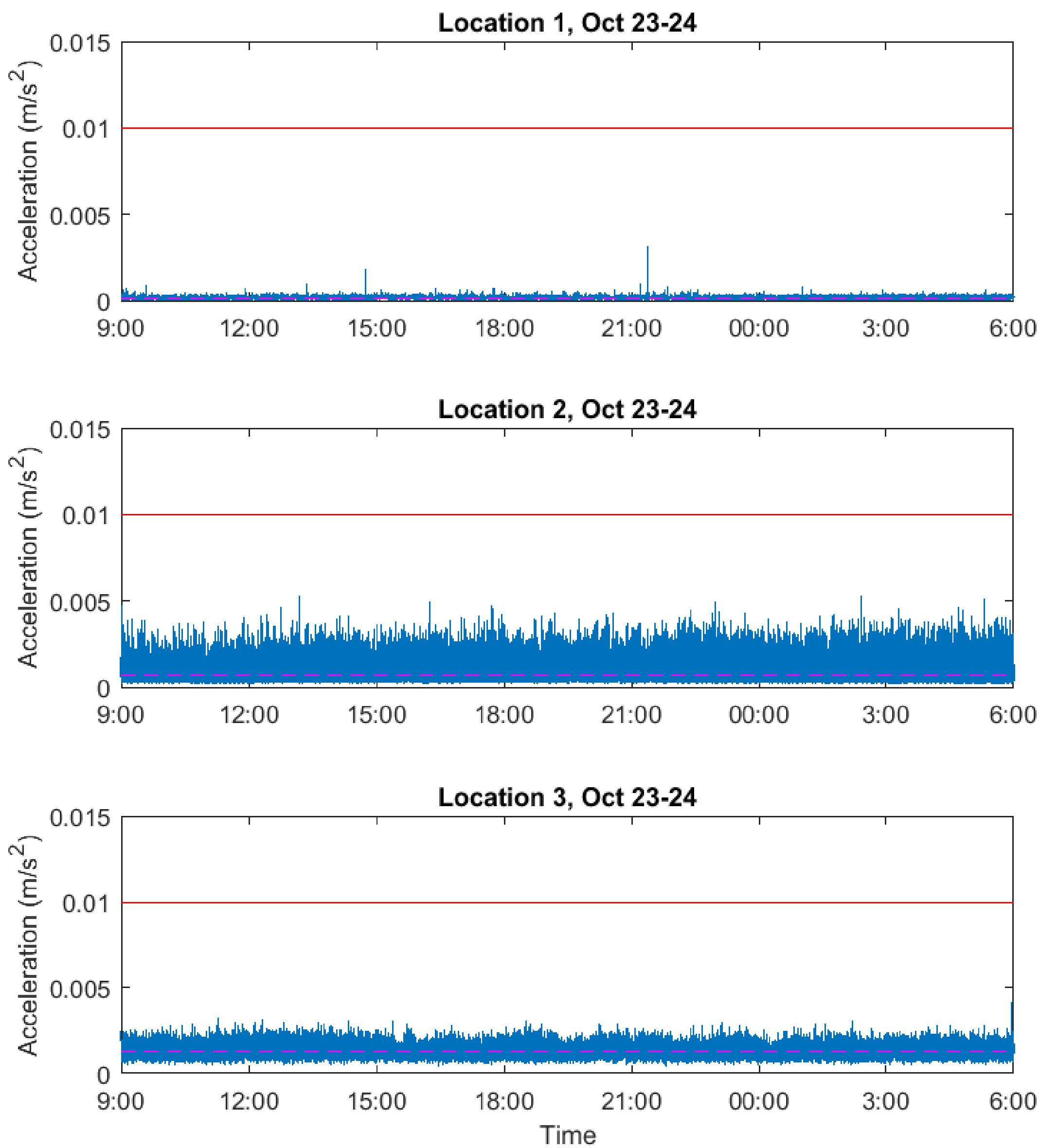

Figure C.7. RMS particle accelerations at Locations 1, 2, and 3 on October 23-24, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.8 Daily Report (10/24/2017 – 10/25/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	0

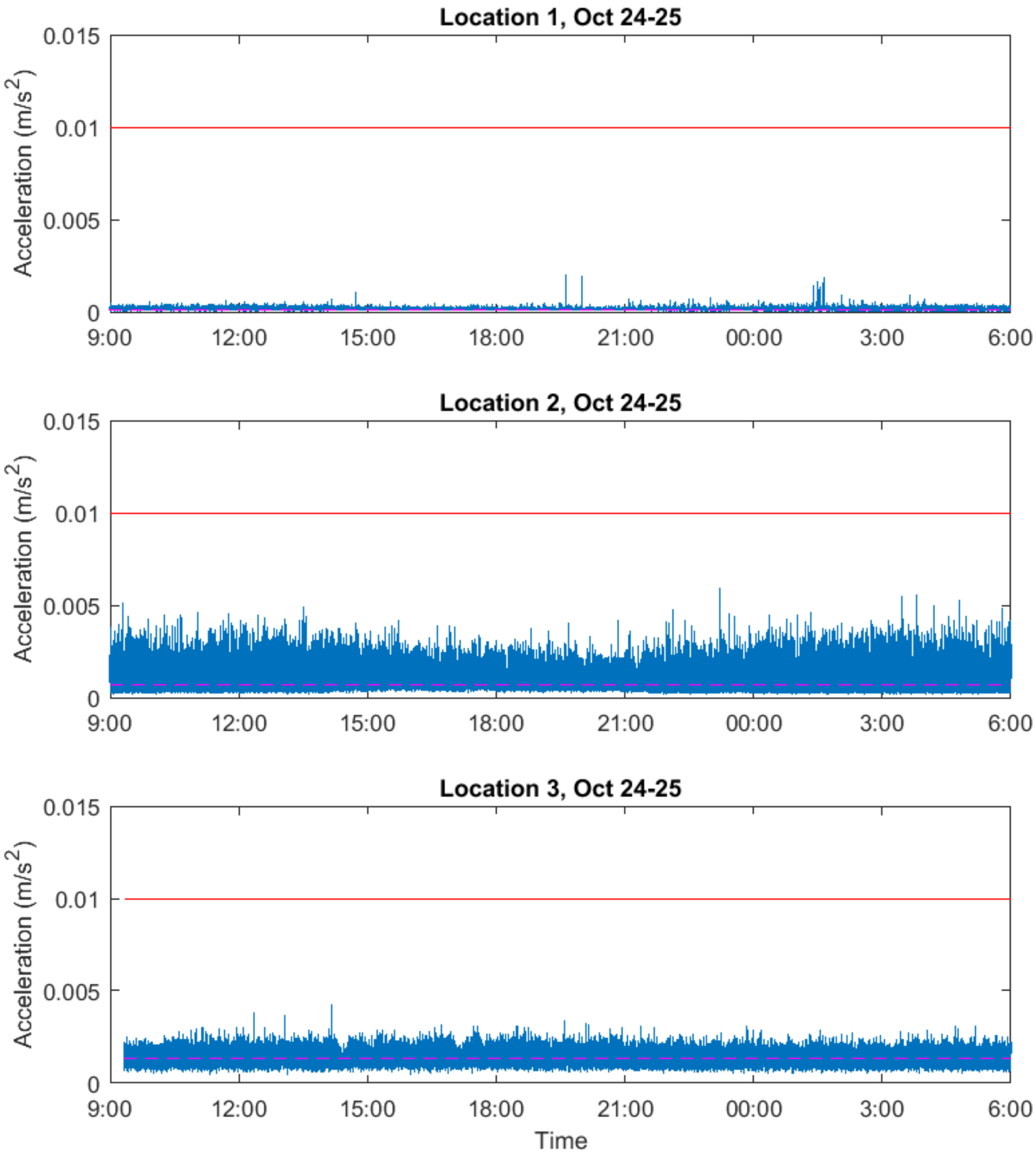

Figure C.8. RMS particle accelerations at Locations 1, 2, and 3 on October 24-25, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.9 Daily Report (10/25/2017–10/26/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

<table>
<tr><td></td><td>Location 1</td><td>Location 2</td><td>Location 3</td></tr>
<tr><td>Over threshold</td><td>2[a]</td><td>0</td><td>12[b]</td></tr>
<tr><td colspan="2">[a] The over-limit duration occurred at:
25-Oct-2017 19:41:30
25-Oct-2017 20:15:21</td><td colspan="2">[b] The over-limit duration occurred at:
25-Oct-2017 22:53:05
26-Oct-2017 00:20:37
26-Oct-2017 00:20:38
26-Oct-2017 00:20:39
26-Oct-2017 00:21:21
26-Oct-2017 00:21:41
26-Oct-2017 00:21:42
26-Oct-2017 00:21:43
26-Oct-2017 00:21:44
26-Oct-2017 00:21:45
26-Oct-2017 00:22:11
26-Oct-2017 00:25:32</td></tr>
</table>

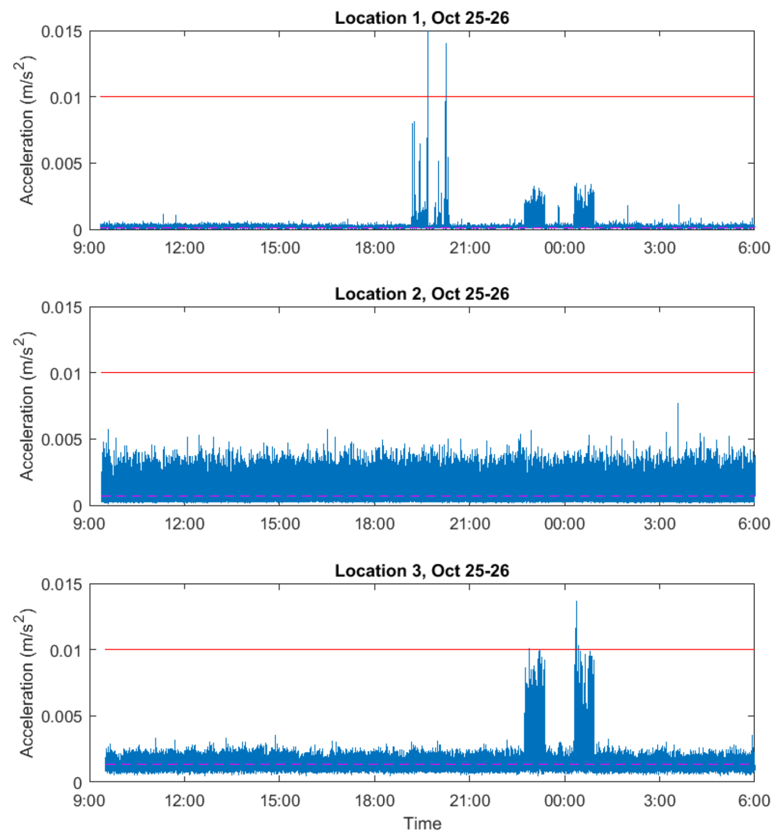

Figure C.9. RMS particle accelerations at Locations 1, 2, and 3 on October 25-26, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.10 Daily Report (10/26/2017–10/27/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM)

	Location 1	Location 2	Location 3
Over threshold	0	0	0

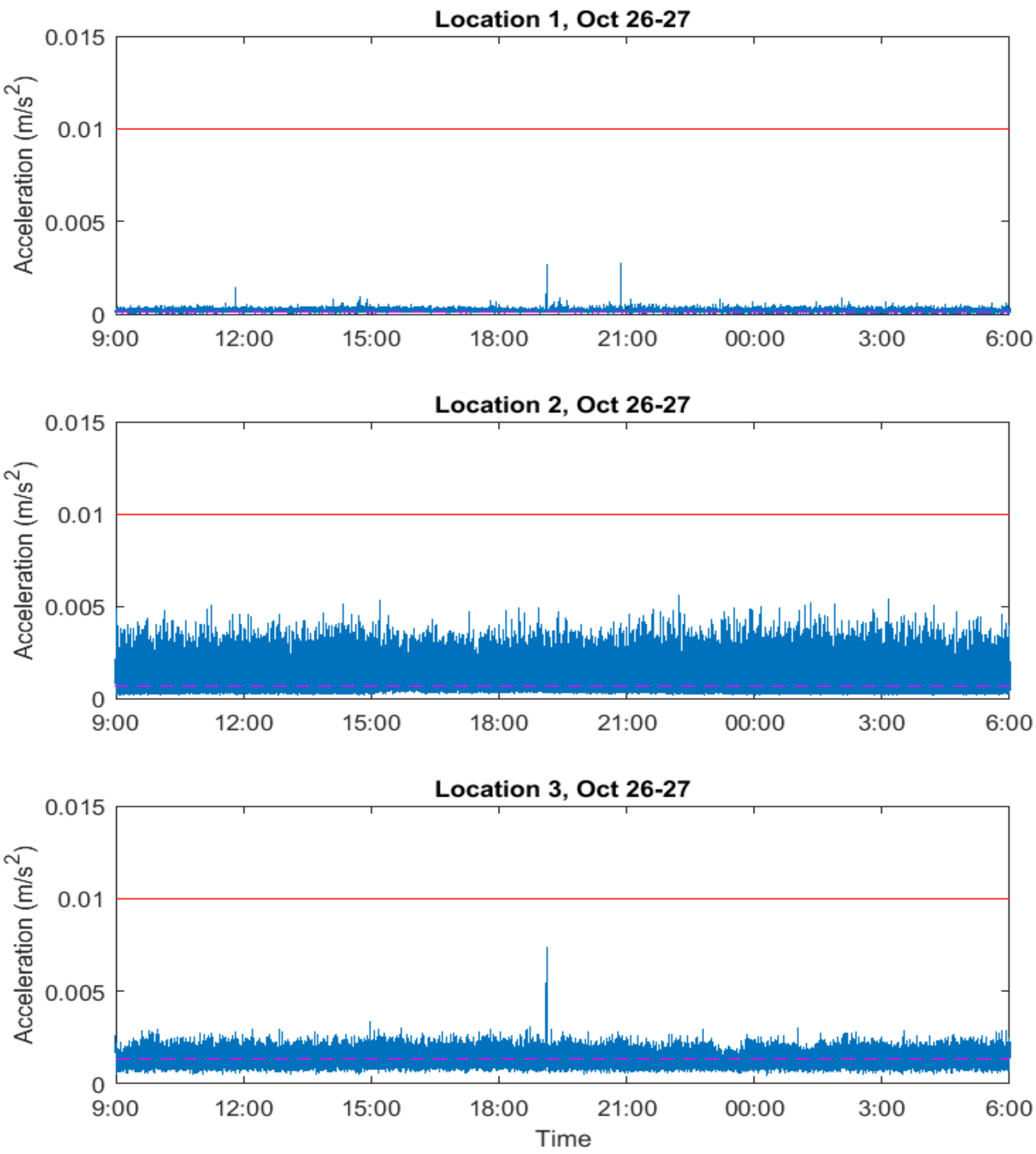

Figure C.10. RMS particle accelerations at Locations 1, 2, and 3 on October 26-27, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.11 Daily Report (10/27/2017–10/28/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	0

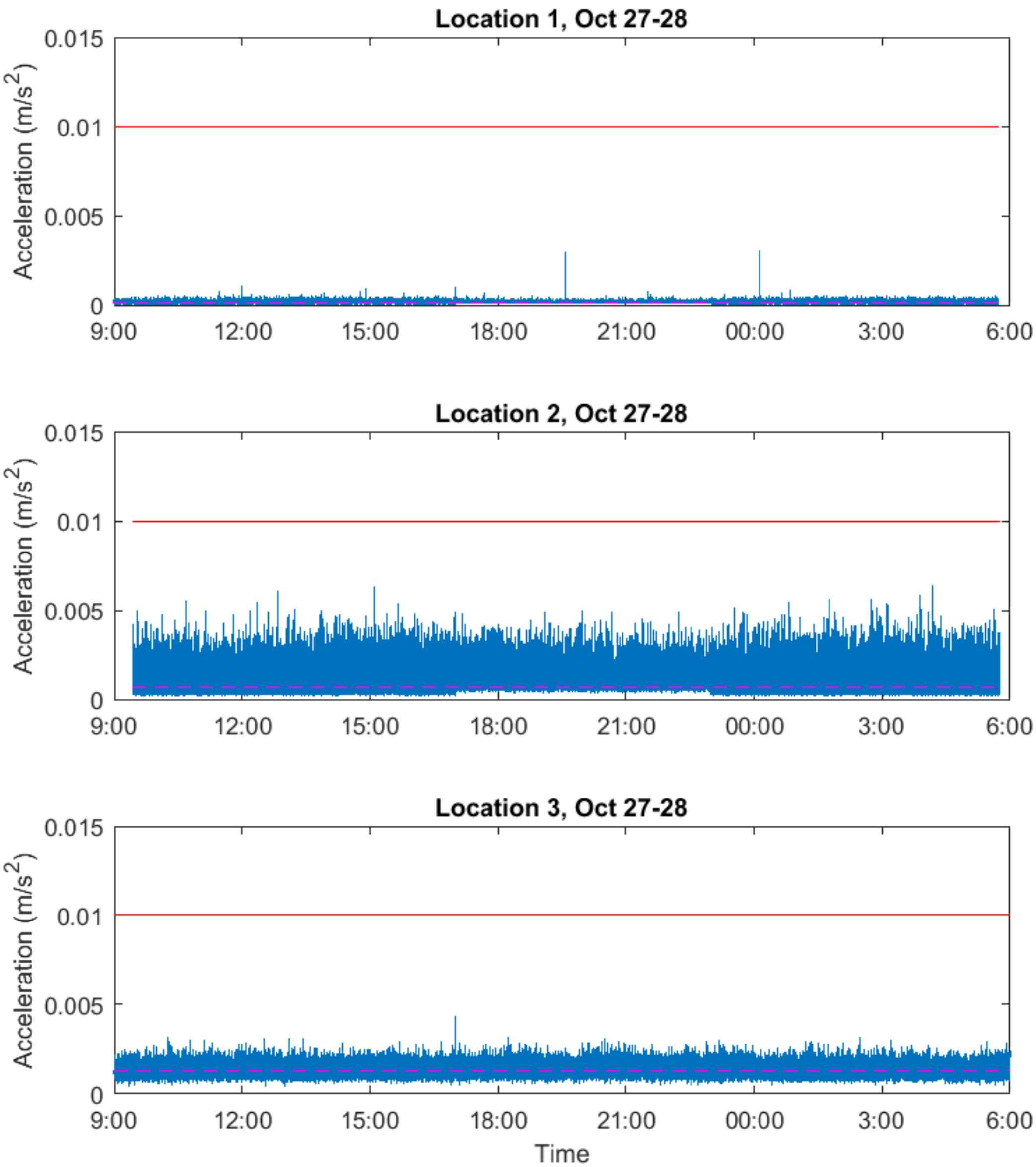

Figure C.11. RMS particle accelerations at Locations 1, 2, and 3 on October 27-28, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.12 Daily Report (10/28/2017–10/29/2017)

Duration (seconds) over threshold and trigger level at three locations during the constructions period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	0

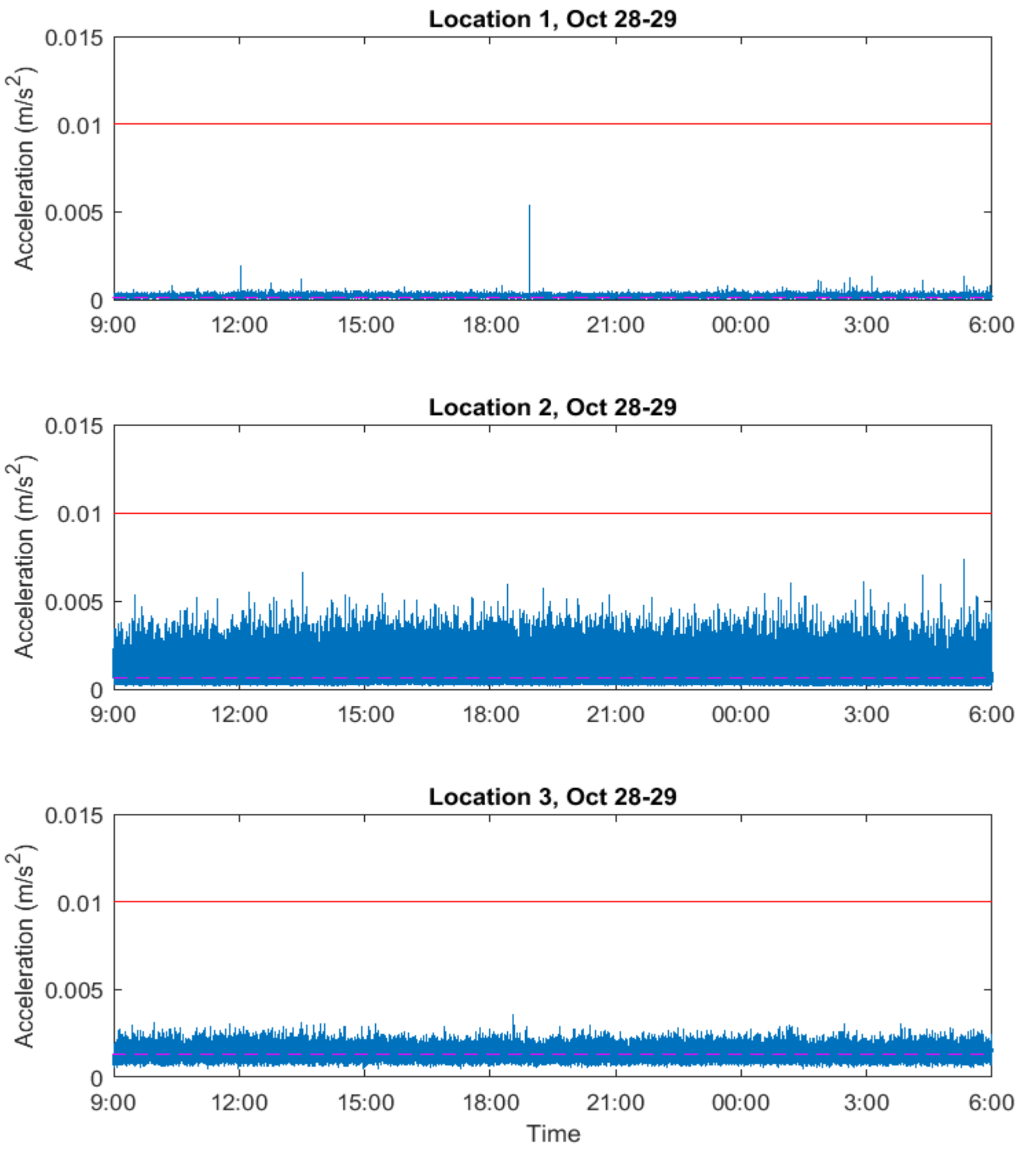

Figure C.12. MS particle accelerations at Locations 1, 2, and 3 on October 28-29, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.13 Daily Report (10/29/2017–10/30/2017)

Duration (seconds) over threshold and trigger level at three locations during the construction period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0*	0

* There was one-second over-limit measurement at site 2 at 14:50:13, October 29th, outside the construction period.

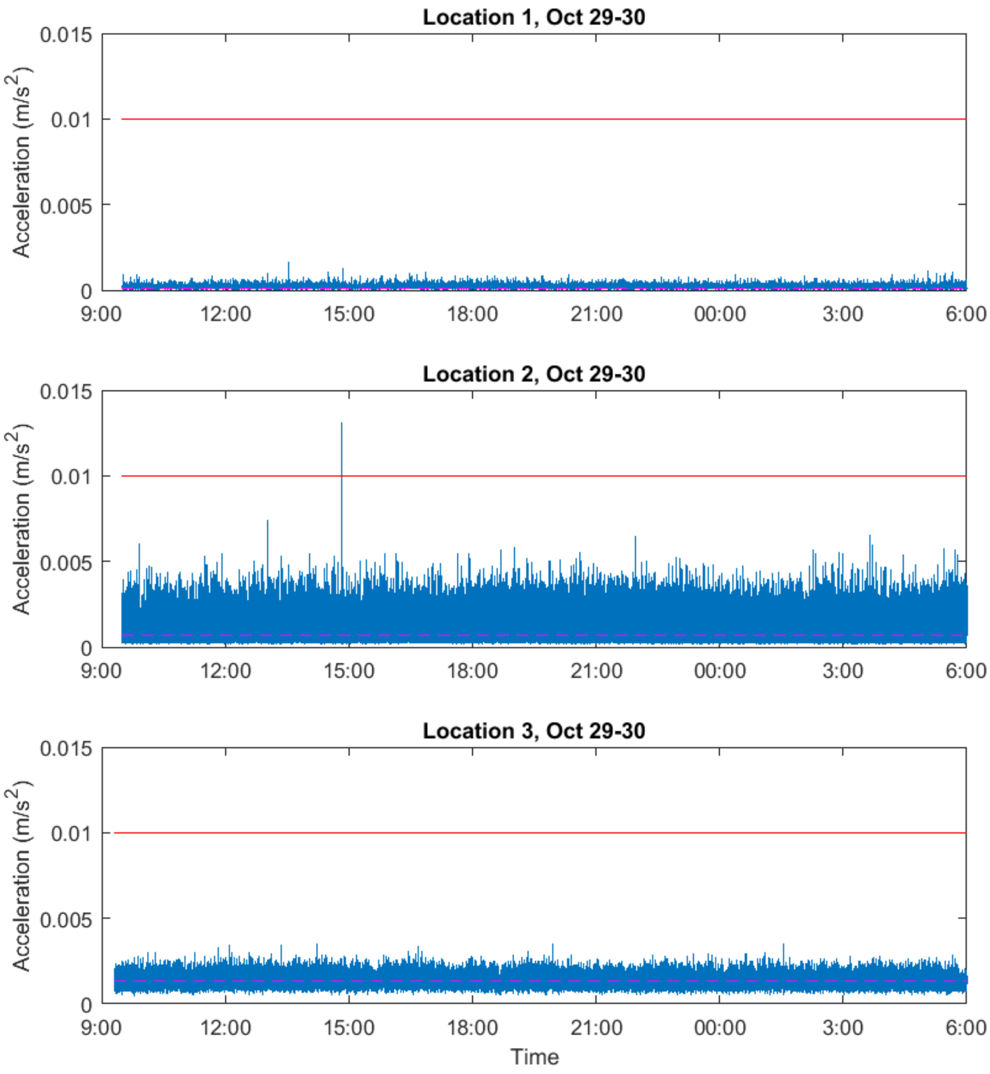

Figure C.13. RMS particle accelerations at Locations 1, 2, and 3 on October 29-30, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

C.14 Daily Report (10/30/2017–10/31/2017)

Duration (seconds) over threshold and trigger level at three locations during the construction period (6PM to 6AM).

	Location 1	Location 2	Location 3
Over threshold	0	0	0

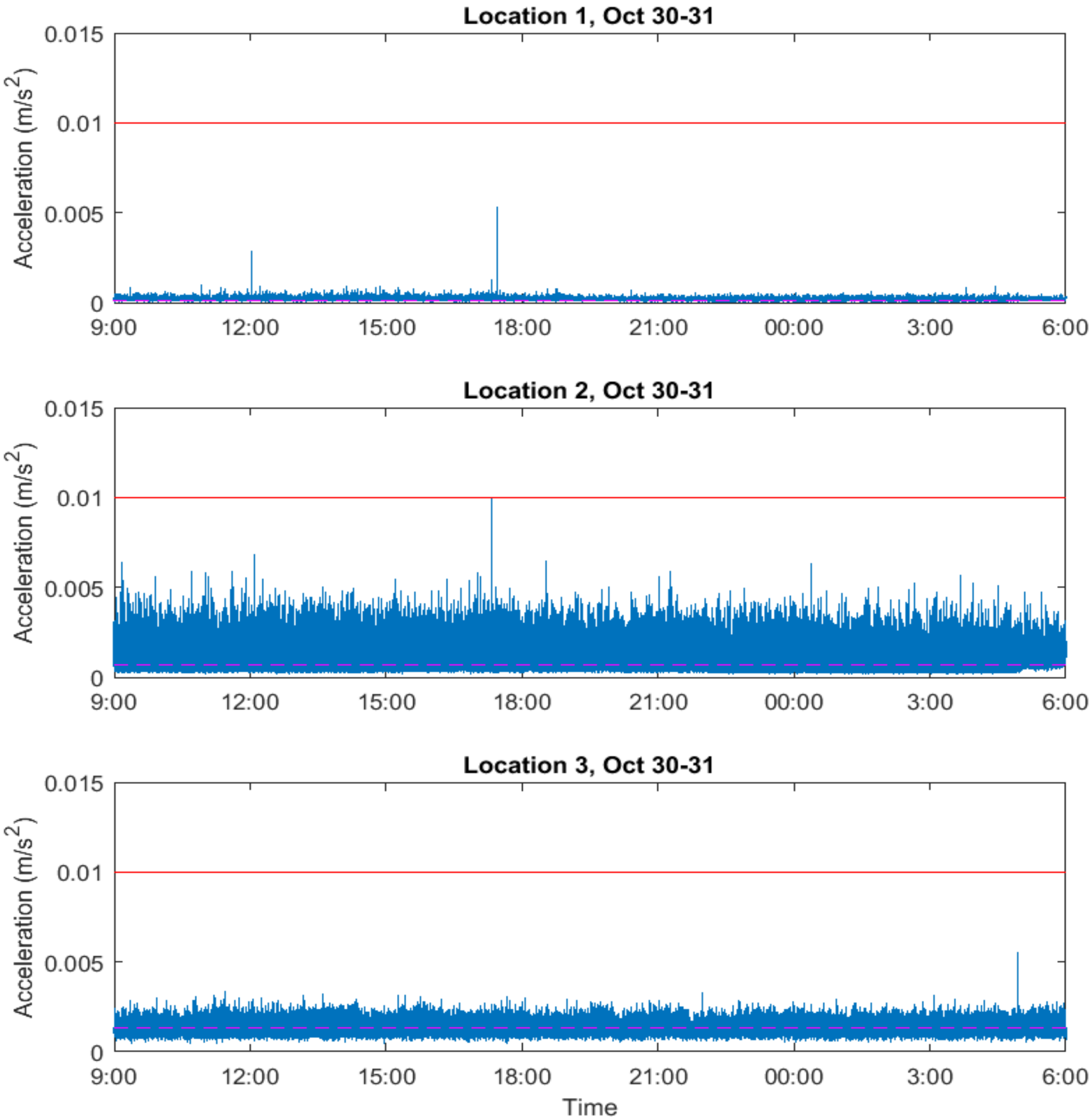

Figure C.14. RMS particle accelerations at Locations 1, 2, and 3 on October 30-31, 2017. The magenta dash line represents the mean baseline RMS particle acceleration calculated from October 5 to 16 at each location. The red line shows the 0.01 m/s^2 threshold of the RMS particle acceleration.

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