Pile-Driving Noise Measurements at WETA Downtown San Francisco Ferry Terminal Expansion Project:

15 June 2017–07 November 2017

Submitted to:

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A - Time History of Pile Driving

List of Abbreviated Terms

μPa	microPascal
APE	American Piledriving Equipment
cSEL	cumulative SEL
dB	decibel(s)
dB re 1 μPa	dB referenced to a pressure of 1 microPascal
ESA	Endangered Species Act
ft-lb	foot-pound(s)
Hz	Hertz
in-lb	inches per pound
kgm	kilogram-meter(s)
kj	kilojoules
kNm	kilometer newton
L_{eq}	Equivalent Sound Level
L_{peak}	Peak Sound Pressure Level
m	meter(s)
SEL	Sound Exposure Level
SLM	Sound Level Meter(s)
SPL	Sound Pressure Level

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Executive Summary

The San Francisco Bay Area Water Emergency Transportation Authority (WETA) is expanding berthing capacity at the Downtown San Francisco Ferry Terminal (Ferry Terminal), located at the San Francisco Ferry Building (Ferry Building), to support existing and future planned water transit services operated on San Francisco Bay by WETA and WETA's emergency operations. The National Oceanic and Atmospheric Administration (NOAA)/National Marine Fisheries Service (NMFS) Biological Opinion dated 30 June, 2014, the California Department of Fish and Wildlife (CDFW) Incidental Take Permit Number -2081-2015-013-07; and the NMFS Incidental Harassment Authorization dated 28 June, 2016 require hydroacoustic monitoring during the driving of the piles. The Hydroacoustic Monitoring Plan dated January 2016 states: "[T]*wo (2) hydrophones would be placed; one at ten meters, a second hydrophone placed at 124 meters. A third hydrophone may be used to assist in establishing the distance to the various safety zones if needed. All hydrophones are to be placed at mid depth or at least one meter below the surface when possible."* The CDFW permit also required "*The Permittee shall conduct real time hydroacoustic monitoring during all 42-inch pile installation and monitor at a minimum 10 percent of the 24-36-inch diameter steel and concrete pile installation activities to measure efficacy of the sound attenuation system and to determine if the anticipated SPLs and associated distances from piles differ from the actual measurements."* Although these monitoring requirements are relevant to impact hammer pile driving, WETA chose to monitor 10 percent of the piles driven with a vibratory hammer to define the distances to the Level A and Level B marine mammal injury and harassment zones. No impact hammer driving occurred at the project site in 2017.

The hydroacoustic data are primarily reported for individual pulses as peak sound pressure level (SPL), root mean square (RMS), and the sound exposure level (SEL); and the accumulated SEL is reported for the driving events.

The water depth ranged from 2 to 3 meters (6 to 10 feet) deep at the location where the piles were driven. Measurements were made at two to fixed positions. The first position was approximately 10 meters (33 feet) from the piles where the water depth ranged from 2 to 3 meters (6 to 10 feet) deep. The second measurement positions ranged from 35 and 154 meters (115 and 505 feet) from the pile driving where the water depth was 3 to 5 meters (10 to 16 feet) deep. The underwater sound was measured continuously throughout the duration of the driving of those piles.

The 10 second average RMS level measured for the 24 -inch piles ranged from 150 dB to 157 (dB re 1μPa) at 10 meters (33 feet), for the 30-inch piles the 10 second RMS ranged from 146 to 157 (dB re 1μPa) and for the 36-inch piles the 10-second average RMS ranged from 157 to 159 (dB re1μPa). **Table E-1** shows the calculated distances to the 120 dB re 1μPa Level B Harassment Zone per pile size based on the average calculated attenuation rate (see Section 3.13).

Table E-1. Calculated Distances to the Level B Marine Mammal Harassment Zone

Pile Size	Average 10-Second RMS Level @ 10 meters	Calculated Distance to 120 dB Threshold (meters)
24-inch	152[A]	665
30-inch	155[A]	400
36-inch	158[A]	625
Average All Pile Sizes	155[A]	545

[A] - dB re 1μPa

1. Introduction

A summary of the pile driving events are detailed in **Table 1.** The driving of various types of piles were measured, including 24-inch, 30-inch, and 36-inch steel shell piles.

Table 1. Summary of Vibratory Pile-Driving Activities

Pile Type and Size	Dates	Hammer Type
24-inch steel	9/6; 9/11; 9/14; 10/31; 11/7	APE King Kong Vibratory Hammer
30-inch steel	6/15; 7/28; 9/14	
36-inch steel	8/11; 8/16	

This report is organized as follows: **Section 1** – Description of the Study Areas, **Section 2** – Descriptions of Measurements, and **Section 3** – Measurement Results and Analysis. A Glossary of Acoustic Terms and Acronyms is provided in Subsection 3.2

Supplementary content includes: **Appendix A** – Time History of Pile Driving and Removal, **Appendix B** – One-Third Octave Band Spectrum Data.

1.1 Description of the Project Study Areas

This section of the report outlines the different locations and provides a brief description of the types of piles where underwater noise levels were measured and the type of pile-driving equipment that was used during the pile driving operations.

The Downtown San Francisco Ferry Terminal Expansion Project (Project) is located in San Francisco Bay within the City of San Francisco, San Francisco County (See **Figure 1**). The Project is located approximately 0.5 miles northwest of the San Francisco Bay Bridge at approximately 37.47'47.58"N, 122.23'29.73"W. The Project site is bounded by Pier 1 to the north and Pier 14 to the south.

The expansion project occurred in the San Francisco Bay. **Figure 1** indicates the location of the South Basin where the work area occurred. **Figure 2** indicates the location of the piles monitored.

Noise measurements were made during the installation of steel shell piles from 15 June through 07 November 2017. The piles were fully installed with a vibratory hammer. The peak sound pressure level (SPL), 10-second root mean square (RMS) SPL, sound exposure level (SEL), and cumulative SEL (cSEL) were recorded at two fixed locations — one between 9 meters (30 feet) and 15 meters (49 feet), a second distant location ranging from approximately 35 meters (115 feet) to 200 meters (656 feet). The piles were driven in with an APE-King Kong Vibratory hammer.

Figure 1. Location of WETA Downtown Ferry Terminal Expansion Project

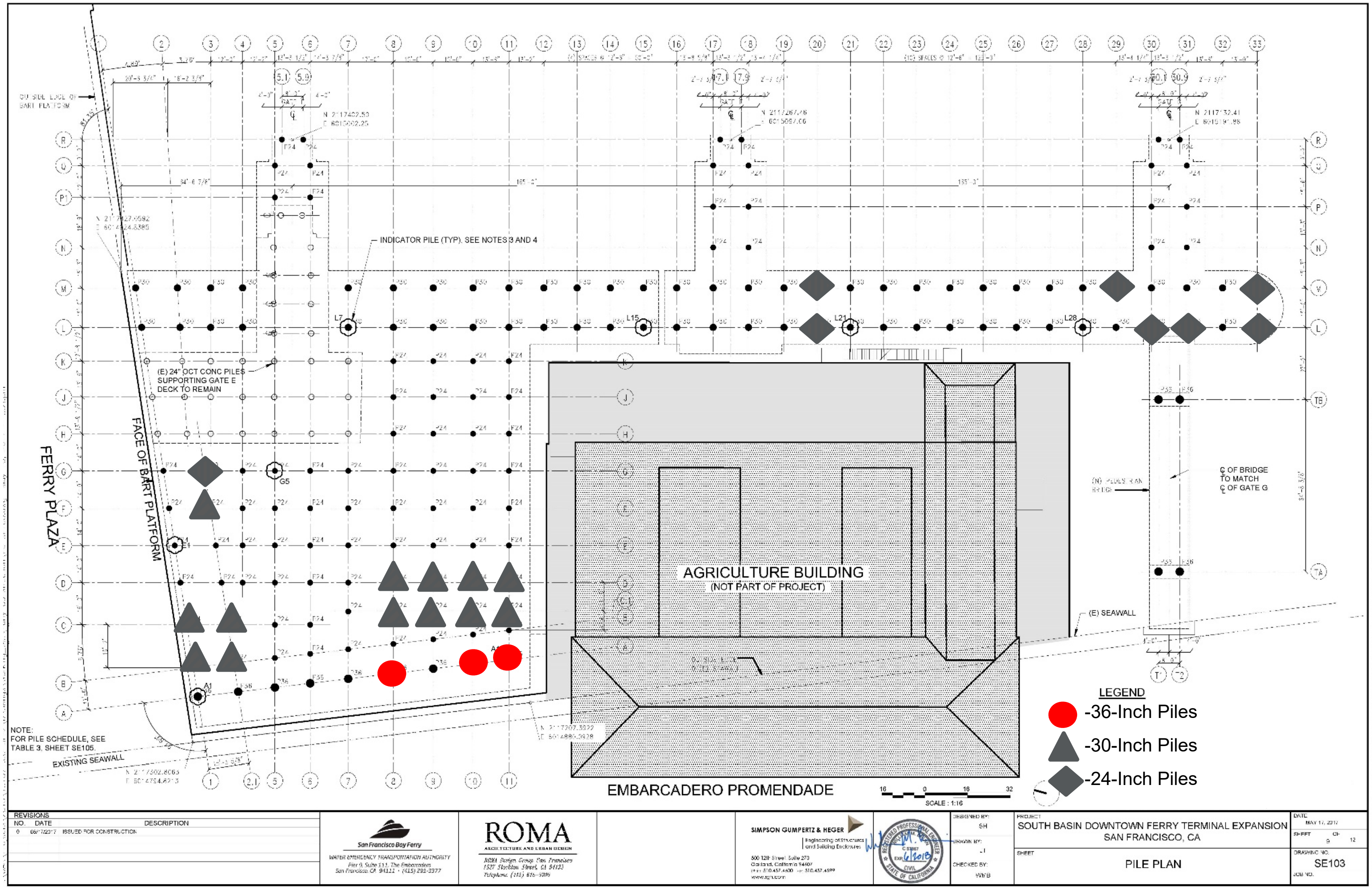

Figure 2. Location of Piles Monitored

1.2 Monitoring Equipment

Measurements were made by manned systems; **Figure 3** shows a sample of the type of equipment used. Reson Model TC-4033 hydrophones with PCB in-line charge amplifiers (Model 422E13) were used. The hydrophones were fed through an in-line charge amplifier into Larson Davis Model 831 Precision Sound Level Meters (LDL 831 SLM). The LDL 831 then outputs the signal to a Roland R-05 solid-state digital data recorder. The output of the LDL 831 can be adjusted. The multi-gain signal conditioner provides the ability to increase the signal strength (i.e., add gain) so that measurements are made within the dynamic range of the instruments used to analyze the signals.

Figure 3. Typical Underwater Monitoring Equipment

During Vibratory driving, the maximum peak SPL (LZ_{peak}), fast RMS SPL (LZF_{max}), and the 1-second SEL (LZ_{eq}) were measured "live" using the LDL 831. The LDL 831 SLM provided measurements of the un-weighted results for each data type, including the one-third octave band spectra for the 1-second LZ_{eq}. Additional analyses of the acoustical impulses were performed using the LDL 831 SLMs as well. The LDL 831 captures the signal and stores the measurement data that are retrieved at the completion of a day of measurements.

1.2.1 Underwater System Acoustic Calibration

The measurement systems were calibrated prior to use in the field with a G.R.A.S. Type 42AA pistonphone and hydrophone coupler. A pistonphone is an acoustical calibrator used to generate a precise sound pressure for the calibration of instrumentation microphones. The pistonphone, when used with the hydrophone coupler, produces a continuous 136.4 dB re 1 μPa (dB referenced to a pressure of 1 microPascal) tone for the TC-4033 hydrophones at 250 Hertz (Hz). The tone measured by the SLM was recorded at the beginning of the recordings. The system calibration status was checked at the beginning of each measurement day by both measuring the calibration tone and recording the tone on the solid-state digital data recorder. The pistonphones were certified at an independent facility.

All field notes were recorded in water-resistant field notebooks. Such notebook entries include calibration notes, measurement positions (i.e., distance from source, depth of sensor), measurement conditions (e.g., currents, sea conditions, etc.), system gain settings, and the equipment used to make each measurement. Notebook entries were copied after each measurement day and filed for safekeeping. Digital recordings were also copied and stored for subsequent analysis, if needed.

2. Description of Measurements

2.1 Underwater Sound Descriptors

Acoustic monitoring typically reports data in several required formats, depending on the type of pile driving and the type of acoustic measurement. Impact pile driving produces pulse-type sounds, while vibratory pile installation produces a more continuous type of sound.

For this report, vibratory driving is all that was completed and measured. The data reporting included the average one-third octave band frequency spectrum over the entire pile-driving event. Additionally, the 1-second Equivalent Sound Level (L_{eq}) data during the pile-driving events were averaged in 10-second intervals.

2.2 Pile Driving and Acoustic Monitoring Events

Pile-driving activities and acoustic monitoring events are summarized at the beginning of the Introduction in **Section 1** in **Table 1**. During vibratory pile driving, distances between the piles and the measurement locations were recorded (summarized in **Table 2 in Section 3.1.1)**.

There was a total of eleven 36-inch, sixty-three 30-inch, and ninety-one 24-inch steel shell piles to be installed as part of this project. While the permit only required hydroacoustic monitoring when the piles were driven with an impact hammer, WETA chose to monitor 10 percent of the piles driven with a vibratory hammer to define the distances to the Level A and Level B marine mammal injury and harassment zones. To accomplish this underwater sound measurements were conducted for twenty-three vibratory pile-driving events, which included thirteen 24-inch steel shell piles, eight 30-inch steel shell pile, and three 36-inch steel shell pile. **Appendix A** contains the results for all the vibratory pile driving of piles. No impact hammer pile driving occurred at the project site in 2017.

2.2.1 Background/Ambient Sound Data

Example of Ambient Underwater Sound Data

Ambient levels were measured prior to and following pile-driving events at each of the distant measurement locations. Although ambient measurements were also made before and after pile driving at the near positions, those systems were set up to measure higher pile-driving sounds than the distant measurement systems. As a result, ambient levels before and after pile-driving conditions likely contain electronic instrument noise as well. Typically, measurements began several minutes before pile driving and continued several minutes after pile driving (see Time History Plots in **Appendix A**).

If sound levels measured during pile driving were abnormally high due to inadequate testing conditions, such as ferry boats docking and idling adjacent to the measurement site, the same high levels would appear in the ambient data as well, proving not to be caused by pile driving. Furthermore, by taking ambient measurements before and after pile-driving events, effects of the changing environmental conditions on the results were observed. These ambient data are discussed in the pile-driving results sections. The ambient data were analyzed as RMS levels over a given time. **Figure 4** represents typical ambient data from the 1-second L_{eq} measurements.

The data in the **Figures 4** and **5** were collected on 11 September 2017. Conditions during ambient testing were clear with calm winds and little water disturbance with a flood tide, there are two sets of data for the 70-meter location. The first was taken when there were no ferries at the dock and the second shows the levels with a ferry docked. The frequency spectra shown in **Figure 5** indicate that ambient levels are dominated by sounds below, with the exception of when a ferry is docked then the dominant range is between 630 Hz and 6,300 kHz. Ambient/background results varied with the testing conditions throughout the course of the project.

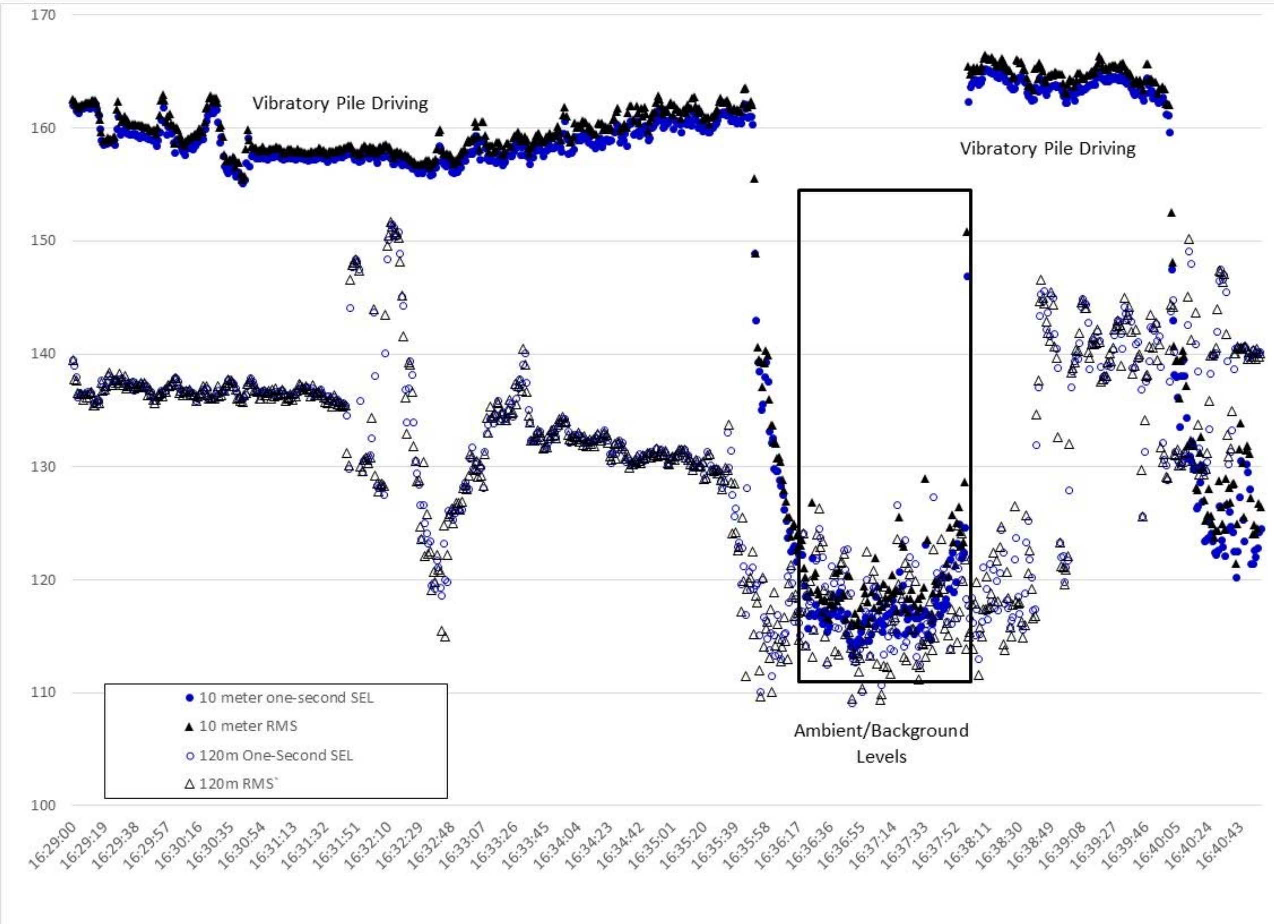

Figure 4. Sample of Ambient/Background Levels

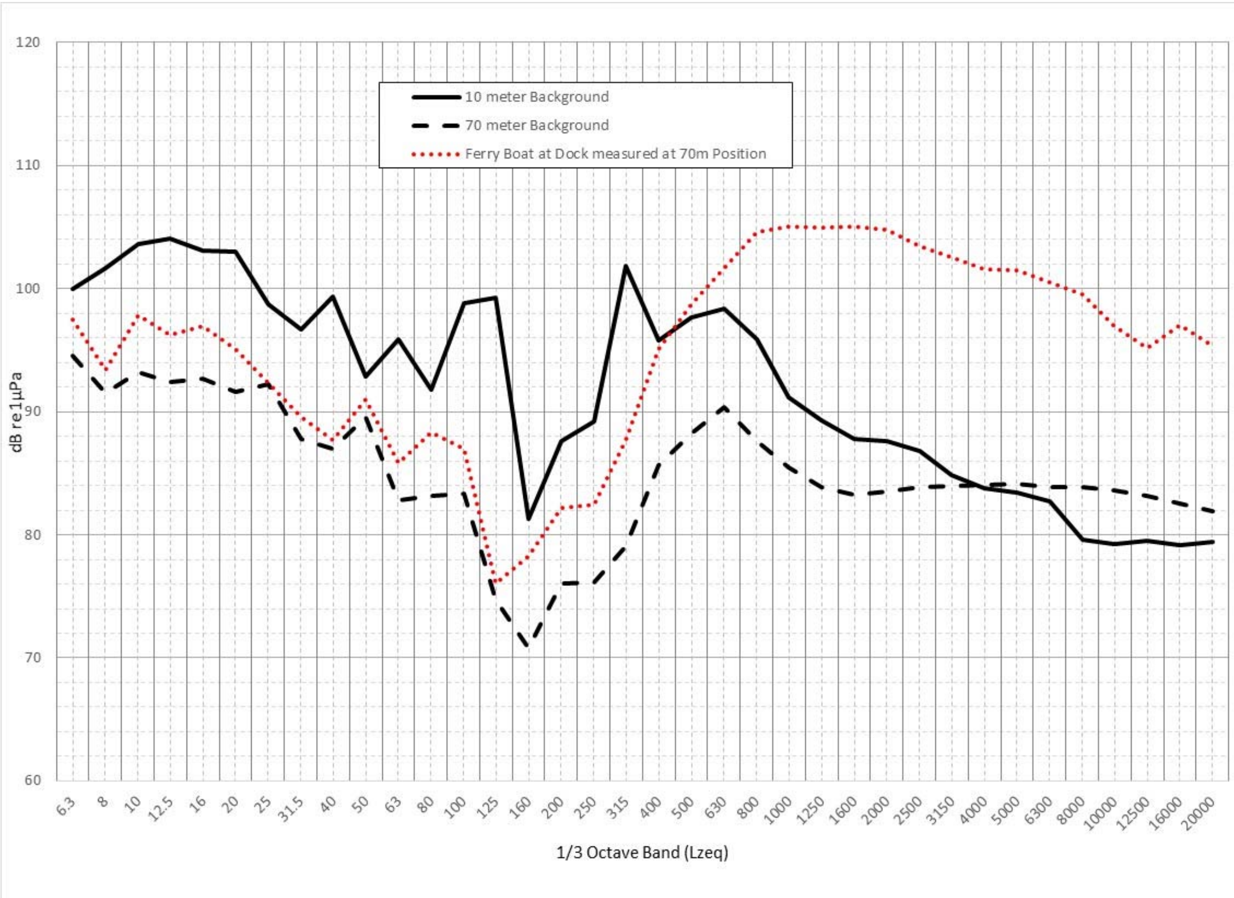

Figure 5. Sample of 1/3 Octave Band Spectra

3. Measurement Results and Analysis

3.1 Summary of Underwater Sound Monitoring Data

3.1.1 Vibratory Pile Driving

Noise monitoring was conducted during a total of 24 vibratory pile installation events —three 36-inch steel shell piles, eight 30-inch steel shell piles, and thirteen 24-inch steel shell piles. Sound levels generated by vibratory pile installations varied considerably during the driving of an individual pile, and from pile to pile. This section discusses the results of the data analysis performed for vibratory pile-driving events. All piles were installed using an APE Model King Kong Vibratory pile driver. The APE king Kong has a maximum eccentric movement of 11,500 in-lbs. with a driving force of 298 tons

Figure 6. APE King Kong (Model 400P2) Vibratory Pile Driver

Table 2 summarizes the daily results of Peak, 10-secoond RMS, 1-second SEL and daily Cumulative SEL SPLs measured during vibratory pile driving throughout the project. Data are summarized for each pile size. The 10-second RMS averaged values are what would be used to determine the extent of the underwater isopleths relative to species-specific exposure criteria. During all of the pile-driving events, the distances to the 190-dB RMS level and 180-dB RMS level, were always less than 10 meters (33 feet). The average sound levels over the duration of the pile-driving event, and the maximum level during the pile-driving event, are shown at each location where data were obtained. The RMS sound pressure levels were averaged in consecutive 10-second periods throughout the pile-driving event.

On 15 June, 2017 an attempt was made to measure from a boat out in the channel, as described in the monitoring plan. After a short period of time it was clear that measurements could not be done safely from a boat. There were too many ferries coming and going at rapid accelerations and large wakes which made the work unsafe. It was decided at that time to measure from the existing docks on both sides of the ferry terminal.

3.1.1.1 24-INCH STEEL SHELL PILES

On 6 September 2017, underwater sound monitoring was performed during the vibratory installation of two 24-inch piles. Measurements were made at distances of 9 to 12 meters (30 to 39 feet), 50 meters (164 feet), and 150 meters (492 feet) from the piles being installed. The majority of the measurements at 150 meters (492 feet) were not used in the measurement data set due to a WETA ferry docking and leaving approximately 30 meters (98 feet) from the measurement site during the pile driving events. There was a four-minute window of time that was used to estimate the levels at the 150-meter (492-foot) location and help calculate the attenuation rate to calculate the distance to the 120 dB re 1μPa RMS criteria. The water depth was approximately 2 meters (7 feet) deep at the piles. At the close position, the water depth was 2 meters (7 feet); at 50-meter (164-foot) location, the water depth was approximately 3.5 meters deep. At the 50-meter (164-foot) location, the noise from the ferry was present; however, the dominant noise source was from the pile driving. The background levels were elevated while the ferry was present

3.1.1.2 30-INCH STEEL SHELL PILES

On 15 June 2017, underwater sound monitoring was performed during the vibratory installation of two piles and the partial installation of a third pile. Measurements were made at distances of 10 meters (33 feet), 154 meters (505 feet), 47 meters (154 feet), and 54 meters (177 feet) from the pile being installed. The water depth was approximately 2.5 meters (8 feet) deep at the piles. Note that it was not possible to measure at exactly 124 meters (406 feet) from the pile due to bay conditions. At the 10-meter (33-foot) position, the water depth was 2.5 meters (8 feet); at the mid-range distance (20 to 22 meters (66 to 72 feet)), the water depth was approximately 2.5 meters (8 feet) deep, and at distant measurement sites, the water depth was approximately 3.5 meters (11 feet) deep.

On 25 July 2017, underwater sound monitoring was performed during the vibratory installation of two piles. Measurements were made at distances of 7 to 10 meters (23 to 33 feet), and 93 meters (305 feet) from the pile being installed. The water depth was approximately 2.5 meters (8 feet) deep at the piles. At the 10-meter (33-foot) position the water depth was 2.5 meters (8 feet); at the 93-meter (305 feet) location, the water depth was approximately 3.5 meters (11 feet) deep. At the 93-meter

(305 feet) location, there was a constant hum in the water at approximately 128 dB RMS. At the beginning of the driving of the second pile (Pile L-20), the humming masked the pile driving. A short measurement was made at the end of the pier where the levels were higher, approximately 143 dB RMS.

On 14 September 2017, underwater sound monitoring was performed during the vibratory installation of three 30-inch piles. Measurements were made at distances of 9 meters (30 feet), 40 meters (131 feet), 50 meters (164 feet), and 125 meters (410 feet) from the pile being installed. The water depth was approximately 2.5 meters (8 feet) deep at the piles. Note that it was not possible to measure at exactly 10 meters (33 feet) from the pile due to the location of the [piles and their proximity to the] docks. At the 9-meter (30-foot) position, the water depth was 2.5 meters (8 feet); at the mid-range distance (40 to 50 meters (131 to 164 feet)) the water depth was approximately 3.5 meters (11 feet) deep, and at the 125-meter (410-foot) measurement site, the water depth was approximately 3.5 meters (11 feet) deep.

3.1.1.3 36-INCH STEEL SHELL PILES

On 11 August 2017, underwater sound monitoring was performed during the vibratory installation of one 36-inch pile. Measurements were made at distances of 10 meters (33 feet), 85 meters (279 feet), and 150 meters (492 feet) from the pile being installed. The measurement at 150 meters (492 feet) was not used in the measurement data set due to a WETA ferry docking and leaving approximately 30 meters (98 feet) from the measurement site during the pile driving event. The water depth was approximately 2 meters (7 feet) deep at the piles. At the 10-meter (33-foot) position, the water depth was 2 meters (7 feet); at the 85-meter (279-foot) location, the water depth was approximately 3.5 meters (11 feet) deep. At the 85-meter (279-foot) location, the noise from the ferry was present; however, the dominant noise source was from the pile driving. The background levels were elevated while the ferry was present.

On 16 August 2017, underwater sound monitoring was performed during the vibratory installation of two 36-inch piles. Measurements were made at distances of 10 meters (33 feet), 125 meters (410 feet), and 175 meters (574 feet) from the pile being installed. The measurement at 175 meters (574 feet) was not used in the measurement data set due to a WETA ferry docking and leaving approximately 30 meters (98 feet) from the measurement site during the pile driving event. The water depth was approximately 2 meters (7 feet) deep at the piles. At the 10-meter (33-foot) position the water depth was 2 meters (7 feet); at the 125-meter (410-foot) location, the water depth was approximately 3.5 meters (11 feet) deep. At the 125-meter (410-foot) location, the dominant noise source was from the pile driving, though the background levels were elevated while the ferry was present. Note in **Figure 7** that the period where the pile driving was occurring (between 16:14 and 16:17) had lower levels than when a ferry boat came in to the docks and remained high until the ferry left. The only portion of the pile driving that was not contaminated at the distant positions was the first portion of the drive. This was a common problem at the distant locations; at times only, short periods of the pile driving could be used in the analysis due to the ferry schedules and the noise from the ferry boats interfering with the pile driving measurements.

3.1.1.4 24-INCH STEEL SHELL PILES

There was a total of thirteen (13) 24-inch piles monitored between 9 September 2017 and 7 November 2017. Typically, the distances to the close measurement site ranged from 9 to 15 meters

(30 to 49 feet) and the distant locations ranged from 50 to 200 meters (164 to 656 feet). The driving time for the 24-inch piles ranged from 3 to over 14 minutes. The water at the piles was generally around 2 meters (7 feet), depending on the tide.

On 6 September, 2017, underwater sound monitoring was performed during the vibratory installation of two 24-inch piles. Measurements were made at distances of 9 to 12 meters (30-39 feet), 50 meters (164 feet), and 150 meters (492 feet) from the piles being installed. The majority of the measurements at 150 meters were not used in the measurement data set due to a WETA ferry docking and leaving approximately 30 meters (98 feet) from the measurement site during the pile driving events. There was a four-minute window of time that was used to estimate the levels at the 150-meter location and help calculate the attenuation rate to calculate the distance to the 120 dB re 1μPa RMS criteria. The water depth was approximately 2 meters (7 feet) deep at the piles. At the close position, the water depth was 2 meters (7 feet); at 50 (164 feet) location the water depth was approximately 3.5 meters (11 feet) deep. At the 50-meter (164 feet) location the noise from the ferry was present however the dominant noise source was from the pile driving, the background levels were elevated while the ferry was present.

On 11 September, 2017, underwater sound monitoring was performed during the vibratory installation of two 24-inch piles. Measurements were made at distances of 9 to 15 meters (30 to 49 feet), 65 to 70 meters (213 to 230 feet), there was no attempt to measure at 150 meters (492 feet) due to the ferry boat schedule. The water depth was approximately 2 meters (7 feet) deep at the piles. At the close position, the water depth was 2 meters (7 feet); at 50-meter (164 feet) location the water depth was approximately 3.5 meters (11 feet) deep.

On 14 September, 2017 one 24-inch steel shell pile was installed. Measurement were taken at 10-meter (33 feet), 50 meters (164 feet) and 150 meters (492 feet) from the piles being installed. The measurements at 150 meters (492 feet) location were not used in the measurement data set due to a WETA ferry docking and leaving approximately 30 meters (98 feet) from the measurement site during the pile driving events. Measurements for the near location were made from the pile driving barge in water that was approximately 2 meters (7 feet) deep. The water depth at the distant location was approximately 3 meters (10 feet) deep. At the 50 meters (164 feet) location the background levels were elevated due to some noise sounding like a jack hammer, possibly from work at the BART tunnel adjacent to the project. These levels were below the levels measured from the vibratory pile driving being done at the ferry terminal and did not have an effect on the measured noise levels.

On 31 October, 2017 and 7 November, 2017, a total of eight (8) 24-inch steel shell piles were installed. Due to the location of the piles being installed the closest access for the near measurements ranged from 12 to 15 meters (39 to 49 feet) from the piles being installed. The distance to the far measurement sites ranged from 35 to 200 meters (115 to 656 feet). On 31 October, 2017 the data from the distant locations, 100 to 200 meters (330 to 656 feet), was relatively clear from ferry boat activities during the pile driving and the signals were clear of interference or noise from the ferry boats.

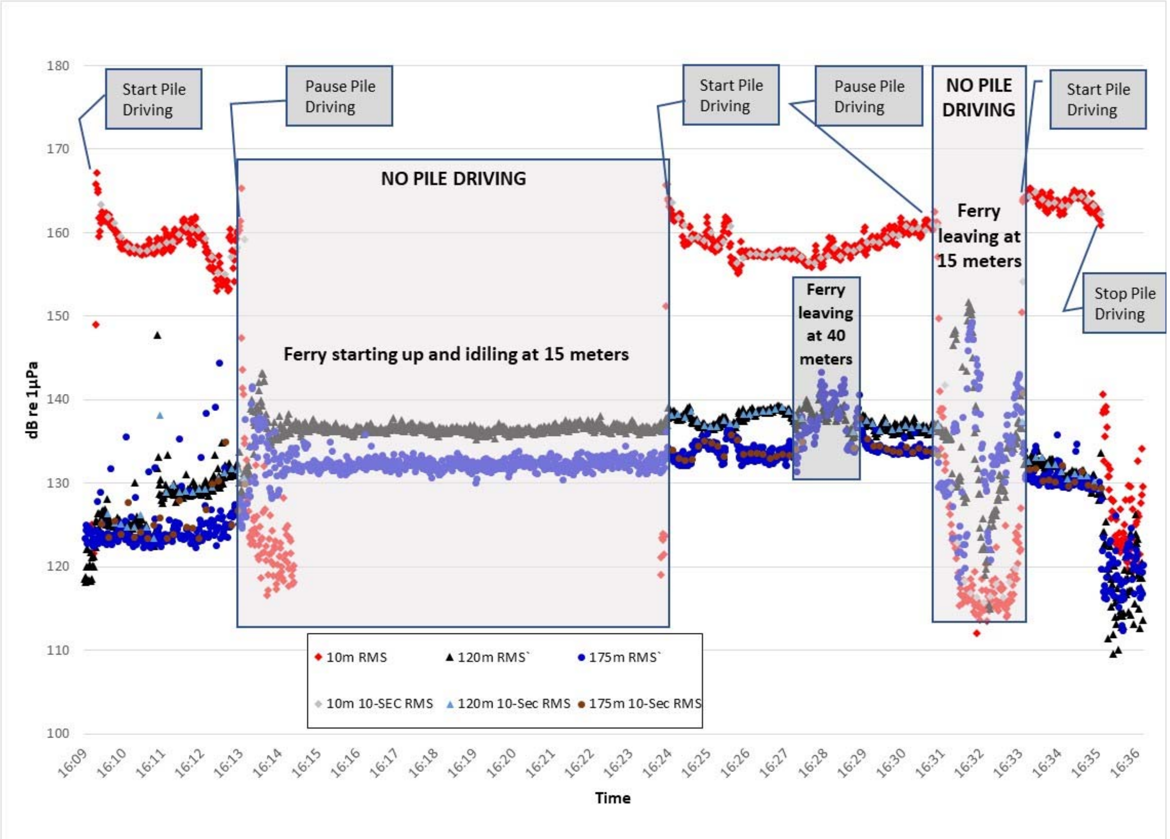

Figure 7. Sample of 16, August 2017 Vibratory Pile Driving

Vibratory pile-driving acoustical data are provided in graphical format in **Appendix A**. A time history plot of the 1-second sound pressure levels is provided for each location and pile type. The average RMS was calculated by taking the average of the 10-second RMS levels for the entire event, any breaks in the driving were not part of the calculation. These values are shown in **Table 2.** Also shown in **Table 2** are the measured distances of each measurement.

Table 2. Statistics for Vibratory Pile Driving

Pile	Pile Size	Driving Time[1]	Distance	Peak dB re 1µPa	RMS (10 Sec average) dB re 1µPa		SEL dB re 1µPa		Cumulative SEL per pile dB re 1µPa²-sec
				Maximum	Mean	Range	Mean	Range	
June 15, 2017									
L30	30-inch	9:05	10 meters	163	152	121-157	152	122-157	179
			154 meters[2]	<150	117	109-127	117	109-127	145
L31	30-inch	7:24	10 meters	171	146	128-155	146	129-156	173
			47meters	168	132	122-145	132	126-148	160
M29	30-inch	11:47	10 meters	171	146	126-157	146	130-157	176
			54 meters	164	133	129-149	133	128-146	163
July 25, 2017									
M20	30-inch	11:44	10 meters	181	150	119-160	147	114-162	183
			93 meters	159	135	122-144	135	119-144	167
L20	30-inch	10:51	7 meters	183	156	139-166	155	120-171	187
			93 meters	160	133	126-144	130	125-144	163
August 11, 2017									
A11	36-inch	14:09	10 meters	191	157	153-173	155	132-173	186
			85 meters	162	134	125-141	134	124-146	165
			150 Meters	Noise from Ferry operations overshadowed the pile driving noise					
August 16, 2017									
A8	36-inch	12:50	10 meters	187	159	139-167	159	159-168	188
			120 meters	167	134	122-148	134	123-150	164
			175 meters	Noise from Ferry operations overshadowed the pile driving noise					
A10	36-inch	5:54	10 meters	177	157	152-163	156	130-164	183
			120 meters	Noise from Ferry operations overshadowed the pile driving noise					
September 6, 2017									
B1	24-inch	8:44	9 meters	175	152	148-157	152	146-159	179
			50 meters	158	131	122-139	130	122-140	159
C1	24-inch	13:23	12 meters	177	152	145-157	152	121-160	181
			49 meters	158	138	123-143	137	121-146	168
September 11, 2017									
B2.1	24-inch	7:59	9 meters	178	157	153-161	156	151-161	183
			70 meters	158	137	118-145	137	118-145	167

Pile	Pile Size	Driving Time[1]	Distance	Peak dB re 1µPa	RMS (10 Sec average) dB re 1µPa		SEL dB re 1µPa		Cumulative SEL per pile dB re 1µPa²-sec
				Maximum	Mean	Range	Mean	Range	
C2.1	24-inch	8:32	15 meters	178	154	145-158	153	133-158	181
			65 meters	158	137	125-144	137	118-145	167
September 14, 2017									
F2.1	24-inch	8:41	10 meters	169	148	137-156	147	129-157	176
			50 meters	152	131	117-137	131	116-139	162
G2.1	30-inch	12:31	9 meters	170	153	149-157	153	148-161	182
			50 meters	152	134	125-140	134	126-140	163
L33	30-inch	4:14	40 meters	161	136	132-140	136	126-144	161
			125 meters	149	121	115-128	121	114-129	146
M33	30-inch	5:58	40 meters	164	139	133-145	138	122-145	164
			125 meters	149	120	115-127	120	114-129	147
October 31, 2017									
C1-9	24-inch	3:04	12 meters	168	150	144-154	148	135-156	174
			35 meters	159	143	134-151	142	131-151	167
			200 meters[2]	138	121	118-128	118	112-129	142
C1-11	24-inch	14:22	12 meters	171	155	151-160	154	134-163	184
			35 meters	160	142	126-150	143	131-150	174
			100 meters	160	136	128-140	135	121-144	167
C1-8	24-inch	2:58	12 meters	174	151	145-156	150	139-157	174
			35 meters	162	143	137-149	142	135-150	166
			100 meters	149	133	125-140	131	122-141	157
C1-10	24-inch	11:02	12 meters	178	156	154-159	155	139-159	192
			35 meters	165	145	132-150	144	130-151	174
			100 meters	152	136	130-139	135	125-139	164
November 7, 2017									
D-8	24-inch	5:29	15 meters	175	151	145-159	150	124-160	177
			89 meters	152	133	129-140	131	118-141	155
D-9	24-inch	6:04	15 meters	174	151	145-159	150	124-161	178
			89 meters	159	131	126-138	128	119-139	158
D-10	24-inch	5:25	15 meters	182	157	149-162	156	139-162	183
			89 meters	154	136	125-140	134	123-140	162

Pile	Pile Size	Driving Time[1]	Distance	Peak dB re 1µPa	RMS (10 Sec average) dB re 1µPa		SEL dB re 1µPa		Cumulative SEL per pile
				Maximum	Mean	Range	Mean	Range	dB re 1µPa²-sec
D-11	24-inch	5:48	15 meters	172	153	148-161	152	141-161	179
			89 meters	153	134	127-141	132	122-141	161

[1] This time reflects only the time the vibratory hammer was driving a pile. There were breaks in the driving to level piles and adjust the hammer, these times are not reflected in the driving time.

[2] Only portions of this data were used in the analysis due to outside interference (ferry boats) during portions of the drive.

3.1.2 Vibratory Pile Driving Propagation and Threshold Distances

The data in **Table 2** were used to calculate the propagation rates or attenuation rates for the various pile types installed with a vibratory hammer. **Table 3** shows the results of these calculations. The acoustic spreading loss curves for each of these conditions are shown in **Figures 8 through 10**. The transmission coefficients can be used to calculate overall distances to the various threshold levels.

3.1.3 Propagation and Threshold Distances

Data in **Table 3** are presented to chart relationships of peak SPLs, RMS SPLs, and SEL's for vibratory driving of the various pile types. The acoustic spreading loss curves for each size of piles are shown in **Figures 8 through 10.** There were only three of the 36-inch piles driven with a vibratory hammer, which minimal data to develop spreading loss curves. The peak spreading loss curve is based on the maximum peak level measured during each event. The RMS and SEL curves are based on the average levels measured during each event. The transmission coefficients can then be used to calculate distances to the various threshold levels. Again, note that data for 36-inch diameter piles there were only three piles driven, so the data used is limited.

Table 3. Summary of Attenuation Rates for Vibratory Pile-Driving Activities (dB per Log [distance])

Pile Type	Average Peak	Average RMS	Average SEL	Overall Average
24-inch steel Shell Pile	18.7	17.3	17.4	17.8
30-inch steel Shell Pile[1]	17.6	21.6	22.4	20.5
36-inch steel Shell Pile[1]	17.1	19.9	20.1	18.7
Overall Average Attenuation Rate				19.0

[1] – Limited Data only two piles with valid distant measurement

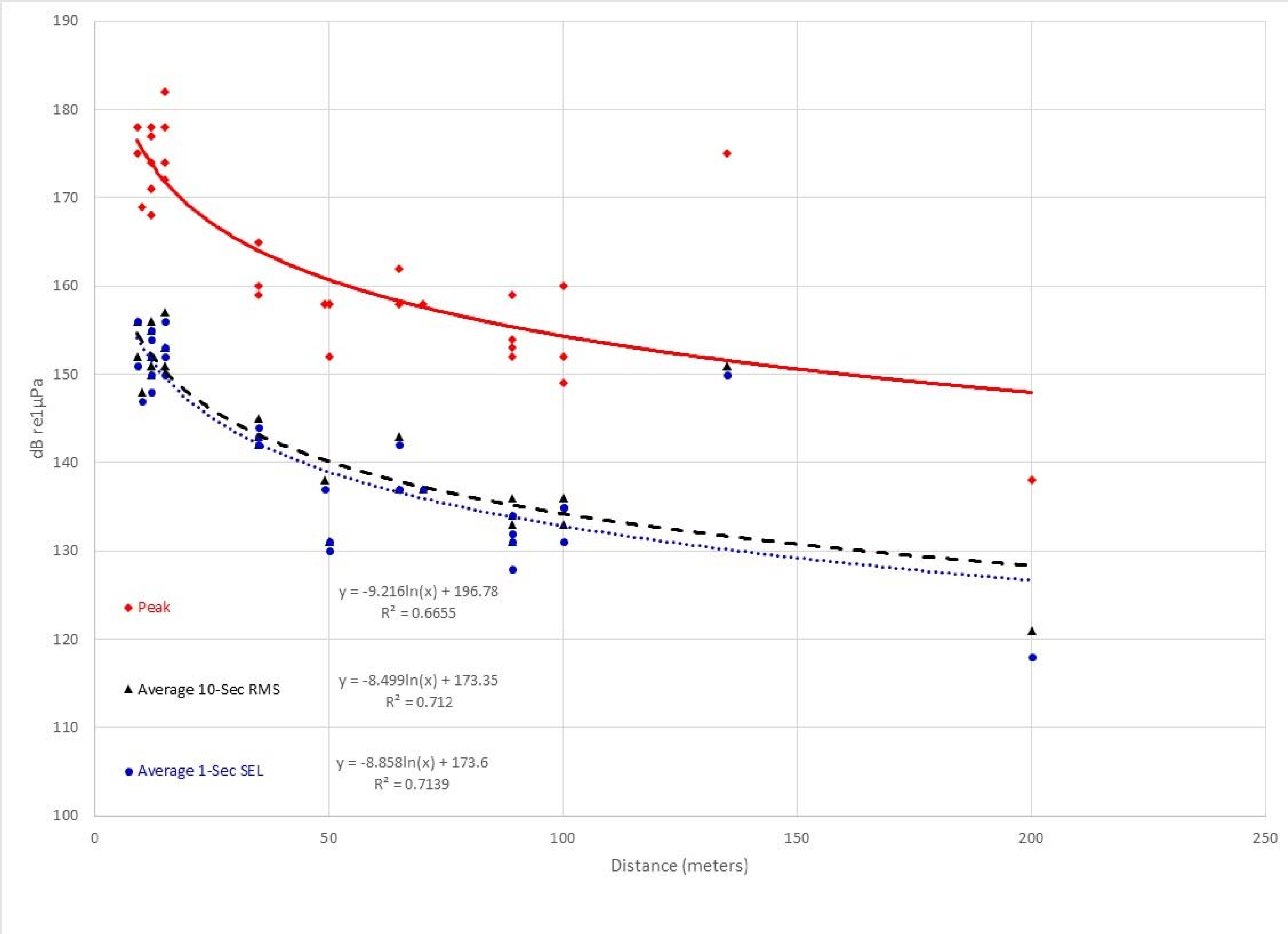

Figure 8. Acoustic Spreading Loss– 24-inch Steel Shell Piles with Vibratory Hammer

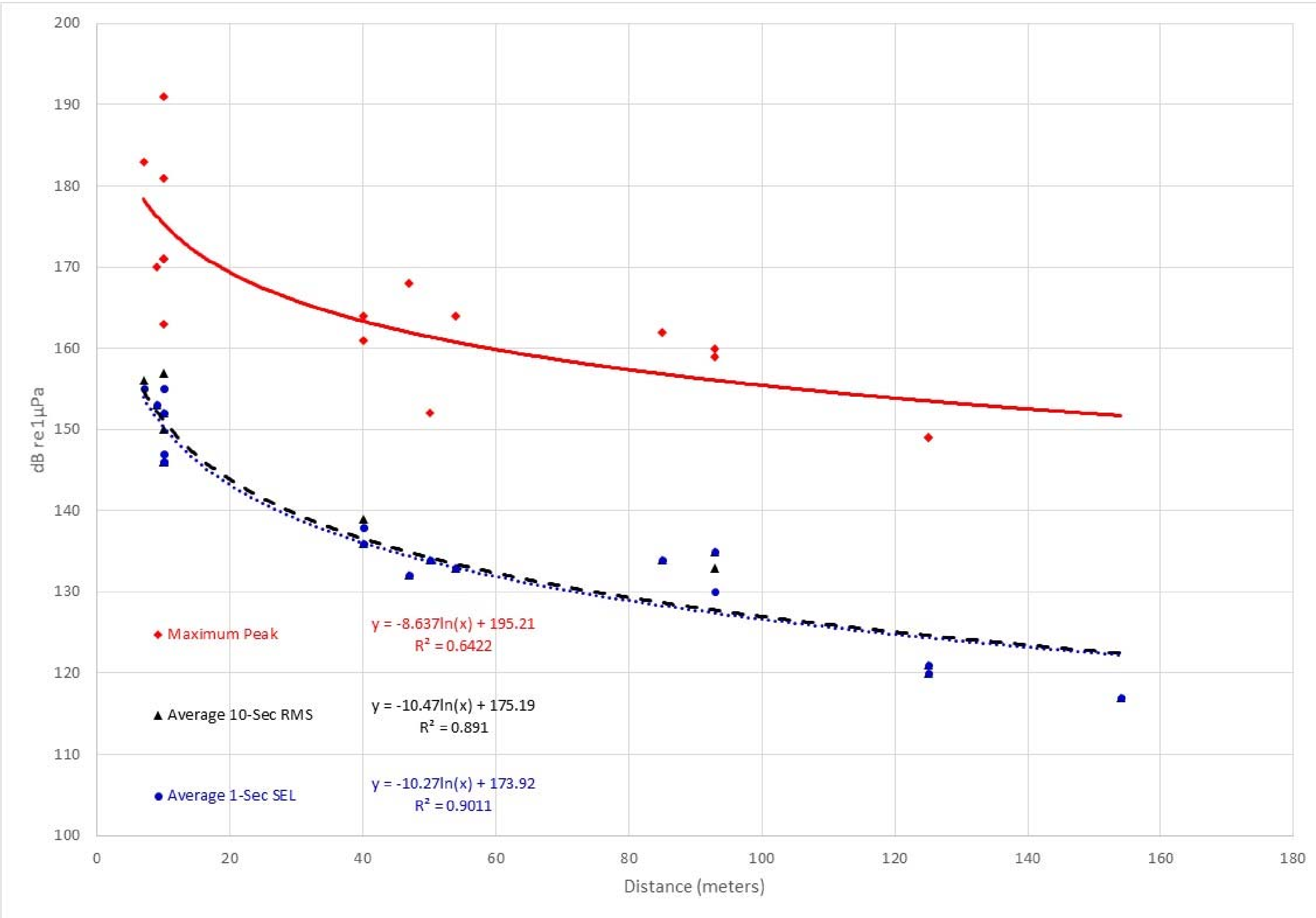

Figure 9. Acoustic Spreading Loss– 30-inch Steel Shell Piles with Vibratory Hammer

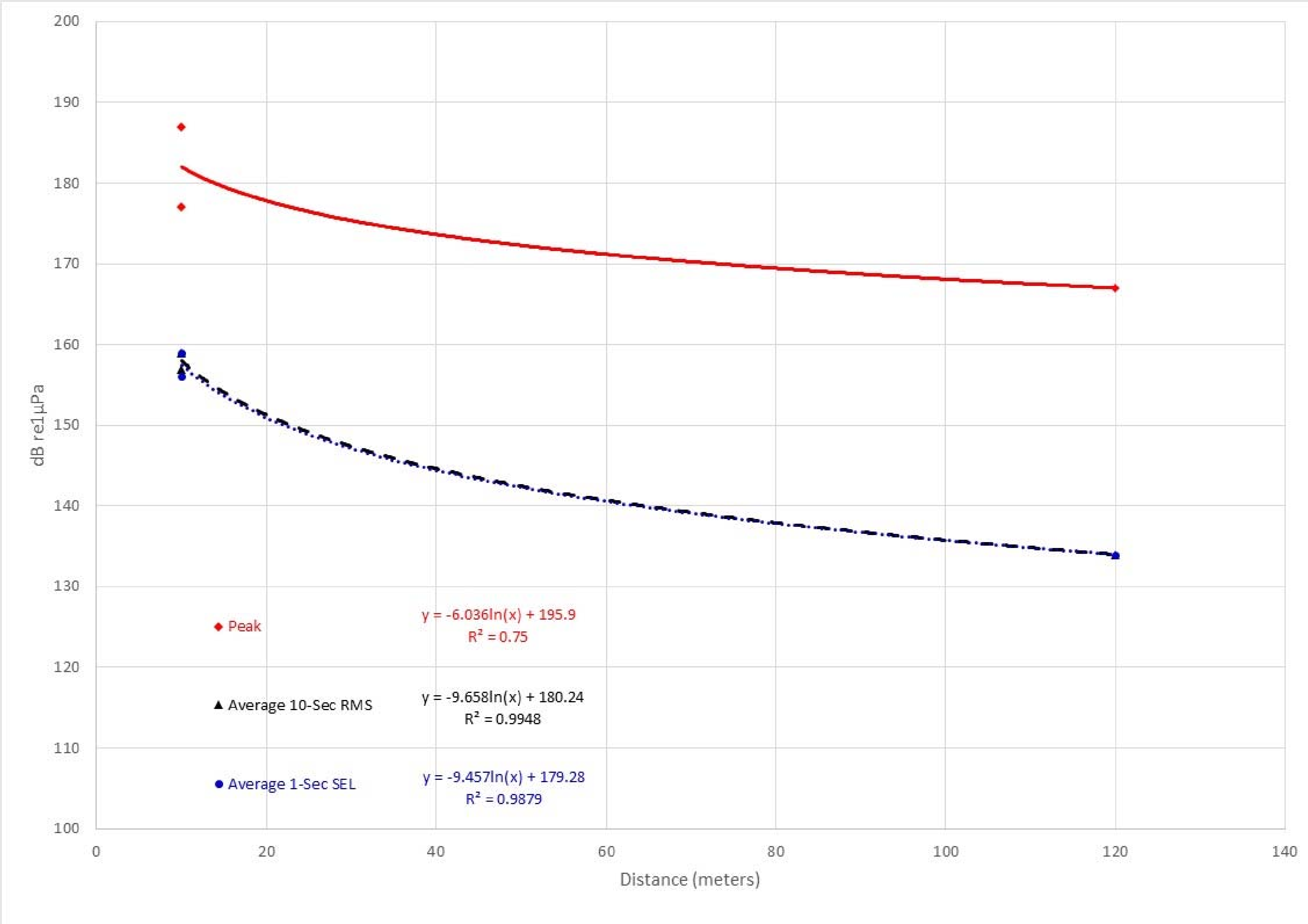

Figure 10. Acoustic Spreading Loss– 36-inch Steel Shell Piles with Vibratory Hammer

3.2 Glossary

Ambient sound – Normal background noise in the environment that has no distinguishable sources.

Ambient sound level – The background sound pressure level at a given location, normally specified as a reference level to study a new intrusive sound source.

Amplitude – The maximum deviation between the sound pressure and the ambient pressure.

Background level – Similar to ambient sound level with the exception that is a composite of all sound measured during the construction period minus the pile removal.

Cumulative sound exposure level (cSEL) – In an evaluation of pile-driving impacts, it may be necessary to estimate the cumulative SEL associated with a series of pile-strike events. cSEL can be estimated from the single-strike SEL and the number of strikes that likely would be required to place the pile at its final depth by using the following equation:

$$cSEL = SEL_{single\ strike} + 10*\log(\#\ of\ pile\ strikes)$$

Decibel (dB) – A customary scale most commonly used for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. A unit describing the amplitude of sound, equal to 20 times the logarithm to the base 10 of the ratio of the pressure of the sound measured to the reference pressure. The reference pressure for water is 1 microPascal, and for air it is 20 microPascals (the threshold of healthy human auditory sensitivity).

Fast, Slow, and Impulse – Most sound level meters have two conventional time weightings, F=Fast and S = Slow with time constants of 125 milliseconds (ms) and 1,000 ms, respectively. Some also have I = Impulse time weighting, which is a quasi-peak detection characteristic with rapid rise time (35 ms) and a much slower 1.5-second decay.

- F = 125 ms up and down
- S = 1 second up and down
- I = 35 ms while the signal level is increasing or 1,500 ms while the signal level is decreasing.

Frequency – The number of complete pressure fluctuations per second above and below ambient pressure, measured in cycles per second (Hertz [Hz]). Normal human hearing is between 20 and 20,000 Hz. Infrasonic sounds are below 20 Hz and ultrasonic sounds are above 20,000 Hz.

Frequency spectrum – The distribution of frequencies that comprise a sound.

Hertz (Hz) – The units of frequency where 1 Hz equals 1 cycle per second.

Kilohertz (kHz) – 1,000 Hz.

L_{eq} – *Equivalent Average Sound Pressure Level (or Energy-Averaged Sound Level).* The decibel level of a constant noise source that would have the same total acoustical energy over the same time interval as the actual time-varying noise condition being measured or estimated. Leq values must be associated with an explicit or implicit averaging time in order to have practical meaning. The use of A-weighted, C-weighted, or Z-weighted (flat) decibel units sometimes is indicated by LA_{eq}, LC_{eq}, or LZ_{eq}, respectively.

LZ_{eq} – Z-weighted, L_{eq}, sound pressure level.

LZF – Z-weighted Fast RMS sound pressure level.

LZF_{max} – Maximum Z-weighted Fast RMS sound pressure level.

LZI_{max} – Maximum Z-weighted Impulse RMS sound pressure level.

LZ_{max} – Maximum sound pressure level during a measurement period or a noise event.

LZ_{peak} – Z-weighted peak sound pressure level.

microPascal (μPa) – The Pascal (symbol Pa) is the SI unit of pressure. It is equivalent to one Newton per square meter. There are 1,000,000 microPascals in one Pascal.

Peak sound pressure level (L_{PEAK}) – The largest absolute value of the instantaneous sound pressure. This pressure is expressed in decibels (referenced to a pressure of 1 μPa for water and 20 μPa for air) or in units of pressure, such as μPa or pounds per square Inch.

Root mean square (RMS) sound pressure level – Decibel measure of the square root of mean square (RMS) pressure. For impulses, the average of the squared pressures over the time that comprise that portion of the waveform containing 90 percent of the sound energy of the impulse.

SLM – Sound level meter.

Sound – Small disturbances in a fluid from ambient conditions through which energy is transferred away from a source by progressive fluctuations of pressure (or sound waves).

Sound exposure – The integral over all time of the square of the sound pressure of a transient waveform.

Sound exposure level (SEL) – The time integral of frequency-weighted squared instantaneous sound pressures. Proportionally equivalent to the time integral of the pressure squared. Sound energy associated with a pile driving pulse, or series of pulses, is characterized by the SEL. SEL is the constant sound level in one second, which has the same amount of acoustic energy as the original time-varying sound (i.e., the total energy of an event). SEL is calculated by summing the cumulative pressure squared over the time of the event ($1\mu Pa^2$-sec).

Sound pressure level (SPL) – An expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 μPa for water, and 20 μPa for air and other gases. Sound pressure is the sound force per unit area, usually expressed in microPascals (or microNewtons per square meter), where 1 Pascal is the pressure resulting from a force of 1 Newton exerted over an area of 1 square meter. The SPL is expressed in dB as 20 times the logarithm to the base 10 of the ratio between the pressure exerted by the sound to a reference sound pressure. SPL is the quantity directly measured by a sound level meter.

Z-weighted – Z-weighting is a flat frequency response of 10 Hz to 20 kHz ±1.5 dB. This response replaces the older "Linear" or "Unweighted" responses as these did not define the frequency range over which the meter would be linear.

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A

Time History of Pile Driving

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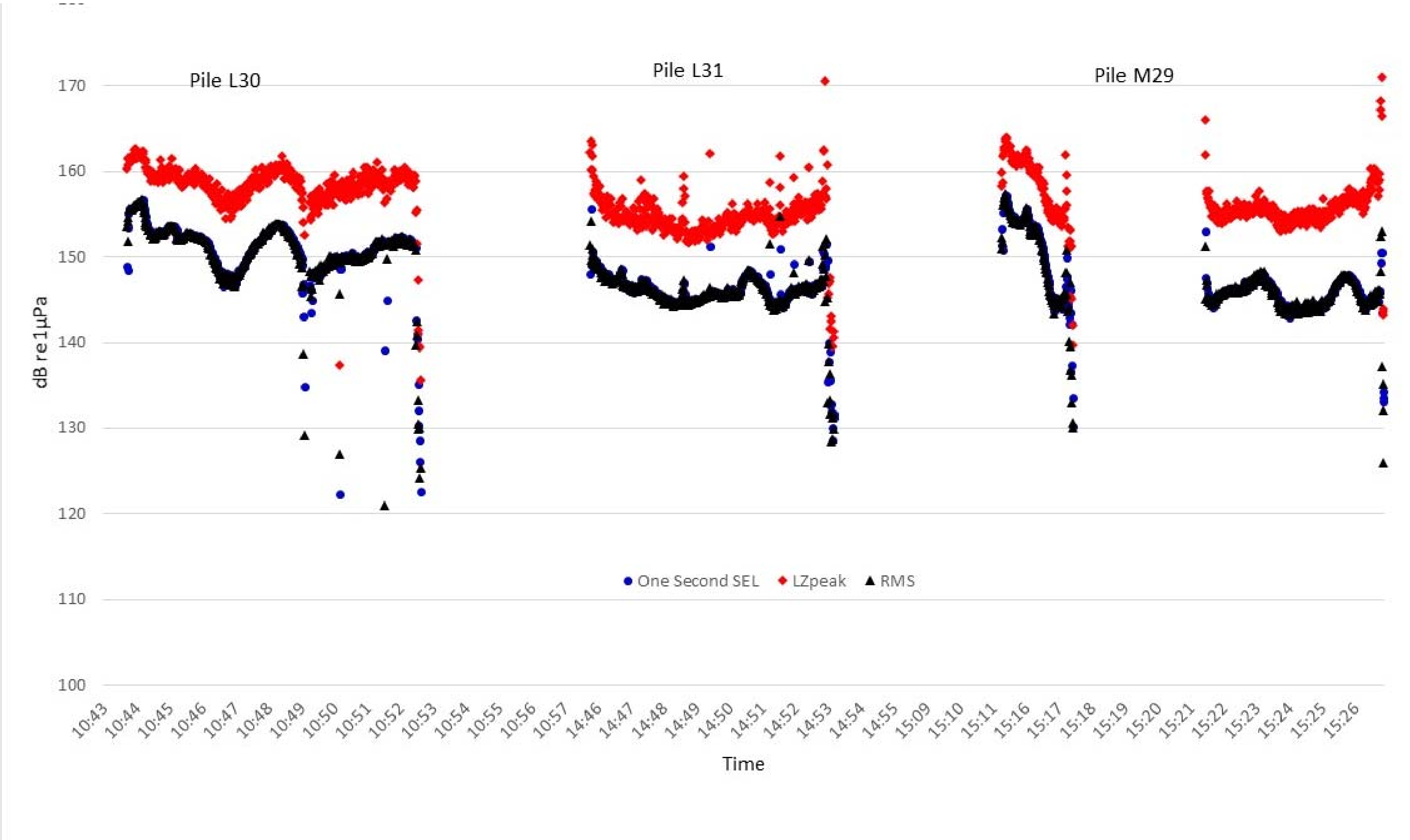

Figure A-1. Underwater Noise Measured at 10 Meters (33 Feet) Vibratory Pile Driving 30-inch Steel Shell Pile, 15 June 2017.

Figure A-2. Underwater Noise Measured at Distant Locations Vibratory Pile Driving 30-inch Steel Shell Piles, 15 June 2017.

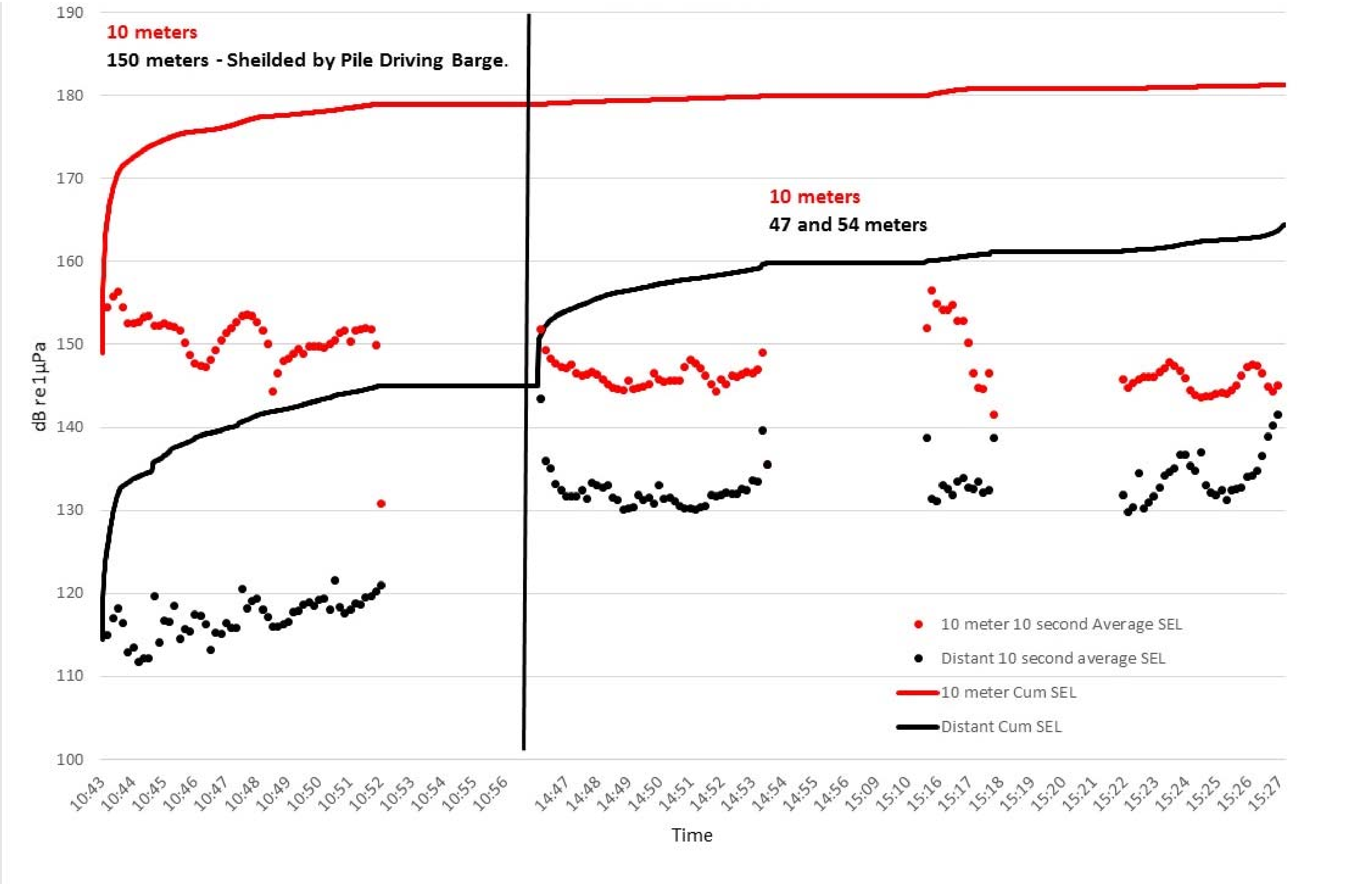

Figure A-3. Cumulative SEL measured for 30-inch Steel Shell Pile, 15 June 2017.

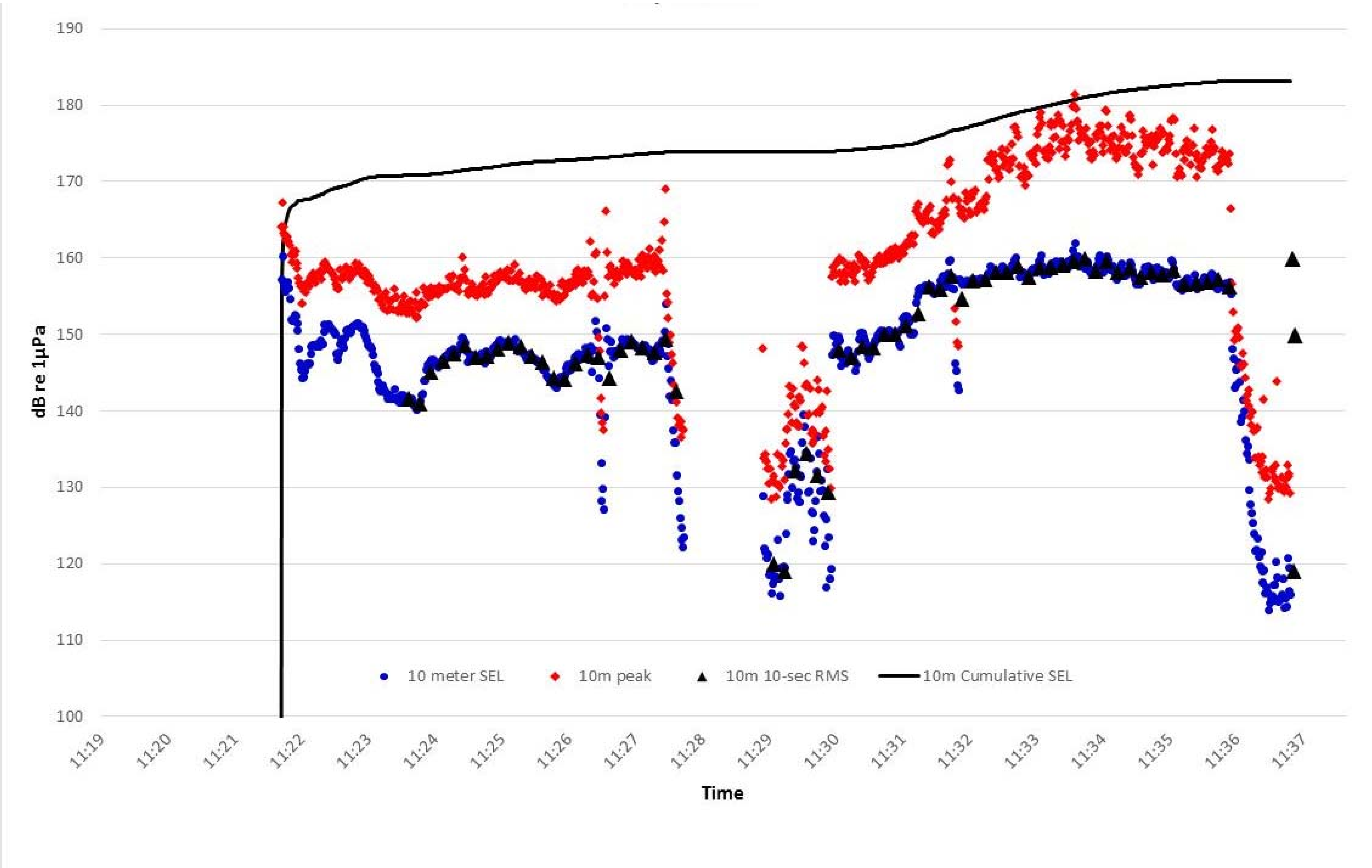

Figure A-4. Underwater Noise Recorded at 10 Meters (33 Feet) Vibratory Pile Driving Pile M20 30-inch Steel Shell Pile, 25 July 2017.

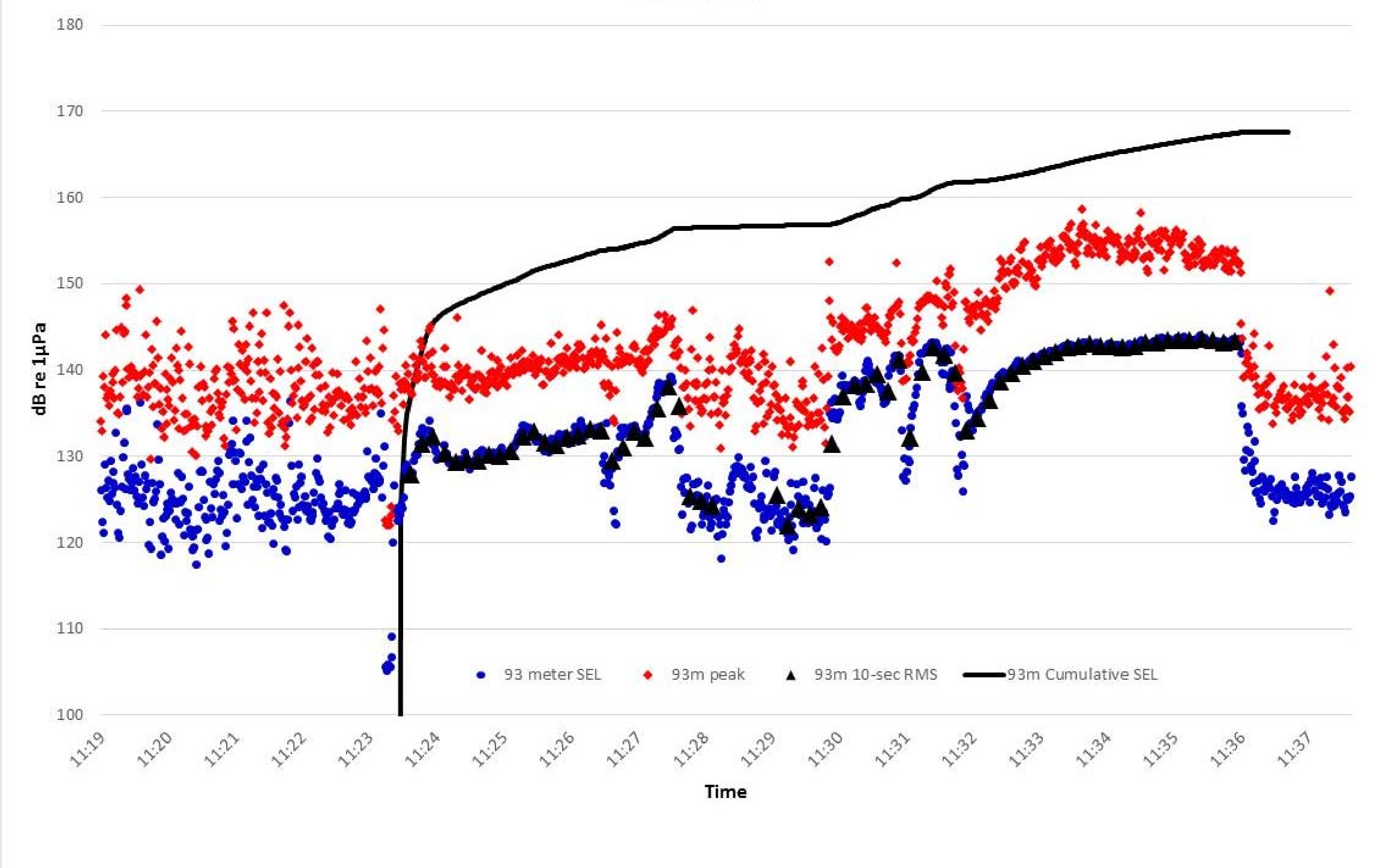

Figure A-5. Underwater Noise Recorded at 93 Meters (305 Feet) Vibratory Pile Driving Pile M20 30-inch Steel Shell Pile, 25 July 2017.

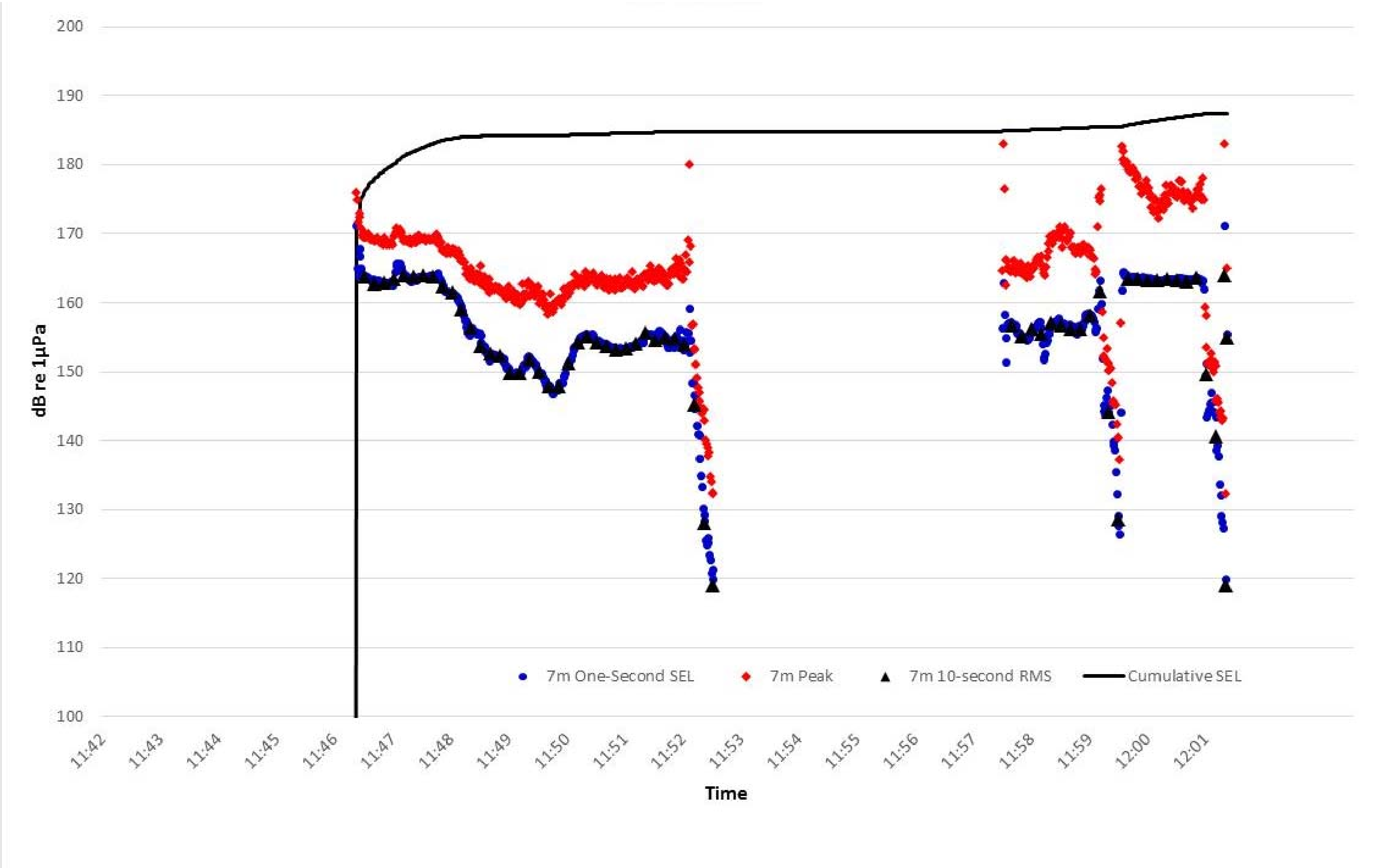

Figure A-6. Underwater Noise Recorded at 10 Meters (33 Feet) Vibratory Pile Driving Pile L20 30-inch Steel Shell Pile, 25 July 2017.

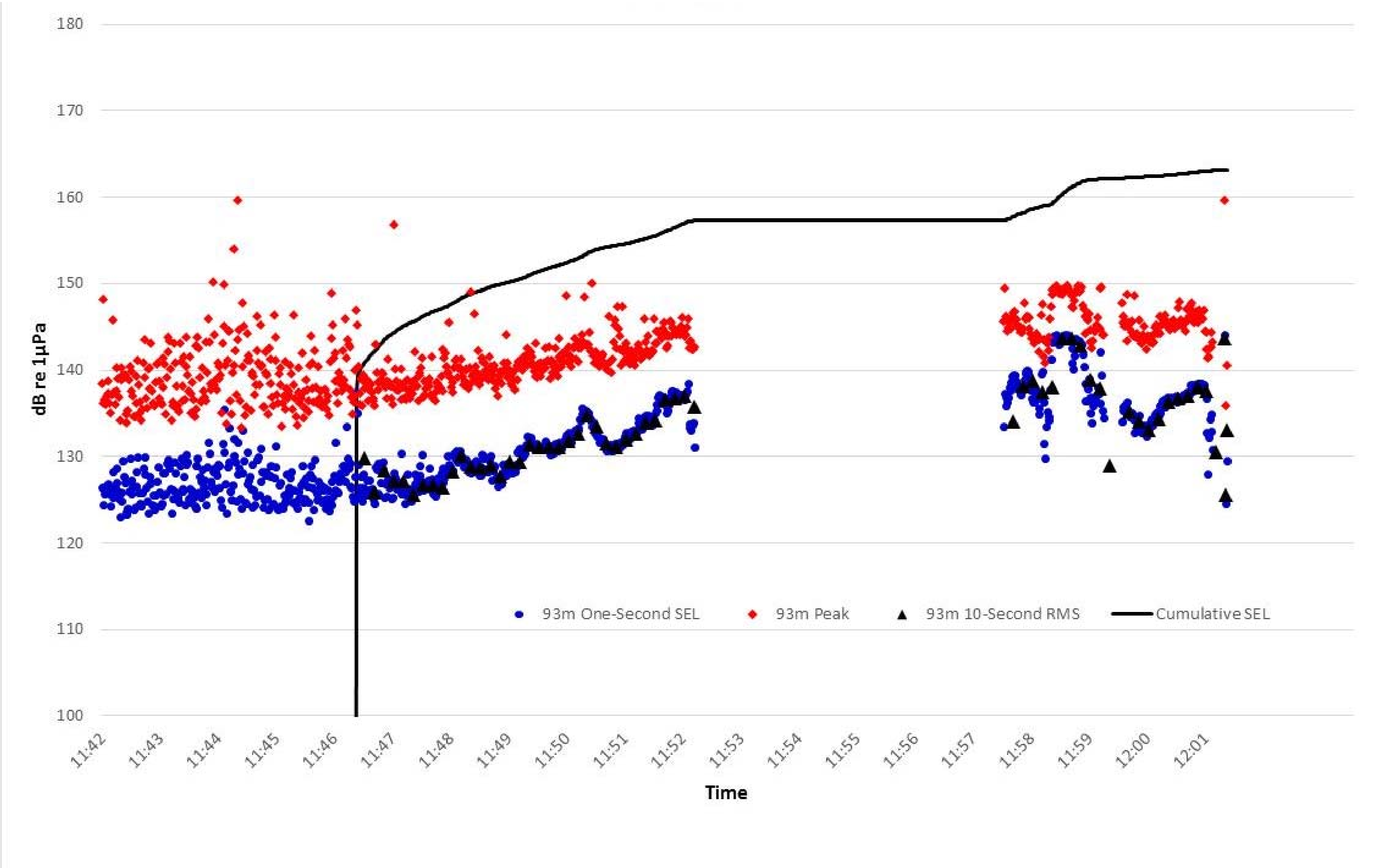

Figure A-7. Underwater Noise Recorded at 93 Meters (305 Feet) Vibratory Pile Driving Pile L20 30-inch Steel Shell Pile, 25 July 2017.

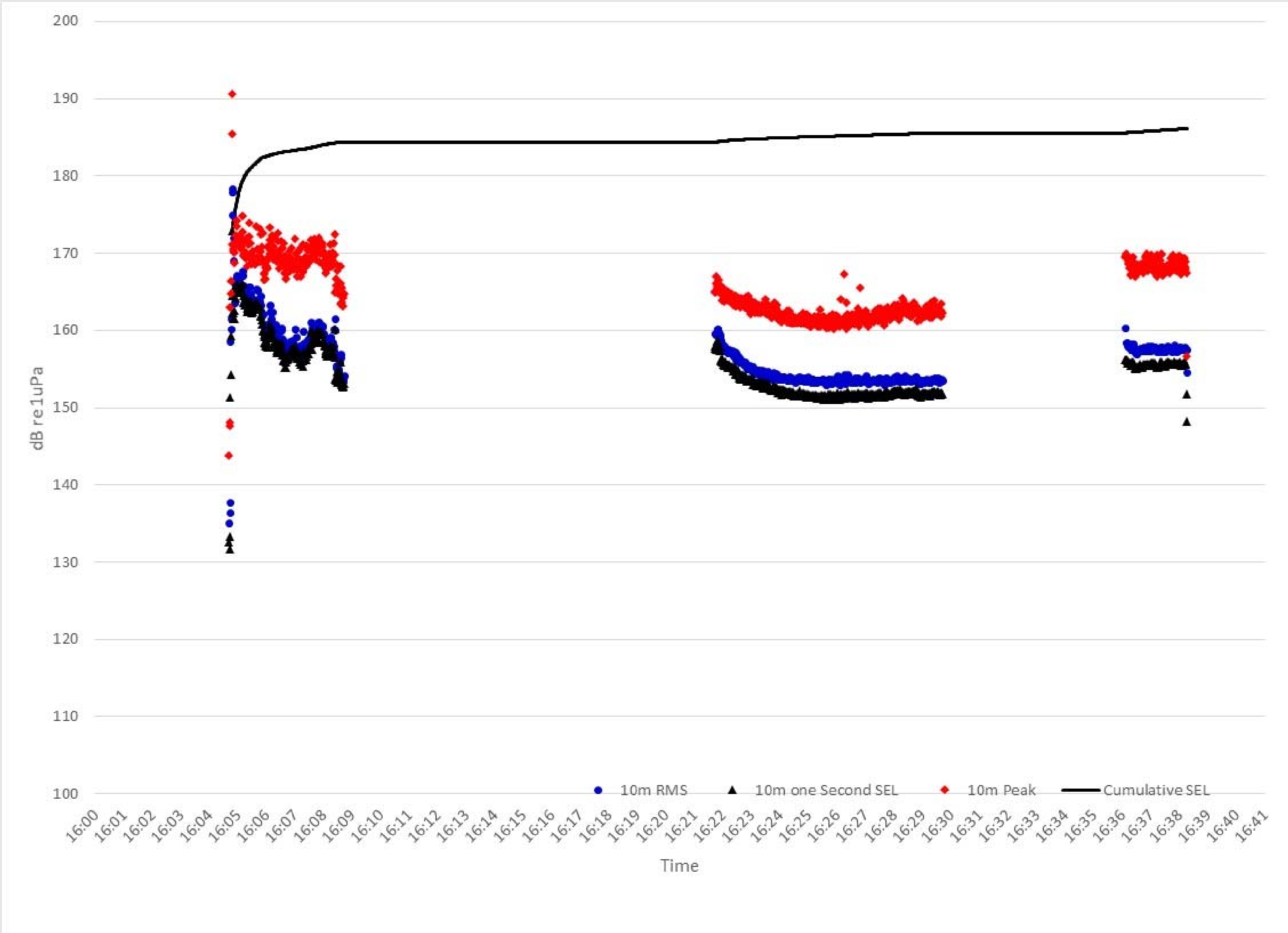

Figure A-8. Underwater Noise Measured at 10 Meters (33 Feet) Vibratory Driving Pile A-11 36-inch Steel Shell Pile, 11 August 2017.

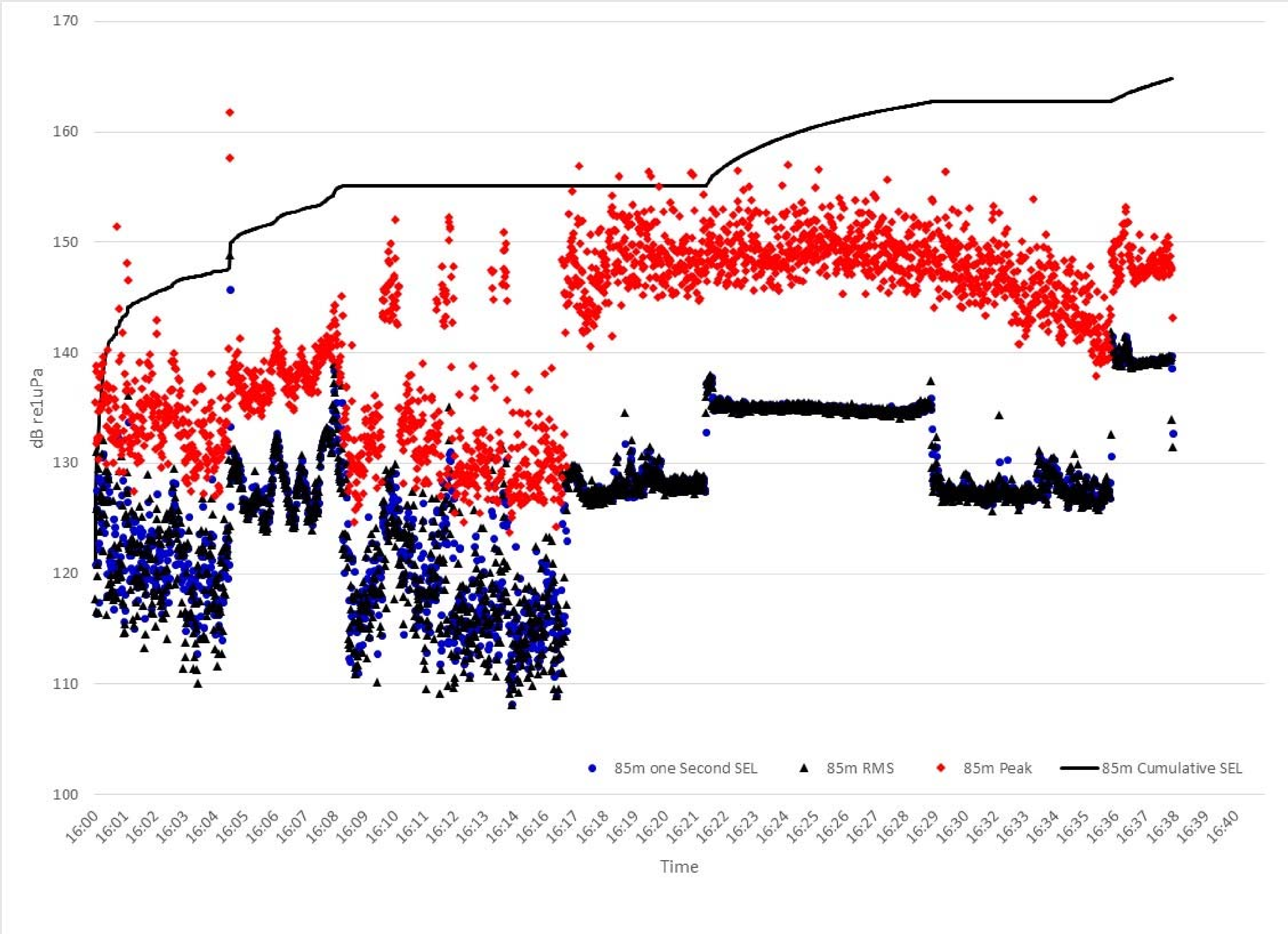

Figure A-9. Underwater Noise Measured at 85 Meters (279 Feet) Vibratory Driving Pile A-11 36-inch Steel Shell Pile, 11 August 2017.

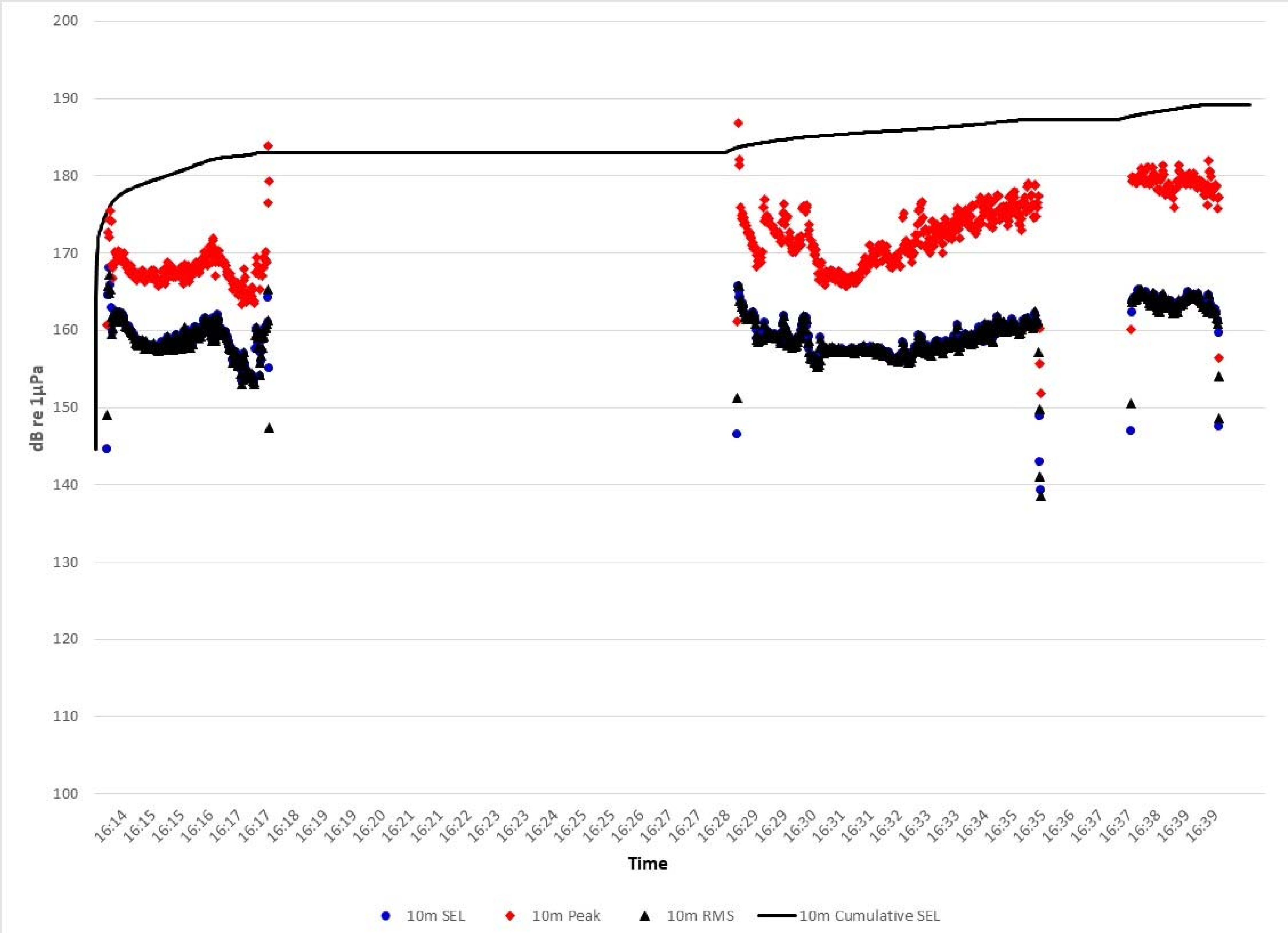

Figure A-10. Underwater Noise Measured at 10 Meters (33 Feet) Vibratory Driving Pile A-8 36-inch Steel Shell Pile, 16 August 2017.

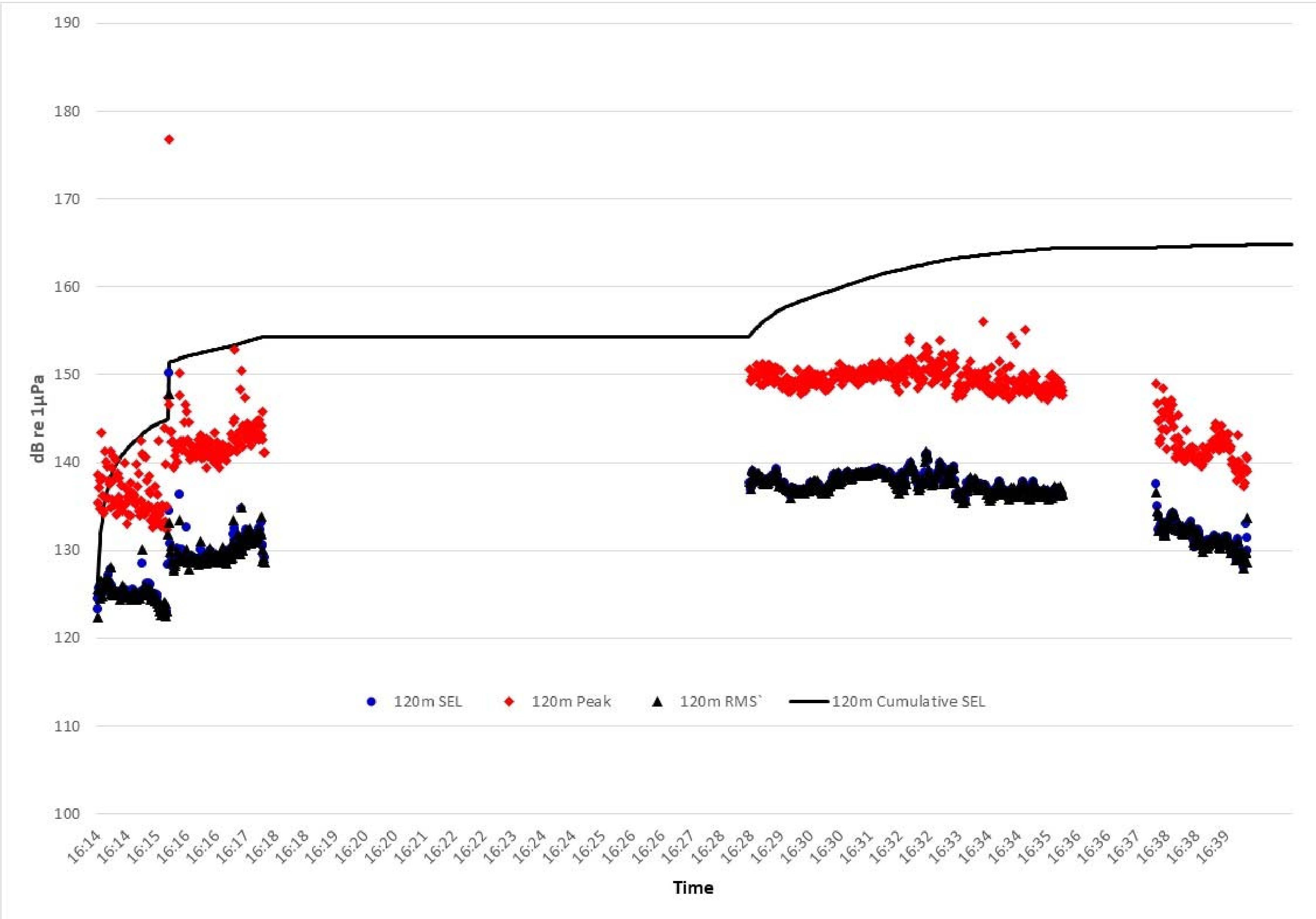

Figure A-11. Underwater Noise Measured at 120 Meters (394 Feet) Vibratory Driving Pile A-8 36-inch Steel Shell Pile, 16 August 2017.

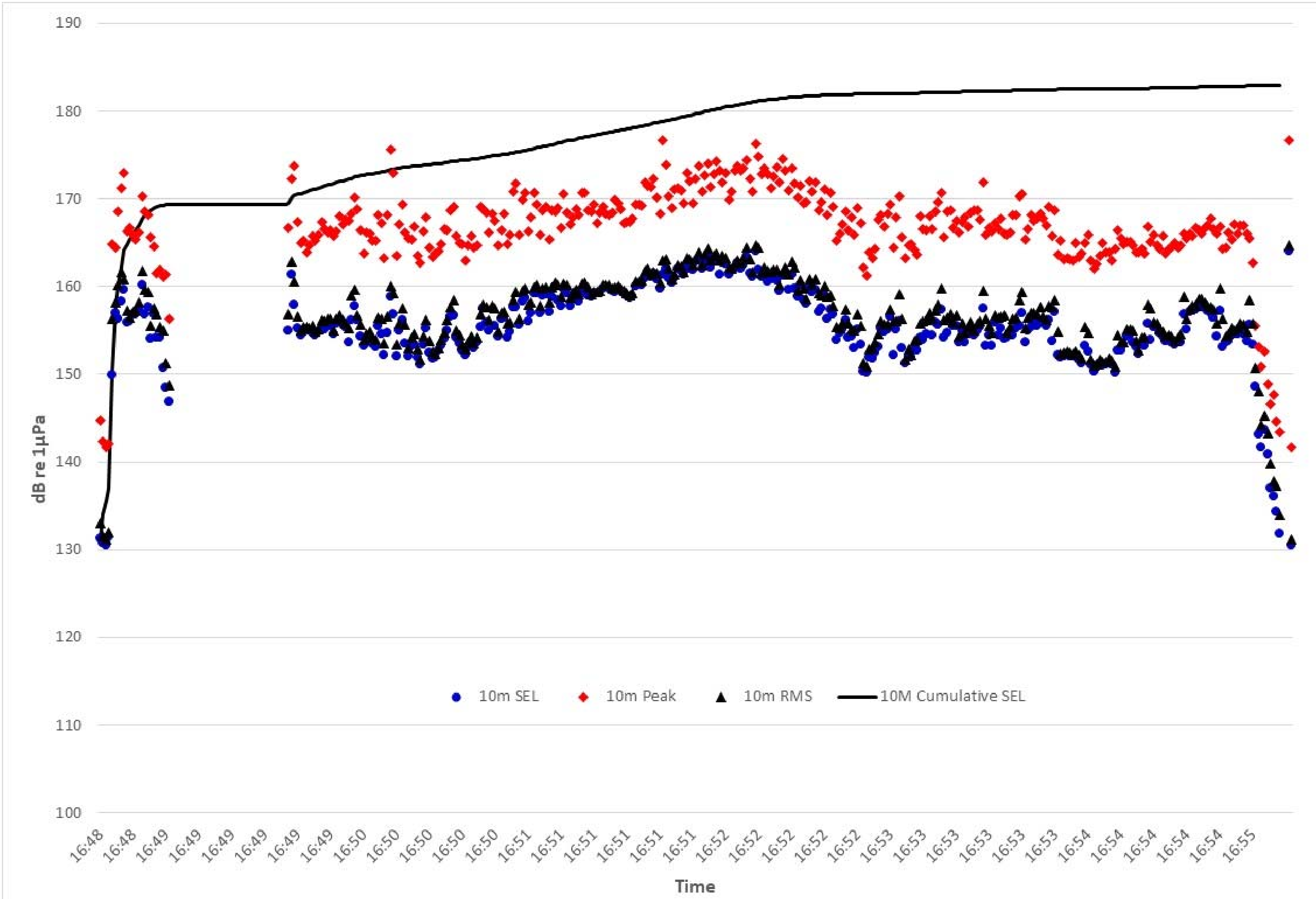

Figure A-12. Underwater Noise Measured at 120 Meters (394 Feet) Vibratory Driving Pile A-10 36-inch Steel Shell Pile, 16 August 2017.

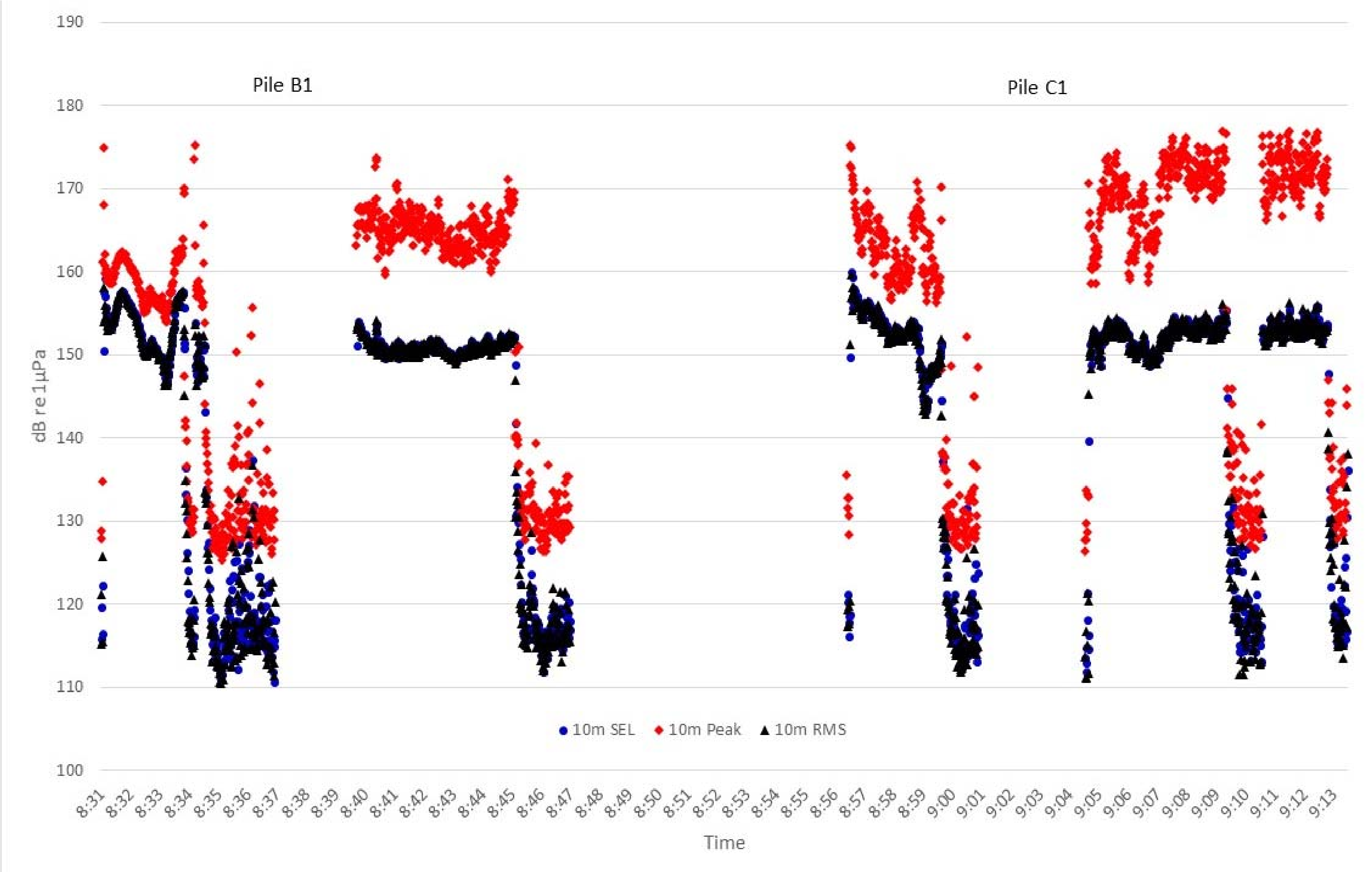

Figure A-13. Underwater Noise Recorded at 9-12 Meters (30-40 Feet) Vibratory Driving 24-inch Steel Shell Pile, 6 September 2017.

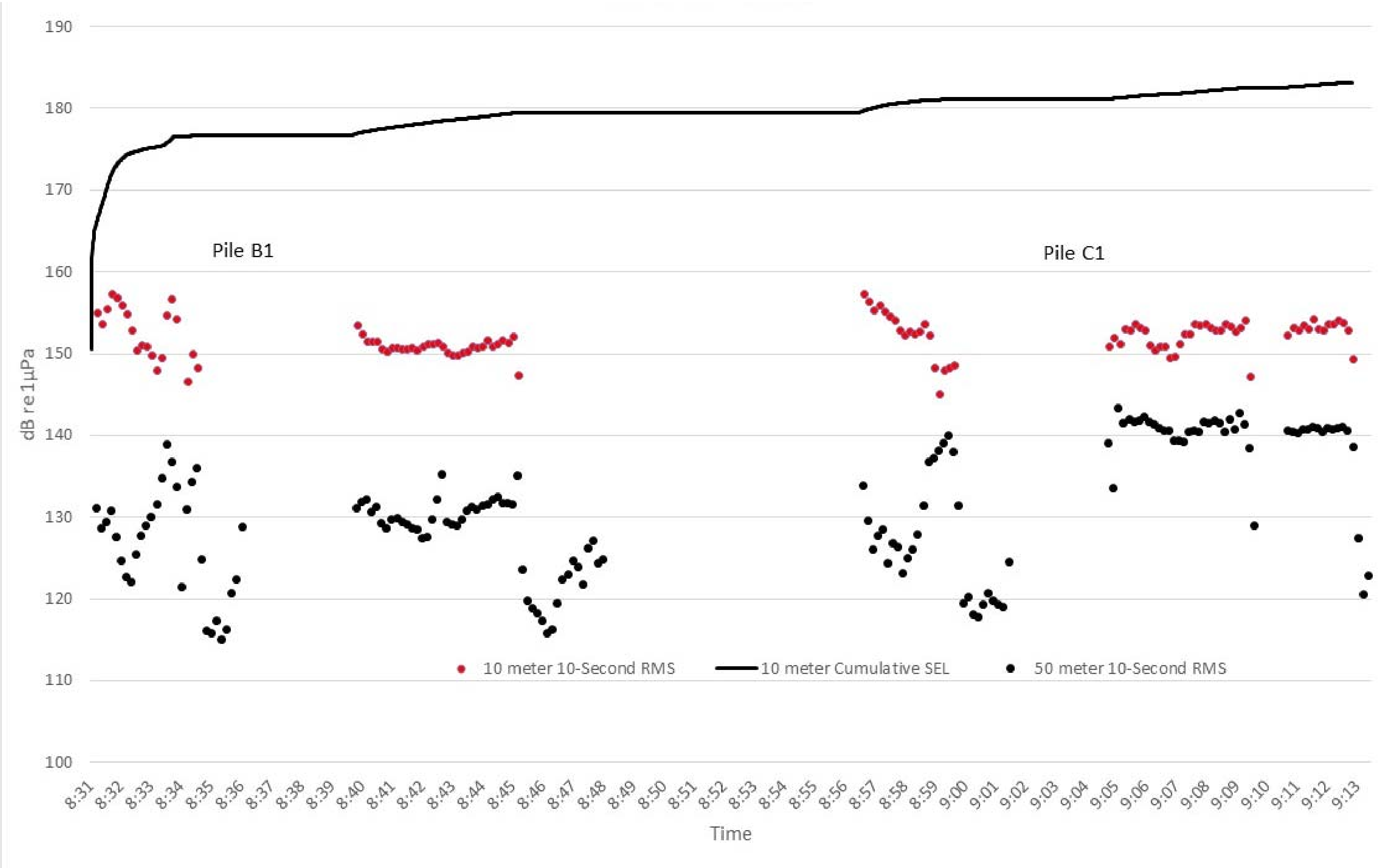

Figure A-14. Cumulative SEL Measured at 9-12 Meters (30-40 Feet) for 24-inch Steel Shell Pile, 6 September 2017.

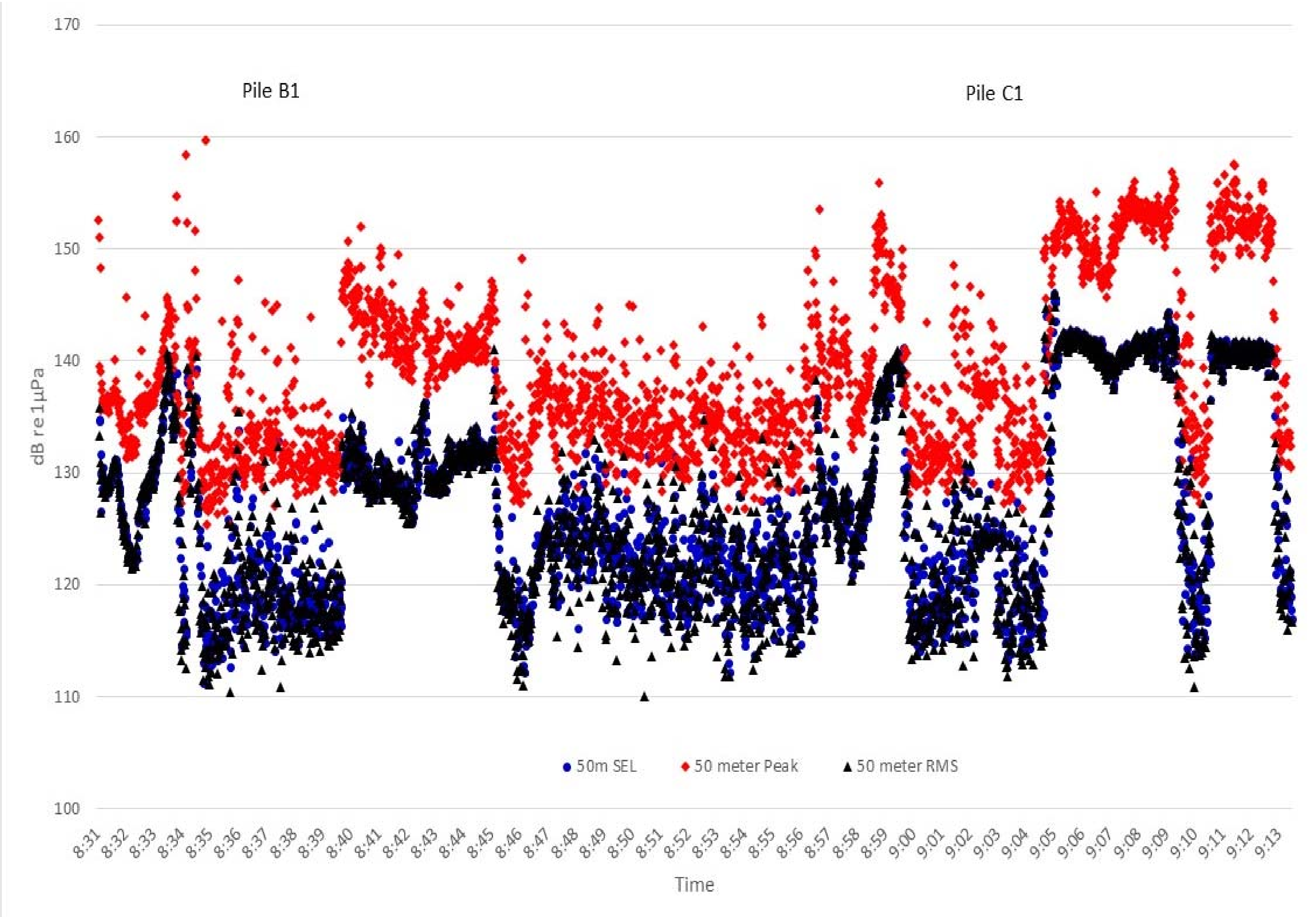

Figure A-15. Underwater Noise Recorded at 50 Meters (164 Feet) Vibratory Driving 24-inch Steel Shell Pile, 6 September 2017

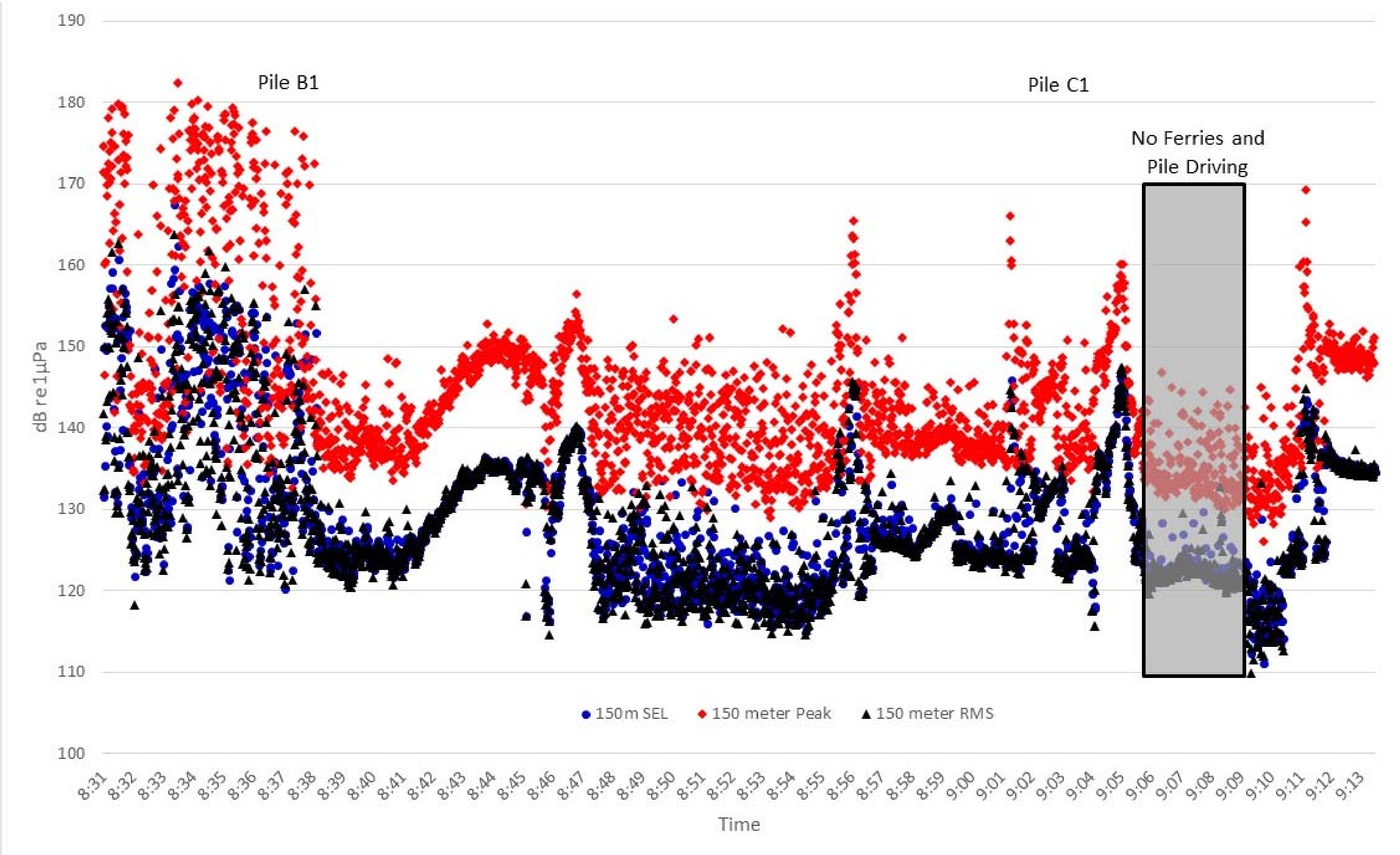

Figure A-16. Underwater Noise Recorded at 150 Meters (492 Feet) Vibratory Driving 24-inch Steel Shell Pile, 6 September 2017

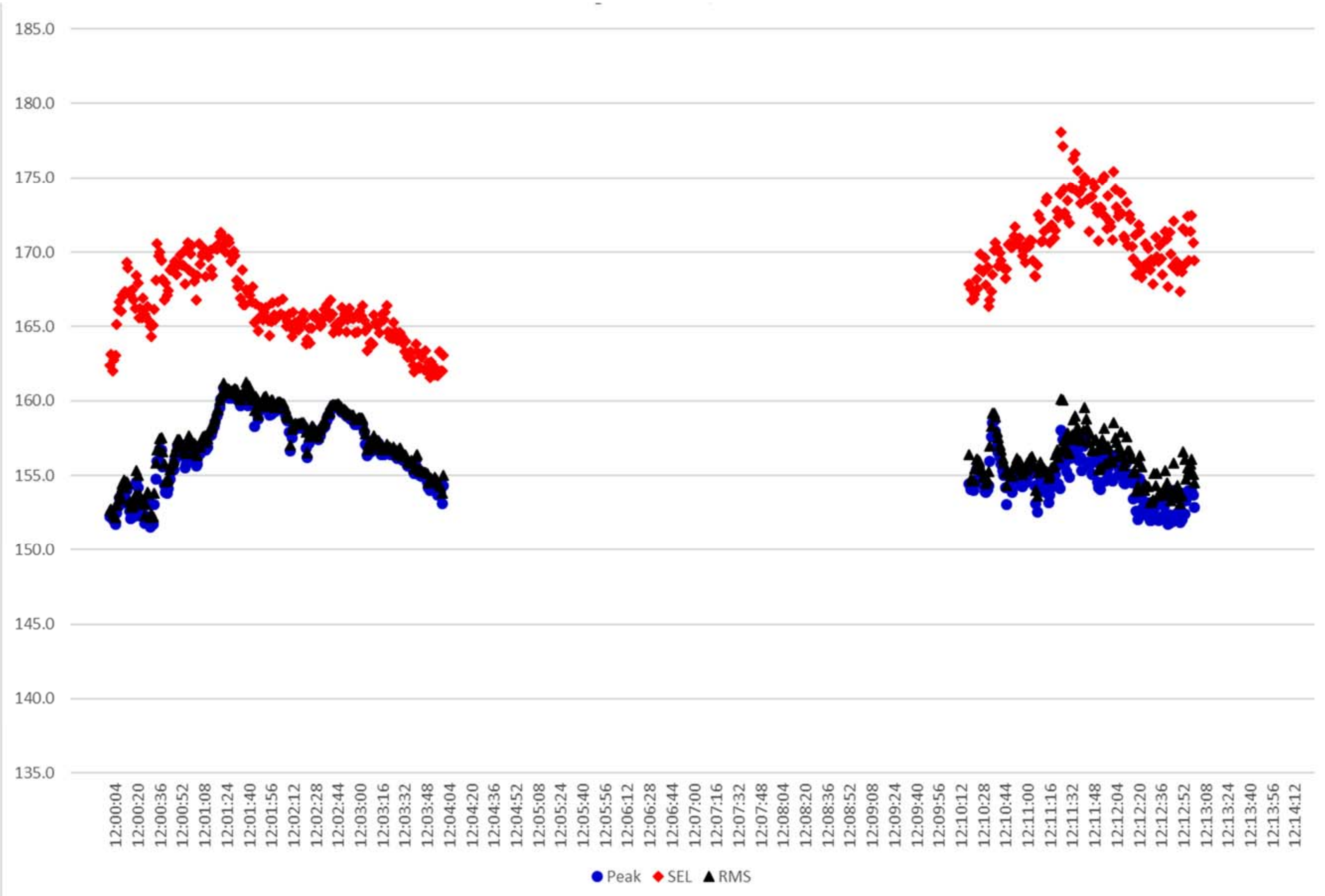

Figure A-17. Underwater Noise Recorded at 9 Meters (30 Feet) Vibratory Driving 24-inch Steel Shell Pile B-2, 11 September 2017

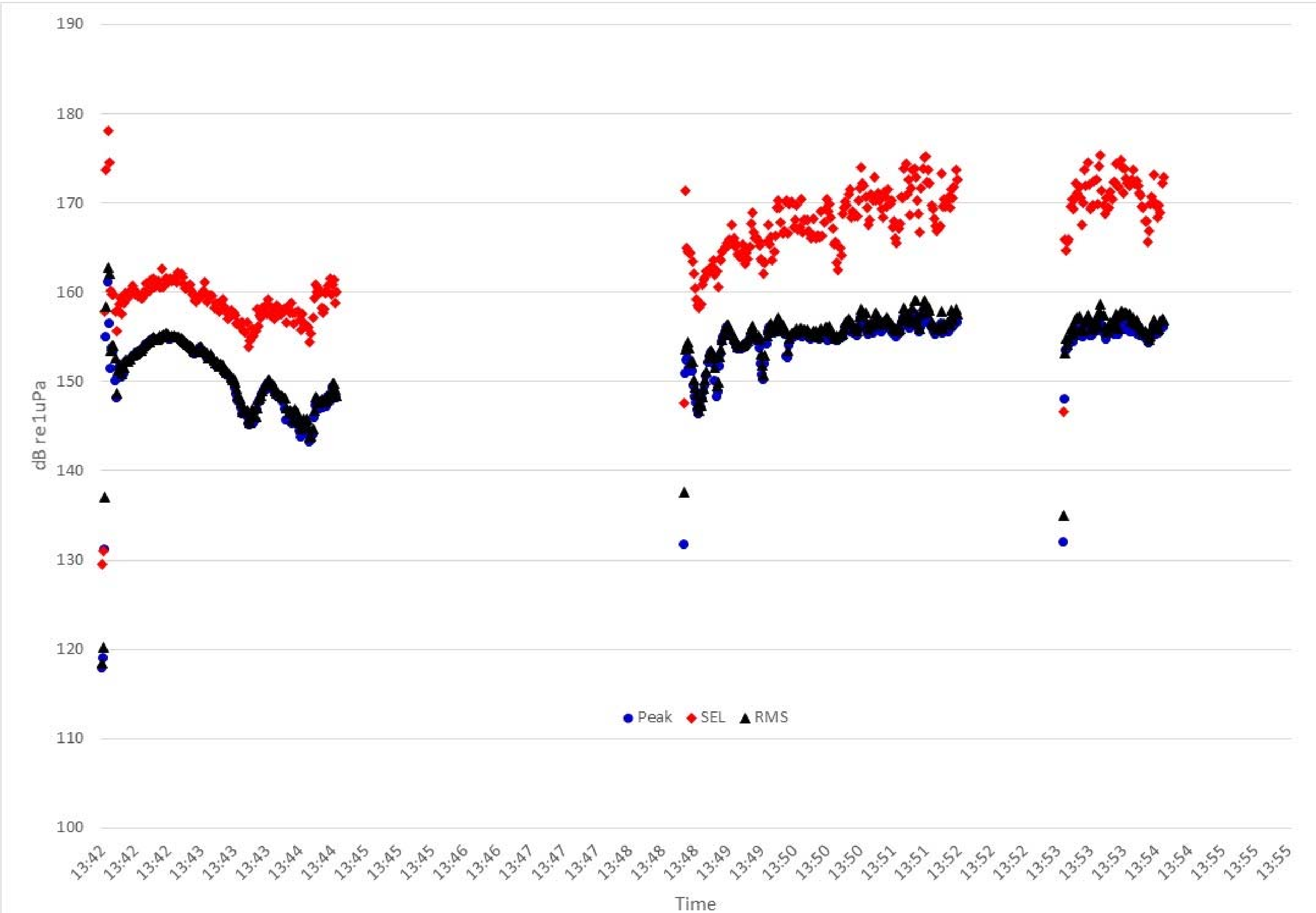

Figure A-18. Underwater Noise Recorded at 15 Meters (49 Feet) Vibratory Driving 24-inch Steel Shell Pile C-2, 11 September 2017

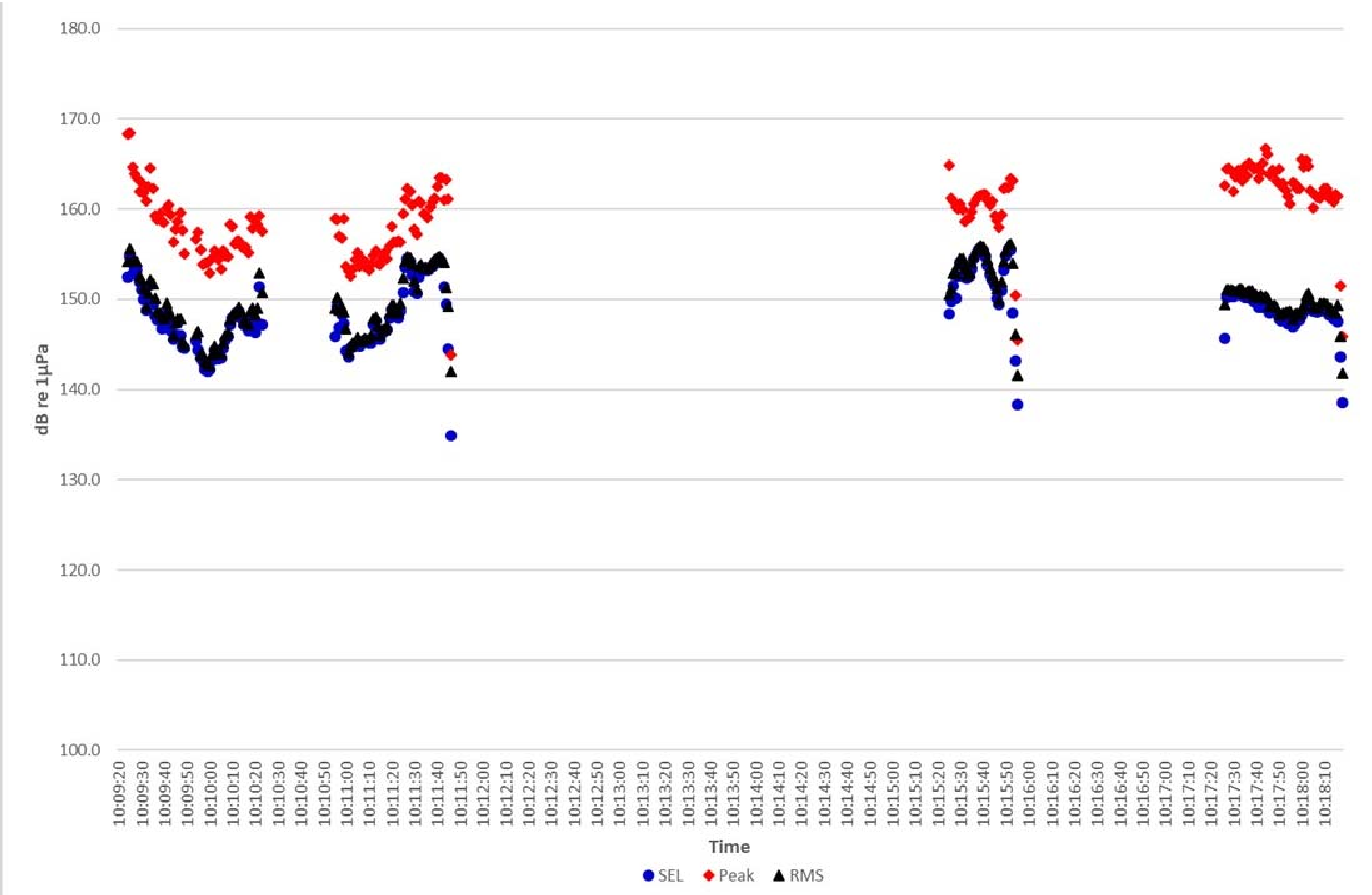

Figure A-19. Underwater Noise Recorded at 10 Meters (33 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-9, 31, October 2017

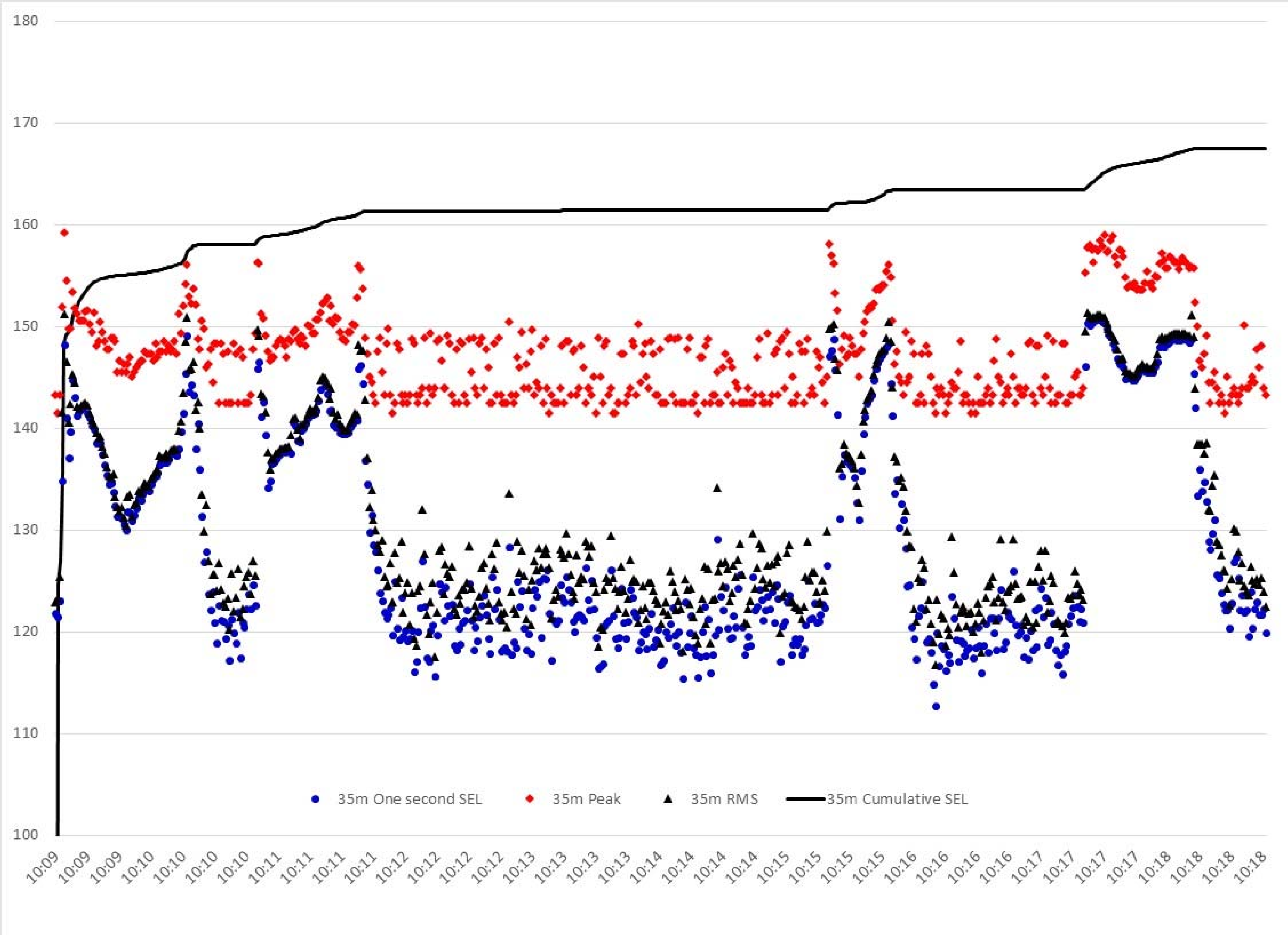

Figure A-20. Underwater Noise Recorded at 35 Meters (115 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-9, 31, October 2017

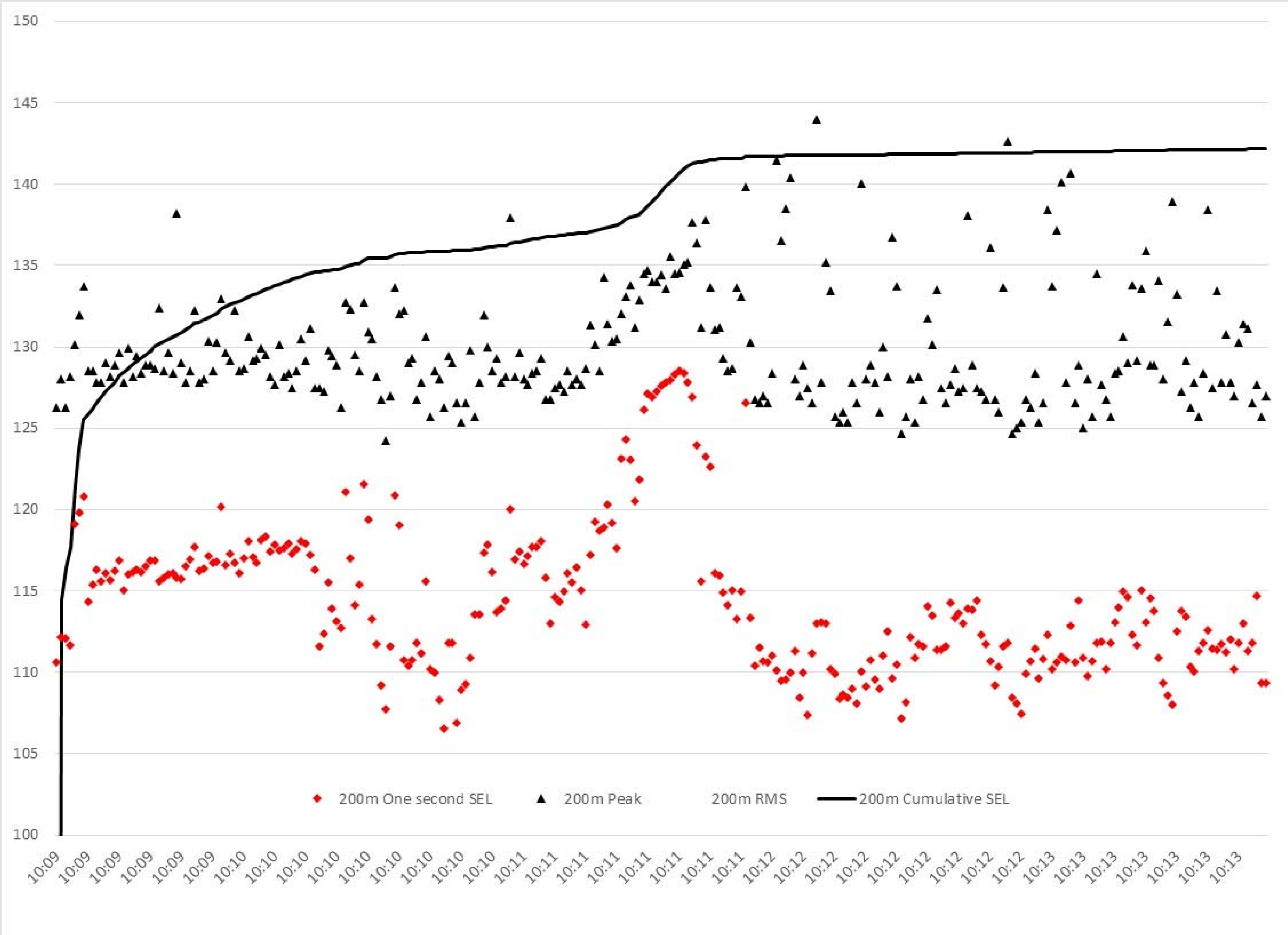

Figure A-21. Underwater Noise Recorded at 200 Meters (656 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-9, 31, October 2017

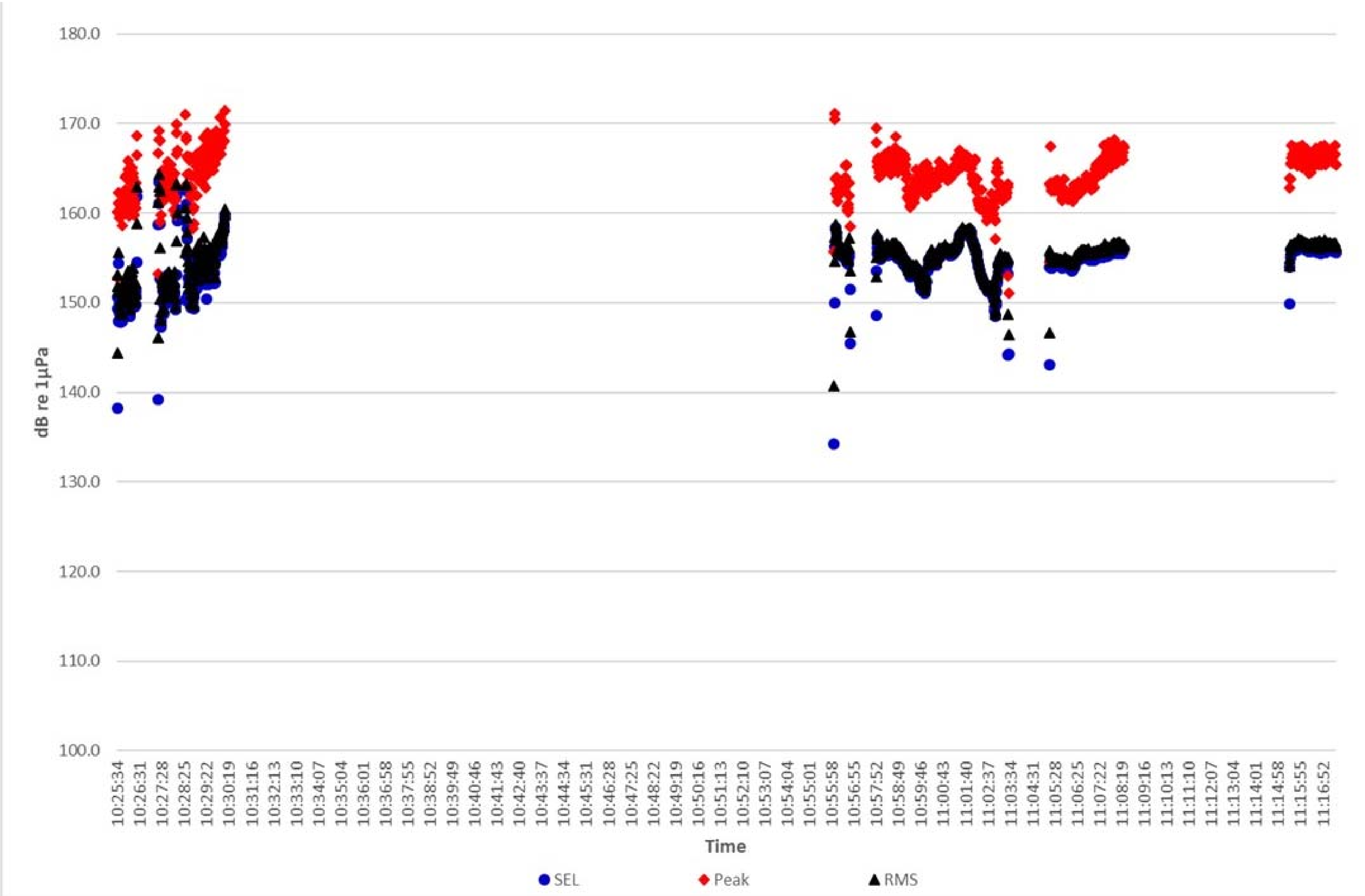

Figure A-22. Underwater Noise Recorded at 12 Meters (39 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-11, 31 October 2017

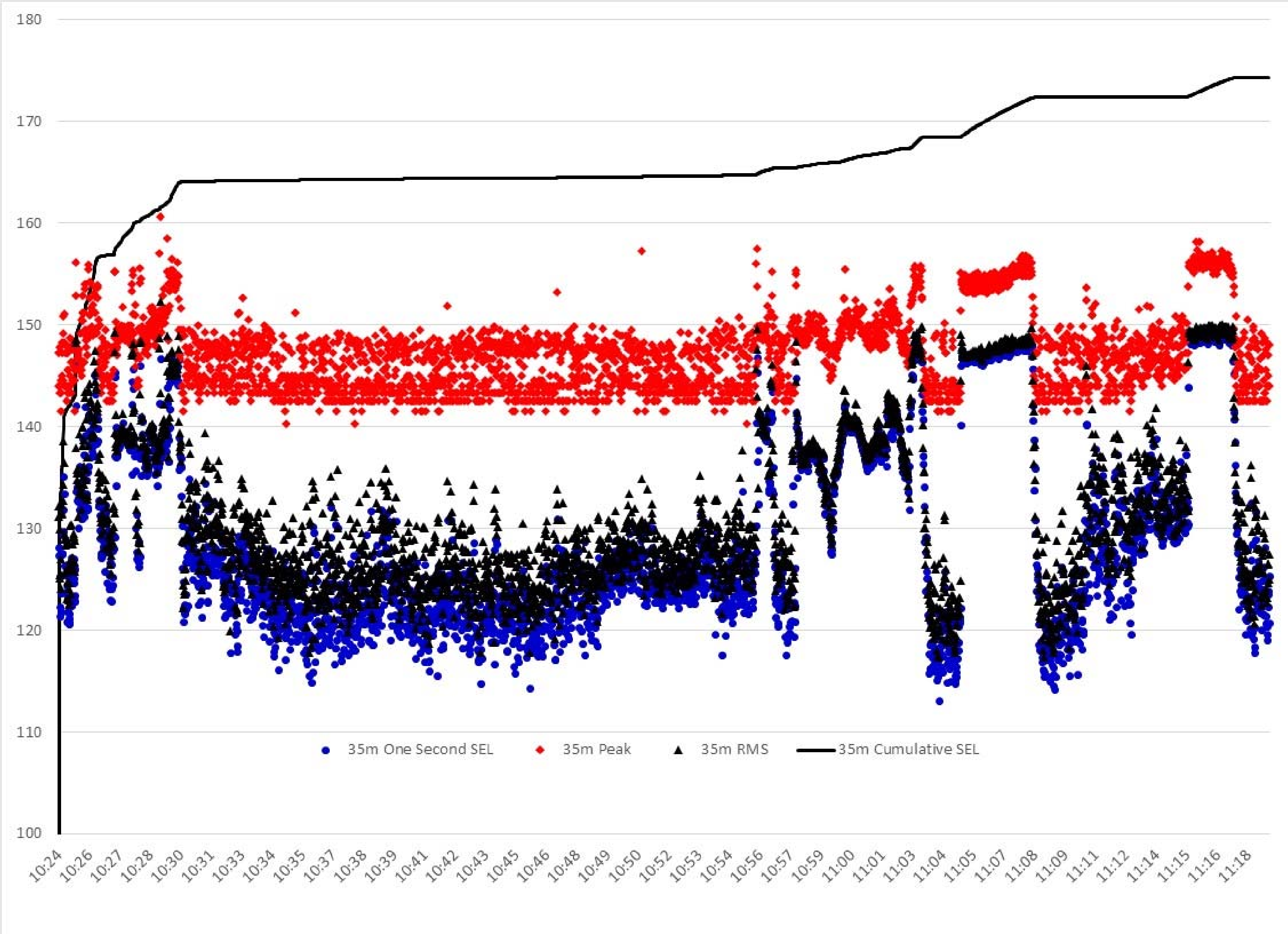

Figure A-23. Underwater Noise Recorded at 35 Meters (115 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-11, 31 October 2017

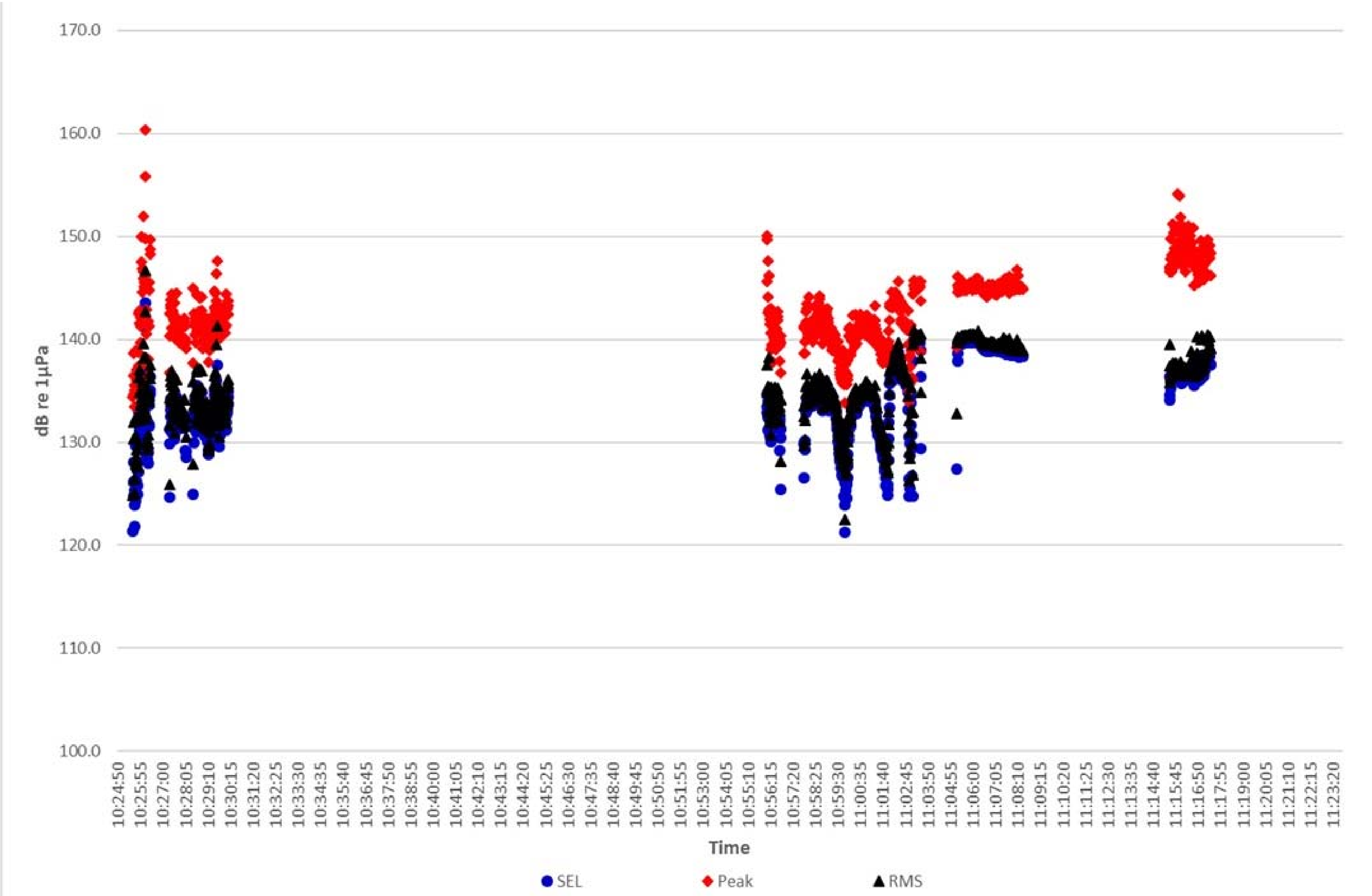

Figure A-24. Underwater Noise Recorded at 100 Meters (328 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-11, 31 October 2017

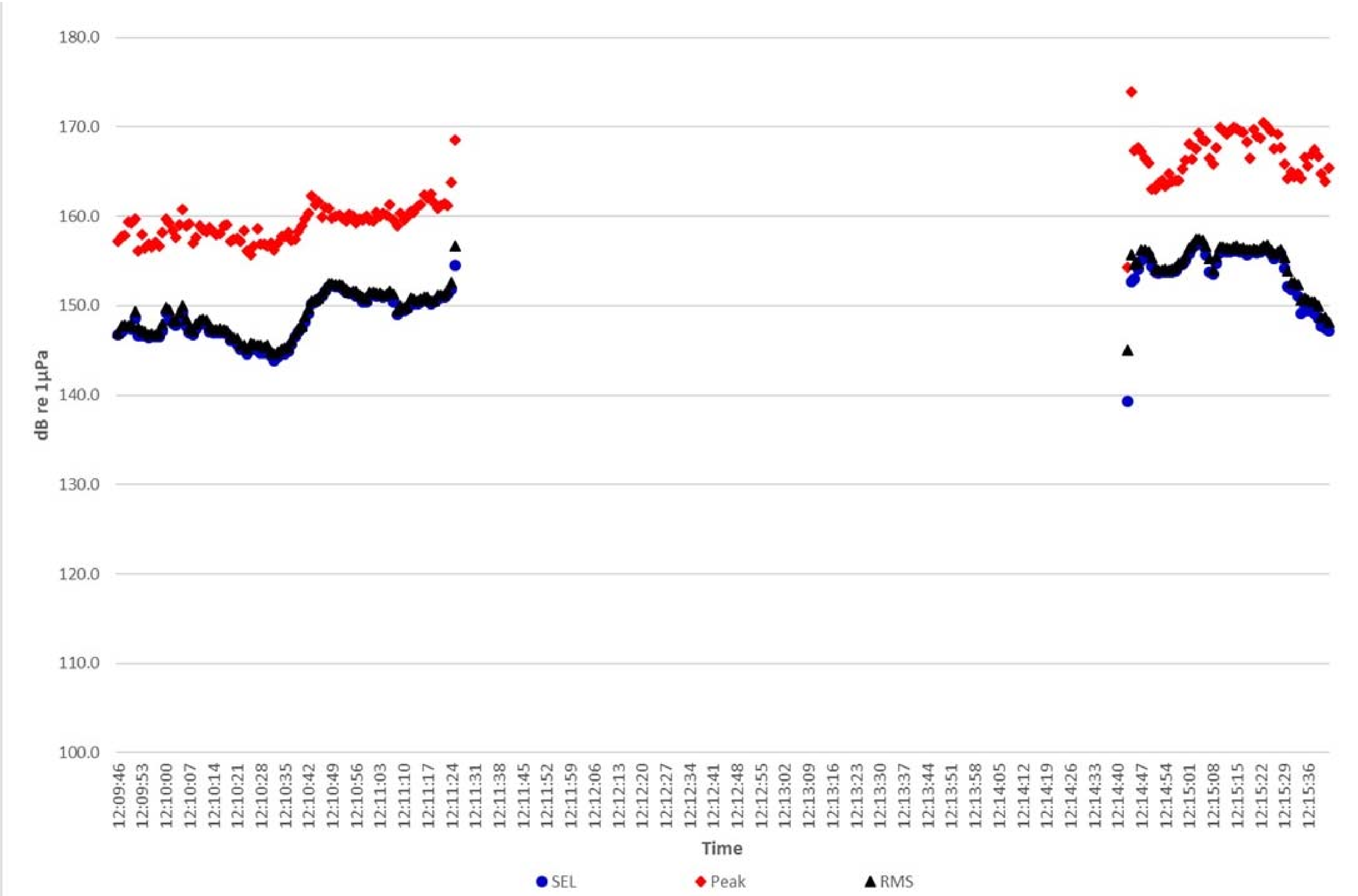

Figure A-25. Underwater Noise Recorded at 12 Meters (39 Feet) Vibratory Driving 24-inch Steel Shell Pile C-8, 31 October 2017

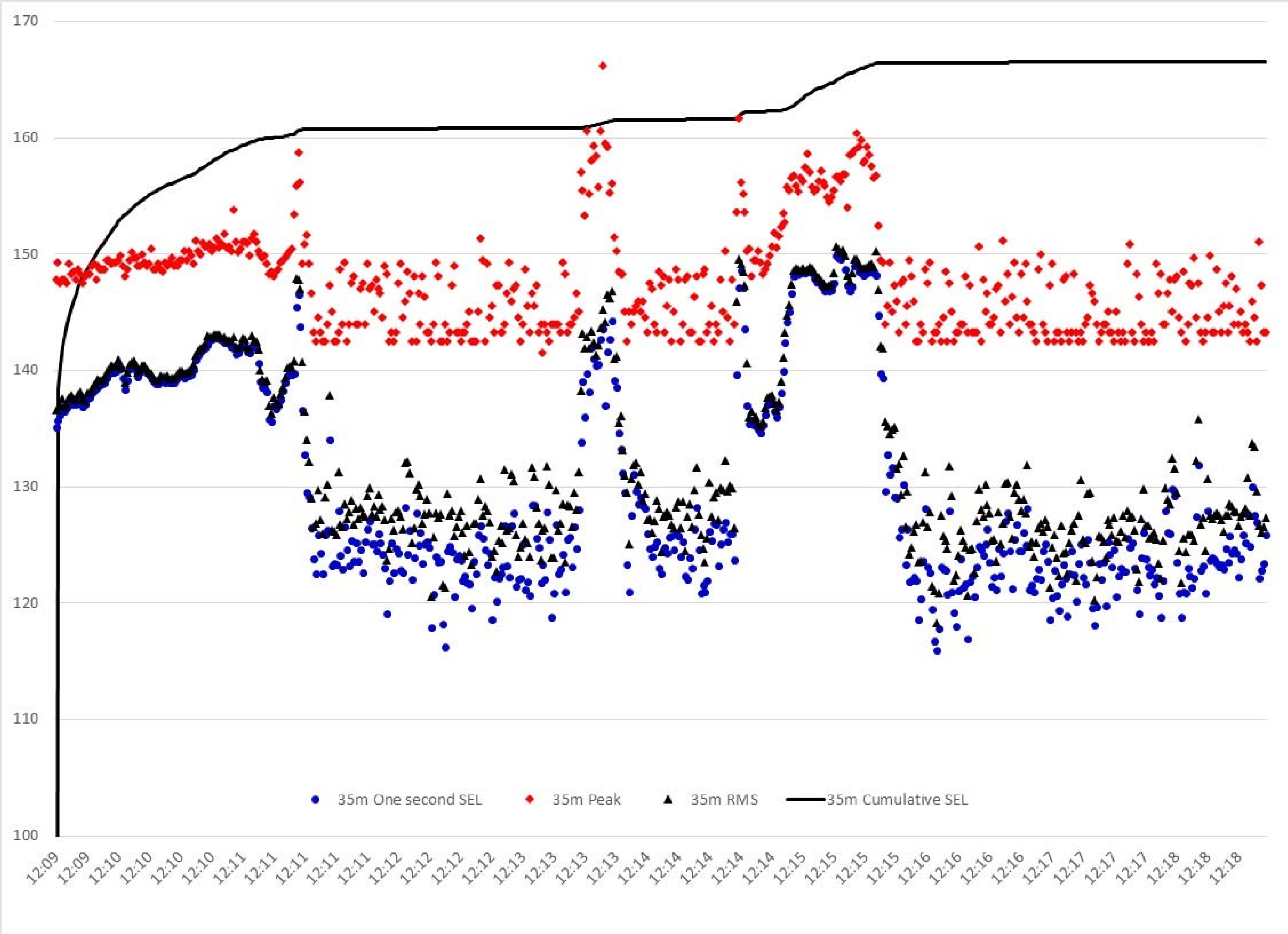

Figure A-26. Underwater Noise Recorded at 35 Meters (115 Feet) Vibratory Driving 24-inch Steel Shell Pile C-8, 31 October 2017

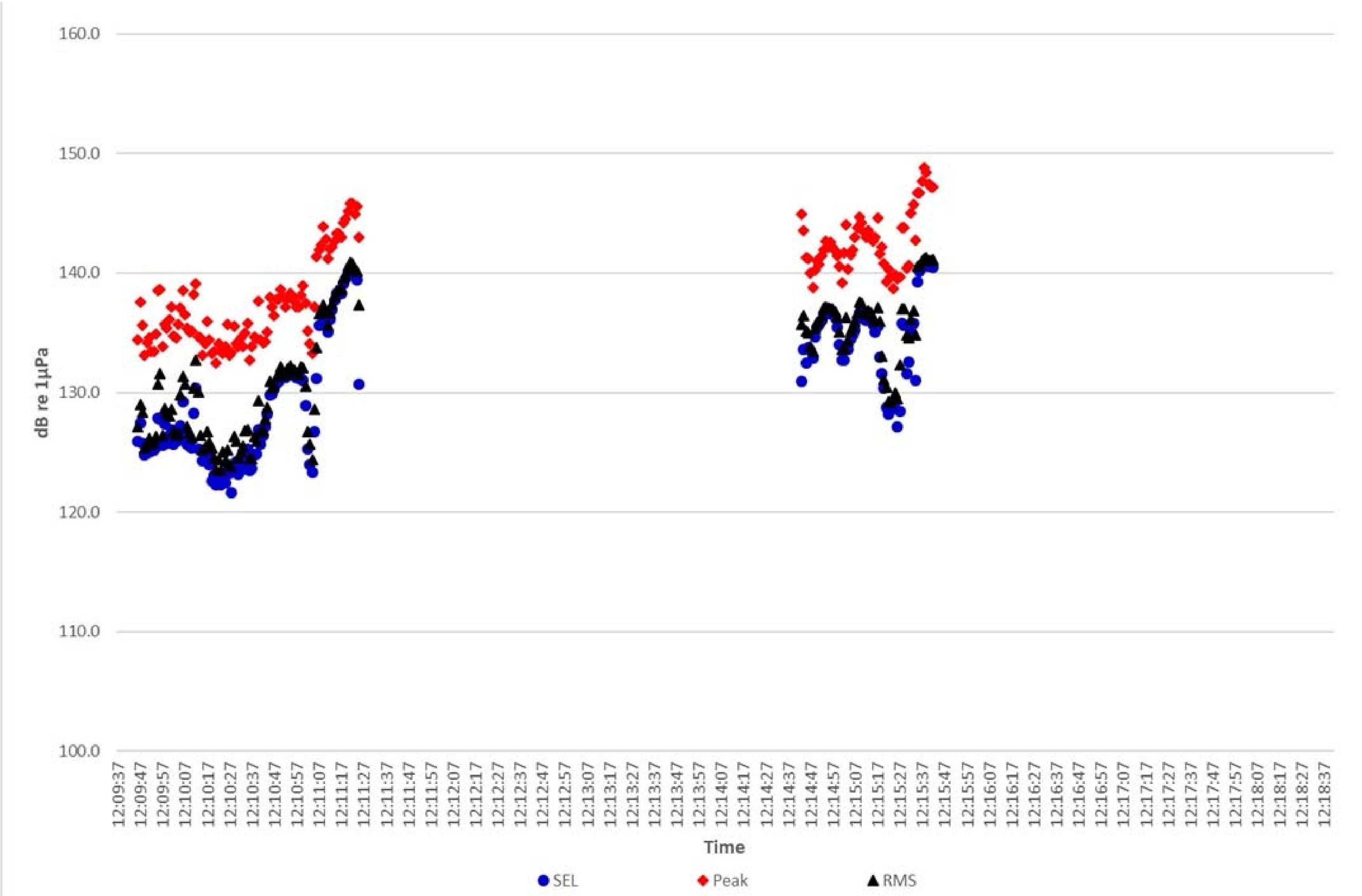

Figure A-27. Underwater Noise Recorded at 100 Meters (328 Feet) Vibratory Driving 24-inch Steel Shell Pile C-8, 31 October 2017

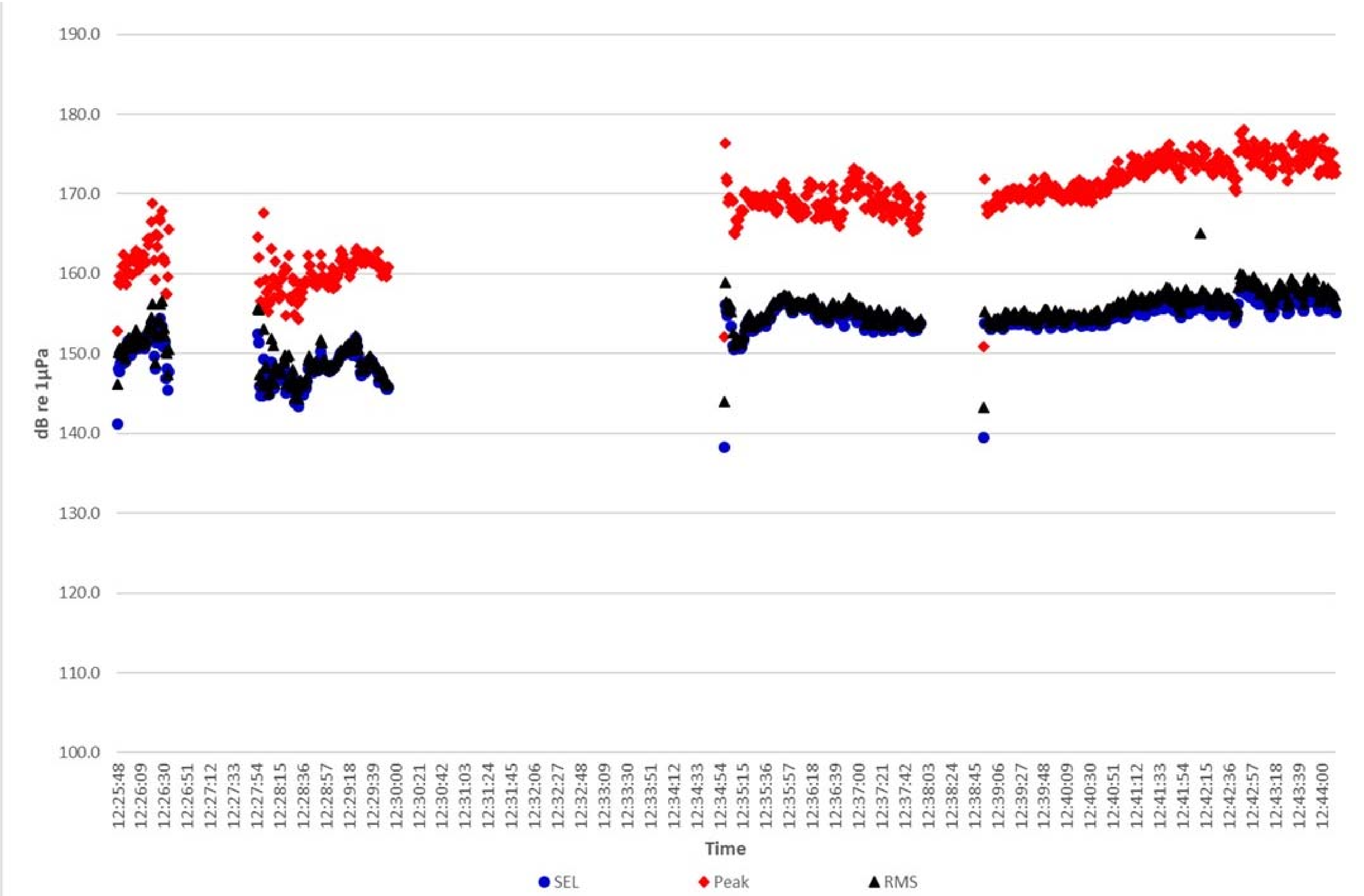

Figure A-28. Underwater Noise Recorded at 12 Meters (39 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-10, 31 October 2017

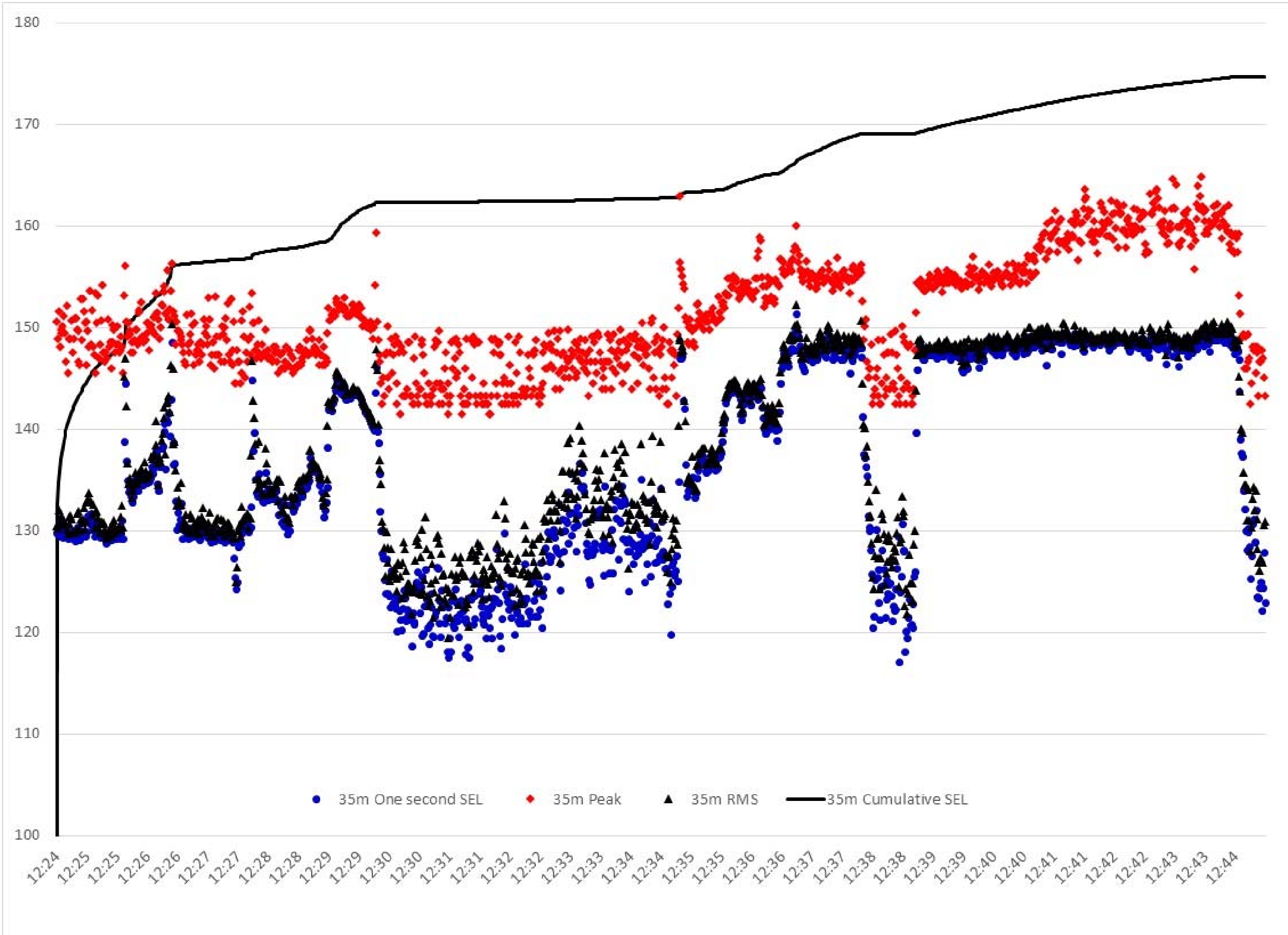

Figure A-29. Underwater Noise Recorded at 35 Meters (115 Feet) Vibratory Driving 24-inch Steel Shell Pile C1-10, 31 October 2017

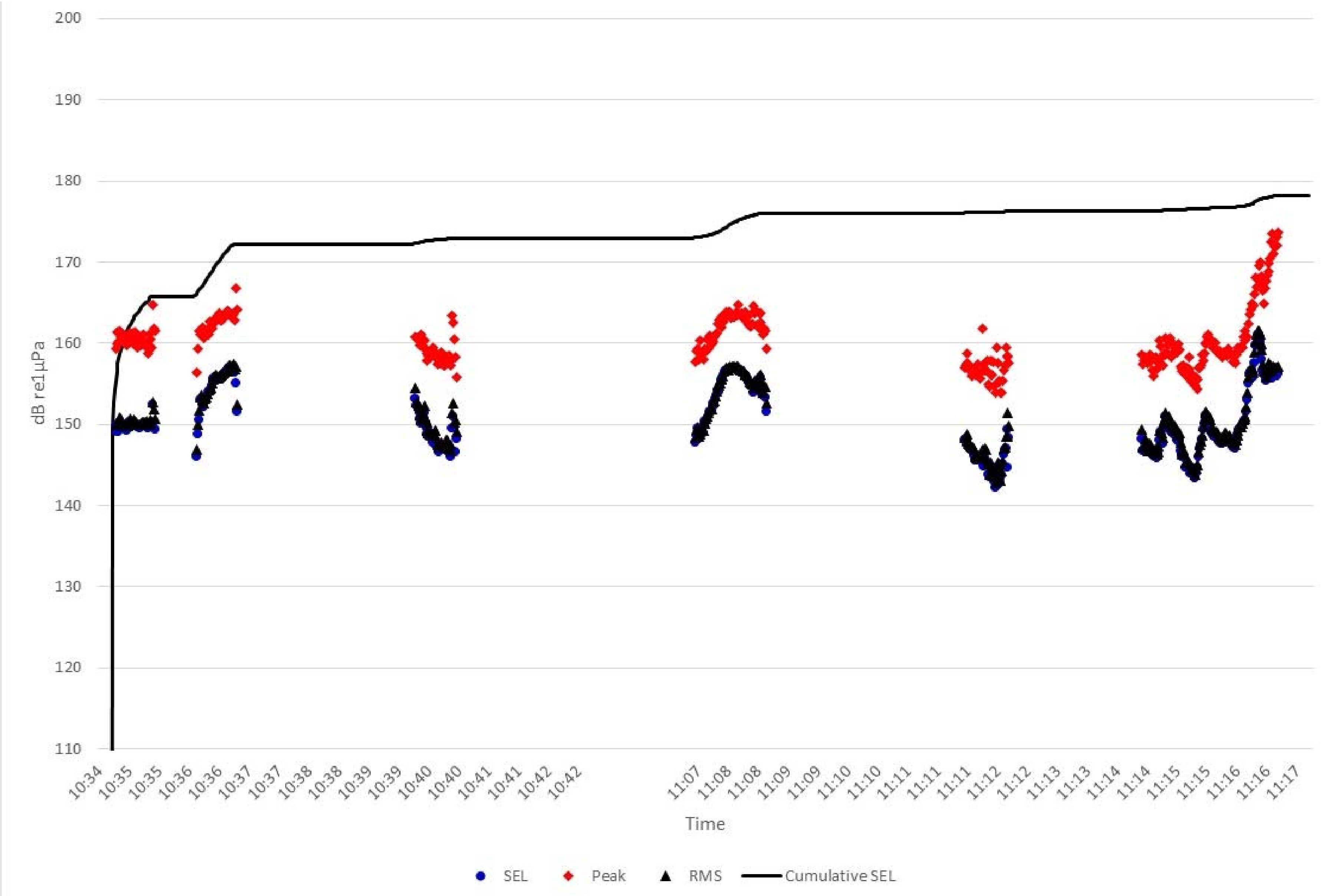

Figure A-30. Underwater Noise Recorded at 15 Meters (49 Feet) Vibratory Driving 24-inch Steel Shell Pile D-9, 7 November 2017

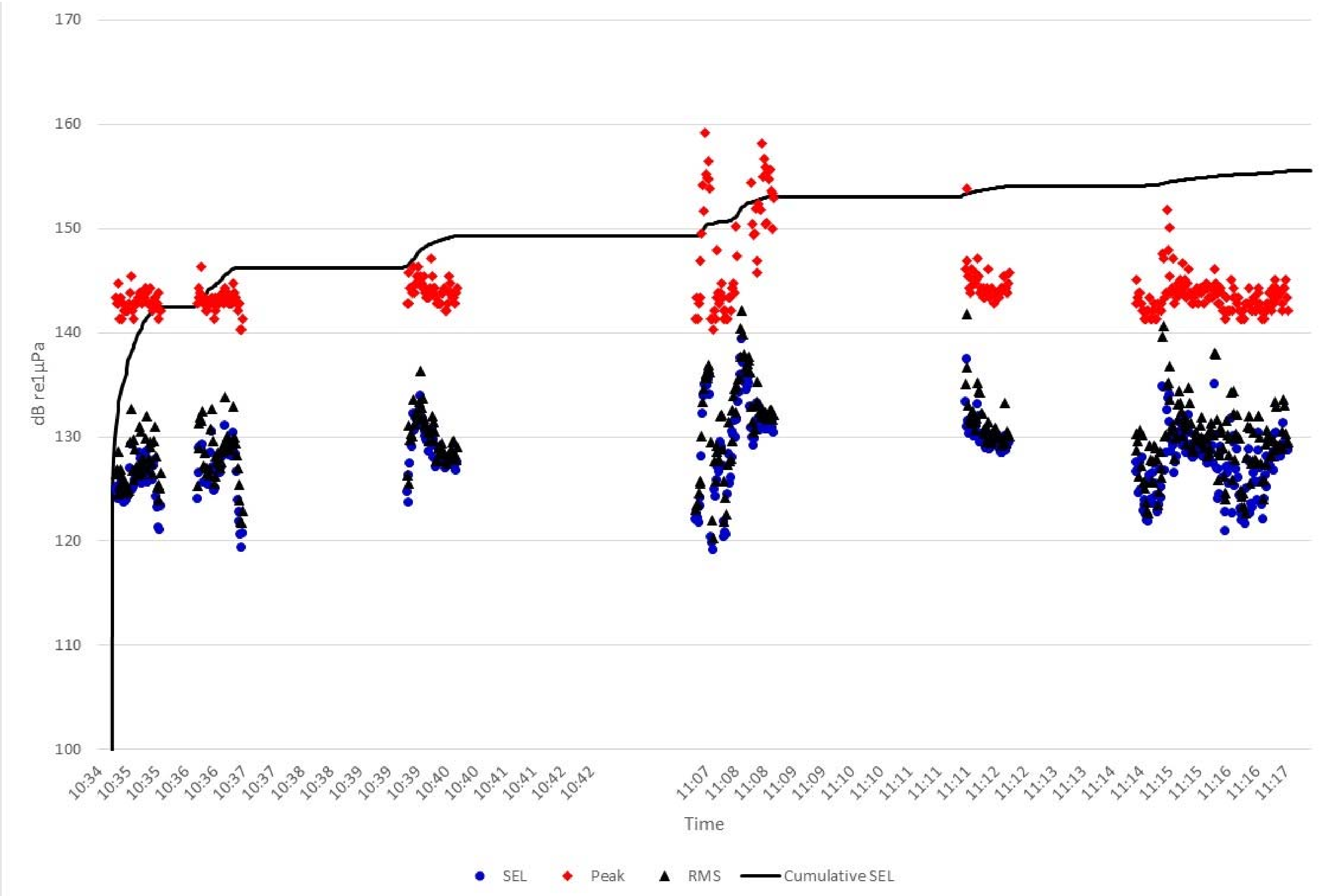

Figure A-31. Underwater Noise Recorded at 89 Meters (292 Feet) Vibratory Driving 24-inch Steel Shell Pile D-9, 7 November 2017

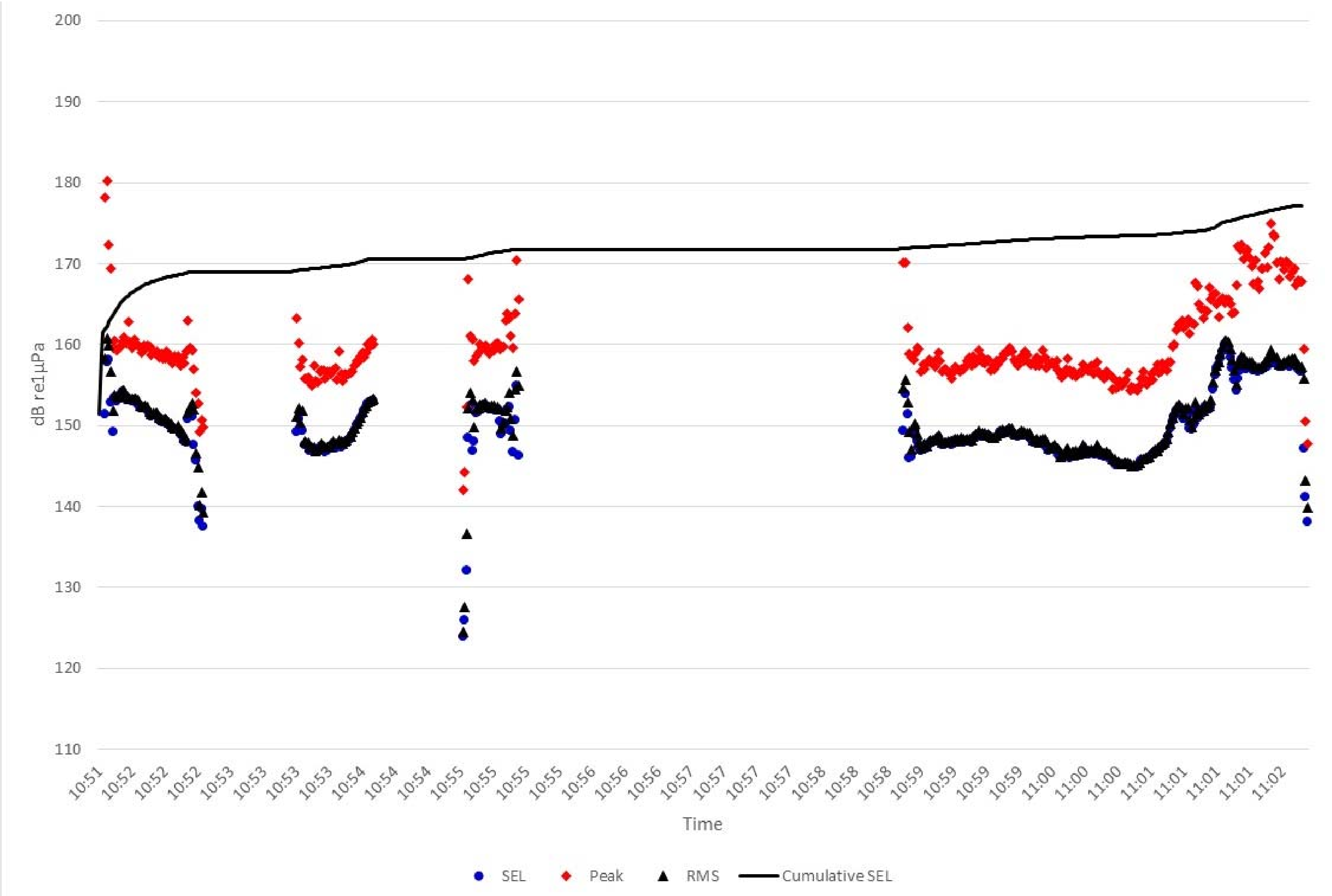

Figure A-32. Underwater Noise Recorded at 15 Meters (49 Feet) Vibratory Driving 24-inch Steel Shell Pile D-8, 7 November 2017

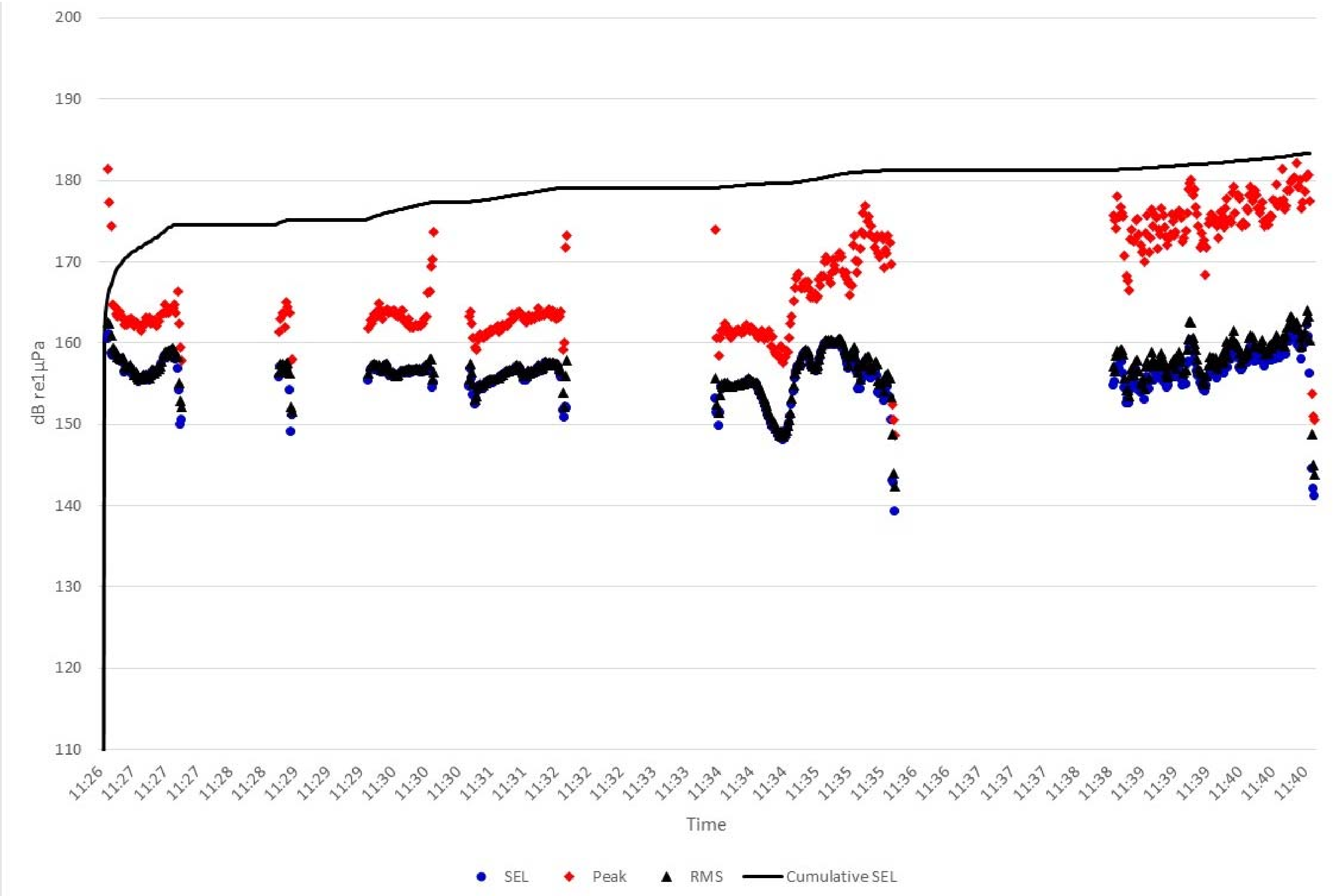

Figure A-33. Underwater Noise Recorded at 89 Meters (292 Feet) Vibratory Driving 24-inch Steel Shell Pile D-10, 7 November 2017

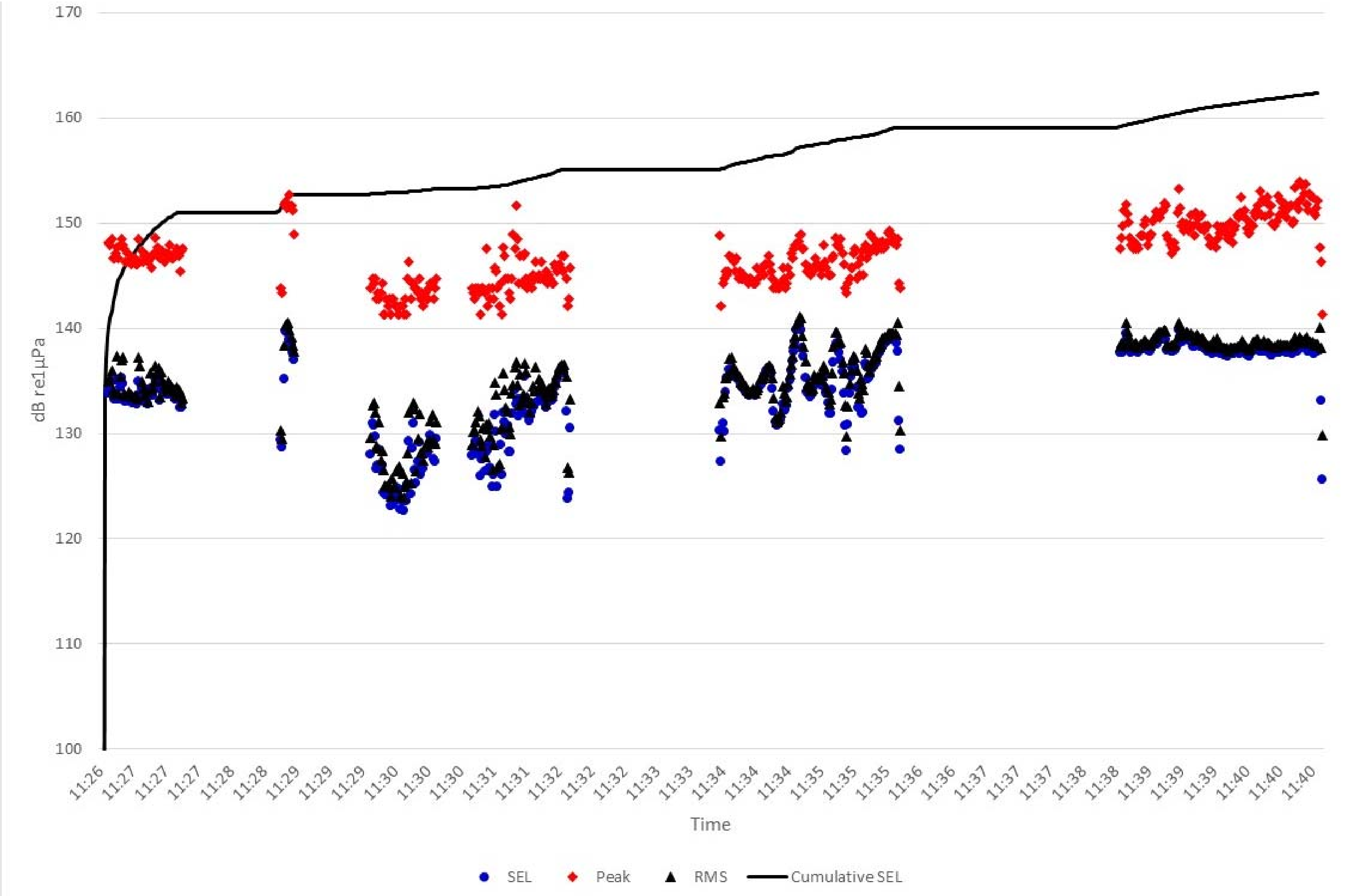

Figure A-34. Underwater Noise Recorded at 15 Meters (49 Feet) Vibratory Driving24-inch Steel Shell Pile D-10, 7 November 2017

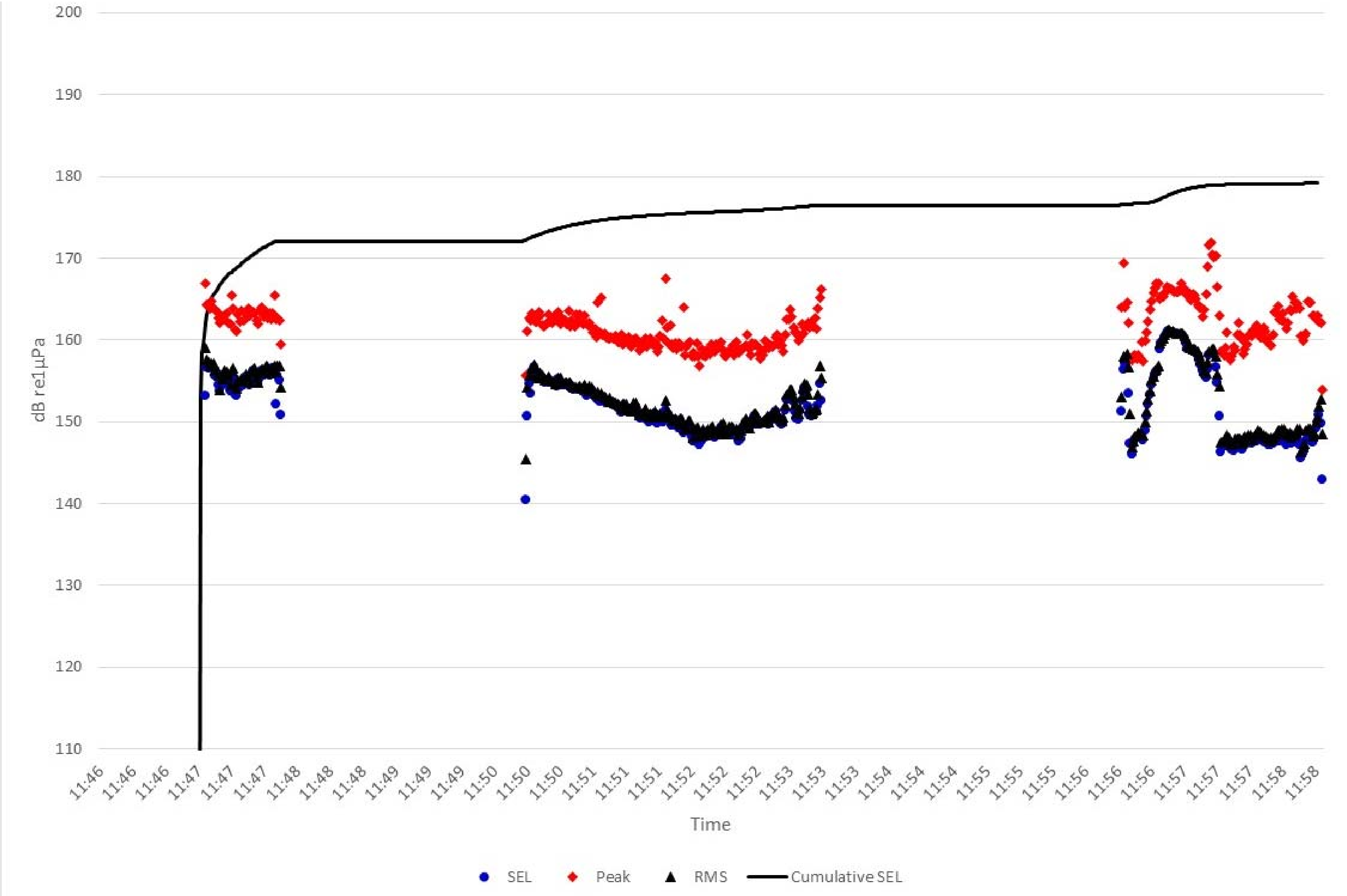

Figure A-35. Underwater Noise Recorded at 89 Meters (292 Feet) Vibratory Driving 24-inch Steel Shell Pile D-11, 7 November 2017

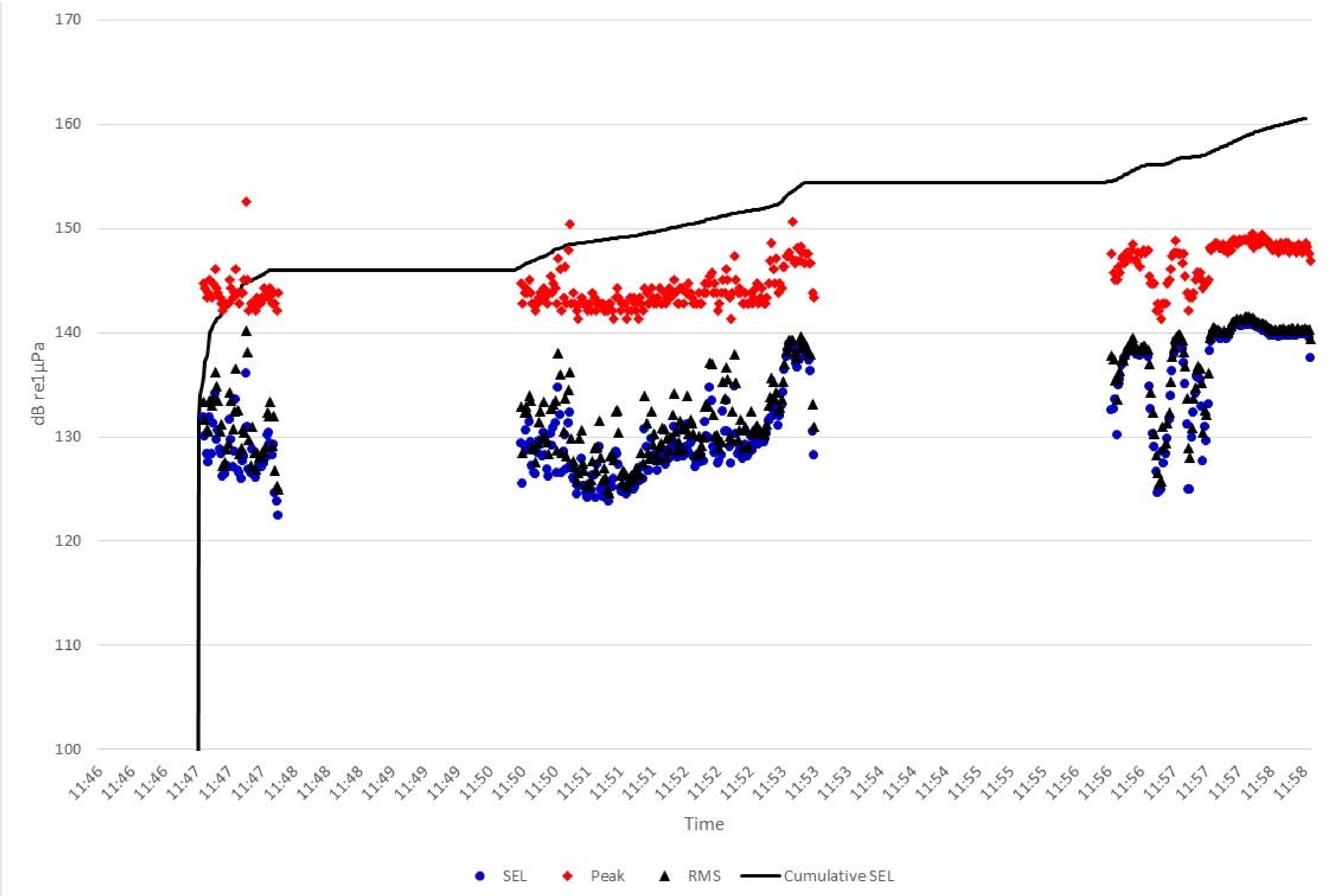

Figure A-36. Underwater Noise Recorded at 89 Meters (292 Feet) Vibratory Driving 24-inch Steel Shell Pile D-11, 7 November 2017

B

1/3 Octave Band Spectrum Data

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Figure B-1. 1/3 Octave Band Spectra for Installation of 24-inch Steel Shell Pile at 15 meters (49 Feet) 09 October 2107.

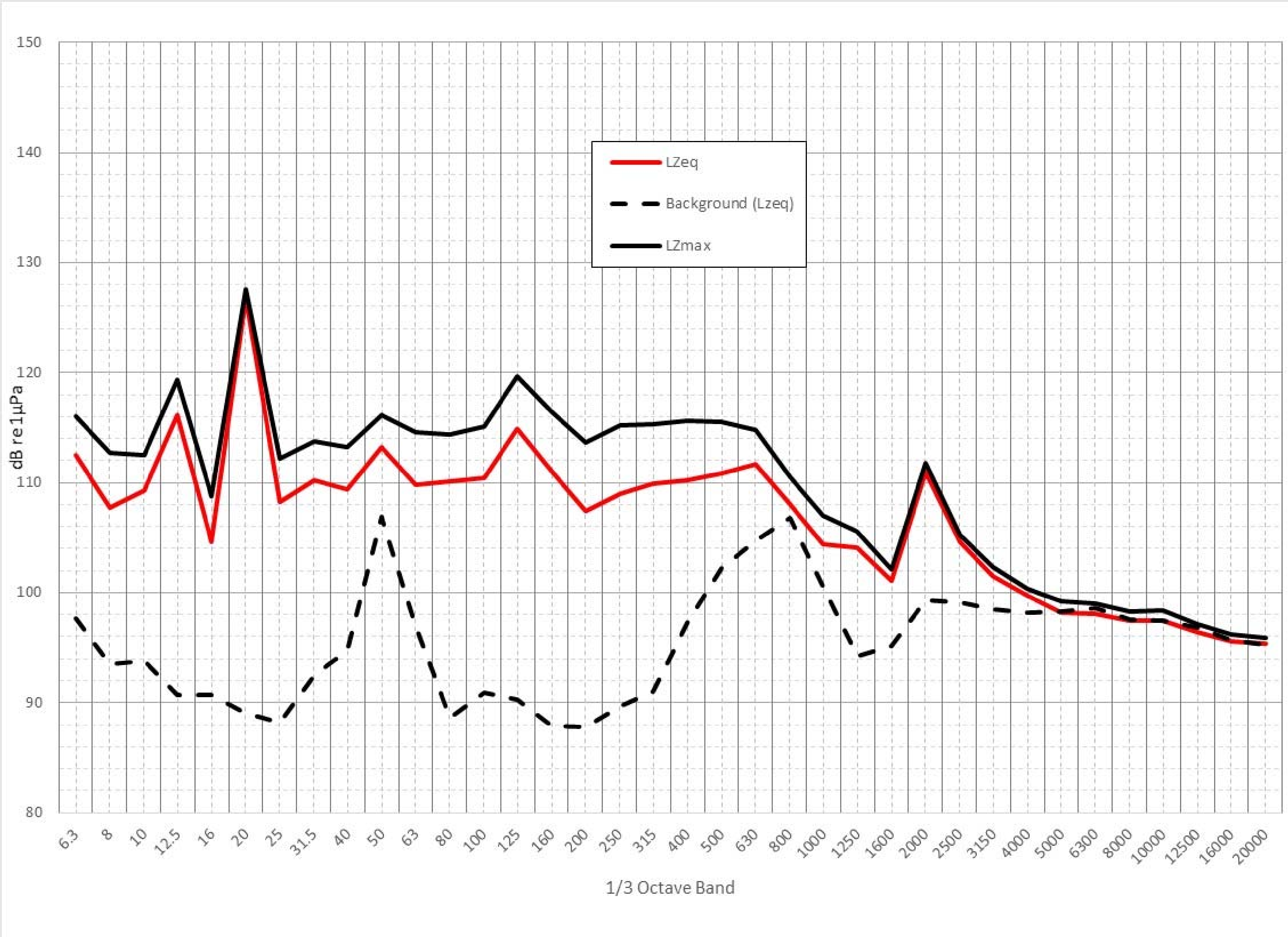

Figure B-2. 1/3 Octave Band Spectra for Installation of 24-inch Steel Shell Pile at 89 meters (292 Feet).

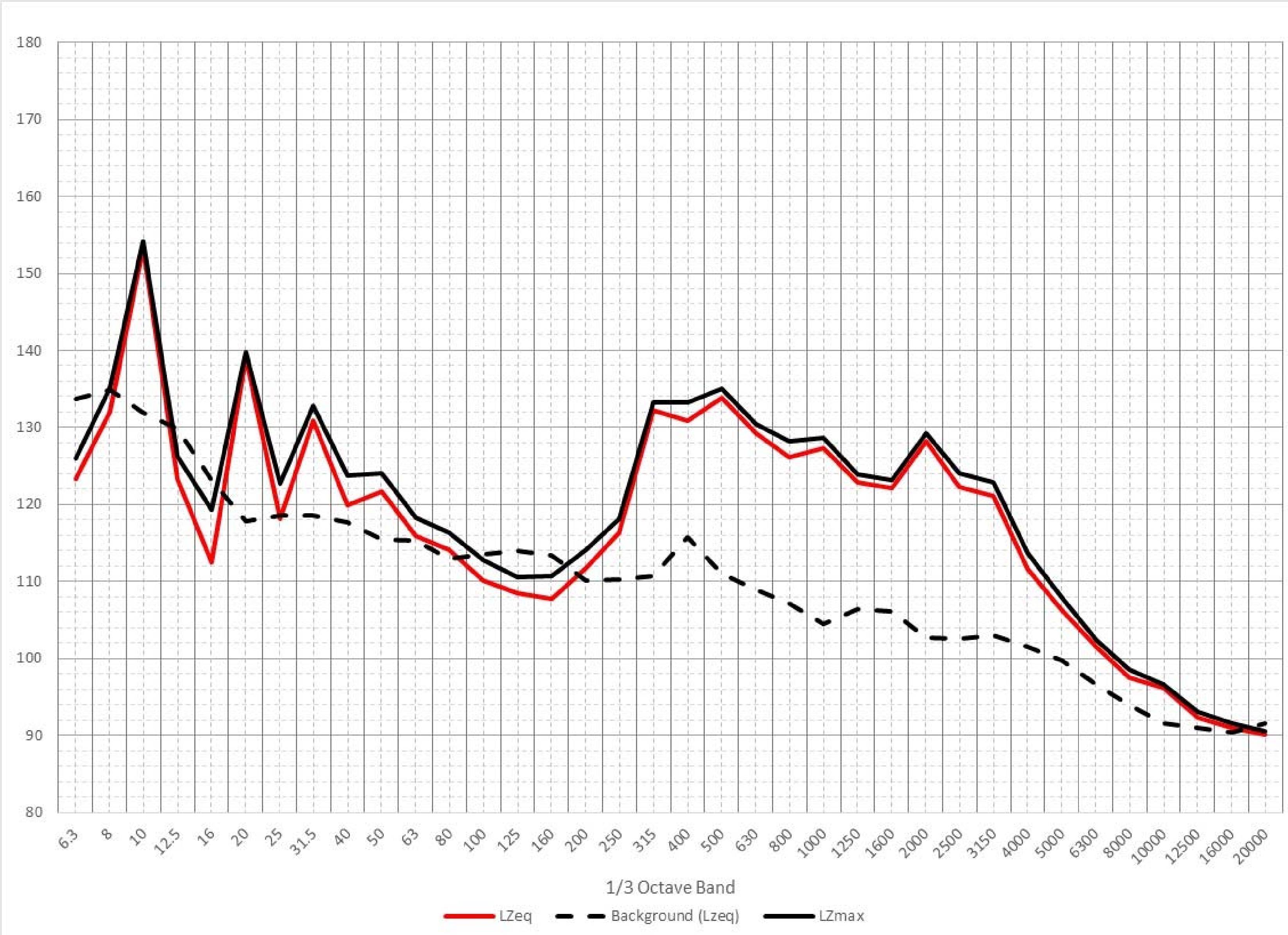

Figure B-3. Typical 1/3 Octave band for Installation of 30-inch Steel Shell Piles at 10 meters (33 Feet).

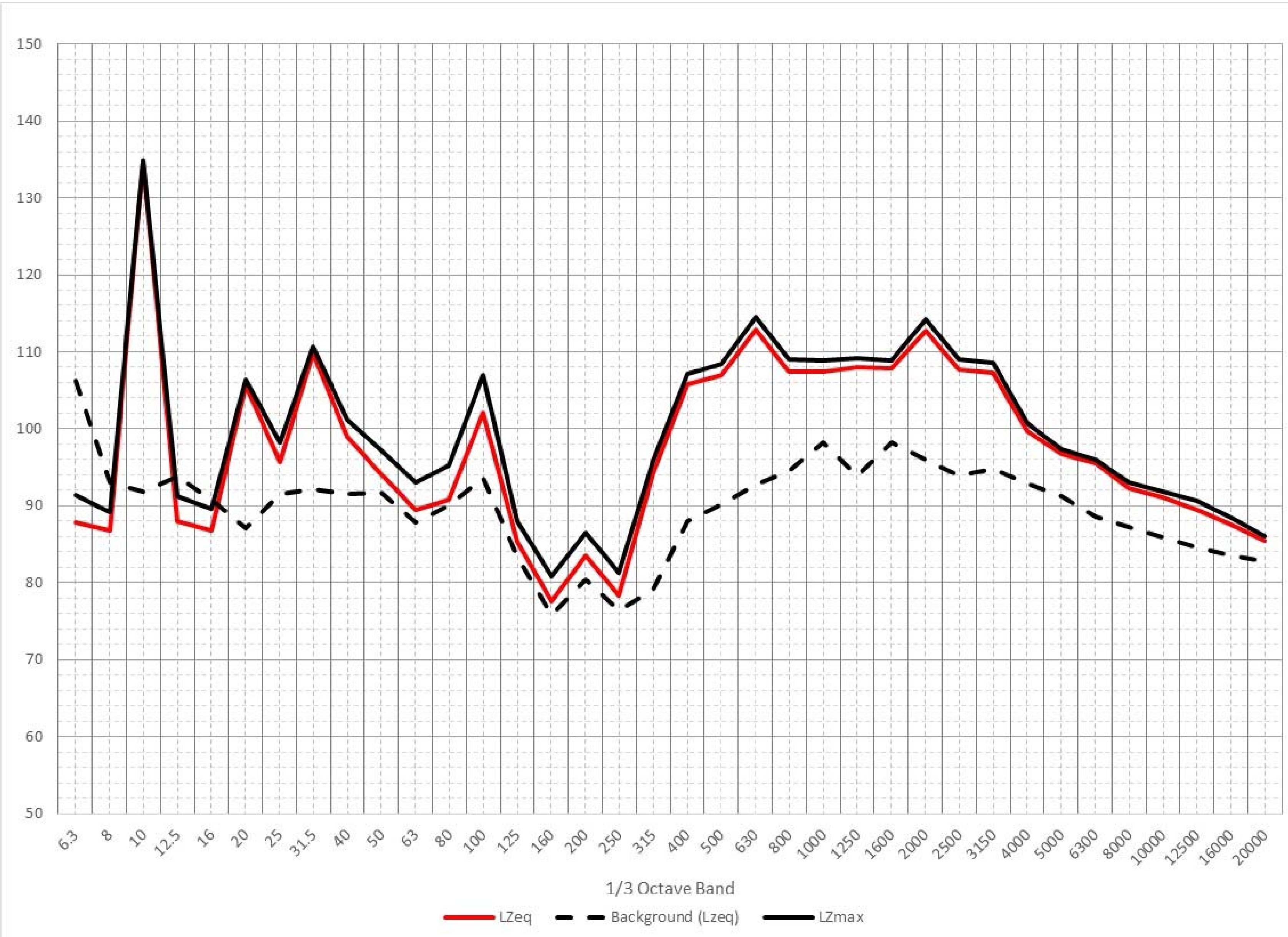

Figure B-4. Typical 1/3 Octave band for Installation of 30-inch Steel Shell Piles at 50 Meters (164 Feet).

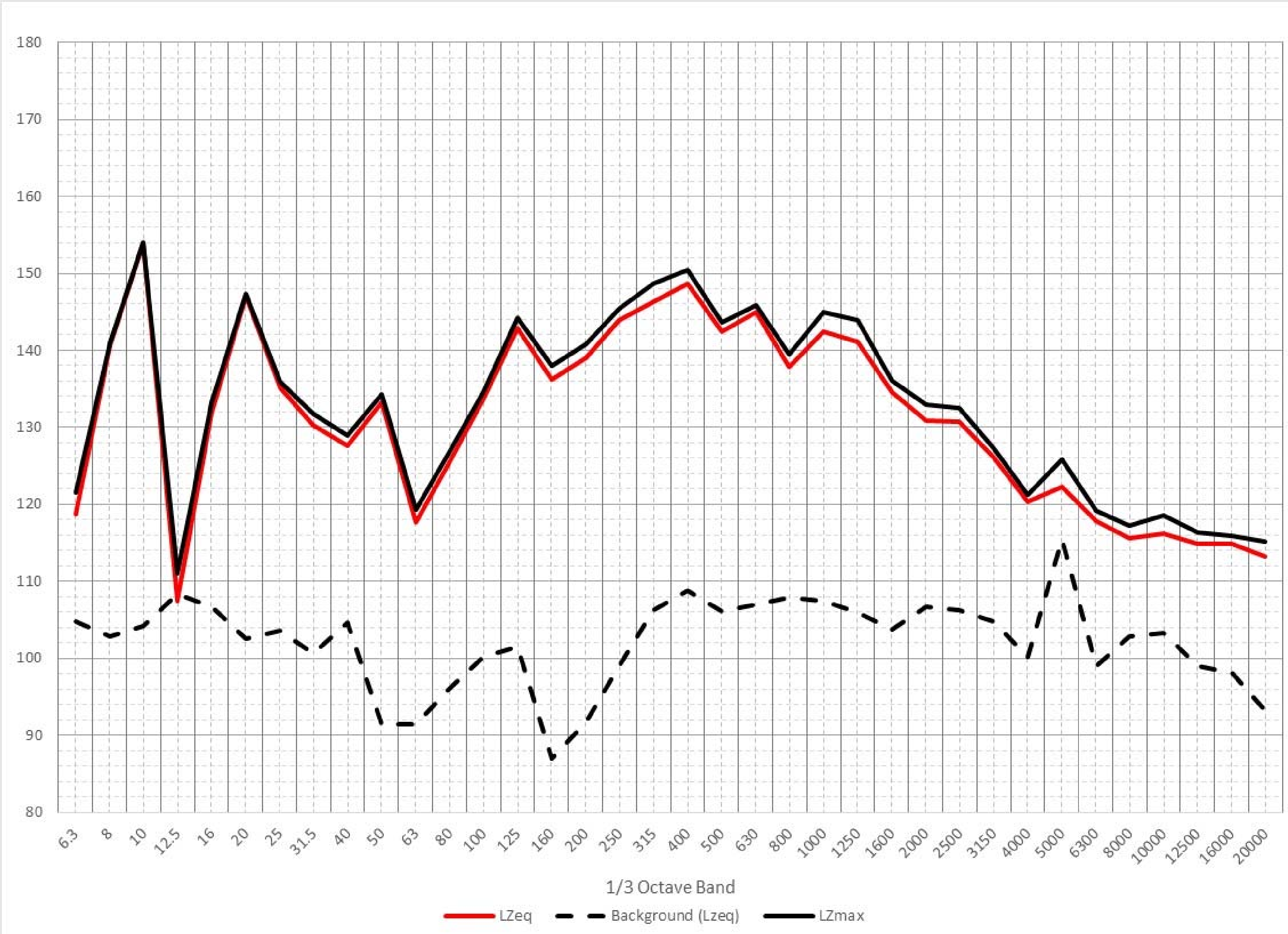

Figure B-5. Typical 1/3 Octave band for Installation of 36-inch Steel Shell Piles at 10 Meters (33 Feet).

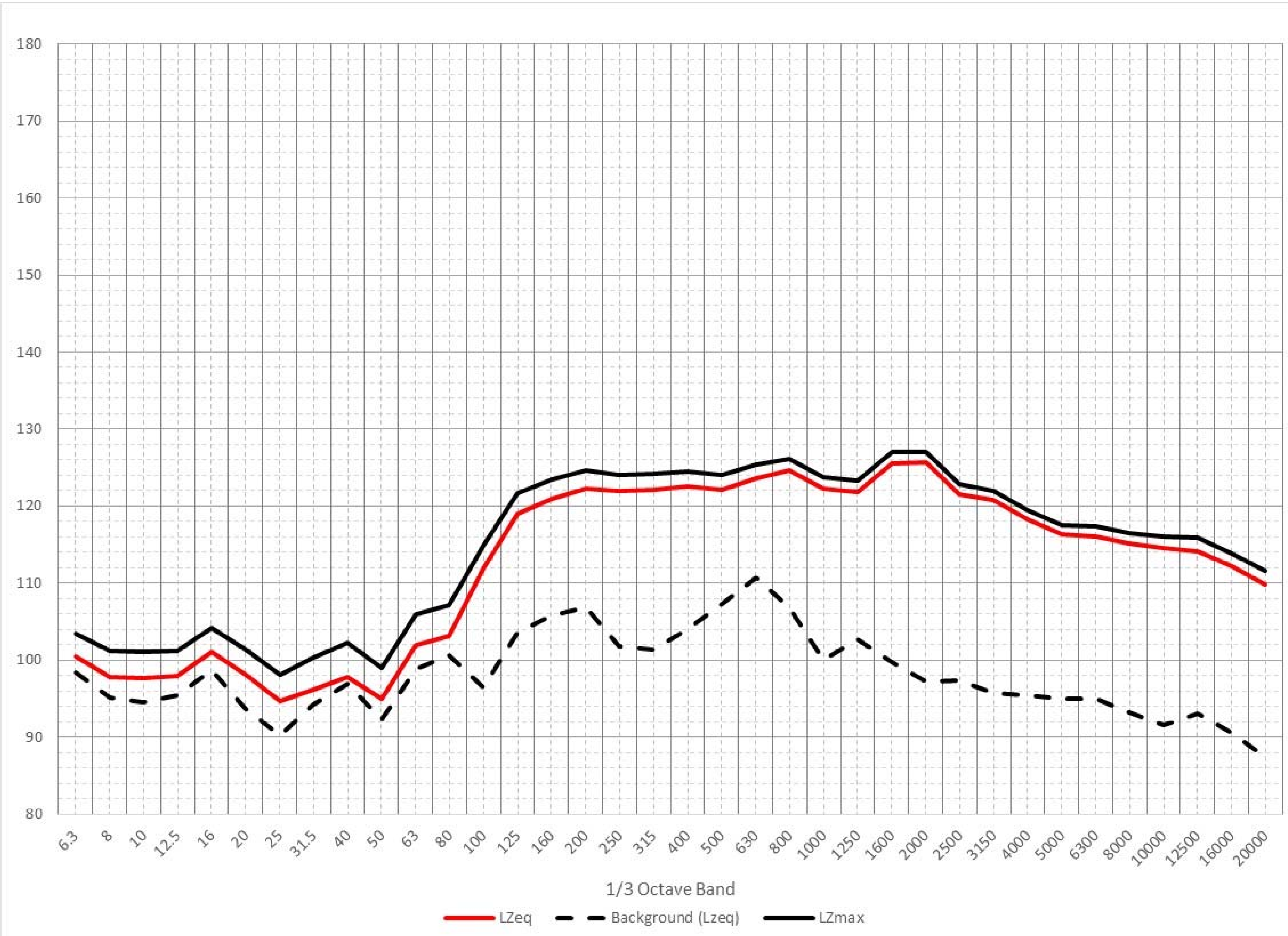

Figure B-6. Typical 1/3 Octave band for Installation of 30-inch Steel Shell Piles at 120 Meters (394 Feet).