Sound Source Characterization of Down-the-Hole Hammering

Thimble Shoal, Virginia

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1. Introduction

JASCO Applied Sciences (JASCO), an ISO 9001 certified company, was contracted by the Chesapeake Tunnel Joint Venture (CTJV) to perform acoustic measurements at Thimble Shoal along the Chesapeake Bay Bridge Tunnel in Virginia, USA (Figure 1). DTH hammering is a new technology being used to create casings for dock pile installation (pile locations shown in Figure 2 and inset in Figure 1). The aim of the measurements is to determine the underwater sound levels produced during DTH hammering.

Figure 1. location of project. Inset shows pile locations drawn in Figure 2

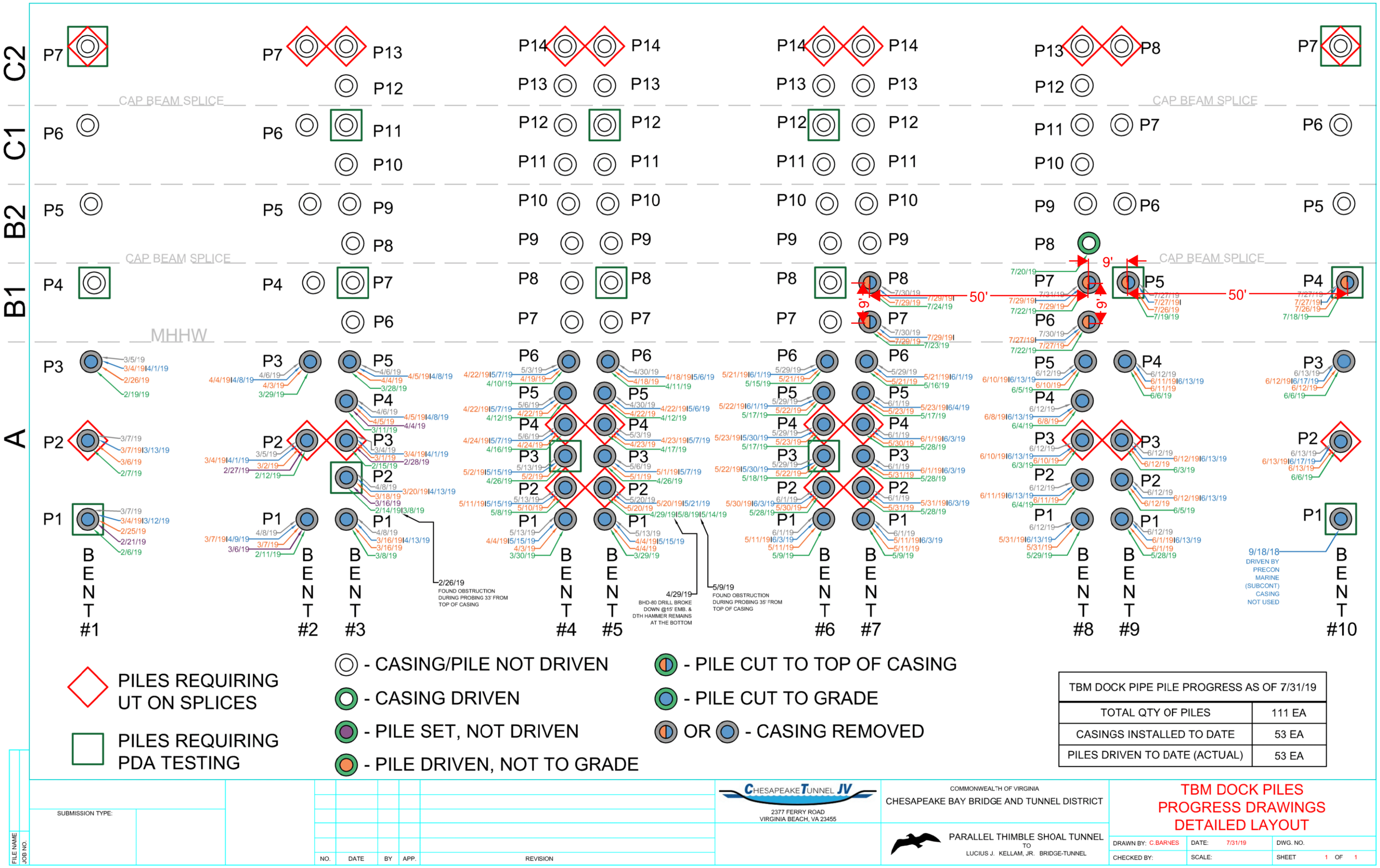

Figure 2. drawing of pile locations

2. Methods

The CTJV submitted an Incidental Harassment Authorization (IHA) application for their proposed Parallel Thimble Shoal Tunnel Project. As part of the IHA approval, an Underwater Noise Monitoring Plan [based on previously published “Noise measurements at bridge drilling site” (Imatra, Finland report (04.05.119)] was included that requires measurements to determine whether the predicted level of 166 dB re 1µPa at 10 m (the median value measured for rock drilling at 10m; Denes et al. 2016) is an acceptable estimate of the sound levels produced by DTH hammering. The current measurement program was designed to determine sound levels produced during DTH hammering through rock at Thimble Shoal, local sound propagation from the DTH hammering, and ambient sound levels (when DTH is not employed).

2.1. Measured Sound Sources

Underwater sound levels were measured during DTH hammering at five pile locations – 3 without bubble curtain attenuation and 2 with bubble curtain attenuation. The locations of the piles are listed in Table 1.

Table 1. Locations of measured piles.

Attenuation	Pile	Latitude	Longitude
No bubble curtain	C10P4	36.96597207	-76.11329579
	C9P5	36.96584035	-76.11334419
	C8P6	36.96580965	-76.11332336
With bubble curtain	C8P7	36.96581664	-76.11335290
	C8P8	36.96582363	-76.11338245

2.2. Data Collection

2.2.1. Acoustic recorders

Underwater sound was recorded on three, fixed-location, Autonomous Multichannel Acoustic Recorders (AMARs, JASCO; Figure 3 Bottom). Each AMAR was fitted with two M8 omnidirectional hydrophones (GeoSpectrum Technologies Inc.), one hydrophone was low-sensitivity (-195 ± 3 dB re 1 V/µPa) to record high-level sounds during DTH near the source and one was higher sensitivity (-165 ± 3 dB re 1 V/µPa) to record lower levels sounds, including ambient levels. The AMARs recorded continuously at 64 000 samples per second for a recording bandwidth of 10 Hz to 32 kHz. The recording channels had 24-bit resolution with a spectral noise floor of ~20 dB re 1 µPa^2/Hz, and a nominal ceiling level of 201 dB re 1 µPa and 171 dB re 1 µPa, for the low and high sensitivity hydrophones respectively. Acoustic data were stored on 1TB of internal solid-state flash memory. As configured, the recorders were capable of continuously recording for >4 weeks.

The recording systems were calibrated using NIST-traceable GRAS 42AC pistonphone calibrators to verify the sensitivity of the recording system as a whole (i.e., the hydrophone, pre-amplifier, and AMAR). Calibration is performed in JASCO’s warehouse lab prior to shipment and upon receipt after project completion. Calibration measurements are also performed before and after each usage in the field. The sensitivity of the system is measured independently of the software that performs the data analysis, which

allows an independent calibration of the analysis software. Field calibration measurements are referenced to the established calibration measurements performed in the warehouse. Post-retrieval calibration measurements are used to verification that no loss of sensitivity occurred during the course of deployment and measurement.

2.2.2. Moorings

Due to high currents near Thimble Shoal, a low-profile, high-flow mooring system was used (Figure 3). These hydrodynamically-shaped instrument moorings reduce flow-induced noise and are ideal for measurements in tidal zones. The moorings are constructed of ¼ inch steel plate with ¼ inch neoprene rubber cover. The moorings are 55.6 × 32.2 × 15.8 in (L x W x H), weigh 472 lbs in air with an AMAR recorder and battery pack (388 lbs in water).

Figure 3. Photos of mooring for proposed sound level measurements of DTH hammering. Top: high-flow mooring. Bottom: high-flow mooring with cover removed to show two AMAR recorders within the mooring.

2.2.3. Deployment locations

AMARs were deployed at three locations (Table 2 and Figure 4) on 26 June 2019 and retrieved on 29 July 2019. Locations were chosen to provide a near field recording at ~10 m from DTH hammering (Station 1), and far field measurements at ~35 m (Station 2) and ~100 m (Station 3).

Table 2. Location and depth of the AMARs deployed for DTH hammering monitoring.

Station	AMAR #	Lat	Long
1	289	36.96591667	-76.11336667
2	294	36.96596667	-76.11361667
3	286	36.96605000	-76.11406667

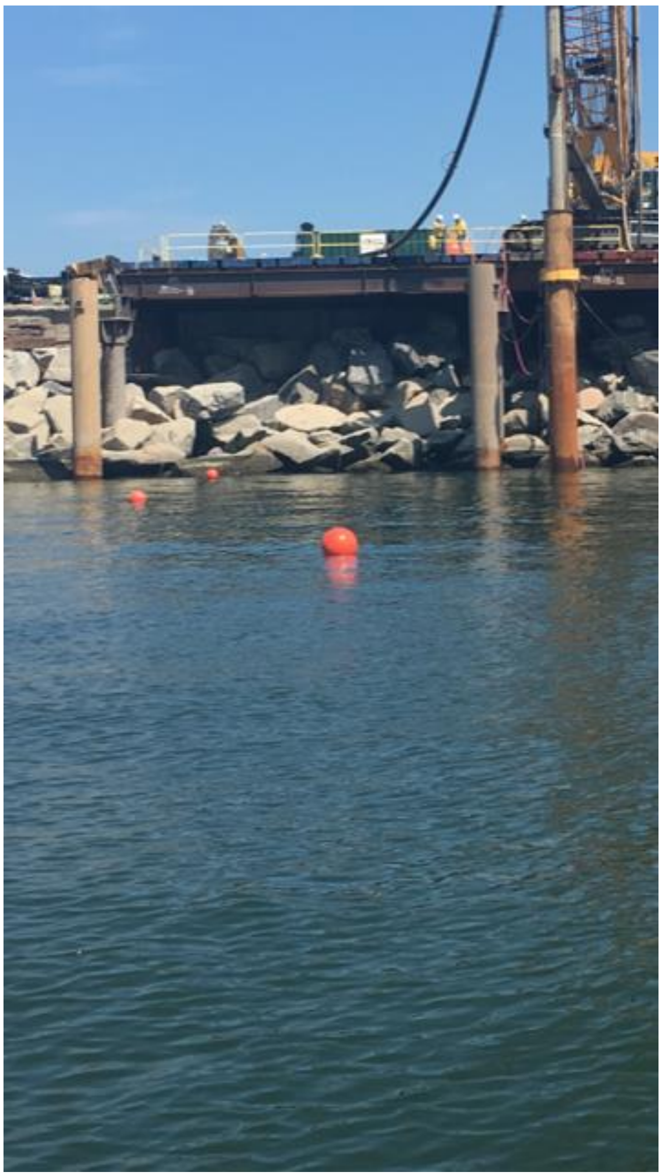

Figure 4. Photo of recorder locations

2.2.4. Sound level compared to range

To estimate the distance to thresholds, the 90% SPL, SEL, and PK levels as a function of range were fit with the following empirical propagation loss equation:

$$90\% \text{ rms SPL} = \text{ESL} - A \log_{10} R \quad (1)$$

where R is the slant range from the source to the acoustic recorder (m), ESL is the effective source level (dB re 1 µPa or dB re 1 µPa²·s), and A is the geometric spreading loss coefficient (dB).

3. Results

3.1. Ambient Sound Levels

Broadband (10 Hz – 31.5 kHz) and decidecade band levels were analyzed in 30-minute intervals from 28 June through 15 July for recordings from Station 3. Sound levels include anthropogenic sources (e.g., vessel noise and possible noise from automotive traffic on the bridge), as well as natural (e.g., wind and rain) and biological noise (e.g., animal vocalization) during the period of analysis. The median SPL for this period was 122.78 dB re 1 µPa, with a maximum level of 155.43 dB. 90% of the time, the SPL was below 130.32 dB (Table 3; Figure 5). Band levels below 31.5 Hz were the largest contributors to the SPL (Figure 6).

Table 3. Broadband ambient sound pressure levels from 28 June through 15 July.

	Minimum	10%	25%	Median	75%	90%	Maximum
SPL (dB re 1 µPa)	113.29	117.90	120.04	122.78	127.13	130.32	155.43

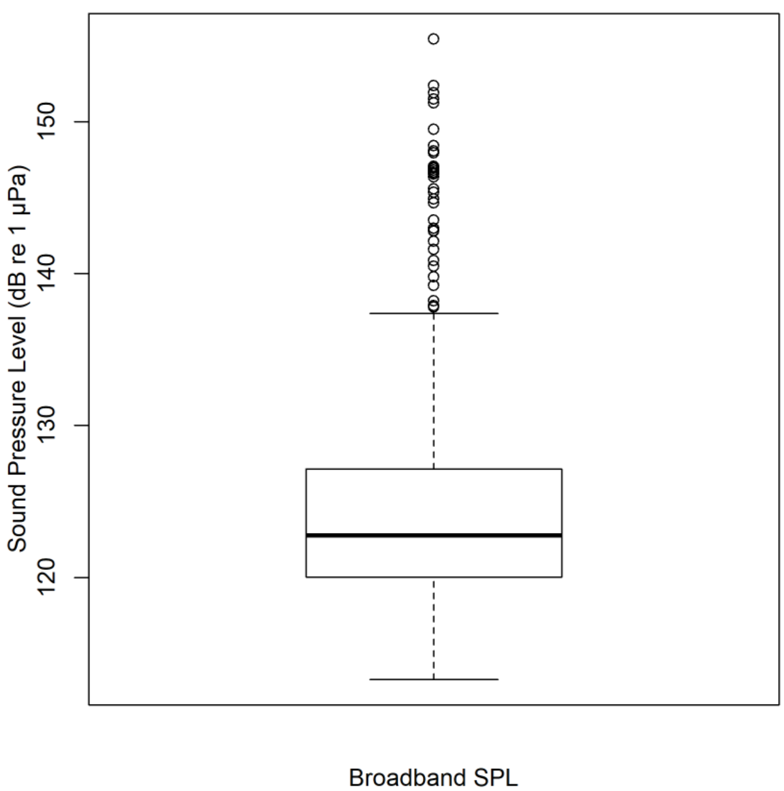

Figure 5. Distribution of ambient broadband SPL (dB re 1 µPa).

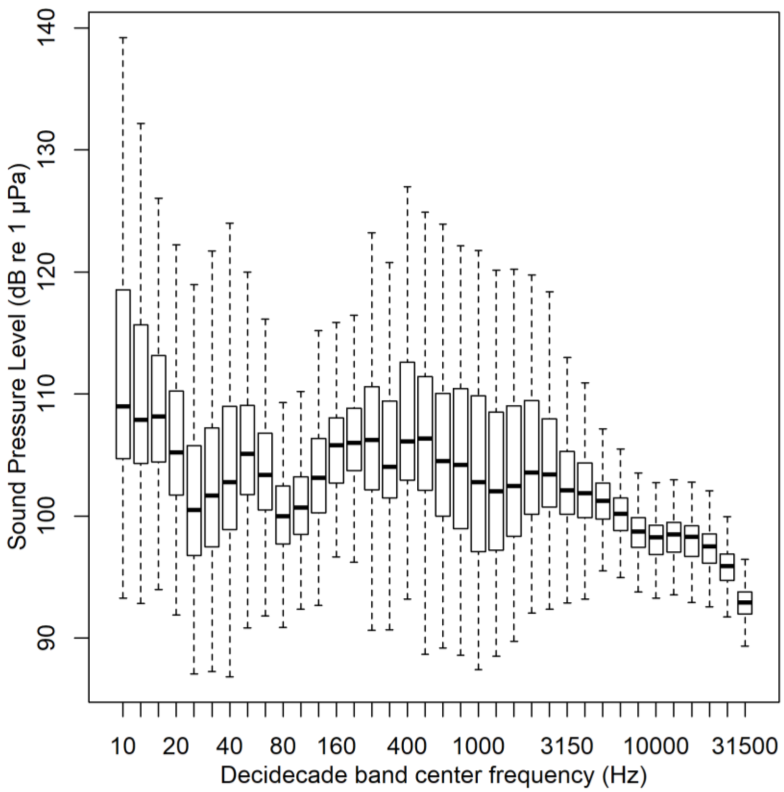

Figure 6. Distribution of ambient decidecade band levels from 10 Hz to 31.5 kHz.

3.2. Source Type and Duration

For regulatory purposes, sound sources are classified as either producing impulsive sounds or non-impulsive sounds. Impulsive sounds, such as impact pile driving, is characterized by short-duration pulses separated by a quiescent interval. Non-impulsive (sometimes referred to as continuous) sounds, such as vibratory pile driving, are longer duration and lack the pulsatile structure of impulsive sounds. The SPL of non-impulsive sounds are relatively consistent throughout the signal whereas SPL of impulsive sounds are markedly greater during the pulse. Southall et al. (2007) suggested that impulsive sounds can be distinguished from non-impulsive sounds by comparing the SPL of a 0.035 s window that includes the pulse and with a 1 s window that may include multiple pulses. If the SPL of the 0.035 s window is 3 dB or more greater than the 1 s window, then the signal is impulsive. Figure 7 shows a representative 1 s sample of DTH hammering and a highlighted (in red) 0.035 s pulse. The SPL of the 0.035 s pulse is 5 dB higher than the SPL of the 1 s sample, so the DTH source can be classified as impulsive.

The average duration of the 90% energy of each pulse at Station 1 (the closest recording location) for each DTH location is shown in Table 4. The mean duration of pulses for DTH locations without bubble curtains was 0.020 s.

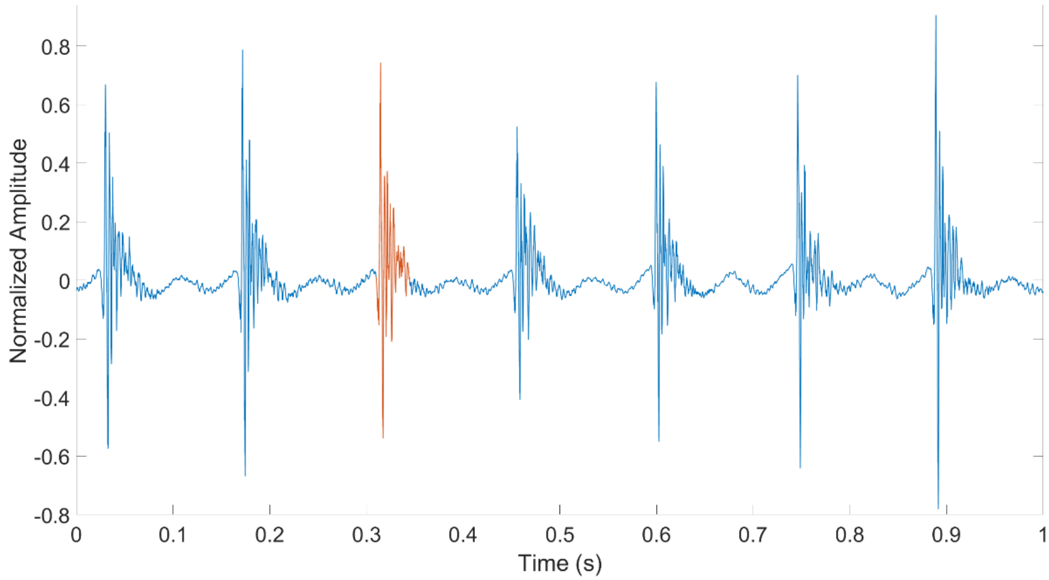

Figure 7. Time-domain waveform of a 1 s sample of DTH hammering. Highlighted in red is a 0.035 s window of a DTH pulse.

Table 4. DTH duration of 90% energy, in seconds, of the pulses at the closest recording station.

DTH location	Station 1
C10P4	0.011294
C9P5	0.025604
C8P8	0.02221
C8P6*	0.022978
C8P7*	0.022956

* with bubble curtain

3.3. Levels over time

Impulses were detected and measured during DTH hammering at the three recording stations. Figures 8 - 22 show the SEL, PK, and SPL of the recorded pulse and the accumulated SEL for DTH hammering at each location. The levels are relatively consistent over time in that first pulses are of similar level as the latter pulses. Appendix B shows the sound levels grouped by location as a function of recording time.

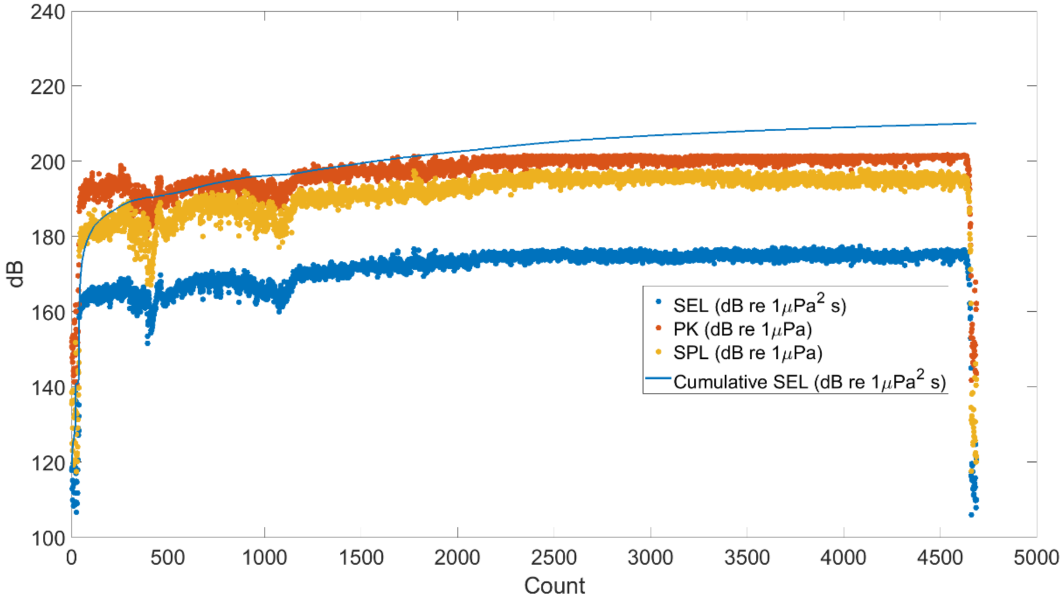

Figure 8. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 1 over time for DTH hammering at location C10P4.

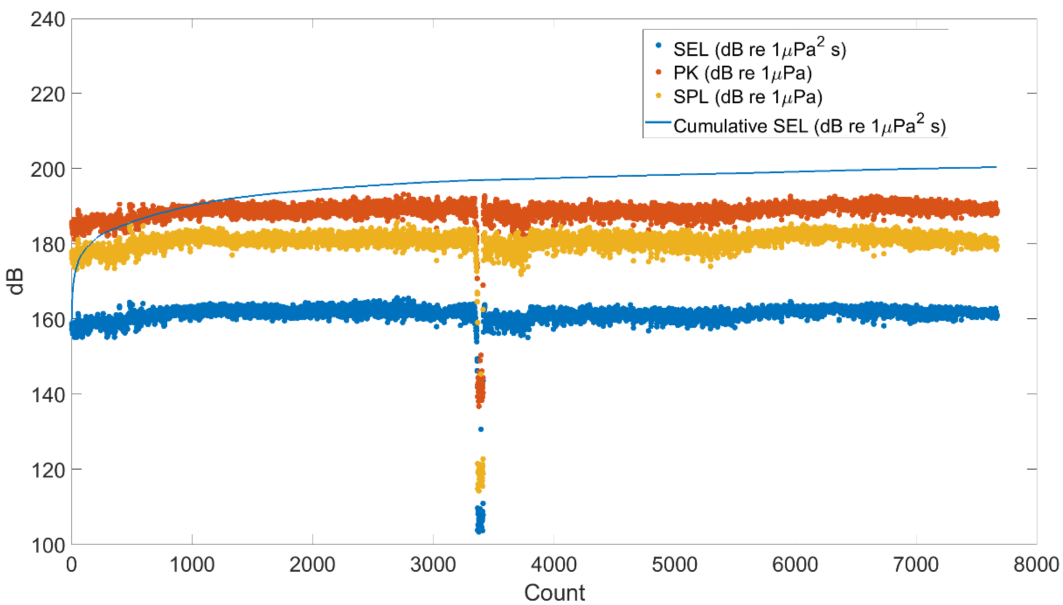

Figure 9. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 2 over time for DTH hammering at location C10P4.

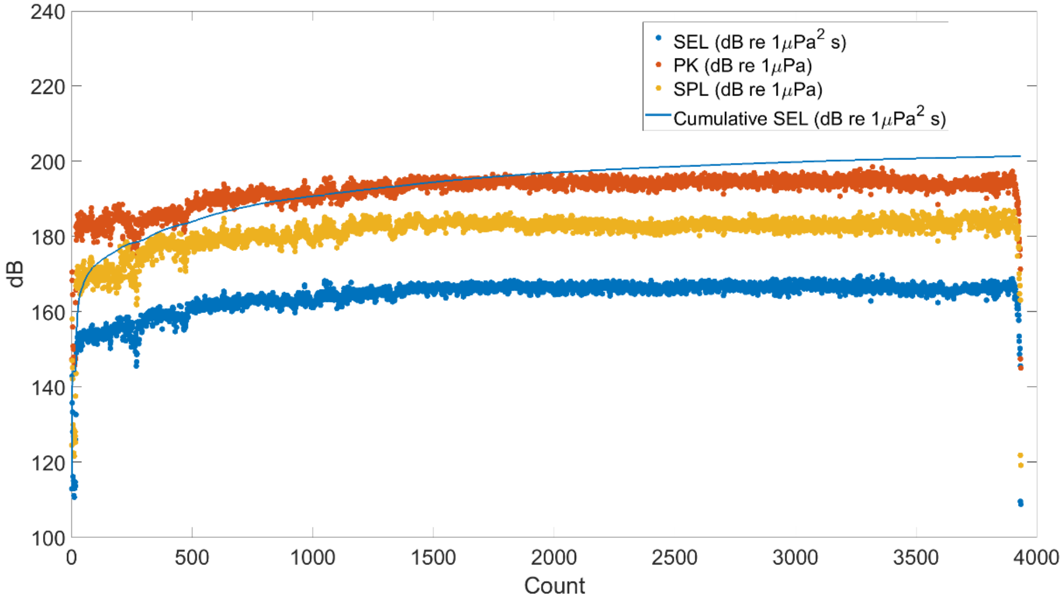

Figure 10. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 3 over time for DTH hammering at location C10P4.

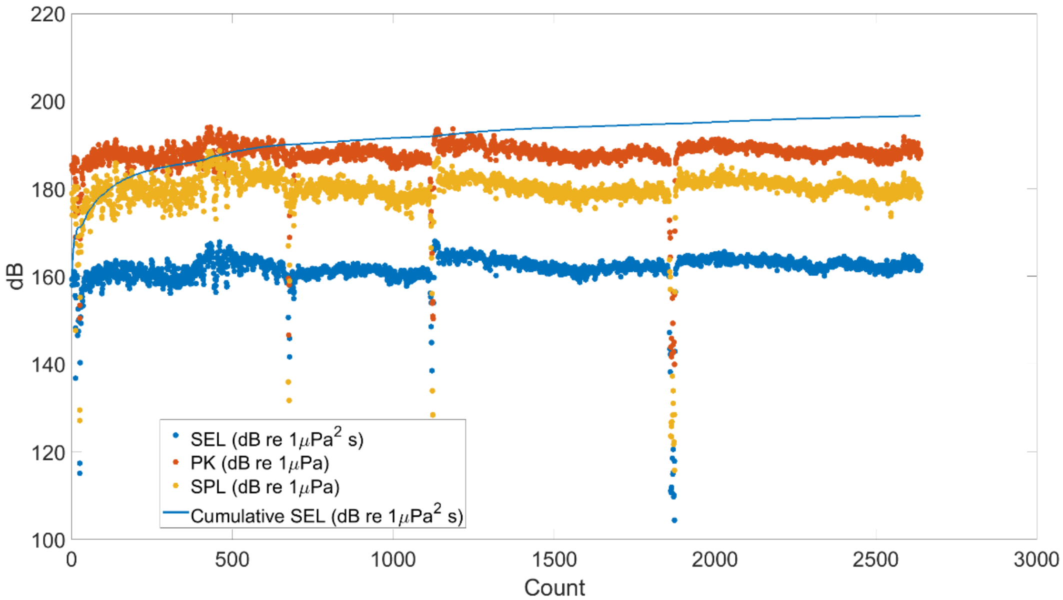

Figure 11. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 1 over time for DTH hammering at location C9P5.

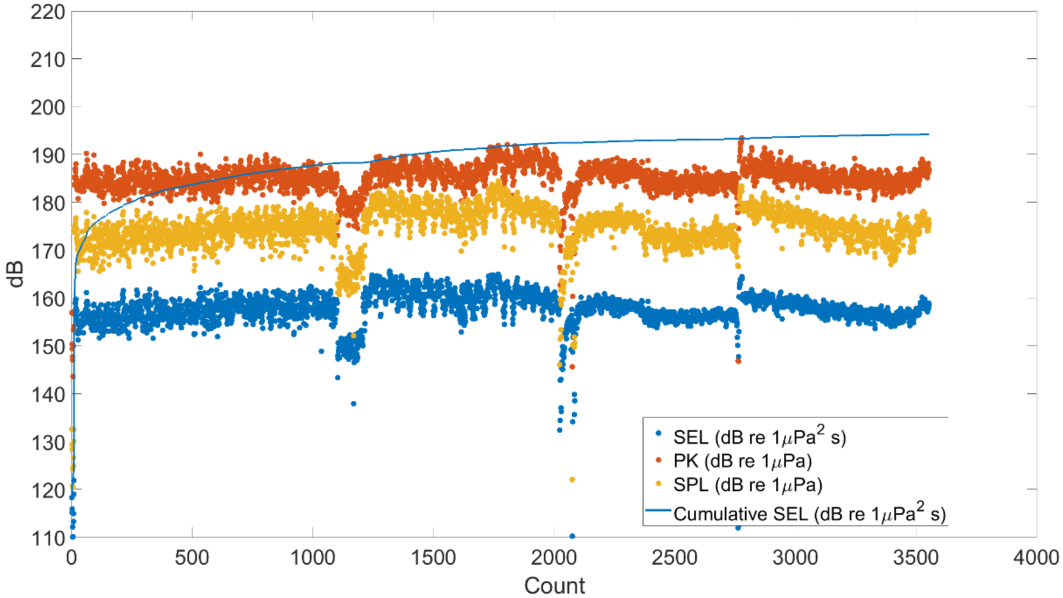

Figure 12. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 2 over time for DTH hammering at location C9P5.

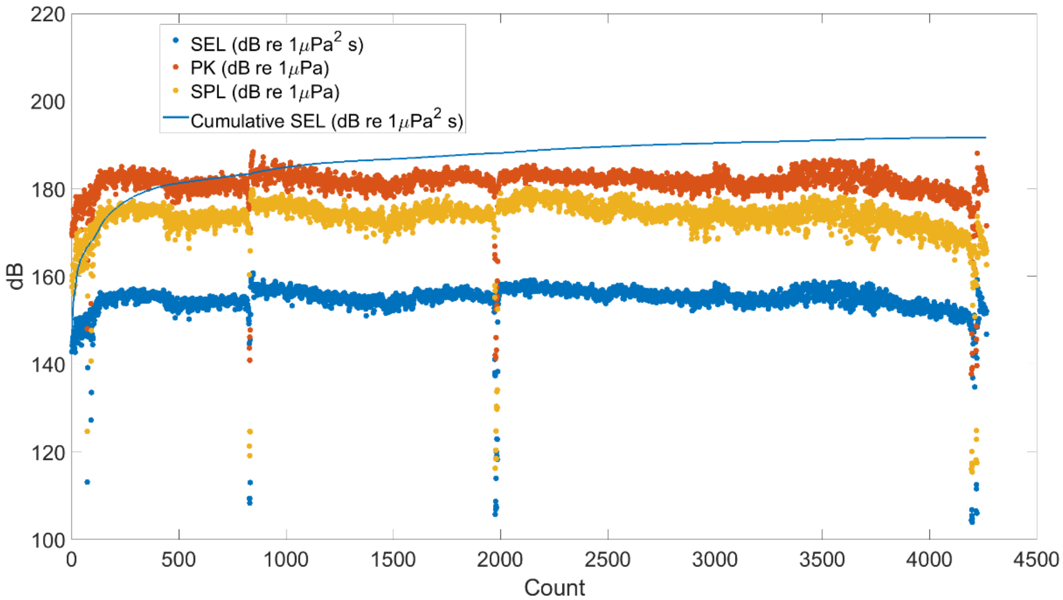

Figure 13. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 3 over time for DTH hammering at location C9P5.

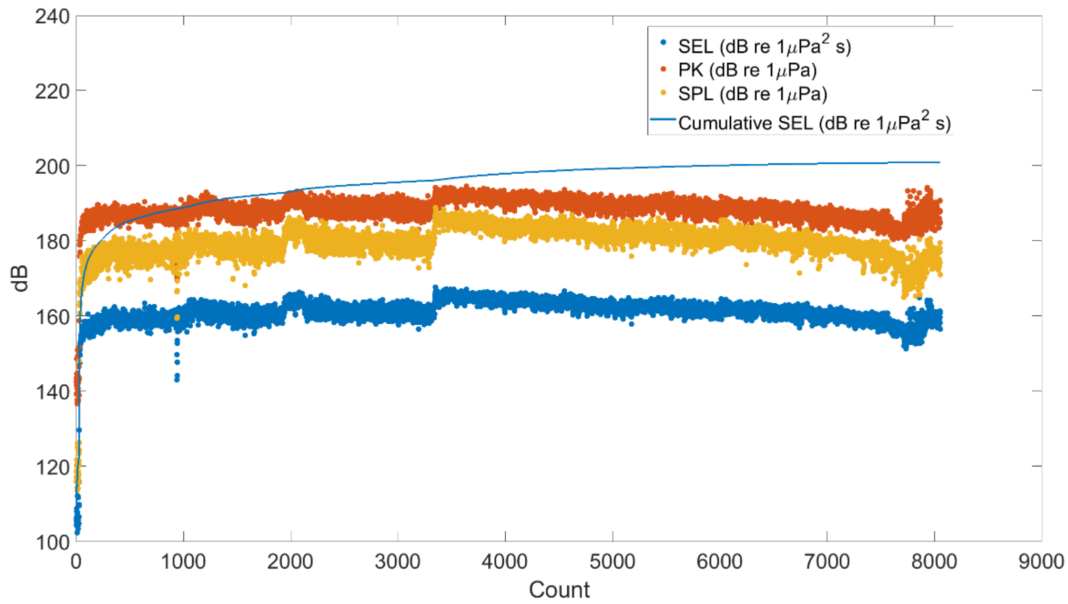

Figure 14. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 1 over time for DTH hammering at location C8P8.

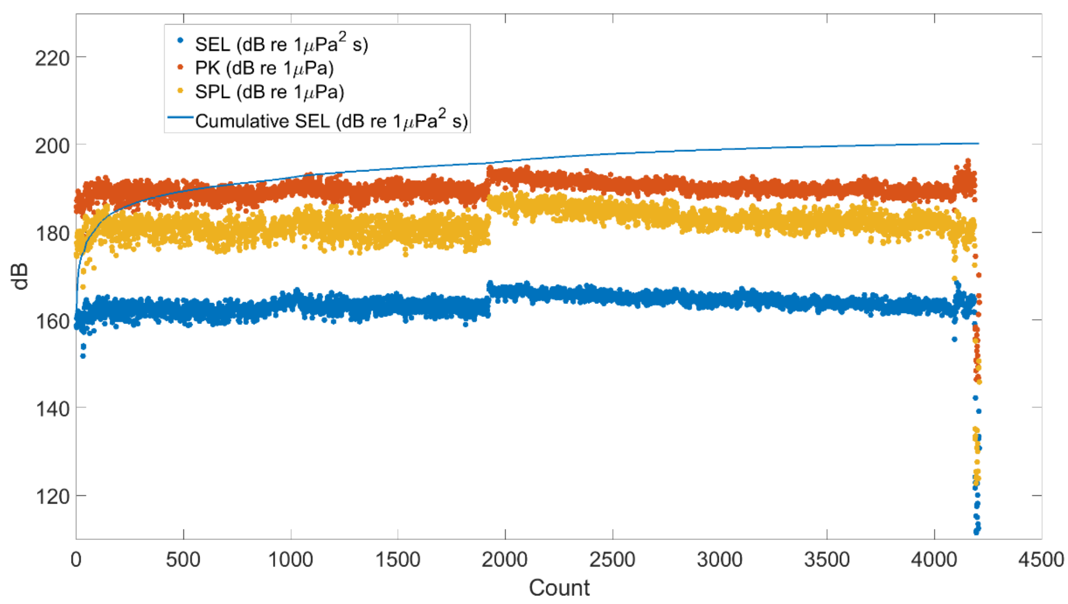

Figure 15. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 2 over time for DTH hammering at location C8P8.

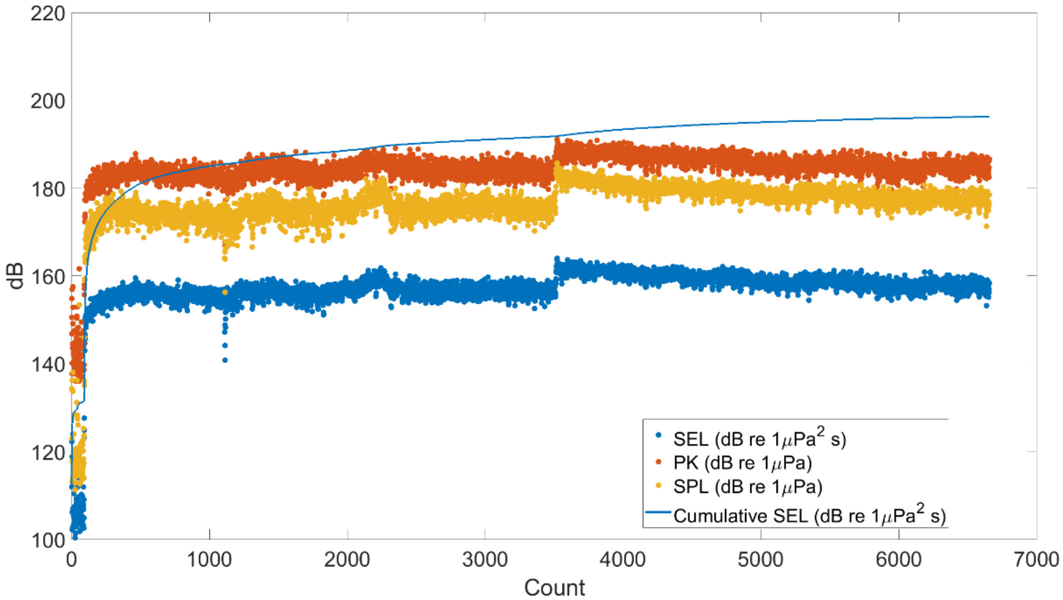

Figure 16. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 3 over time for DTH hammering at location C8P8.

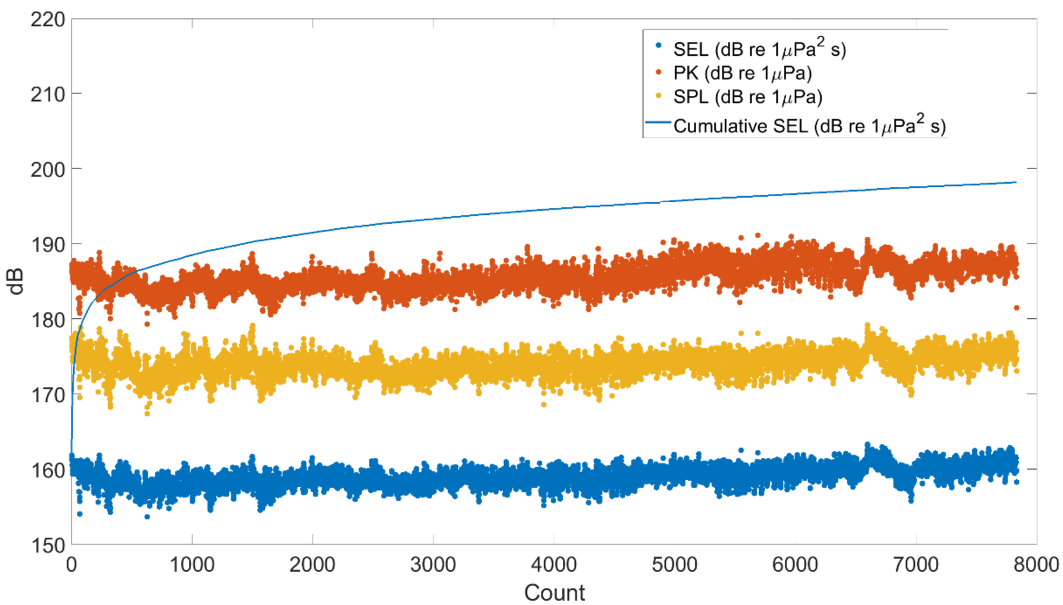

Figure 17. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 1 over time for DTH hammering at location C8P6.

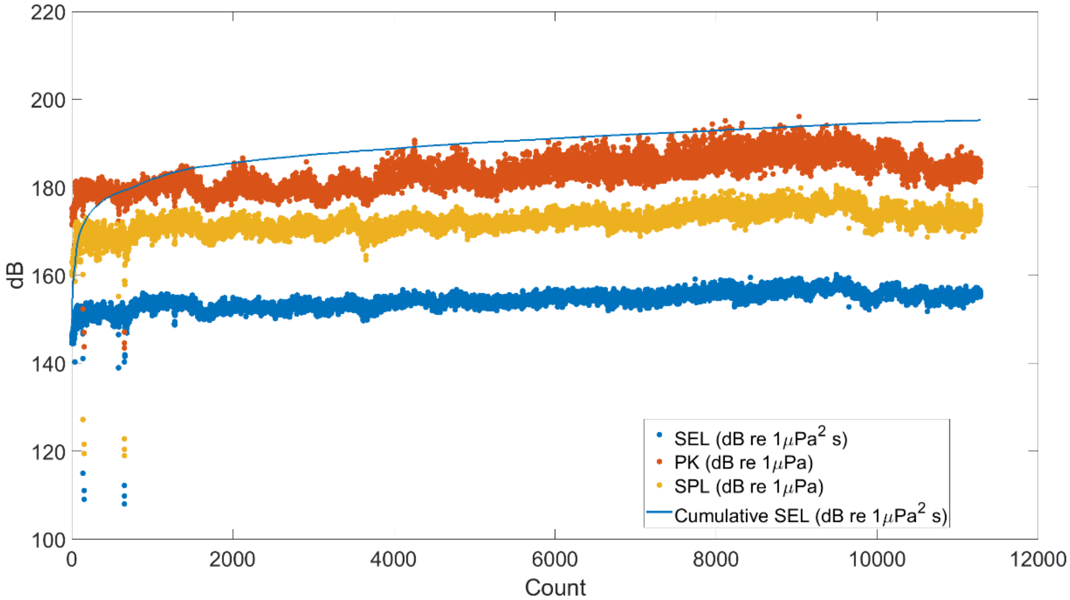

Figure 18. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 2 over time for DTH hammering at location C8P6.

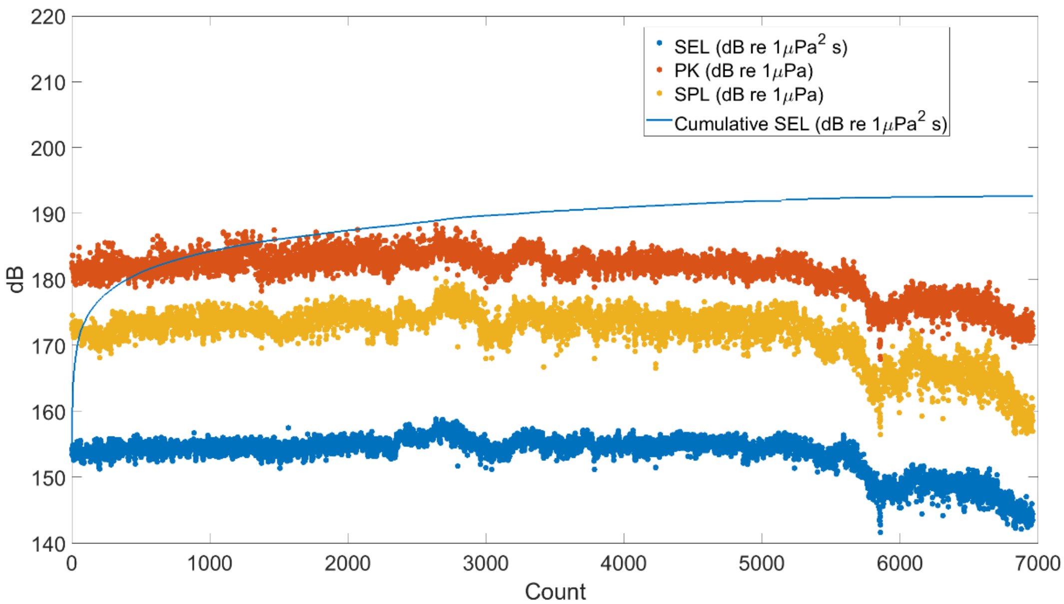

Figure 19. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 3 over time for DTH hammering at location C8P6.

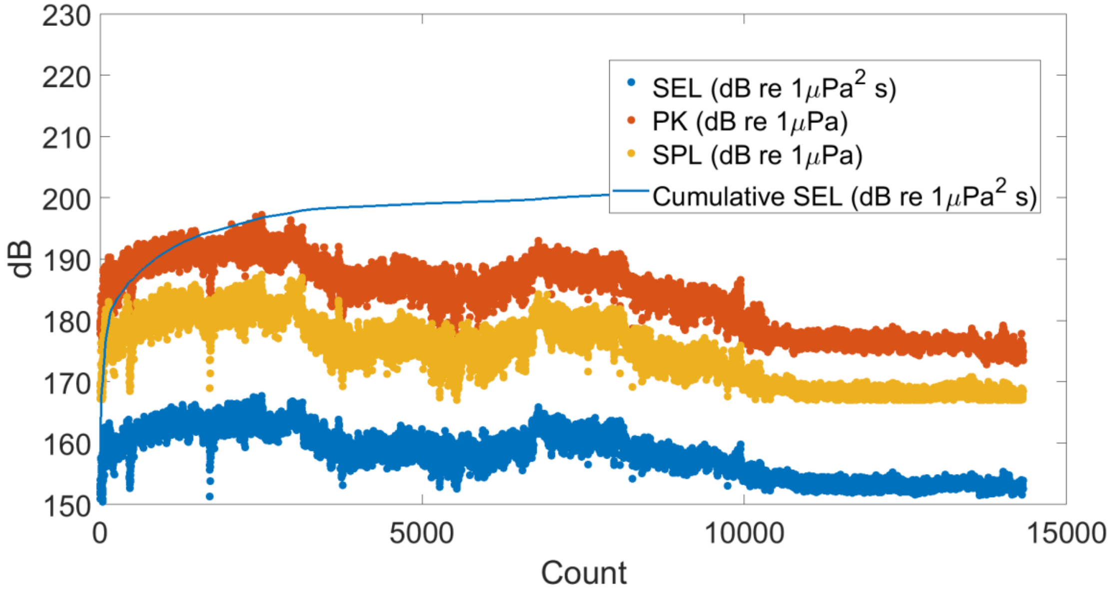

Figure 20. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 1 over time for DTH hammering at location C8P7.

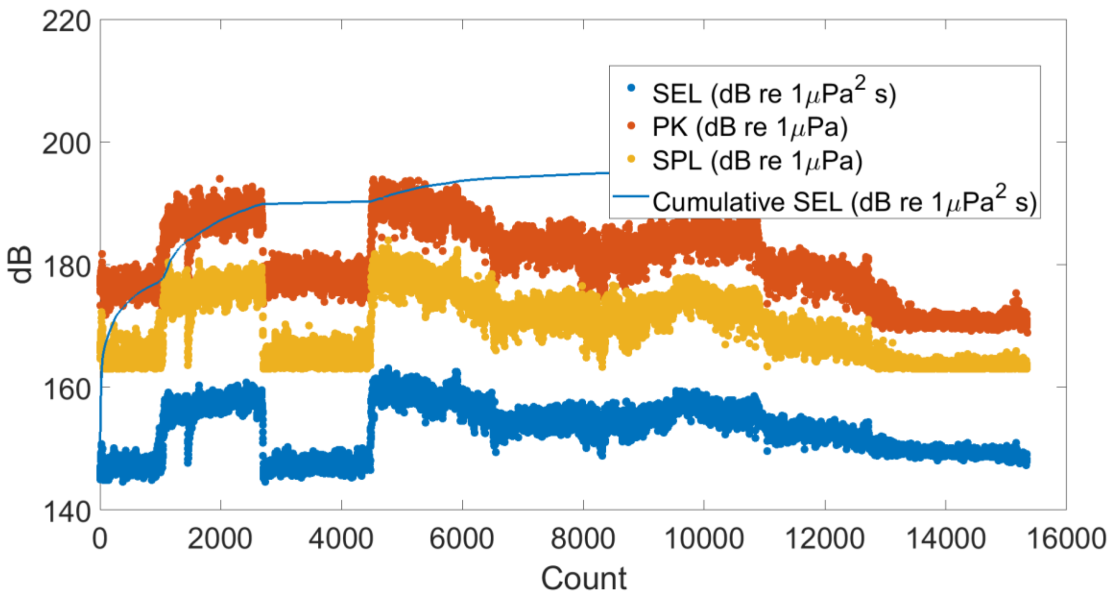

Figure 21. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 2 over time for DTH hammering at location C8P7.

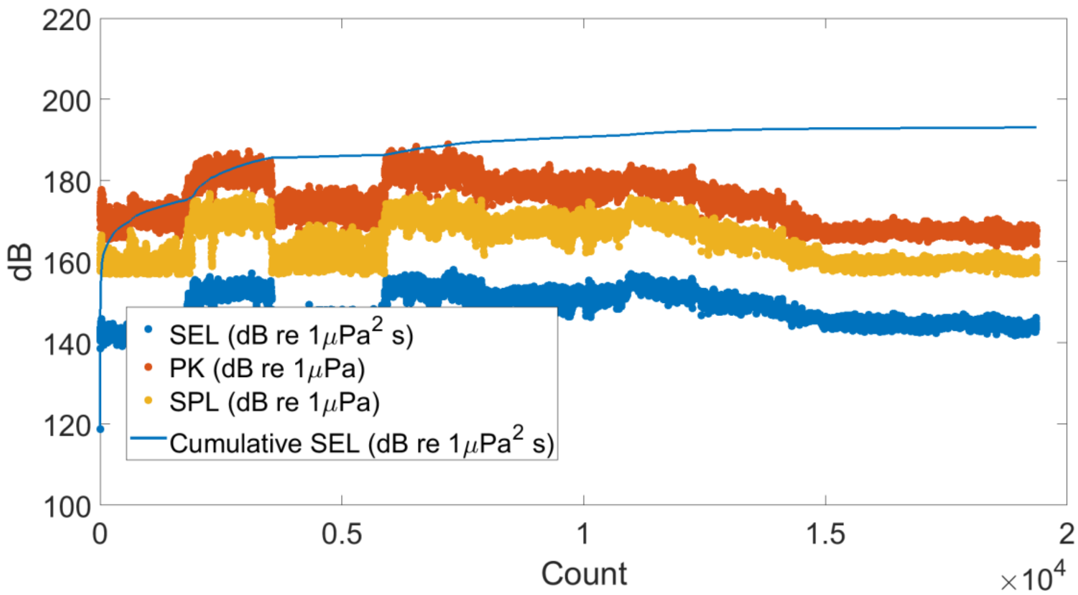

Figure 22. Unweighted single pulse SEL, Unweighted cumulative SEL, PK, and SPL at Station 3 over time for DTH hammering at location C8P7.

3.4. Sound levels as a function distance

The mean sound levels and standard deviations are plotted for SPL (Figure 23), SEL (Figure 24), and PK (Figure 25) for each location without (C10P4, C9P5, and C8P8) and with (C8P7, C8P6) a bubble curtain. While sound levels are highest for C10P4 and C8P8 without a bubble curtain, the levels are similar at C9P5, C8P7, and C8P6 even though C8P7 and C8P6 use a bubble curtain and C9P5 does not. Note that sound levels of C10P4 were loud enough to saturate the recording system at the closest location so those values were not included in range analysis. Sound levels as a function of distance, including weighting SEL for the functional hearing groups are shown in Appendix D.

Table 5 shows the predicted sound level for a single SEL pulse, PK, and SPL for the 90% energy at the DTH hammering locations. For all DTH locations, with and without bubble curtains, the SPL at 10 m exceeded the predicted 166 dB re 1µPa. The average SPL value at 10 m for the DTH location without a bubble curtain was 180 dB re 1µPa, while the average SEL and PK levels were 164 dB re 1µPa^2·s and 190 dB re 1µPa, respectively.

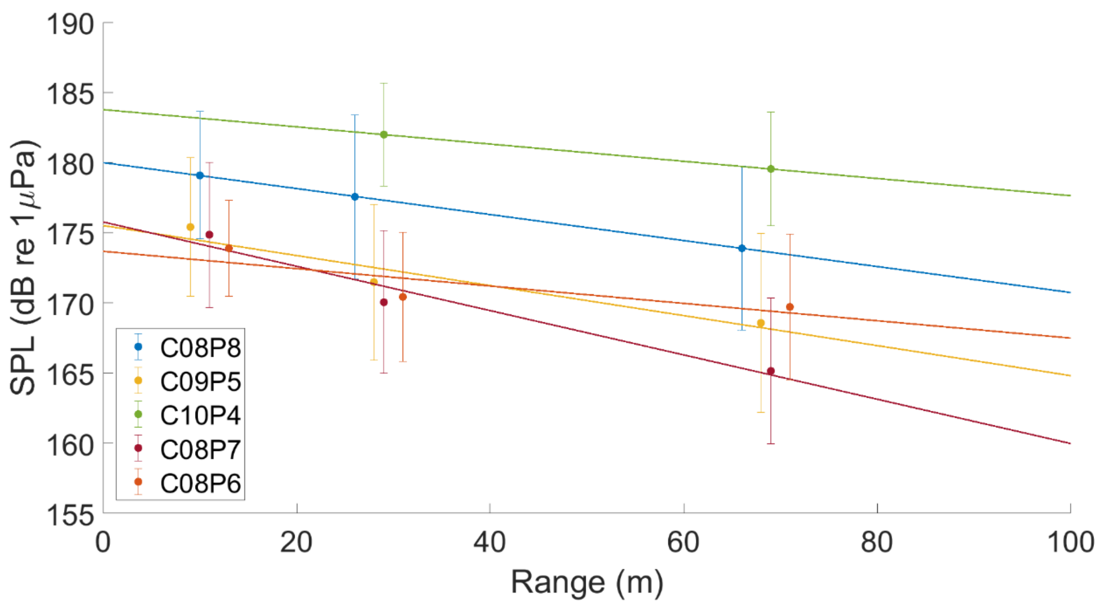

Figure 23. Sound Pressure Level (SPL) of Down-the-hole hammering without (C10P4, C09P5, and C08P8) and with bubble curtain (C08P7, C08P6). Error bars are standard deviation.

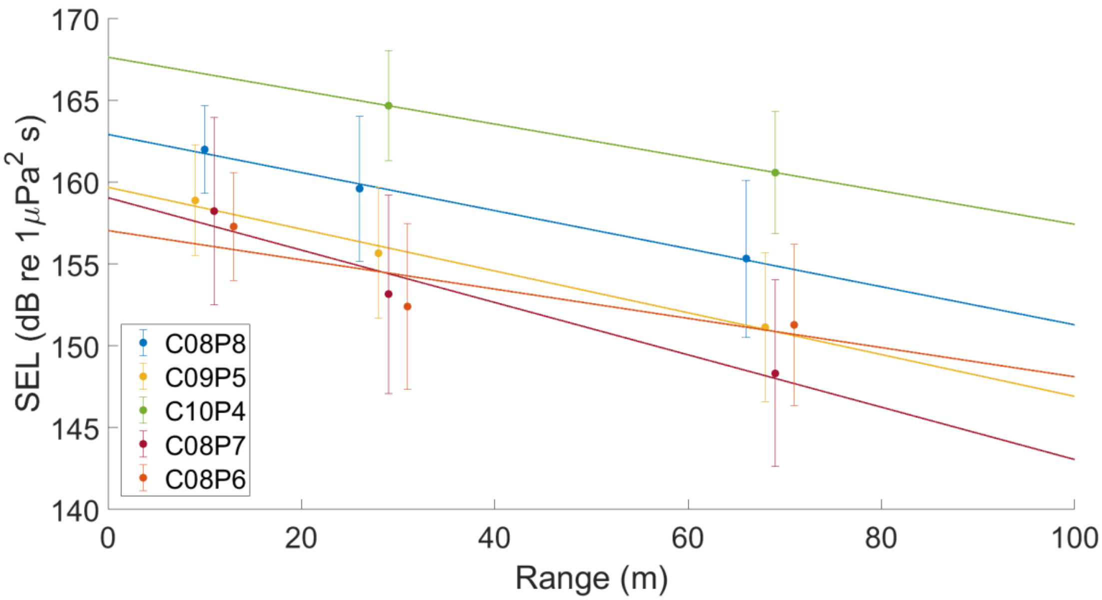

Figure 24. Sound Exposure Level (SEL) of Down-the-hole hammering without (C10P4, C09P5, and C08P8) and with bubble curtain (C08P7, C08P6). Error bars are standard deviation.

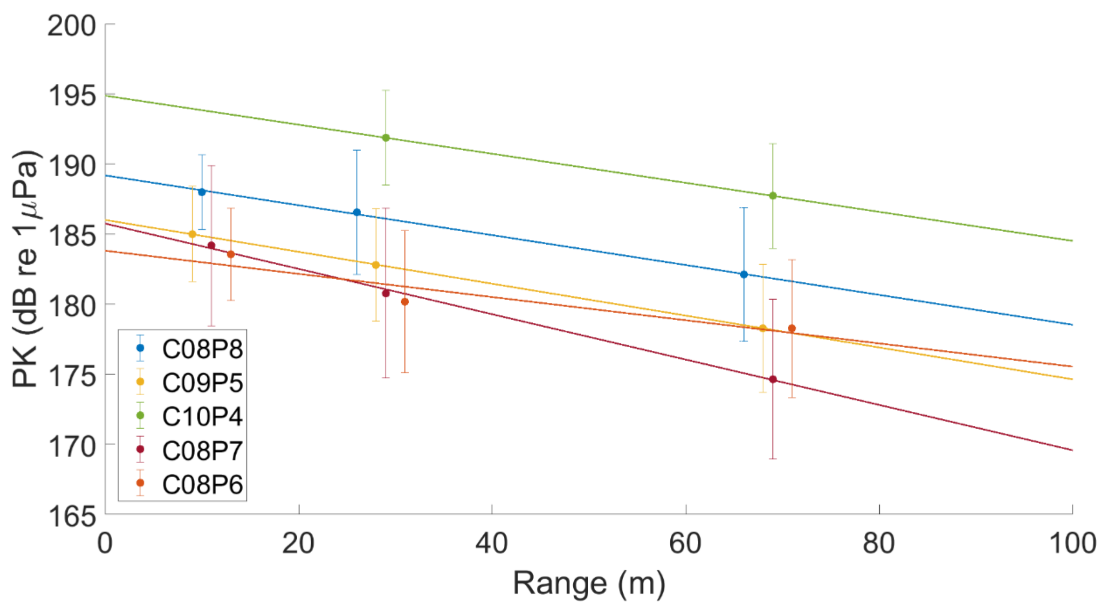

Figure 25. Peak Sound pressure (PK) of Down-the-hole hammering without (C10P4, C09P5, and C08P8) and with bubble curtain (C08P7, C08P6). Error bars are standard deviation.

Table 5. Sound levels of 90% energy 10 m from DTH hammering for SEL (single strike), PK, and SPL.

DTH location	SEL	PK	SPL
C10P4	170.2	197.0	185.5
C9P5	162.6	188.0	179.5
C8P8	159.1	184.6	175.1
C8P6*	158.1	184.2	174.1
C8P7*	158.7	185.3	175.1

* with bubble curtain

3.5. Signal Spectral Content

The spectral band level of the sounds produced by DTH hammering were calculated in decidecade bands. Figures 26 - 30 show that the primary sound energy is between 100 and 1000 Hz, with an additional peak around 1200 Hz. The spectra of the DTH hammering performed with a bubble curtain, C8P7 (Figure 29) and C8P6 (Figure 30) appear to be flatter indicating that the bubble curtain may be attenuating some of the peak energy, though there are not enough examples to produce a convincing trend.

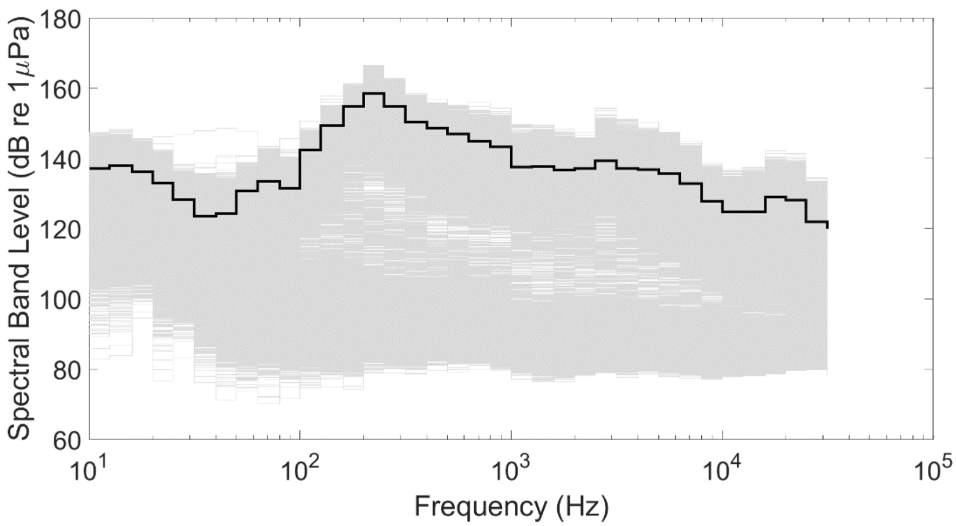

Figure 26. Decidecade spectral band level of sound pressure during Down-the-hole hammering of C10P4

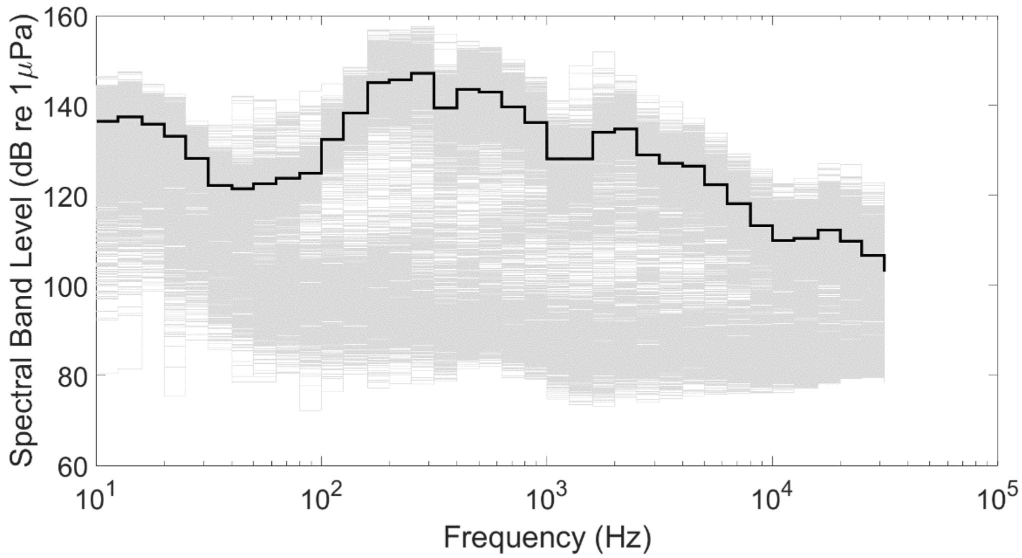

Figure 27. Decidecade spectral band level of sound pressure during Down-the-hole hammering of C09P5

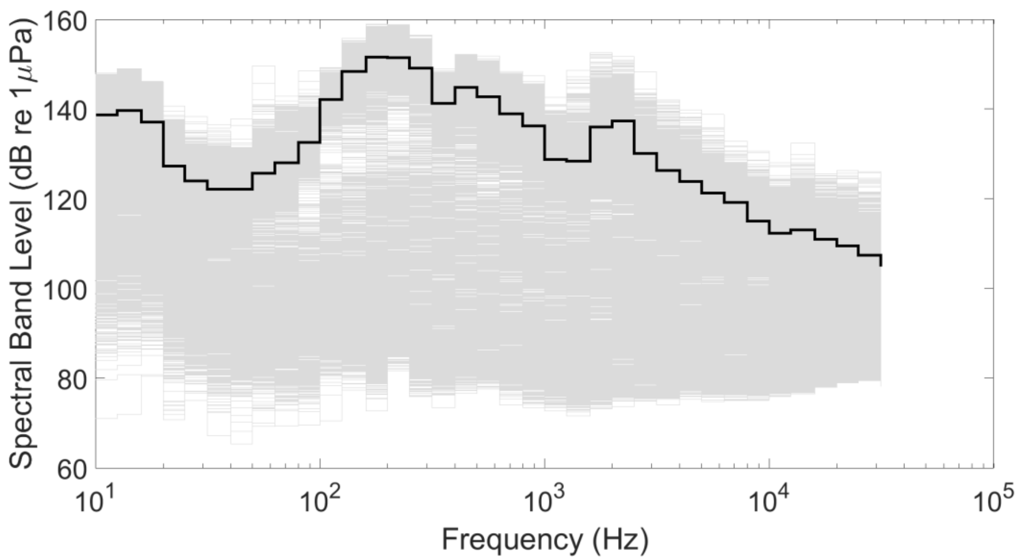

Figure 28. Decidecade spectral band level of sound pressure during Down-the-hole hammering of C08P8

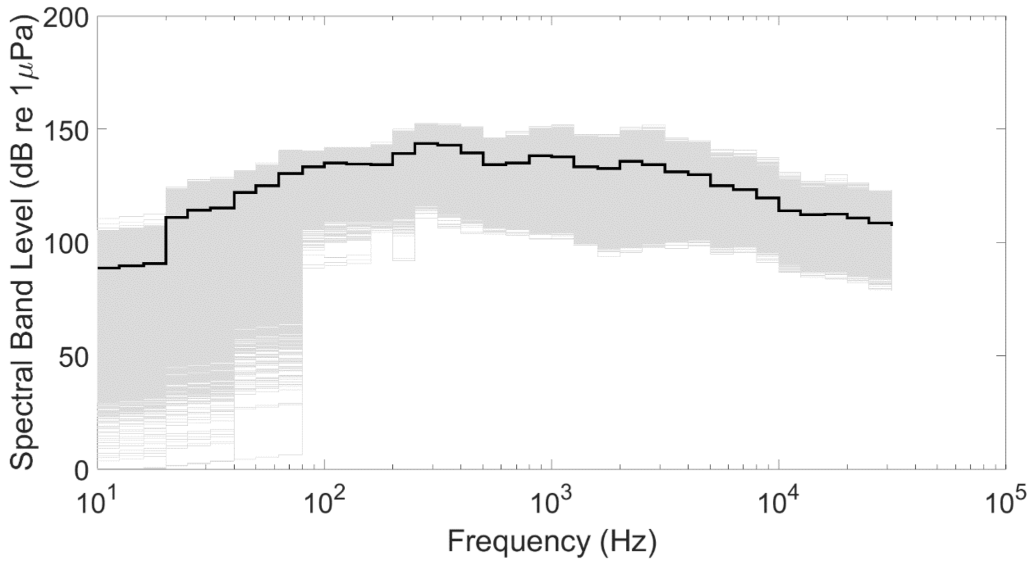

Figure 29. Decidecade spectral band level of sound pressure during Down-the-hole hammering of C08P7

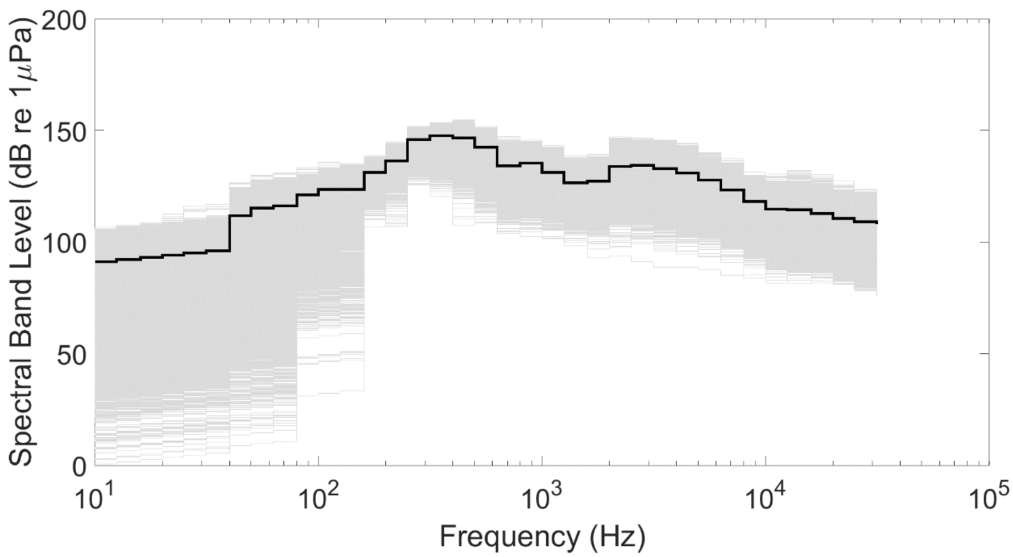

Figure 30. Decidecade spectral band level of sound pressure during Down-the-hole hammering of C08P6 at Station 1

4. Discussion and Conclusion

Underwater sounds were recorded using bottom-mounted flow-shielded moorings at three locations near Thimble Shoal Island of the Chesapeake Bay Bridge Tunnel in Virginia. Ambient sound levels, measured 28 June through 15 July (at Station 3) before DTH construction activities, indicate relatively high background noise levels with a median SPL of 122.78 dB re 1 µPa. The location is near an active shipping and boating channel, and the sound levels may include other construction noise as well as contributions from automotive traffic on the bridge.

Sound from DTH hammering was found to be impulsive based on a >3 dB difference (Southall et al. 2007) in sound pressure level measured over a short (0.035 s) window compared to a longer (1 s) window. Sound levels were determined by detecting and measuring individual pulses of DTH hammering. While initial levels were somewhat lower than later levels, no clear trend in amplitude with penetration depth was evident. All DTH hammering locations exceeded the predicted SPL of 166 dB re 1 µPa at 10 m, with an average SPL among locations of 180 dB re 1 µPa at 10 m (without the use of a bubble curtain). The loudest locations, C10P4 and C8P8, did not use a bubble. DTH hammering at one location, C9P5, without a bubble curtain was approximately the same level as the two locations, C8P7 and C8P6, with a bubble curtain, so an effect of the bubble curtain could not be determined from the measured levels. The spectral band levels of the signals were calculated and it was found that the primary sound energy is between 100 and 1000 Hz. Although a trend could not be established, use of a the bubble curtain did seem to flatten the spectra suggesting the bubble curtain could be attenuating sound levels.

Different metrics are used to determine the potential for injury and behavioral disruption of marine mammals. Potential for injury is assessed using SEL and PK levels (NMFS 2018) while the potential for behavioral disruption is assessed using SPL (NOAA 2005). The SEL levels for DTH hammering of a caisson were well below injury threshold for all hearing groups (Appendix D). With the exception of high-frequency species, the PK levels were also well below the threshold for potential injury (Section 3.4 and Appendix D). As a general statement of DTH, there is some potential for injury to high-frequency cetacea (such as *Kogia* species and harbor porpoise) as the PK levels can exceed 202 dB re 1 µPa within 10 m of DTH hammering for the loudest pulses, but no high frequency species are expected near the project area so no injury is expected. An SPL threshold of 160 dB re 1 µPa is used to assess behavioral disruption of marine mammals exposed to impulsive sound sources. Based on the measured SPL as a function of range (Section 3.4 and Appendix D) the distance to 160 dB re 1 µPa could be several kilometers. These measurements in shallow water near the source and a simple geometric propagation model, however, mean that long distance propagation is difficult to predict. Also, the SPL 160 dB re 1 µPa threshold (NOAA 2005) does not consider the hearing range of the species (unlike injury, no frequency weighting is used). DTH hammering was found to be a low-frequency source (most of the acoustic energy is between 100-1000 Hz), so it is not within the best hearing range of mid-frequency species such as dolphins.

In summary, behavioral responses may be expected, possibly to several kilometers, but no injury could occur.

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Appendix A. Underwater Acoustics

This section provides a detailed description of the acoustic metrics relevant to the modeling study and the modeling methodology.

A.1. Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa in water and p_0 = 20 μPa in air. Because the perceived loudness of sound, especially impulsive noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

The zero-to-peak sound pressure, or peak sound pressure (L_{pk}; dB re 1 µPa), is the decibel level of the maximum instantaneous acoustic pressure in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$L_{p,pk} = 20 \log_{10}\left[\frac{\max(|p(t)|)}{p_0}\right] . \qquad \text{(A-1)}$$

L_{pk} is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of a noise event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure ($L_{pk\text{-}pk}$; dB re 1 µPa) is the difference between the maximum and minimum instantaneous sound pressure, possibly filtered in a stated frequency band, attained by an impulsive sound, $p(t)$:

$$L_{p,pk-pk} = 10 \log_{10}\left\{\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2}\right\} . \qquad \text{(A-2)}$$

The sound pressure level (L_p; dB re 1 µPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s). It is important to note that L_p always refers to an rms pressure level and therefore not instantaneous pressure:

$$L_p = 10 \log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt \Big/ p_0^2\right) , \qquad \text{(A-3)}$$

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying L_p function. For short acoustic events, such as sonar pulses and marine mammal vocalizations, it is important to choose an appropriate time window that matches the duration of the signal. For in-air studies, when evaluating the perceived loudness of sounds with rapid amplitude variations in time, the time weighting function $g(t)$ is often set to a decaying exponential function that emphasizes more recent pressure signals. This function mimics the leaky integration nature of mammalian hearing. For example, human-based fast time-weighted L_p ($L_{p,fast}$) applies an exponential function with time constant 125 ms. A related simpler approach used in underwater acoustics sets $g(t)$ to a boxcar (unity amplitude) function of width 125 ms; the results can be referred to as $L_{p,boxcar\ 125ms}$. Another approach, historically used to evaluate L_p of impulsive signals underwater, defines $g(t)$ as a boxcar function with edges set to the times corresponding to 5% and 95% of the cumulative square pressure function encompassing the duration of an impulsive acoustic event. This

calculation is applied individually to each impulse signal, and the results have been referred to as 90% SPL ($L_{p,90\%}$).

The sound exposure level (L_E; dB re 1 µPa²·s) is the time-integral of the squared acoustic pressure over a duration (T):

$$L_E = 10\log_{10}\left(\int_T p^2(t)dt \Big/ T_0 p_0^2\right), \qquad \text{(A-4)}$$

where T_0 is a reference time interval of 1 s. L_E continues to increase with time when non-zero pressure signals are present. It is a dose-type measurement, so the integration time applied must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over a fixed duration, such as the time of a single event or a period with multiple acoustic events. When applied to impulsive sounds, L_E can be calculated by summing the L_E of the N individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the L_E can be computed by summing (in linear units) the L_E of the N individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right). \qquad \text{(A-5)}$$

If applied, the frequency weighting of an acoustic event should be specified, as in the case of M-weighted SEL (e.g., $L_{E,LF,24h}$). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should also be specified.

Sound particle acceleration is a time-dependent spatial vector quantity. In cylindrical coordinates the acceleration vector $\boldsymbol{a}(t) = \boldsymbol{a}_r(t) + \boldsymbol{a}_z(t)$, where r and z indicate the radial (horizontal) and vertical directions, respectively. The zero-to-peak sound particle acceleration is the largest magnitude of the particle acceleration:

$$a_{pk} = \max\left(|\boldsymbol{a}(t)|\right). \qquad \text{(A-6)}$$

The radial or vertical peak particle acceleration is the peak acceleration for each dimension, i.e., $a_{r,pk} = \max(|\boldsymbol{a}_r(t)|)$ and $a_{z,pk} = \max(|\boldsymbol{a}_z(t)|)$. The peak acceleration level is

$$L_{a,pk} = 20\mathrm{Log}_{10}\frac{a_{pk}}{a_0}, \qquad \text{(A-7)}$$

where a_0 is the reference acceleration of 1 µm/s². Peak acceleration levels in the horizontal or vertical directions are calculated using the peak acceleration in the horizontal or vertical directions, respectively.

The rms acceleration level is the level of the square root of the mean-square acceleration,

$$L_{a,rms} = 10\mathrm{Log}_{10}\frac{\frac{1}{T}\int_T |\boldsymbol{a}(t)|^2 dt}{a_0^2}. \qquad \text{A-8}$$

The rms acceleration level can be calculated in the horizontal or vertical directions using the corresponding components of the acceleration vector.

A.1.1. Decidecade band analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are approximately one-third of an octave (base 2) wide and often referred to as 1/3-octave-bands. Each octave represents a doubling in sound frequency. The center frequency of the ith band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{\frac{i}{10}} \tag{A-9}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith band are defined as:

$$f_{\text{lo},i} = 10^{\frac{-1}{20}} f_c(i) \quad \text{and} \quad f_{\text{hi},i} = 10^{\frac{1}{20}} f_c(i) \tag{A-10}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-1). In this report, the acoustic modeling spans from band −24 ($f_c(-24)$ = 0.004 kHz) to band 14 ($f_c(14)$ = 25 kHz).

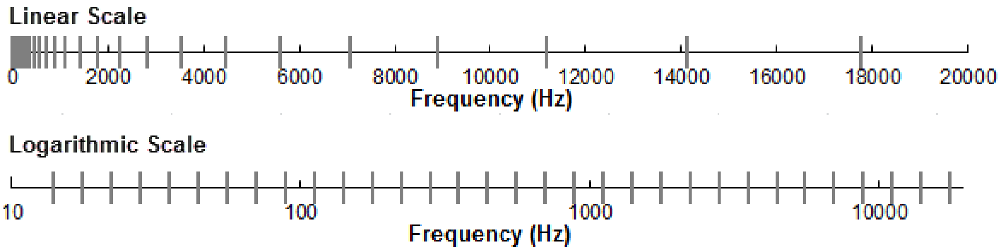

Figure A-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

The sound pressure level in the ith band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{lo,i}$ and $f_{hi,i}$:

$$L_{\text{p},i} = 10 \log_{10} \int_{f_{\text{lo},i}}^{f_{\text{hi},i}} S(f)\, df \tag{A-11}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{\frac{L_{p,i}}{10}} \tag{A-12}$$

Figure A-2 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient noise signal. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the spectral levels, especially at higher frequencies. Acoustic modeling of decidecade bands requires less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

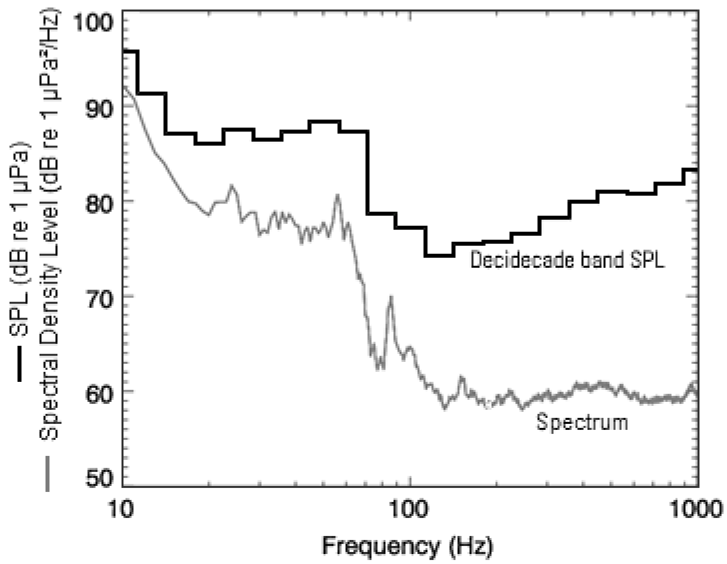

Figure A-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

Appendix B. Auditory (Frequency) Weighting Functions

Weighting functions are applied to the sound spectra under consideration to weight the importance of received sound levels at particular frequencies in a manner reflective of an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007). In this study, multiple weighting functions were used. Southall et al. (2007) were first to suggest weighting functions and functional hearing groups for marine mammals. The weighting functions from Southall et al. (2007) were referred to as m-weighting. For this report the Technical Guidance issued by NOAA (NMFS 2016/2018) included weighting functions and associated thresholds and was used here for determining the ranges for potential injury to marine mammals.

B.1.1. NMFS (2018) frequency weighting functions

In 2015, a U.S. Navy technical report by Finneran (2015) recommended new auditory weighting functions. The auditory weighting functions for marine mammals are applied in a similar way as A-weighting for noise level assessments for humans. The new frequency-weighting functions are expressed as:

$$G(f) = K + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \quad \text{(B-1)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively), phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses acoustic impacts on marine mammals (NMFS 2018). The updates did not affect the content related to either the definitions of M-weighting functions or the threshold values. Table B-1 lists the frequency-weighting parameters for each hearing group. Figure B-1 shows the resulting frequency-weighting curves.

Table B-1. Parameters for the auditory weighting functions recommended by NMFS (2018).

Functional hearing group	a	b	f_1 (Hz)	f_2 (Hz)	K (dB)
Low-frequency cetaceans	1.0	2	200	19,000	0.13
Mid-frequency cetaceans	1.6	2	8,800	110,000	1.20
High-frequency cetaceans	1.8	2	12,000	140,000	1.36
Phocid pinnipeds in water	1.0	2	1,900	30,000	0.75
Otariid pinnipeds in water	2.0	2	940	25,000	0.64

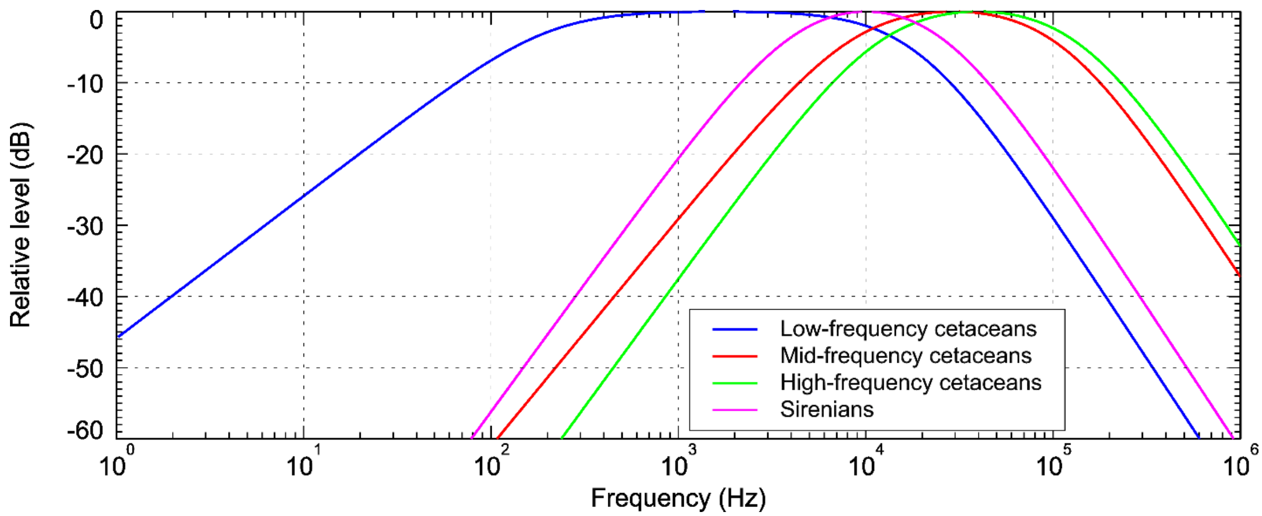

Figure B-1. Auditory weighting functions for the low-, mid-, and high-frequency cetacean and sirenian hearing groups as recommended by NMFS (2018). Sirenian weighting function is from Blackstock et al. (2017).

B.1.2. Source levels

Source levels were determined for DTH-hammering to quantify its inherent loudness. A source level is a measure of the sound emission level of a source at a reference distance of 1 m. For point sources, such as a small transducer, the source levels can be measured directly with a hydrophone 1 m away. For larger sources, such as piles, the source levels are determined indirectly by measuring the sound levels received farther away and back-propagating the levels to the 1 m reference distance. For example, vessels radiate sound from their hulls and propellers, so their source levels must be measured from a distance where the transmission loss from the various sound sources is similar.

Appendix C. Recorded Levels over Time

C.1. C10P4

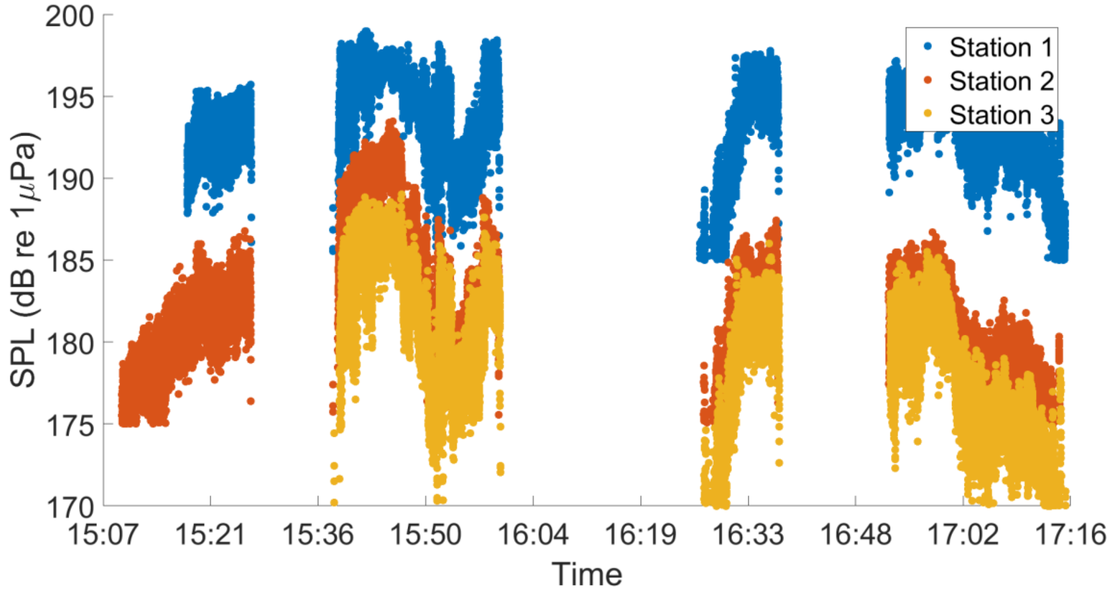

Figure 31. C10P4 recorded Sound Pressure Level (SPL) over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

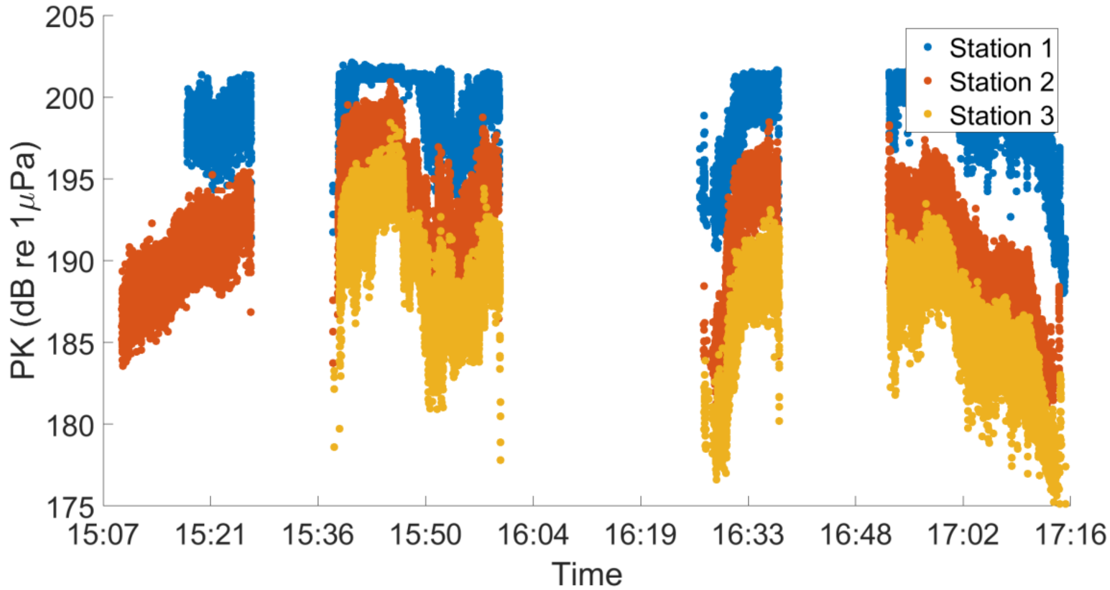

Figure 32. C10P4 recorded Peak Sound Pressure (PK) over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

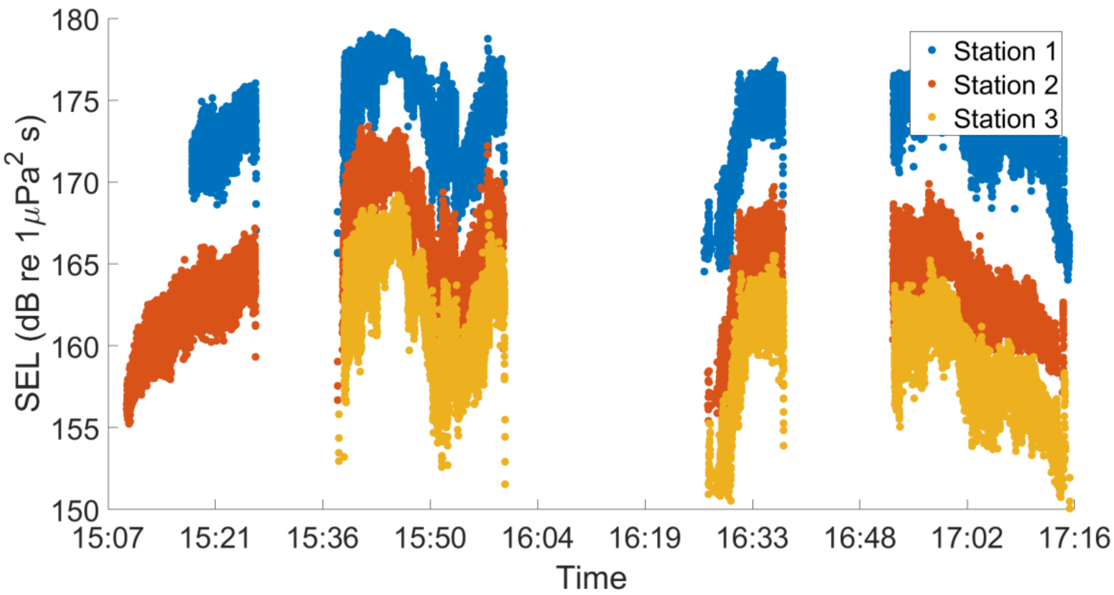

Figure 33. C10P4 recorded Sound Exposure Level (SEL) for single pulses over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

C.2. C8P8

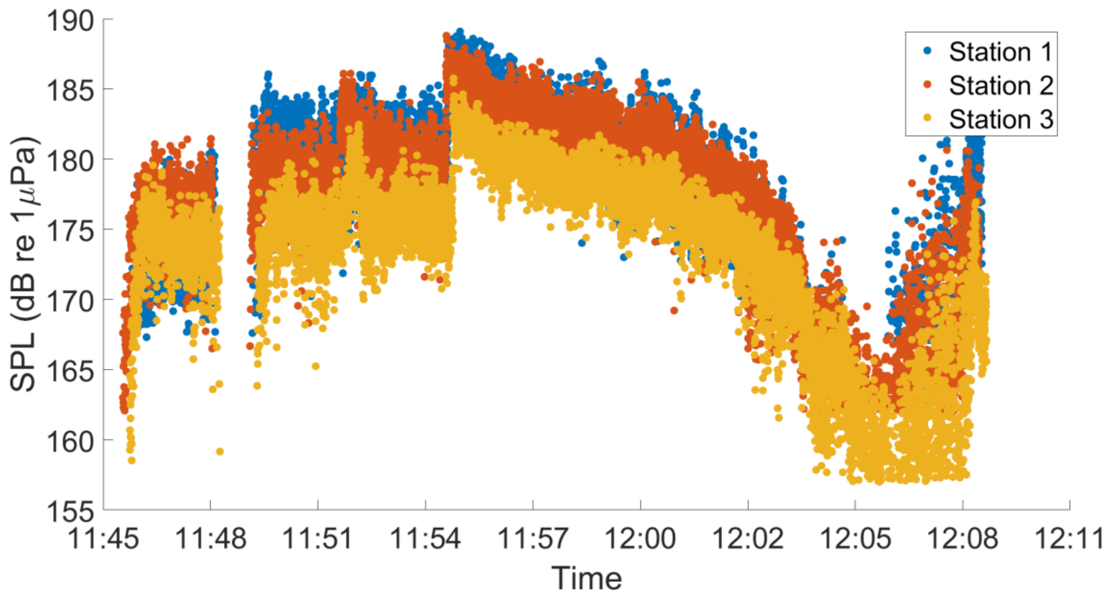

Figure 34. C8P8 recorded Sound Pressure Level (SPL) over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

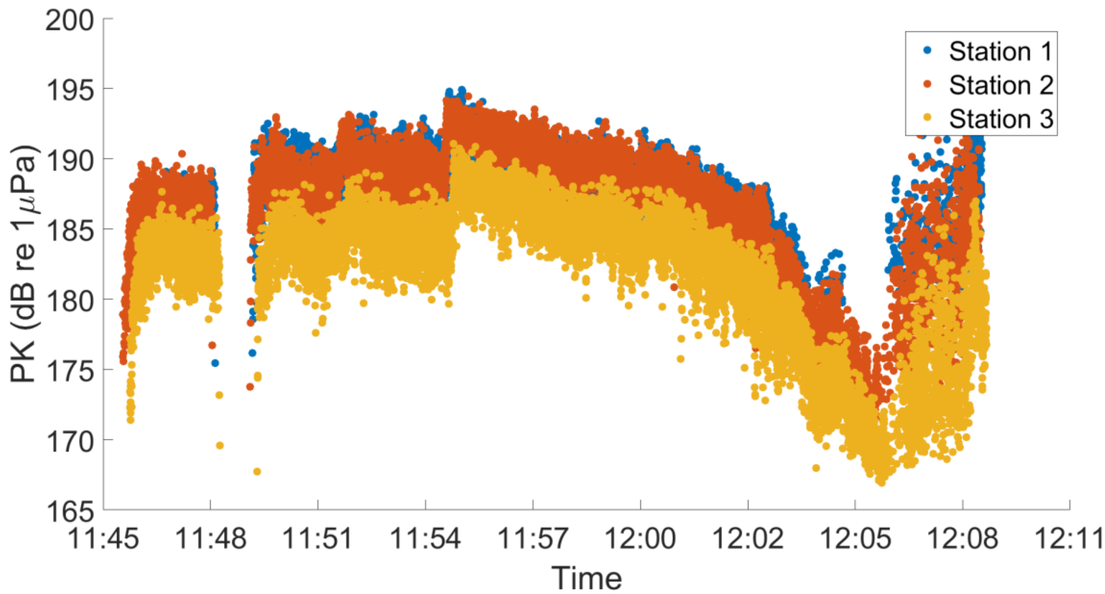

Figure 35. C8P8 recorded Peak Sound Pressure (PK) over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

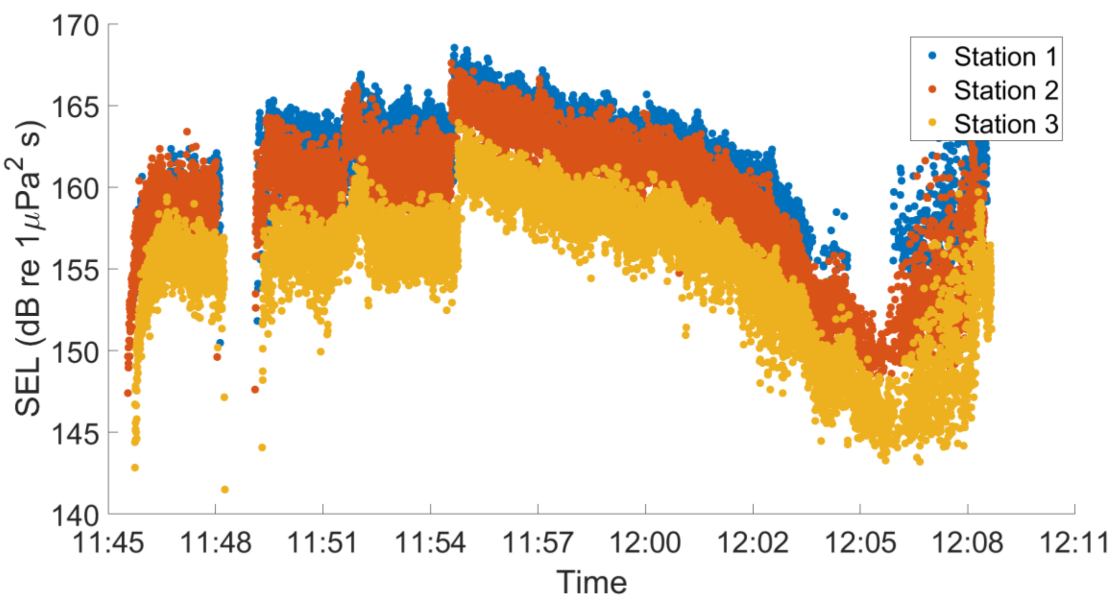

Figure 36. C8P8 recorded Sound Exposure Level (SEL) for single pulses over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

C.3. C8P7

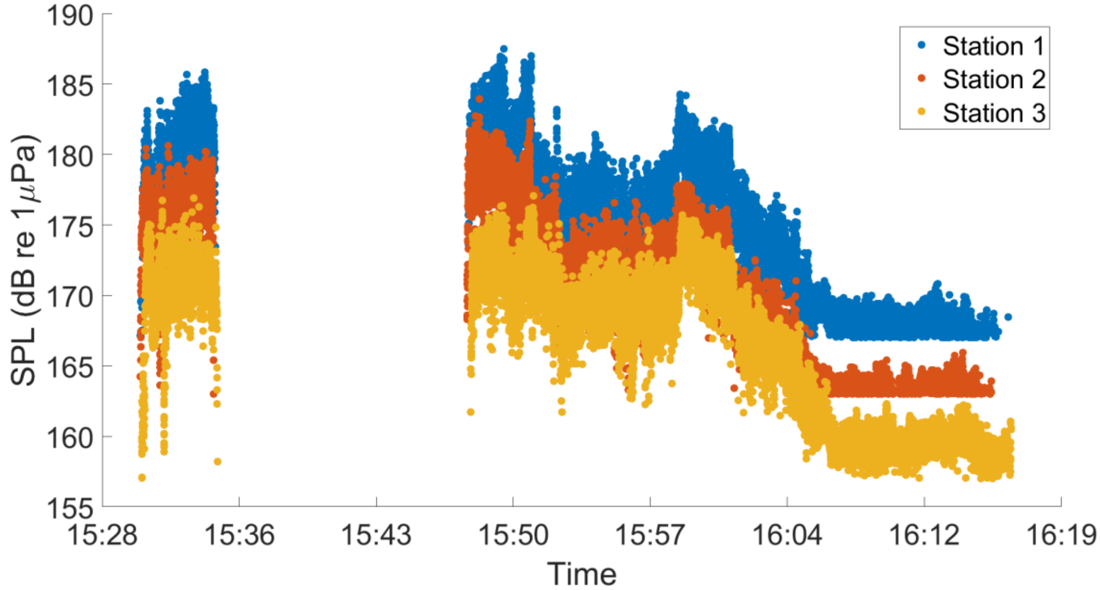

Figure 37. C8P7 recorded Sound Pressure Level (SPL) over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

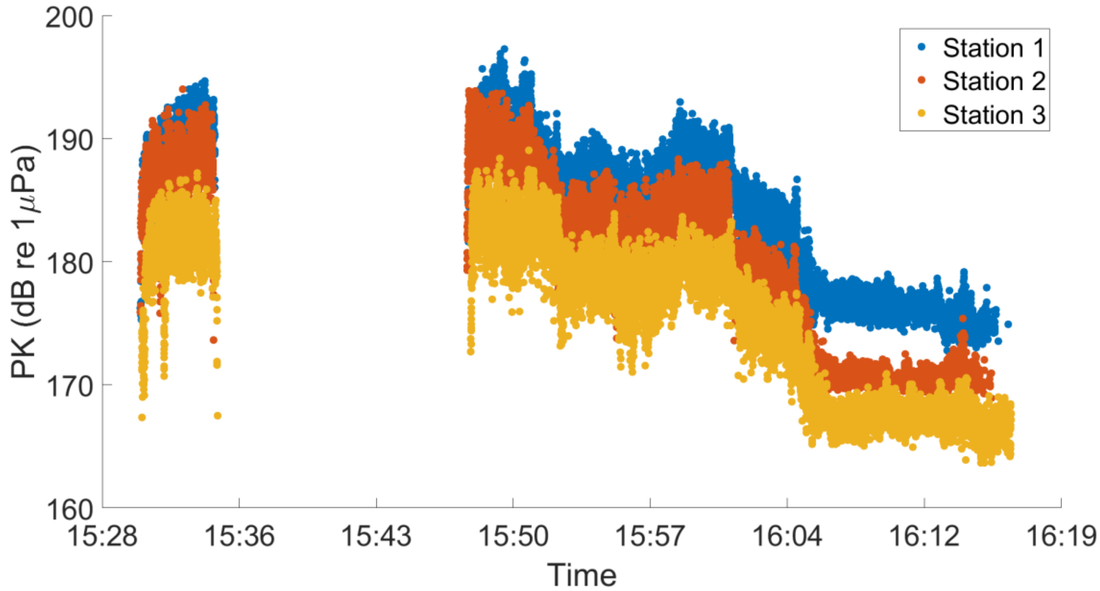

Figure 38. C8P7 recorded Peak Sound Pressure (PK) over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

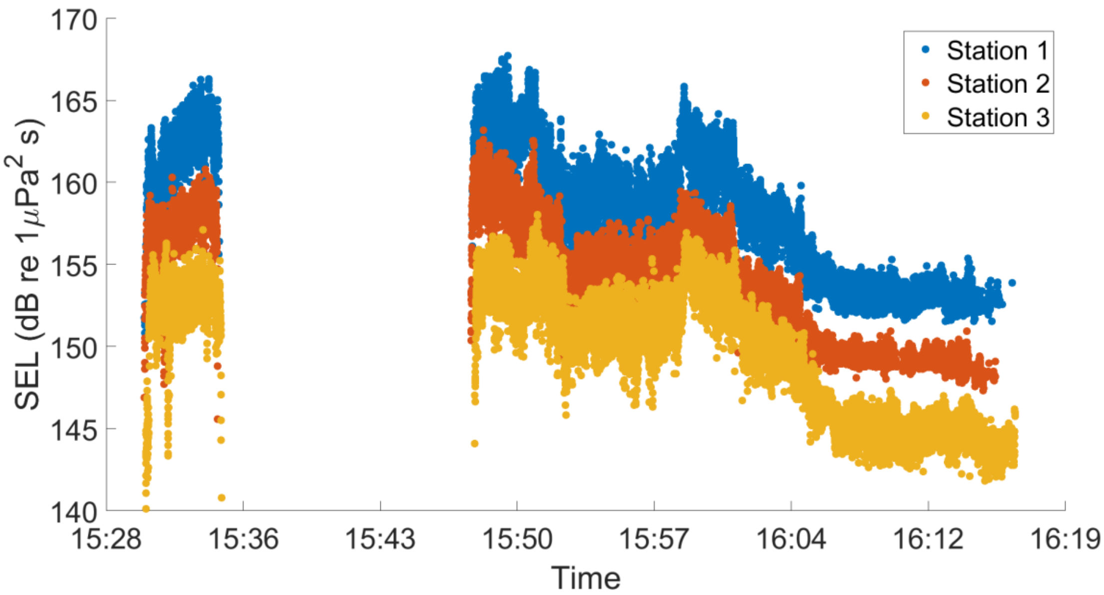

Figure 39. C8P7 recorded Sound Exposure Level (SEL) for single pulses over time for DTH hammering at the closest (Station 1), mid-range (Station 2), and farthest (Station 3) recording sites.

Appendix D. Levels as a function of range

D.1. C10P4

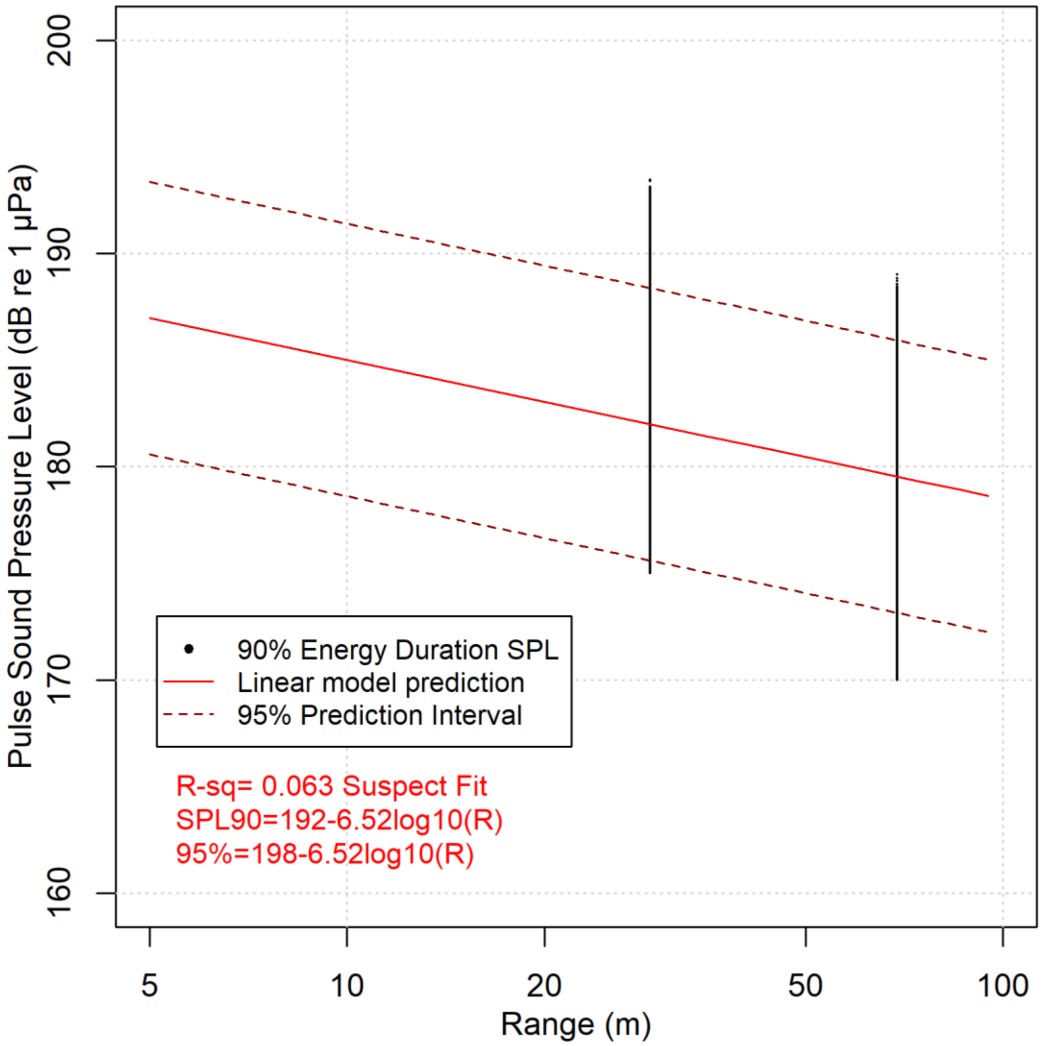

Figure D-1. Sound Pressure Level (SPL) of DTH hammering as a function of range (Stations 2, and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text. Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels.

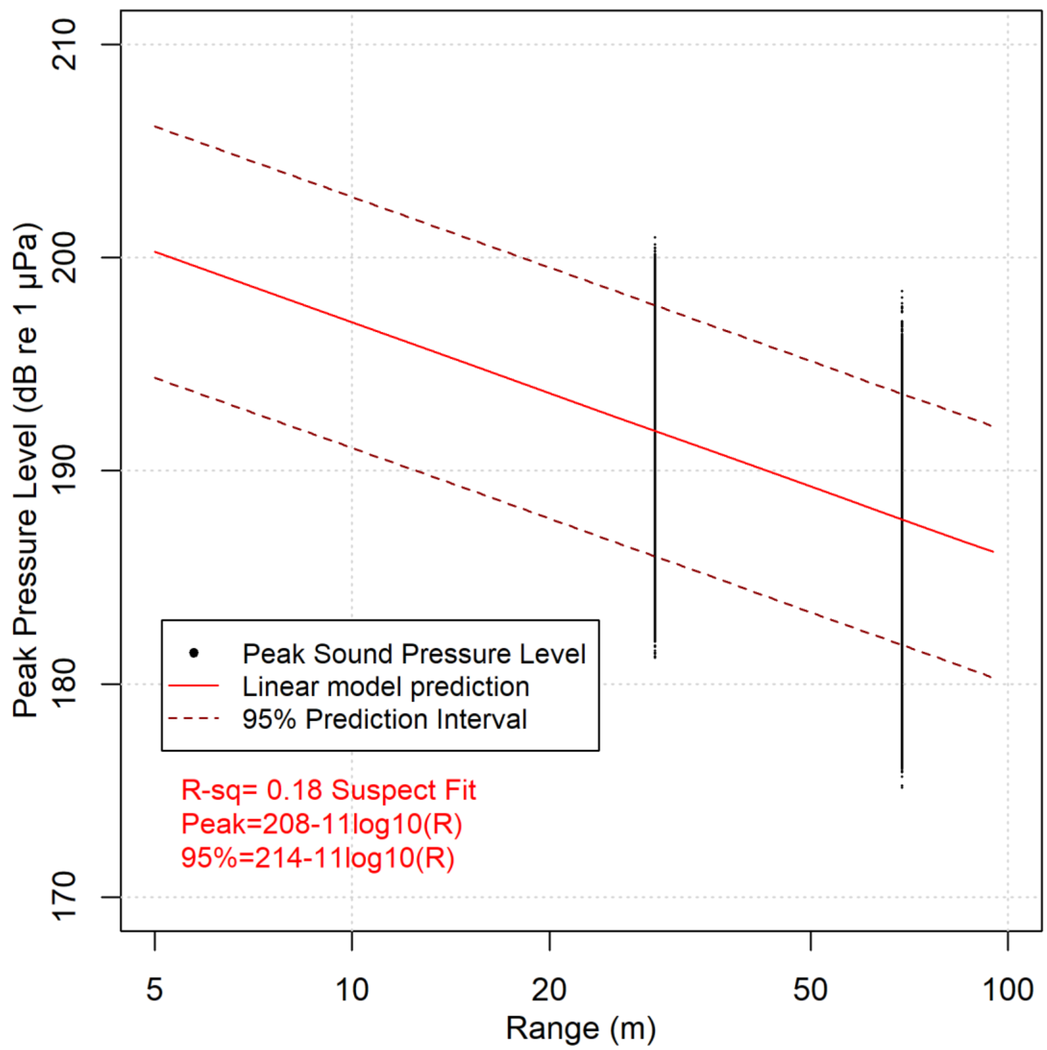

Figure D-2. Peak Sound Pressure (SEL) of DTH hammering as a function of range (Stations 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text. Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels.

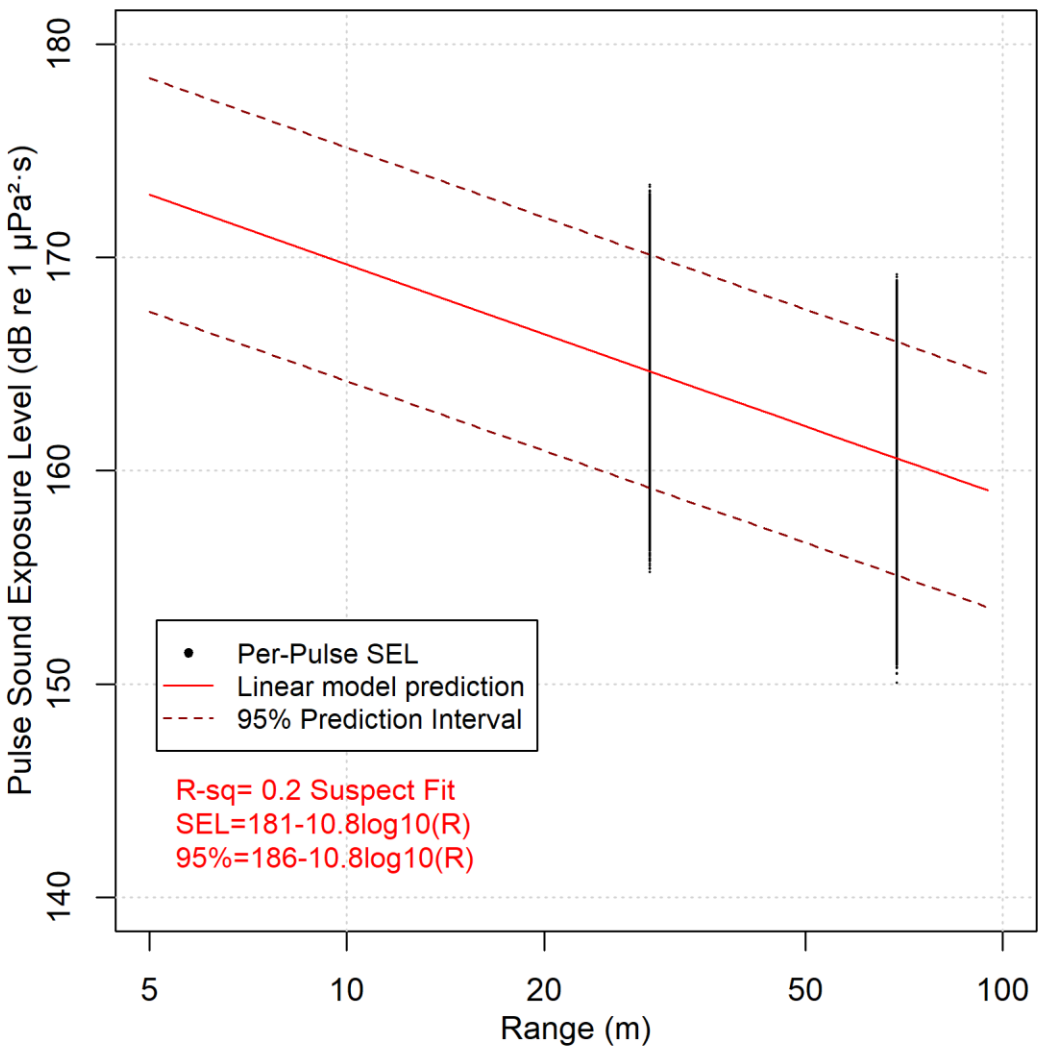

Figure D-3. Per-pulse Sound Exposure Level (SEL) of DTH hammering as a function of range (Stations 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text. Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels

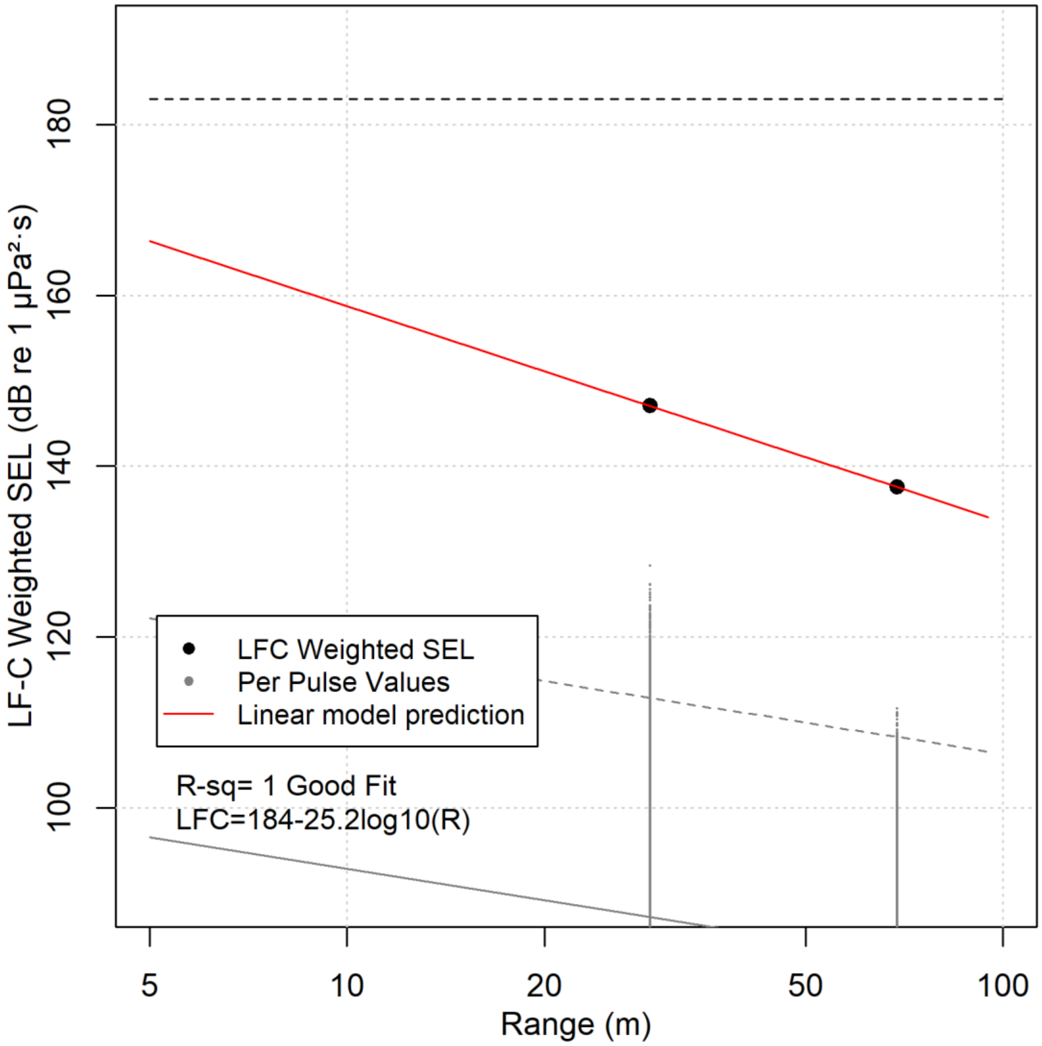

Figure D-4. Low-frequency cetacean (LFC) weighted per-pulse Sound Exposure Level (SEL) and LFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Black dashed line is the threshold for injury at 183 dB re 1µPa^2·s (NMFS 2018). The threshold for injury Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels

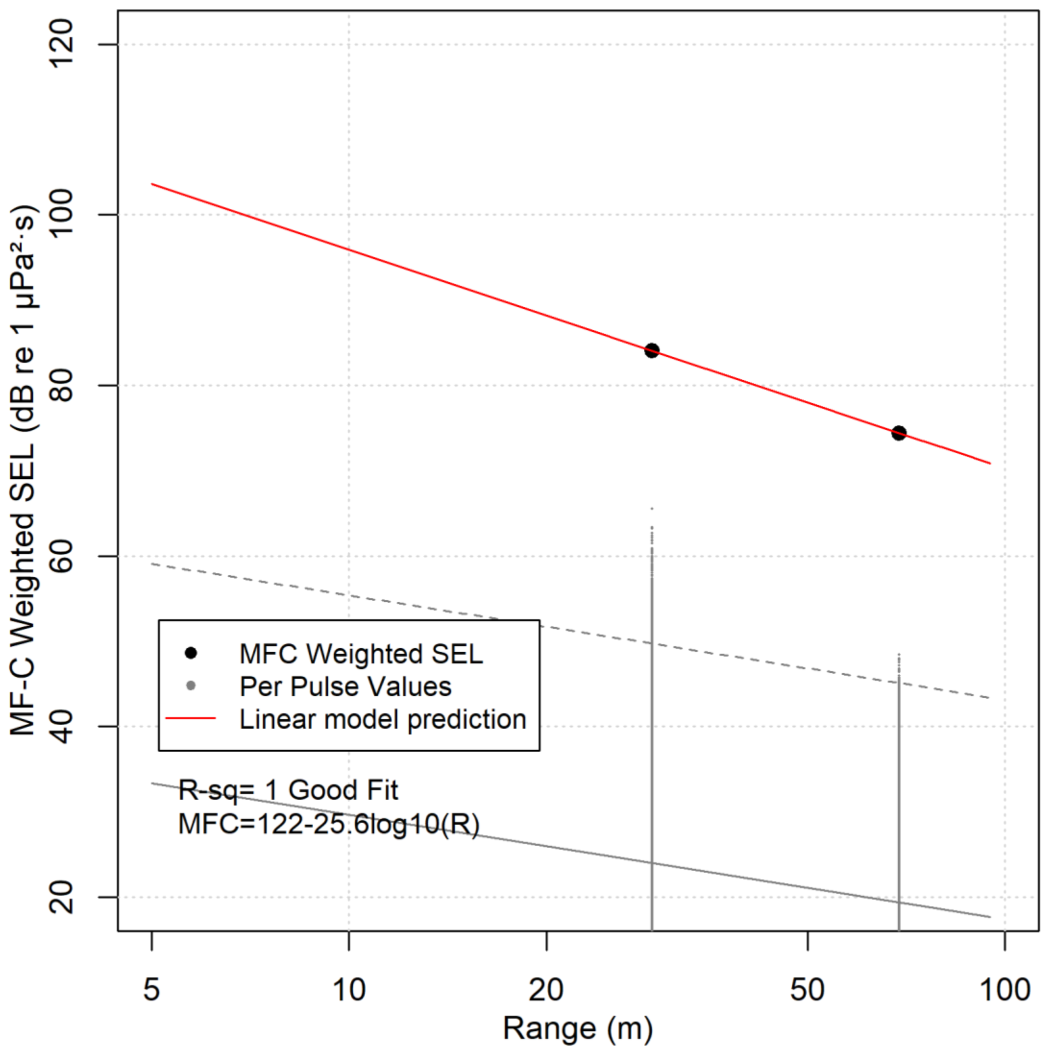

Figure D-5. Mid-frequency cetacean (MFC) weighted per-pulse Sound Exposure Level (SEL) and MFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa^2·s (NMFS 2018). Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels

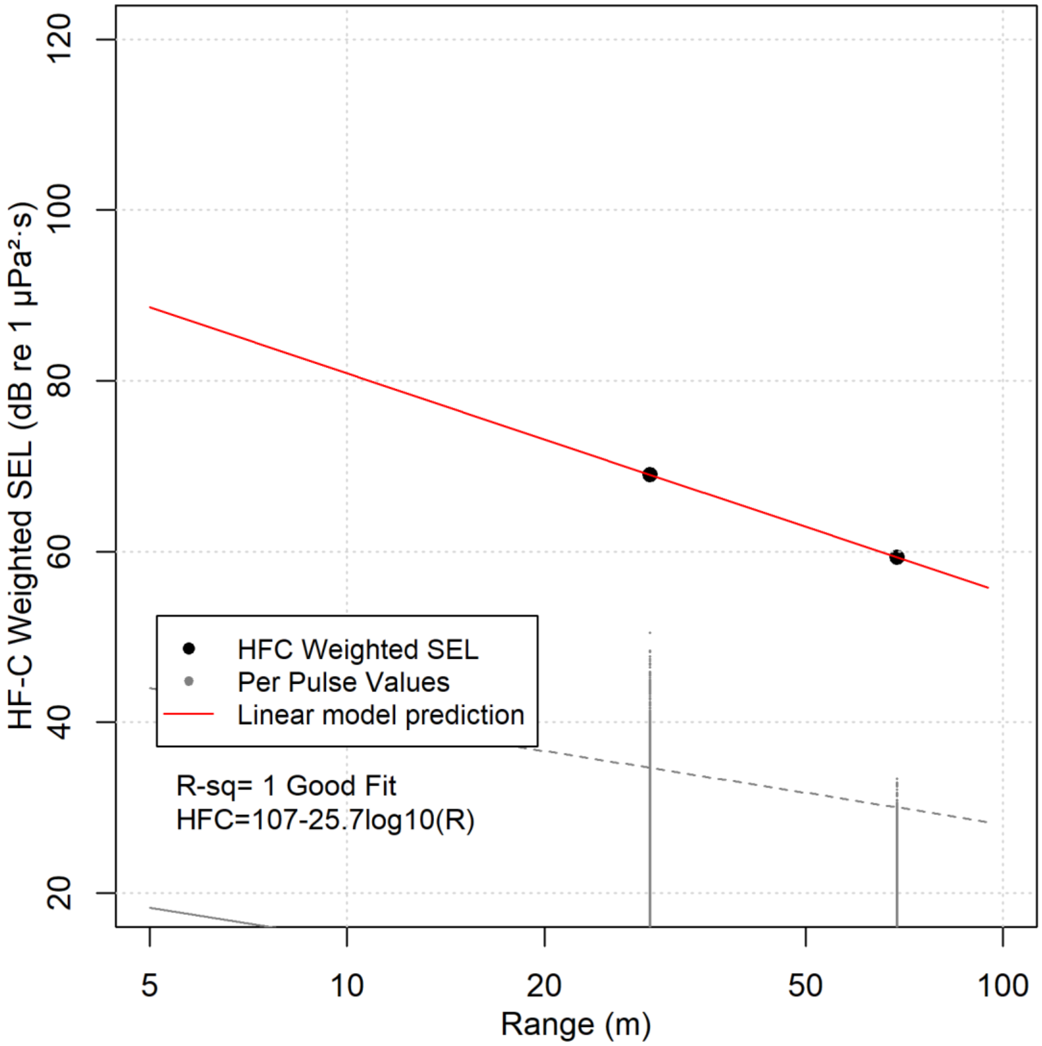

Figure D-6. High-frequency cetacean (HFC) weighted per-pulse Sound Exposure Level (SEL) and HFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 155 dB re 1µPa^2·s (NMFS 2018). Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels

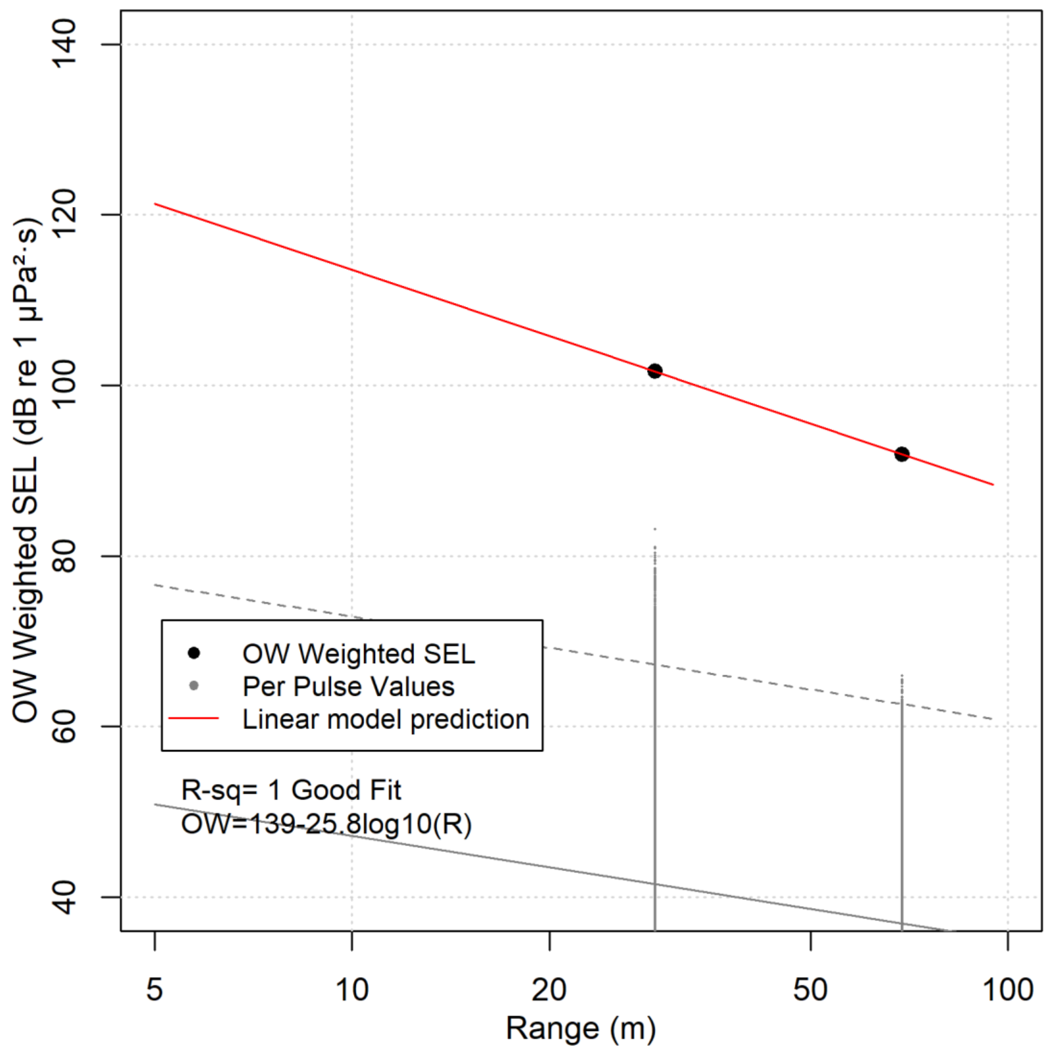

Figure D-7. Otariid underwater (OW) weighted per-pulse Sound Exposure Level (SEL) and OW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 203 dB re 1µPa^2·s (NMFS 2018). Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels

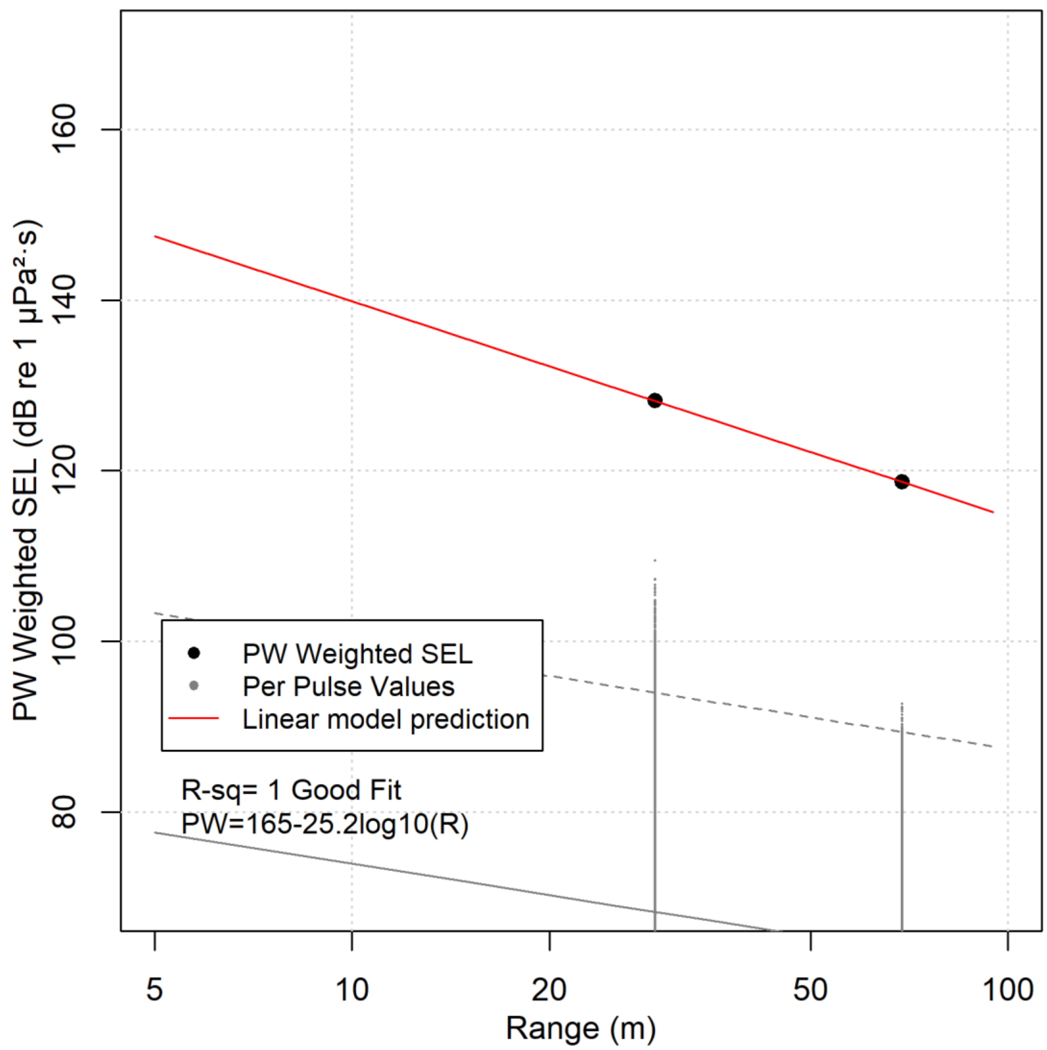

Figure D-8. Phocid underwater (PW) weighted per-pulse Sound Exposure Level (SEL) and PW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa^2·s (NMFS 2018). Note that Station 1 is not included in this plot because the recorder saturated at the closest recorder because of high sound levels

D.2. C8P8

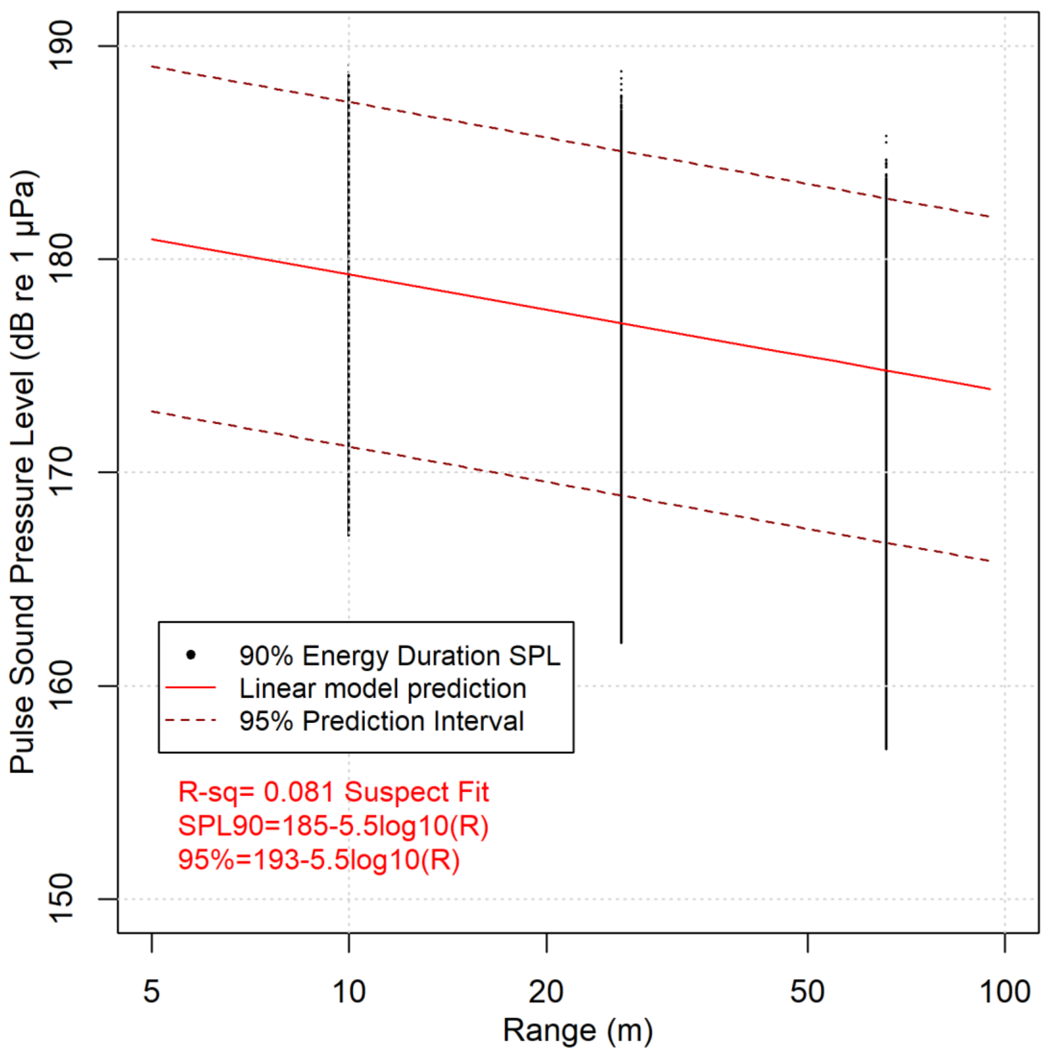

Figure D-9. Sound Pressure Level (SPL) of DTH hammering as a function of range (Stations 1, 2, and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

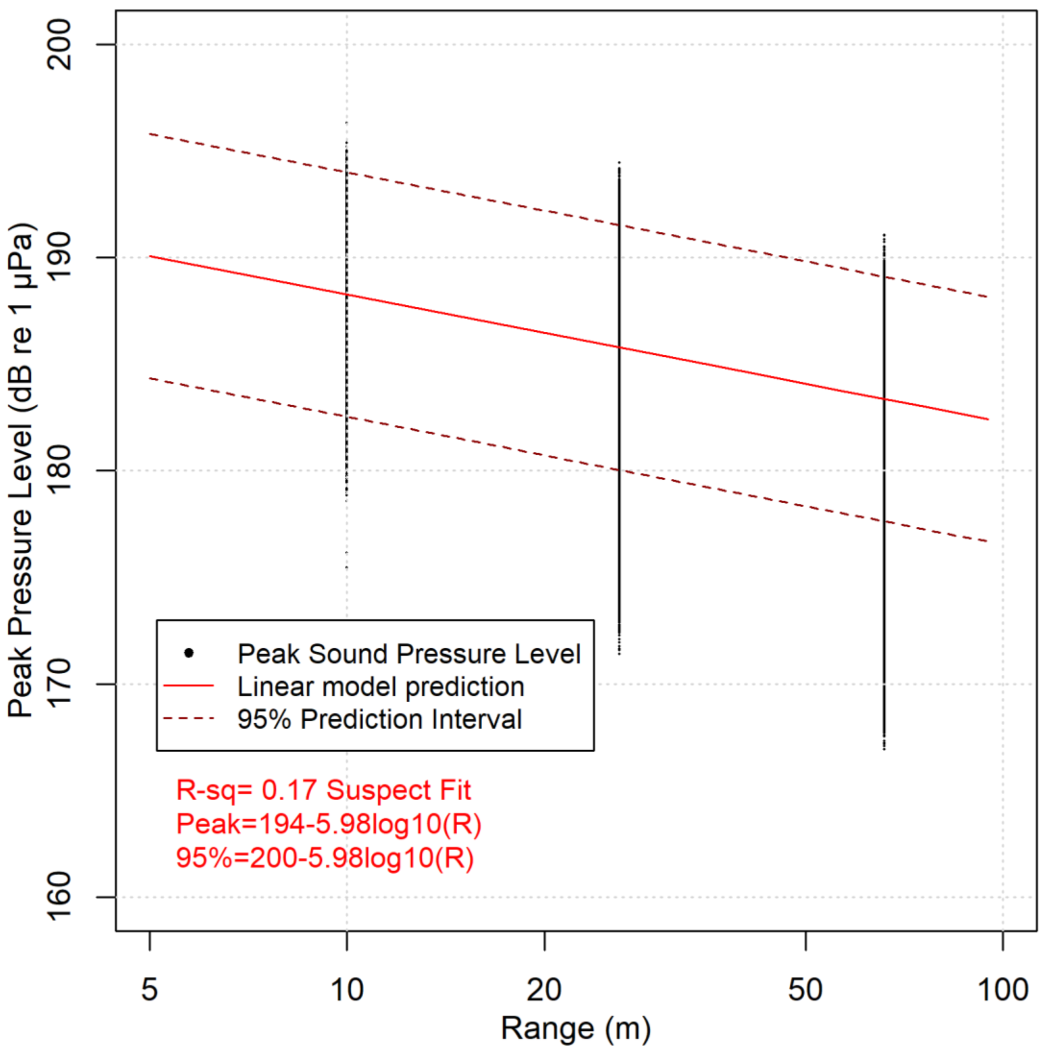

Figure D-10. Peak Sound Pressure (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

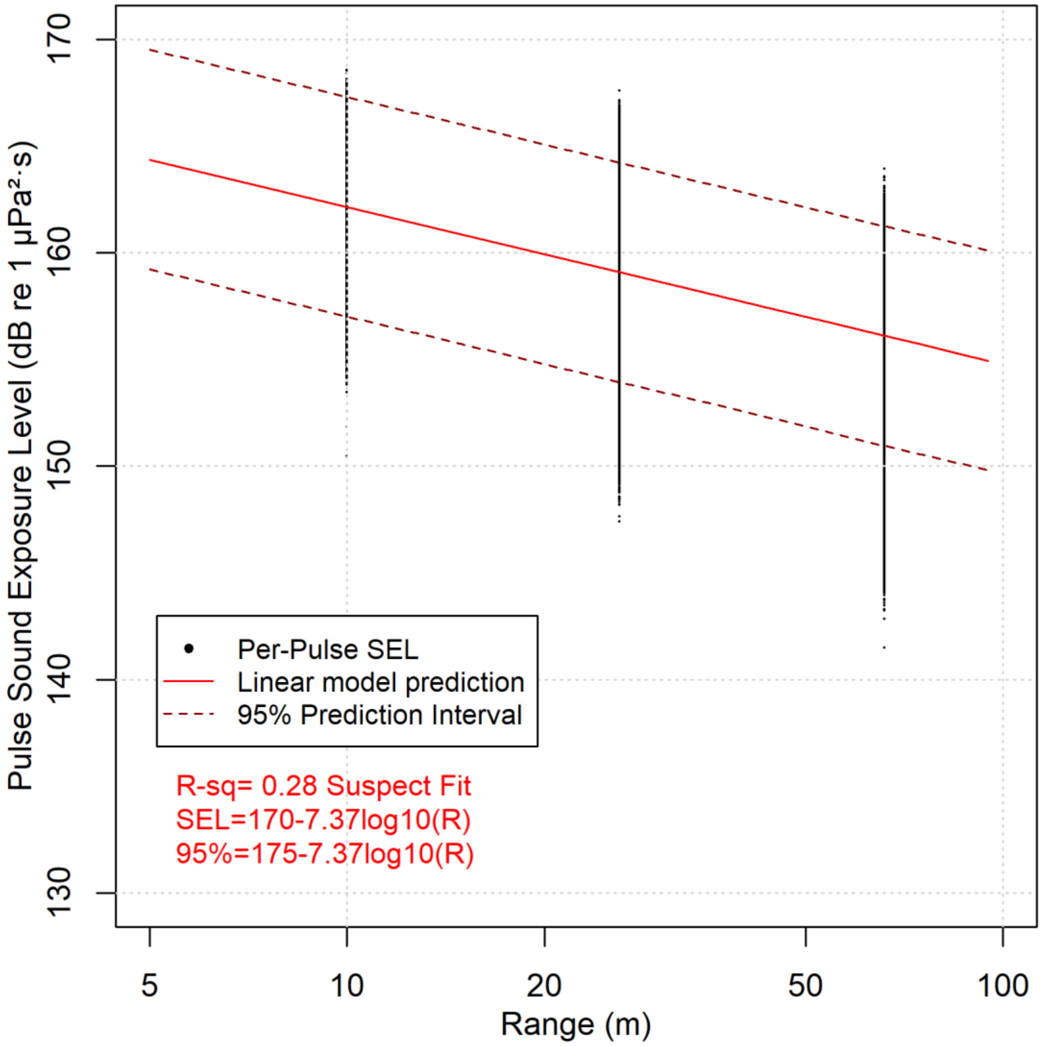

Figure D-11. Per-pulse Sound Exposure Level (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

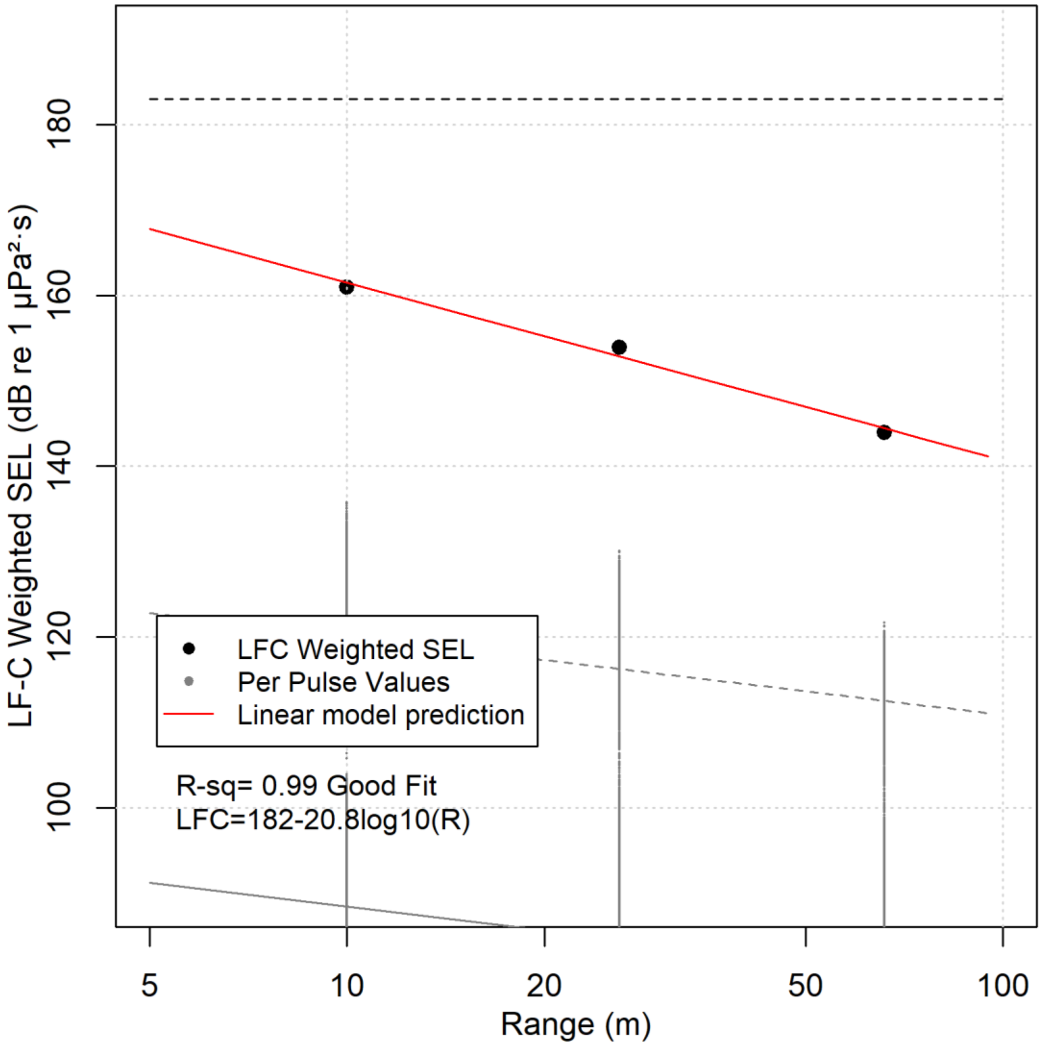

Figure D-12. Low-frequency cetacean (LFC) weighted per-pulse Sound Exposure Level (SEL) and LFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Black dashed line is the threshold for injury at 183 dB re 1µPa^2·s (NMFS 2018).

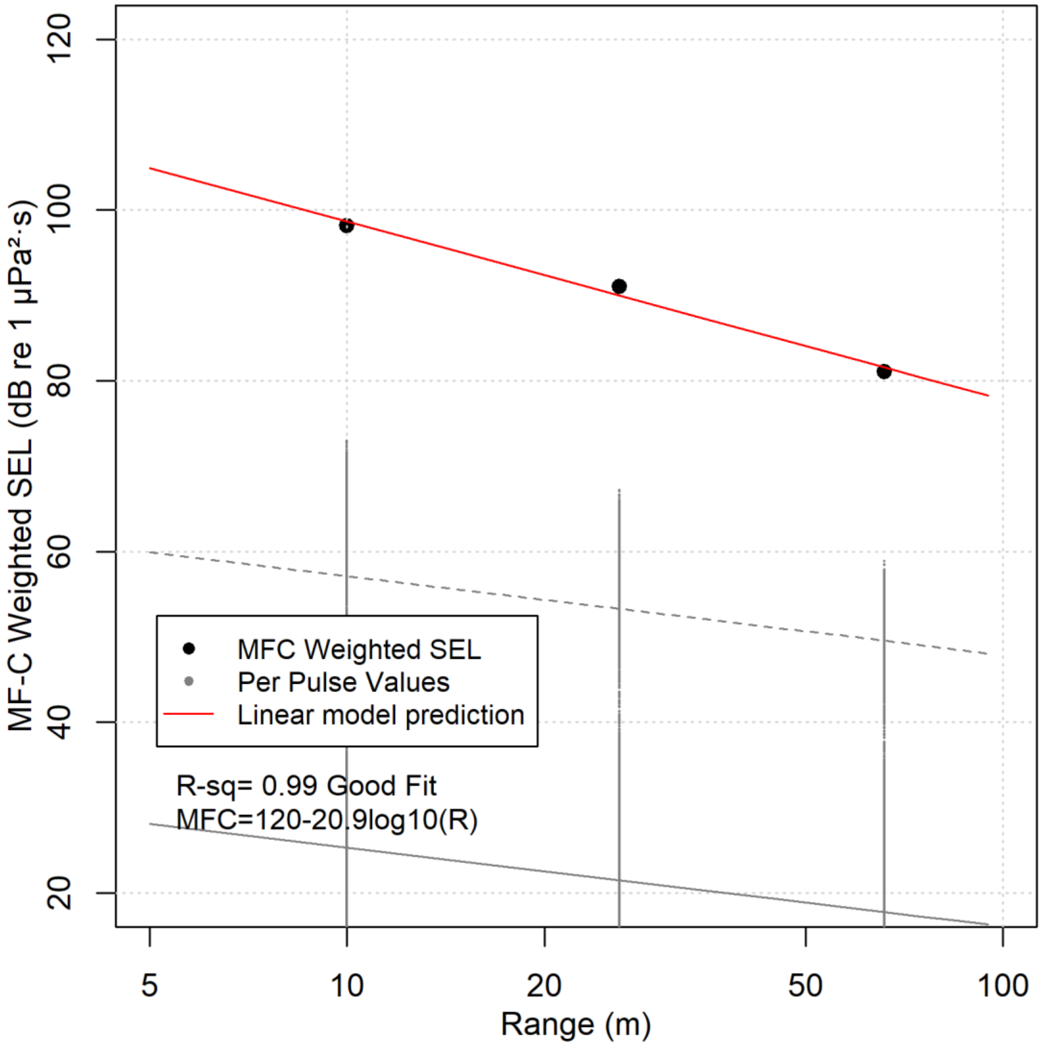

Figure D-13. Mid-frequency cetacean (MFC) weighted per-pulse Sound Exposure Level (SEL) and MFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa^2·s (NMFS 2018).

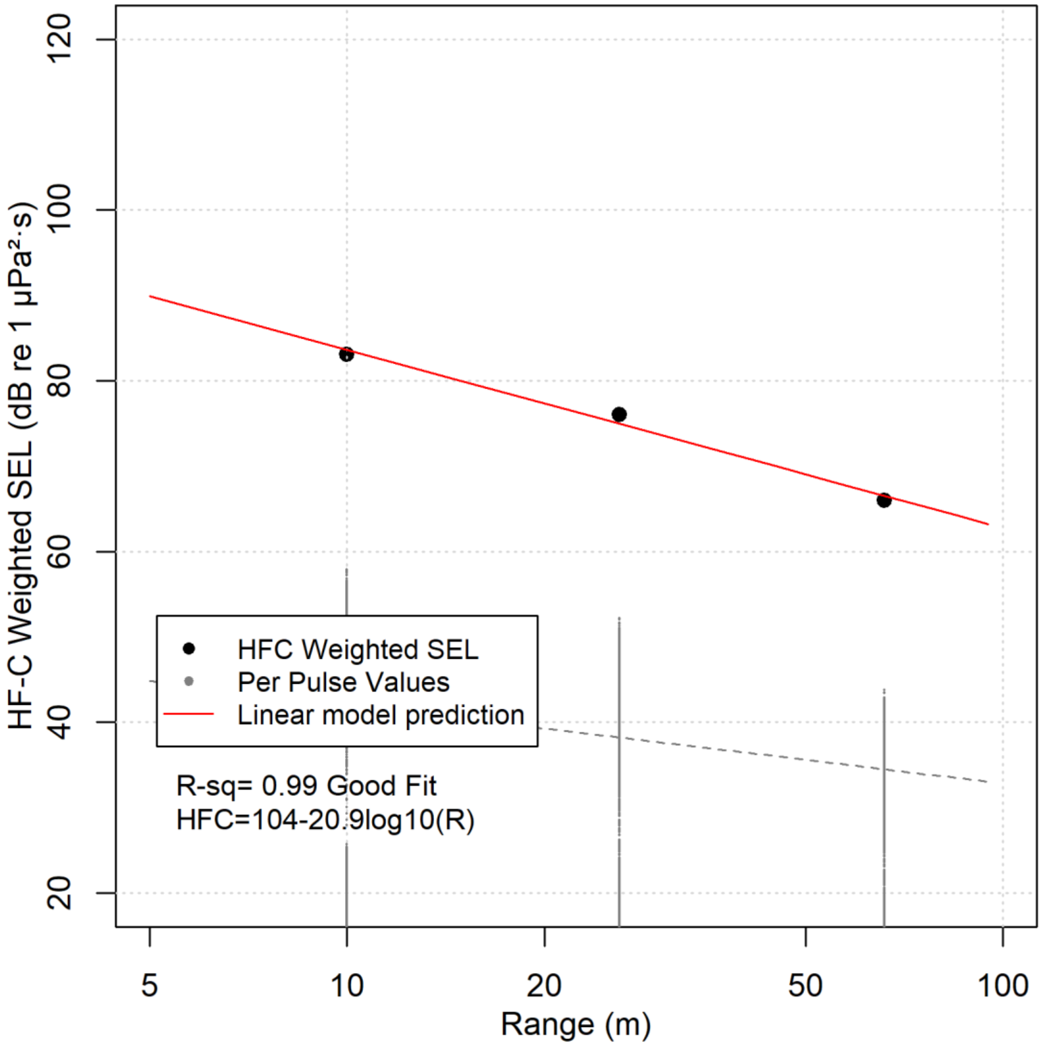

Figure D-14. High-frequency cetacean (HFC) weighted per-pulse Sound Exposure Level (SEL) and HFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 155 dB re 1µPa^2·s (NMFS 2018).

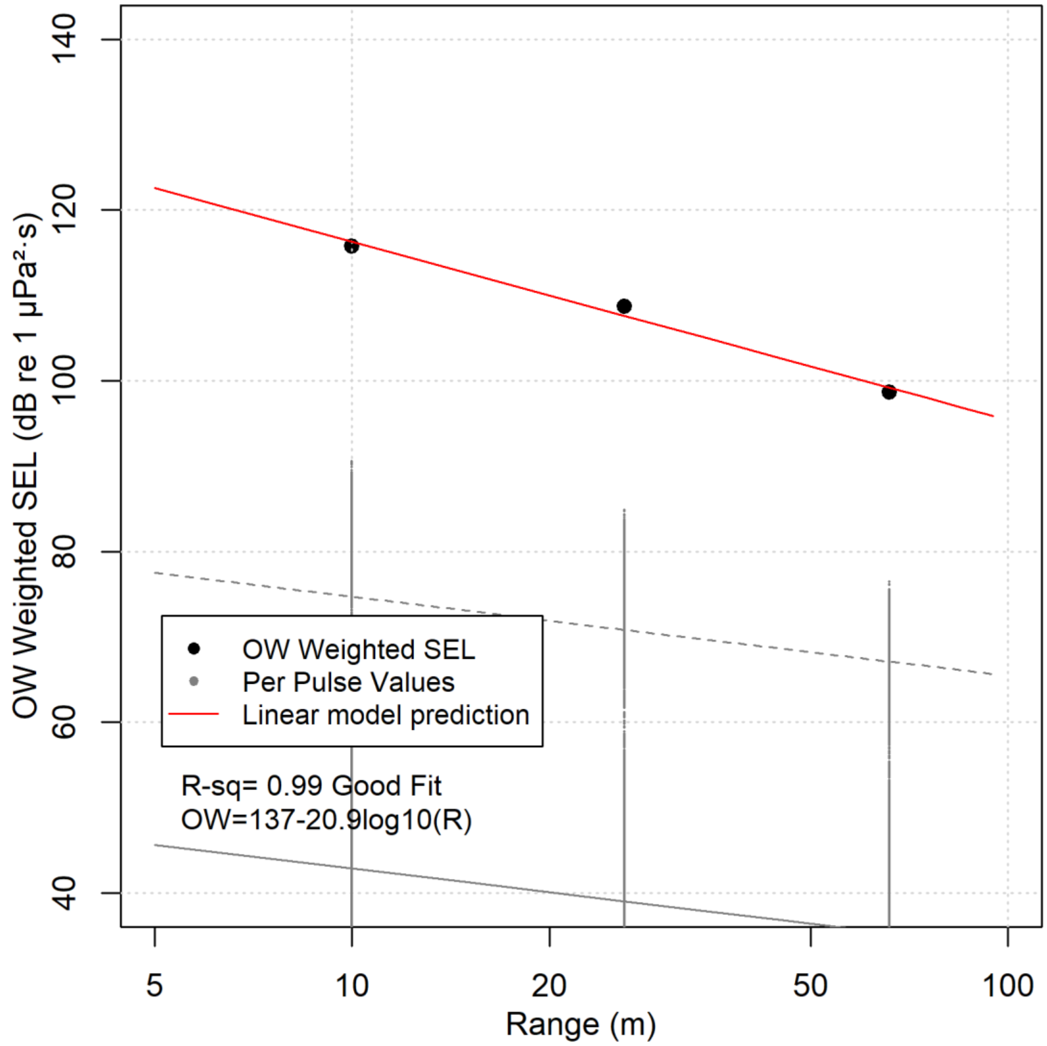

Figure D-15. Otariid underwater (OW) weighted per-pulse Sound Exposure Level (SEL) and OW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 203 dB re 1µPa^2·s (NMFS 2018).

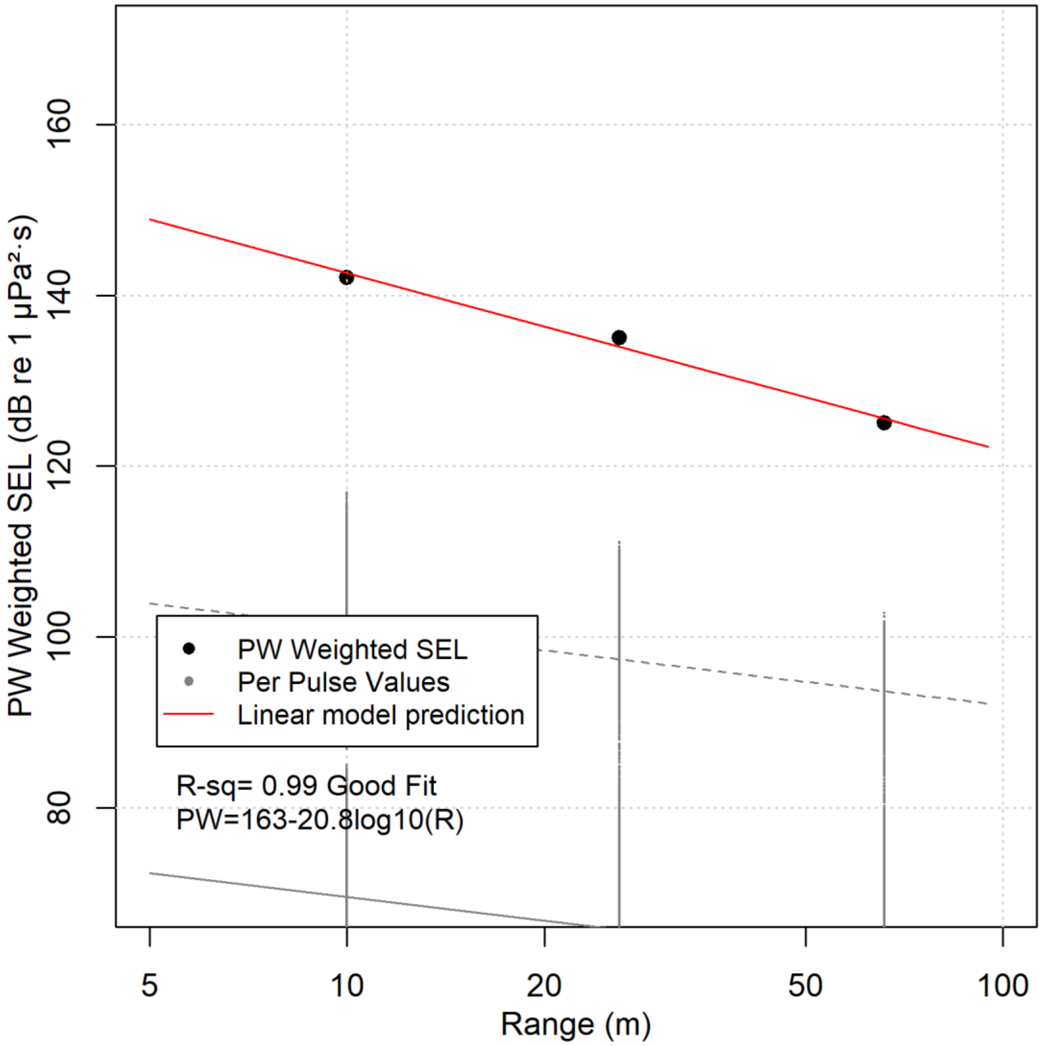

Figure D-16. Phocid underwater (PW) weighted per-pulse Sound Exposure Level (SEL) and PW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa^2·s (NMFS 2018).

D.3. C9P5

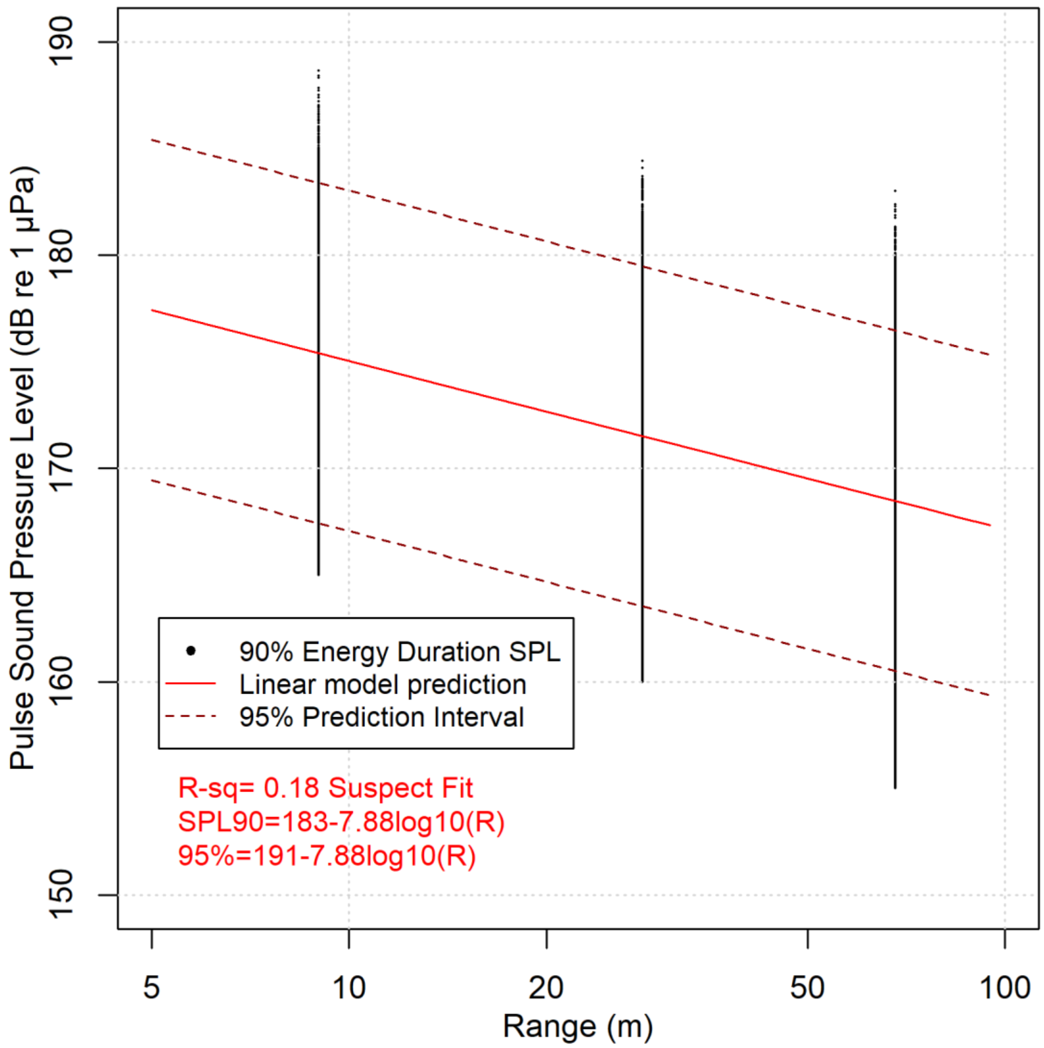

Figure D-17. Sound Pressure Level (SPL) of DTH hammering as a function of range (Stations 1, 2, and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

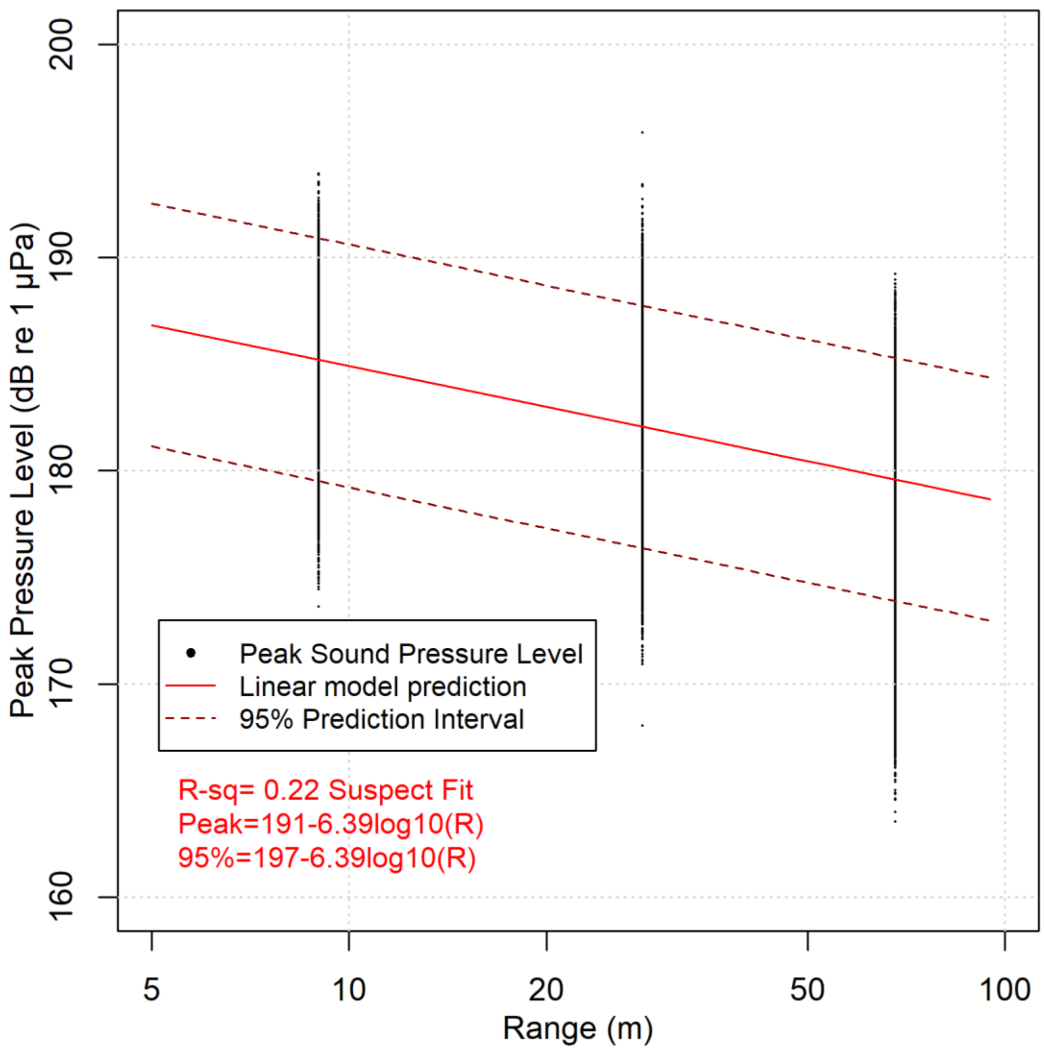

Figure D-18. Peak Sound Pressure (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

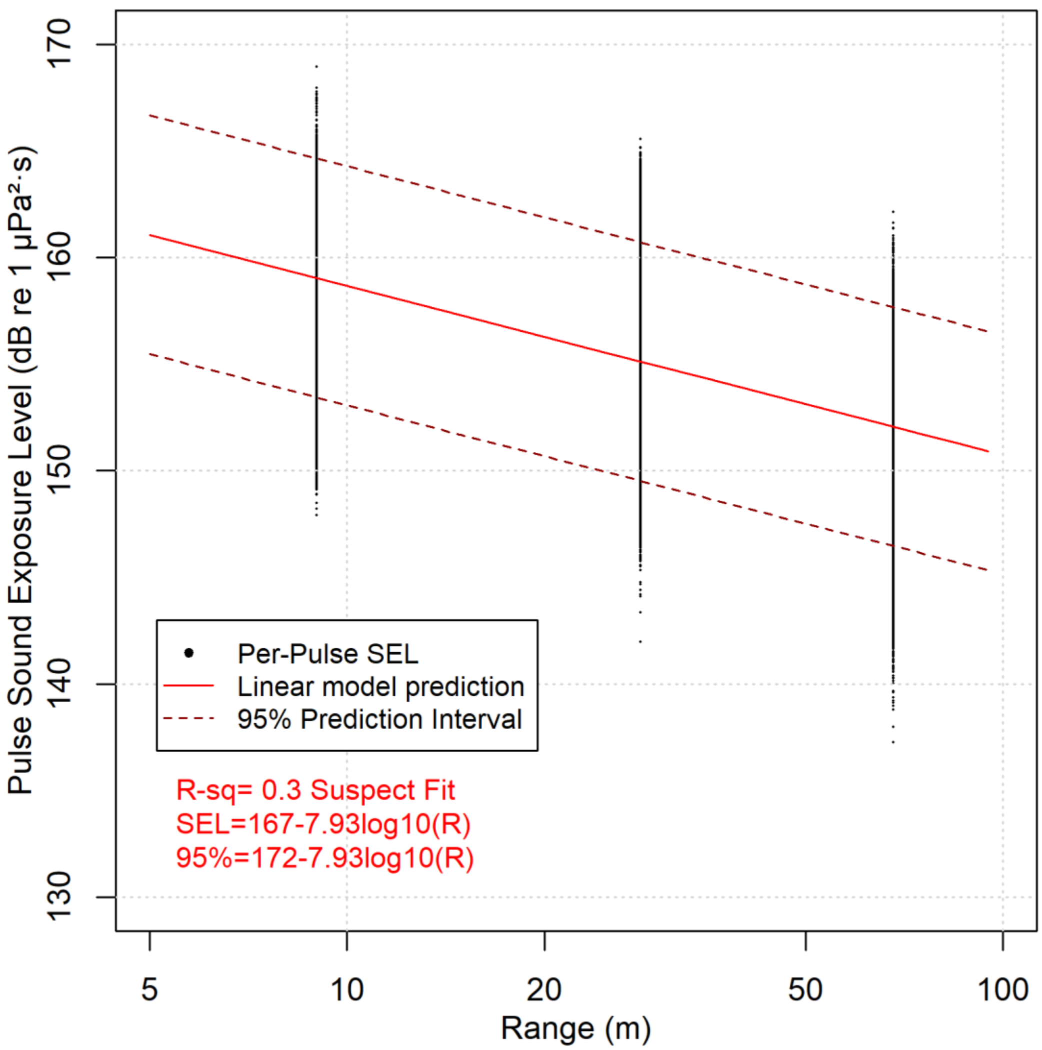

Figure D-19. Per-pulse Sound Exposure Level (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

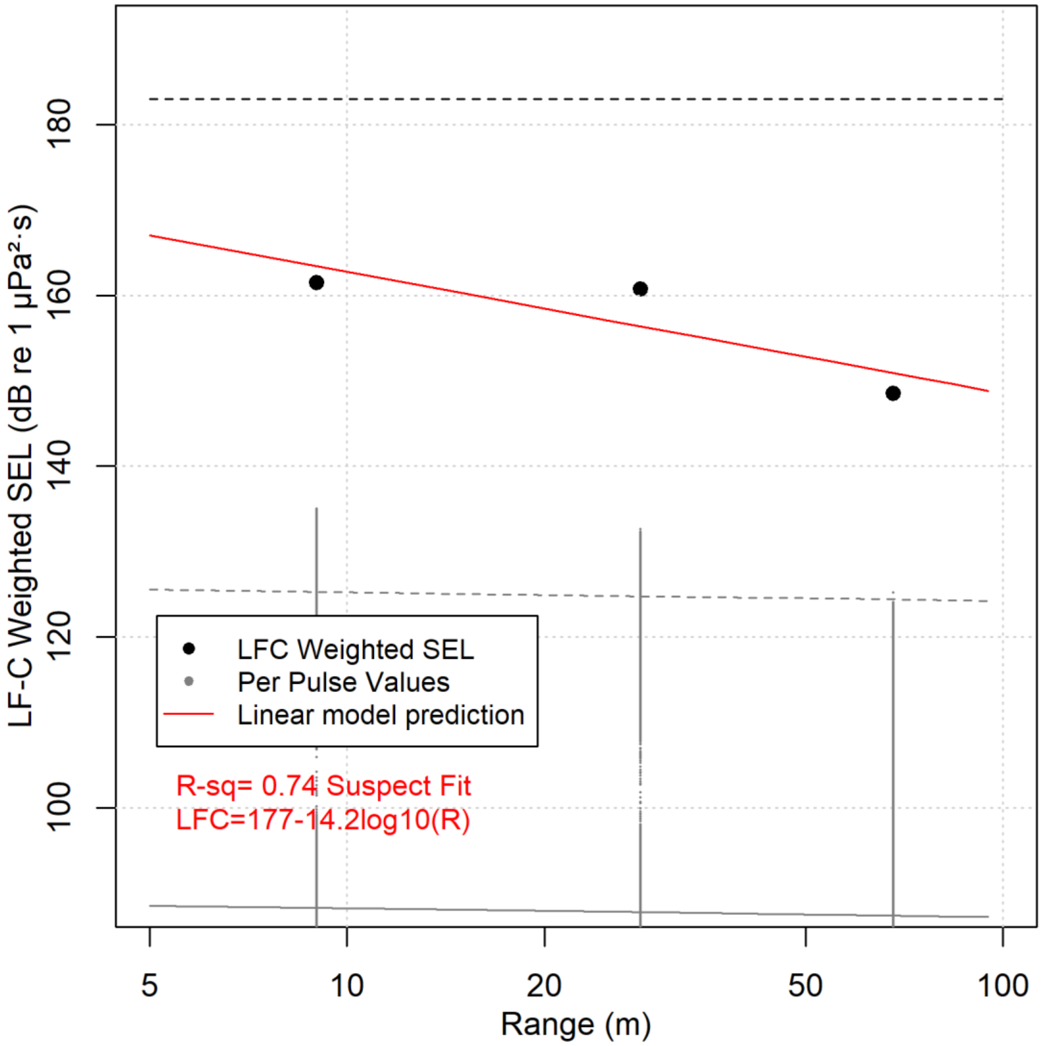

Figure D-20. Low-frequency cetacean (LFC) weighted per-pulse Sound Exposure Level (SEL) and LFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Black dashed line is the threshold for injury at 183 dB re 1µPa^2·s (NMFS 2018).

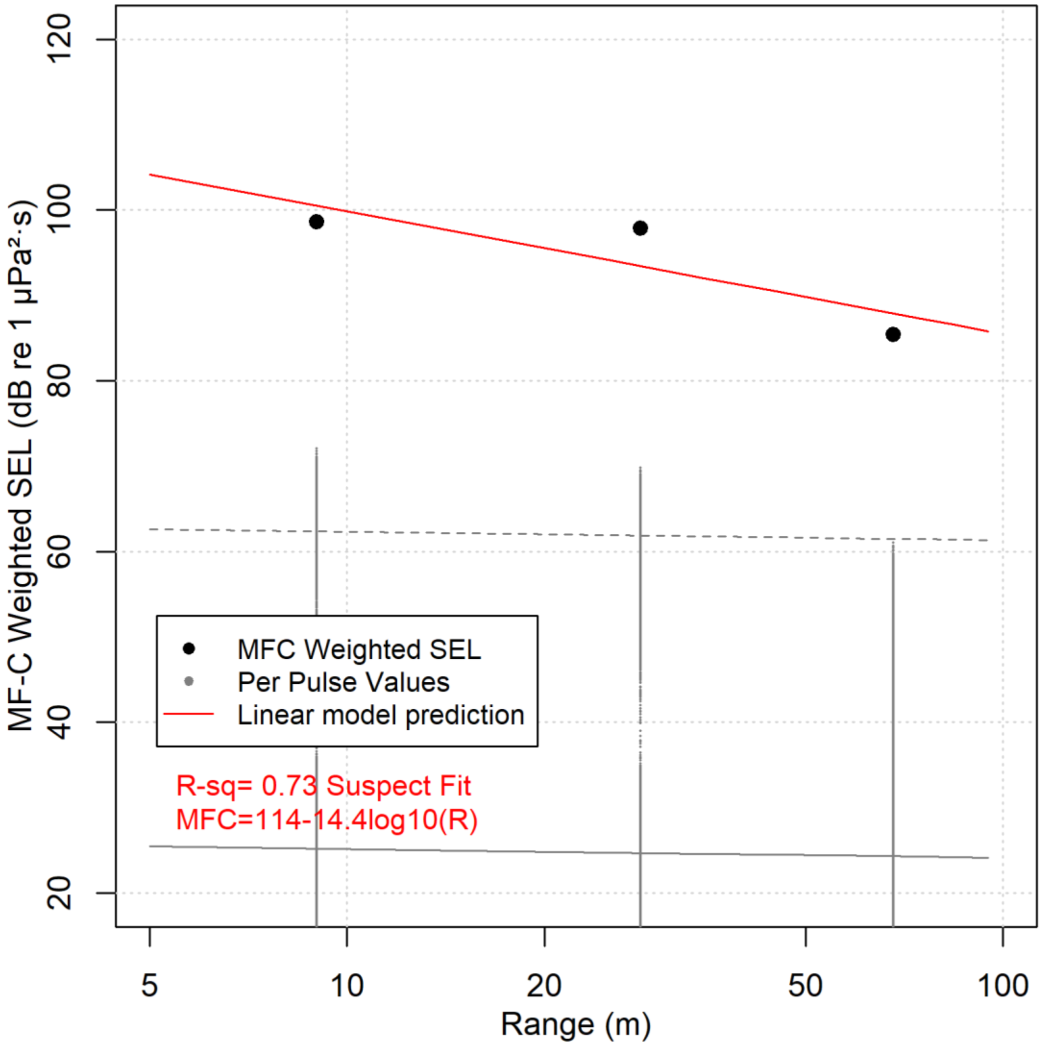

Figure D-21. Mid-frequency cetacean (MFC) weighted per-pulse Sound Exposure Level (SEL) and MFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa^2·s (NMFS 2018).

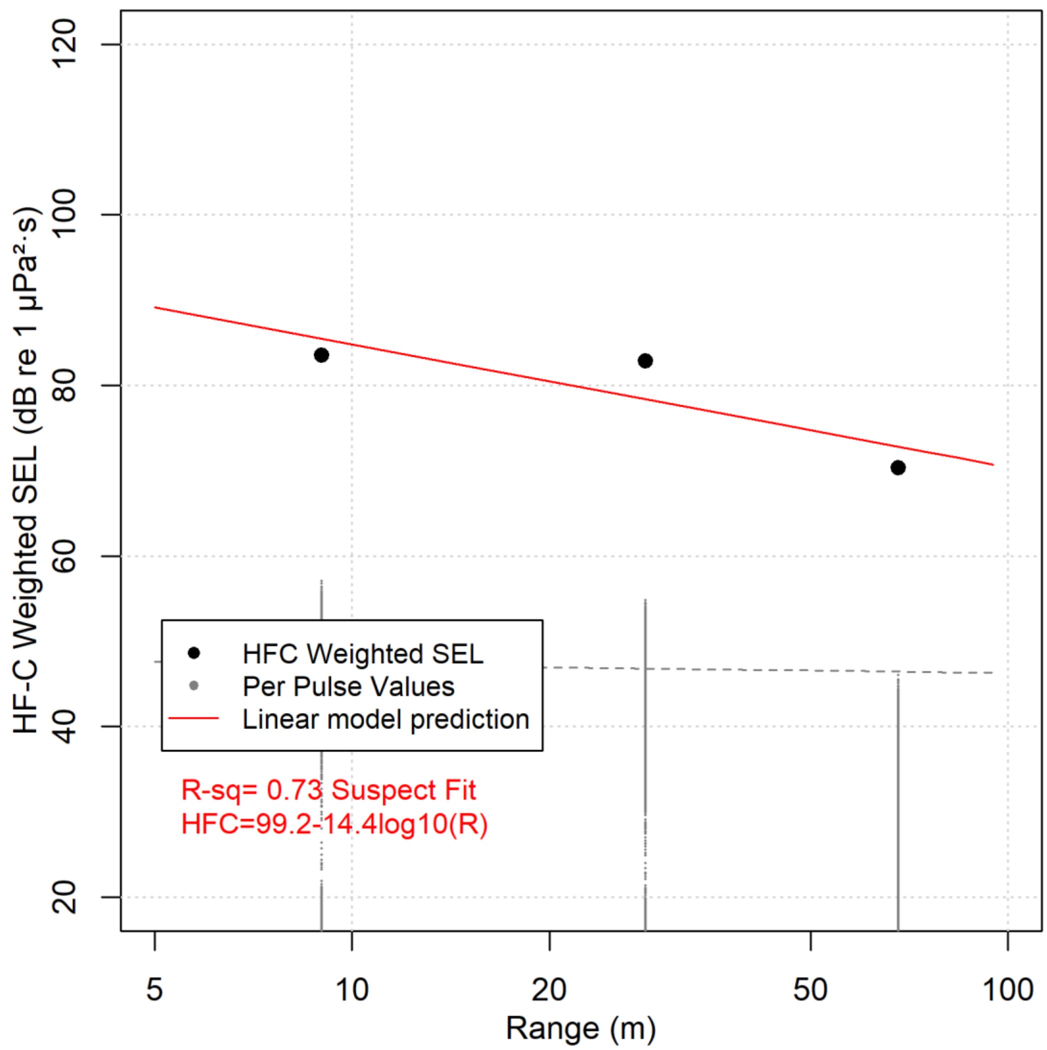

Figure D-22. High-frequency cetacean (HFC) weighted per-pulse Sound Exposure Level (SEL) and HFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 155 dB re 1µPa^2·s (NMFS 2018).

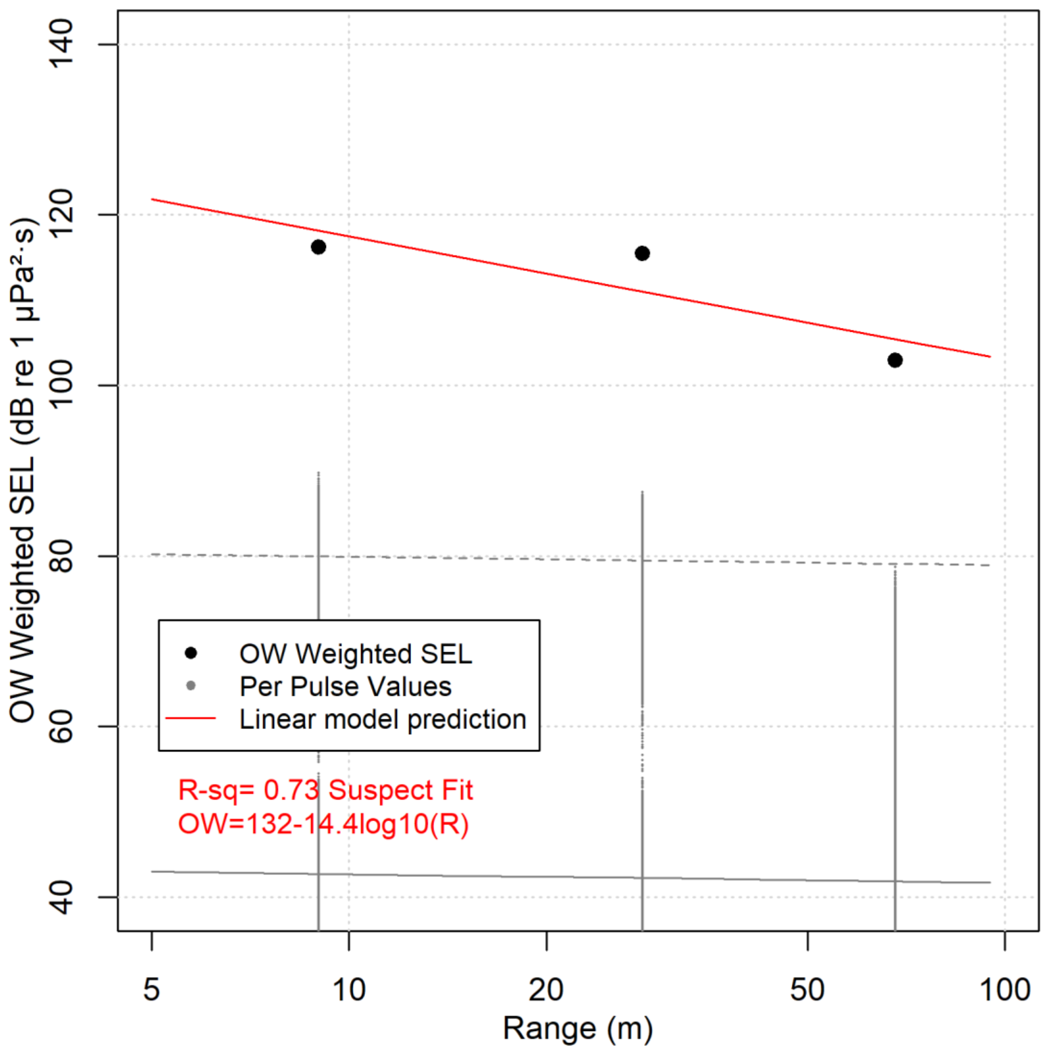

Figure D-23. Otariid underwater (OW) weighted per-pulse Sound Exposure Level (SEL) and OW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 203 dB re 1µPa^2·s (NMFS 2018).

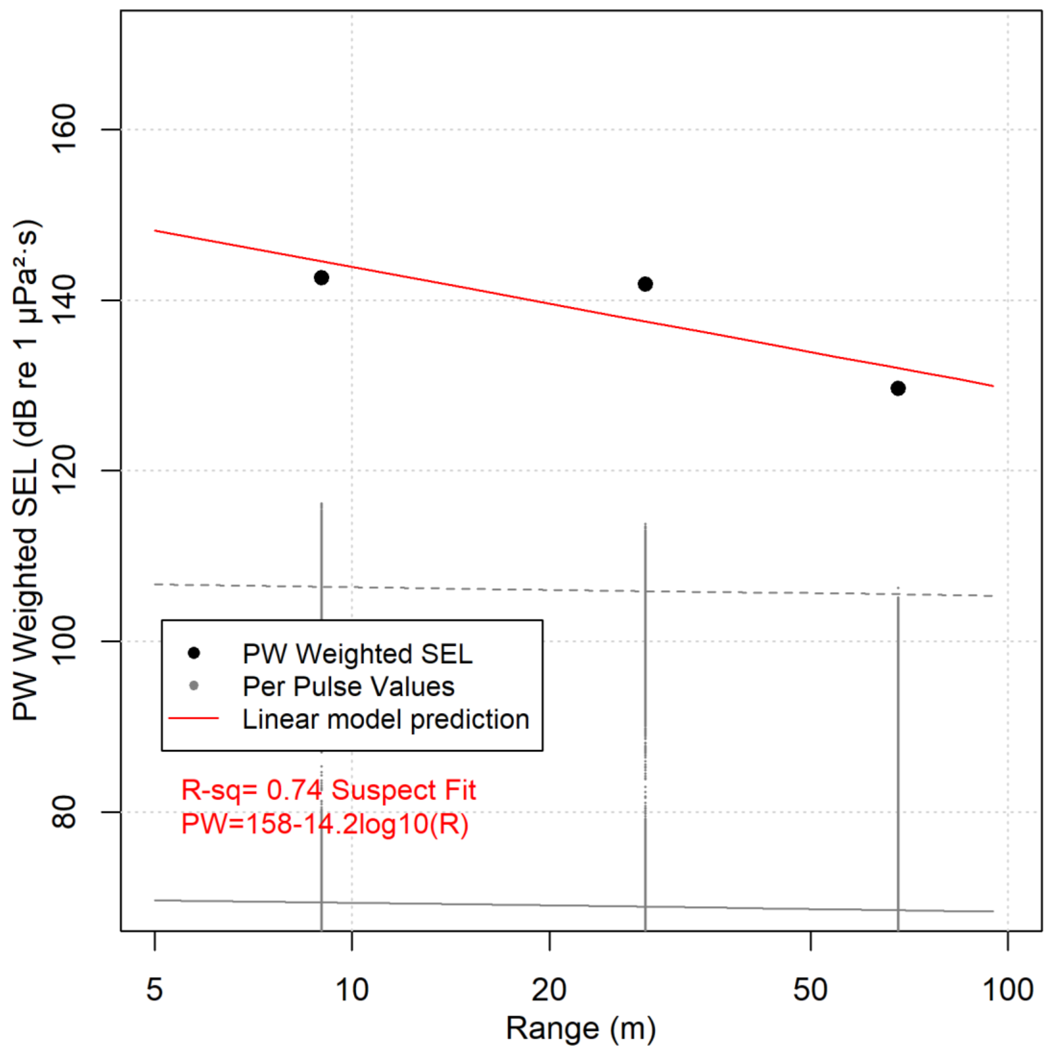

Figure D-24. Phocid underwater (PW) weighted per-pulse Sound Exposure Level (SEL) and PW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text.

D.4. C8P6 (with bubble curtain)

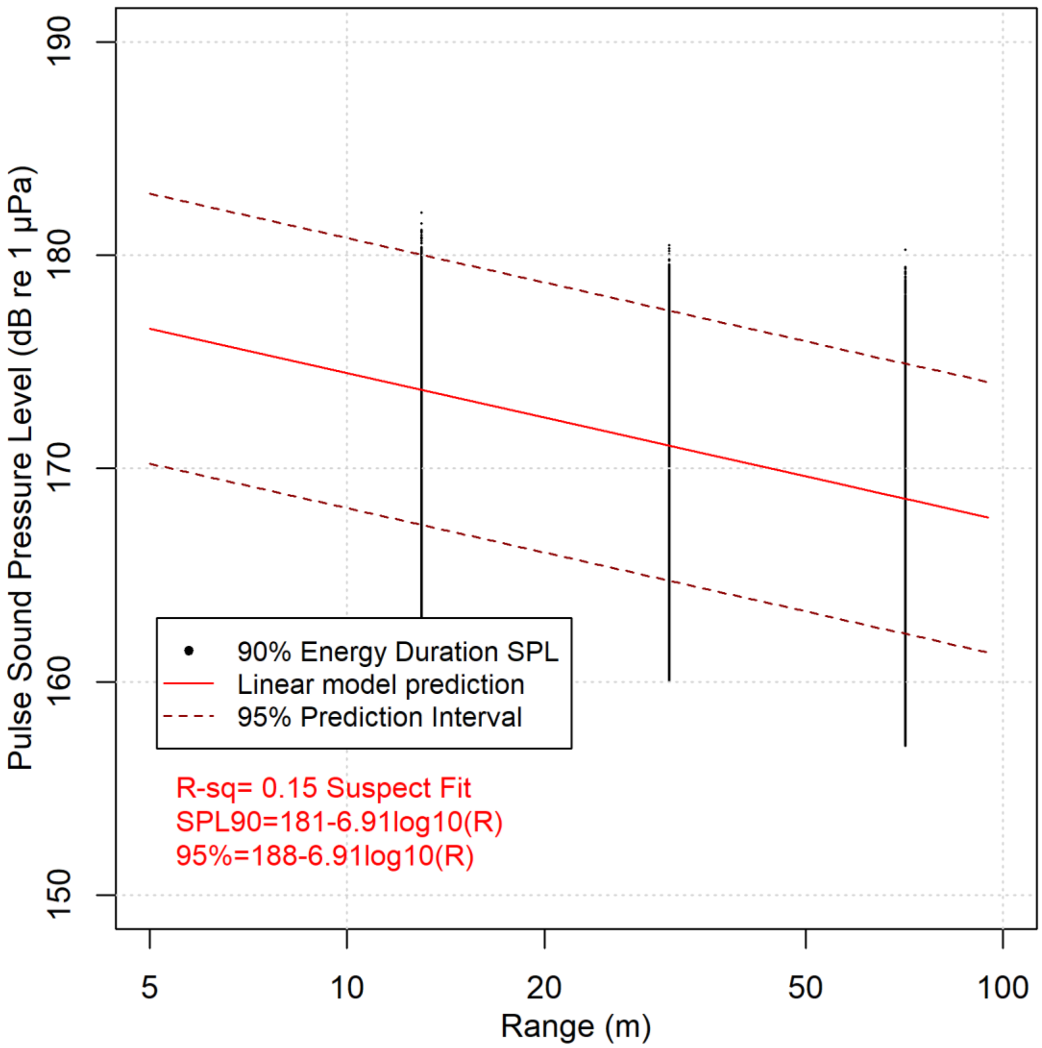

Figure D-25. Sound Pressure Level (SPL) of DTH hammering as a function of range (Stations 1, 2, and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

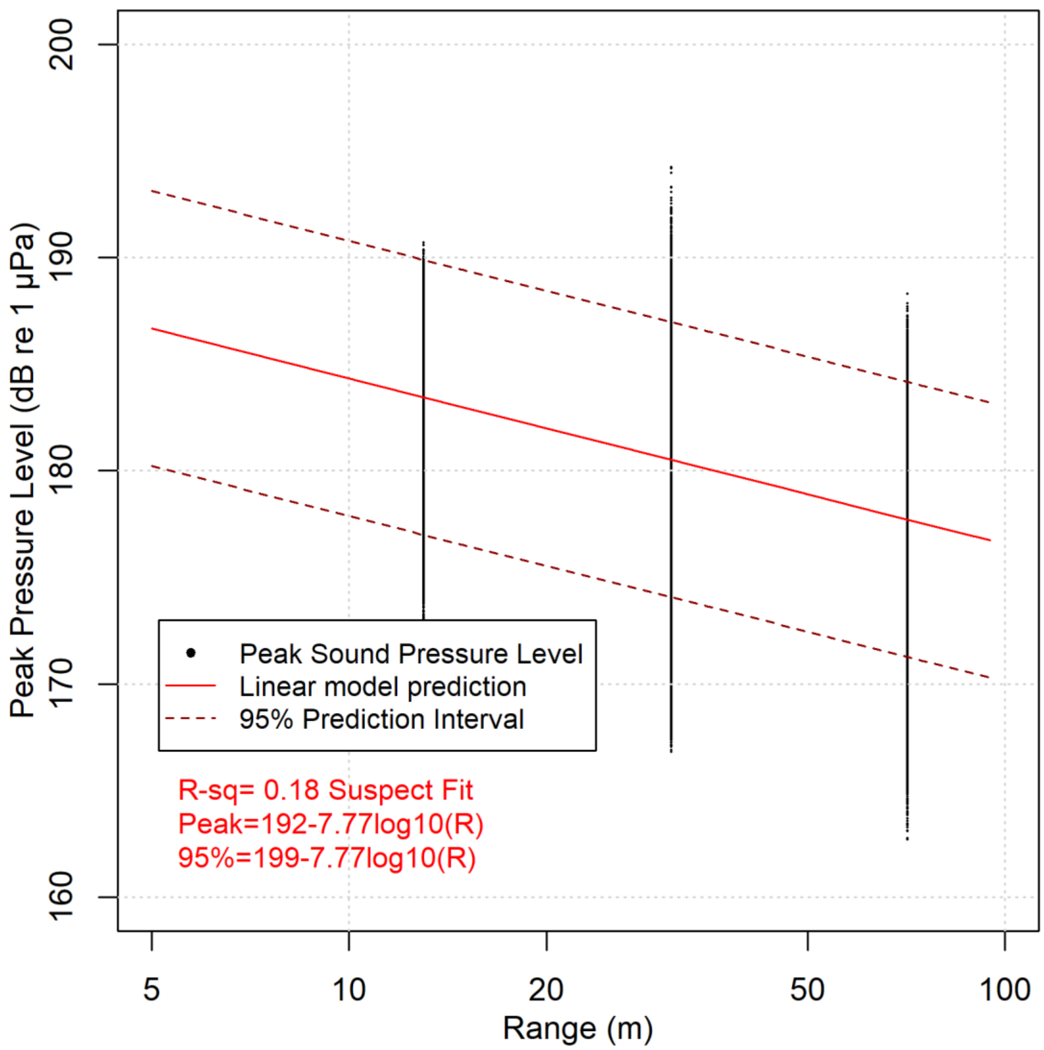

Figure D-26. Peak Sound Pressure (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

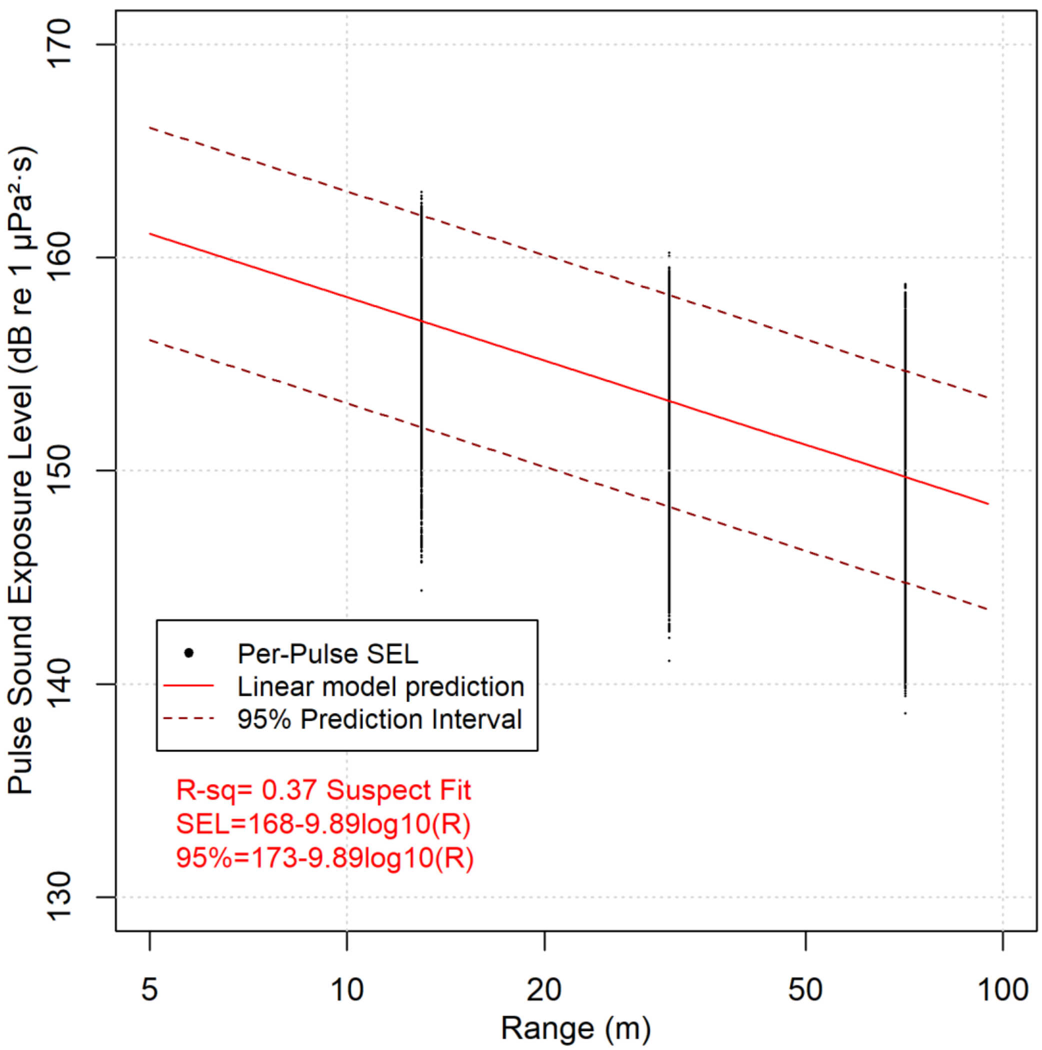

Figure D-27. Per-pulse Sound Exposure Level (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

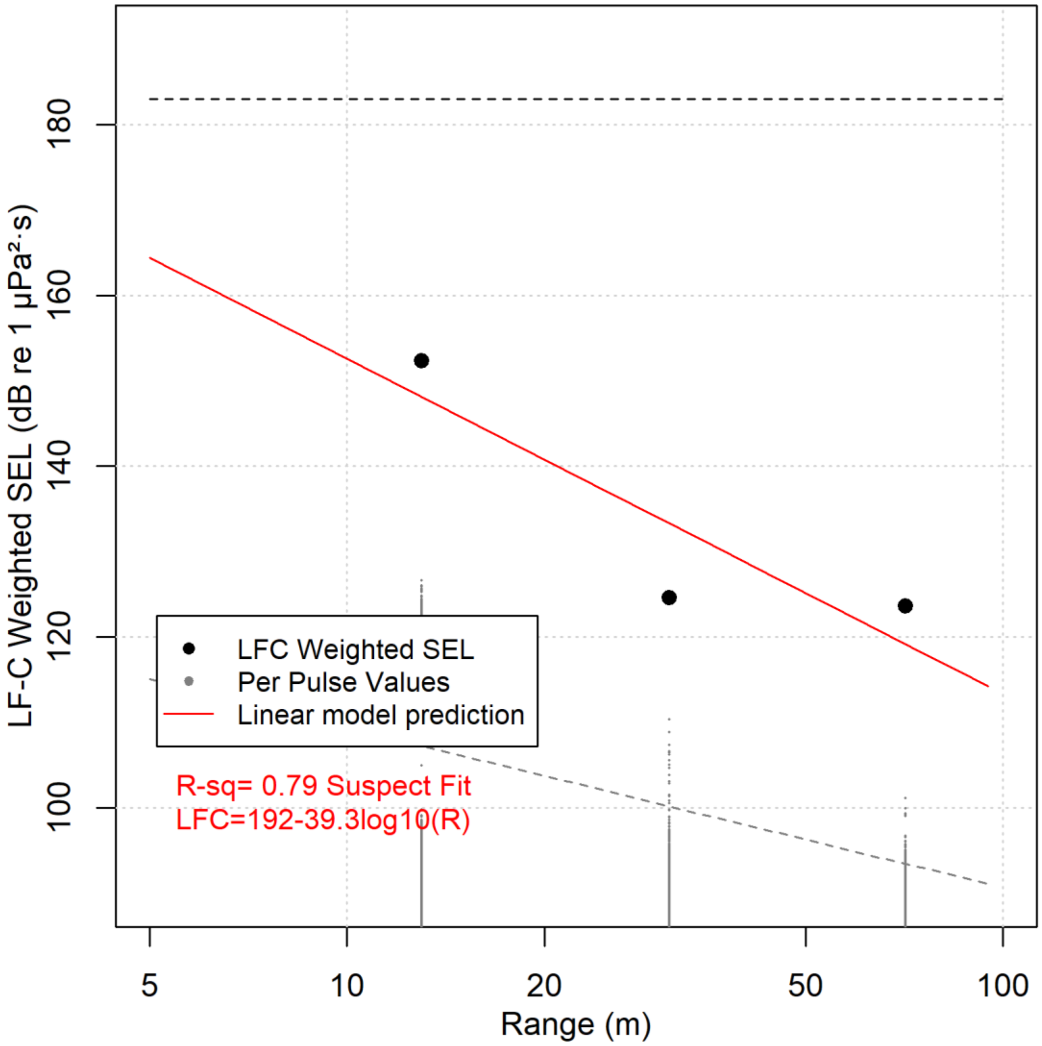

Figure D-28. Low-frequency cetacean (LFC) weighted per-pulse Sound Exposure Level (SEL) and LFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Black dashed line is the threshold for injury at 183 dB re 1µPa^2·s (NMFS 2018).

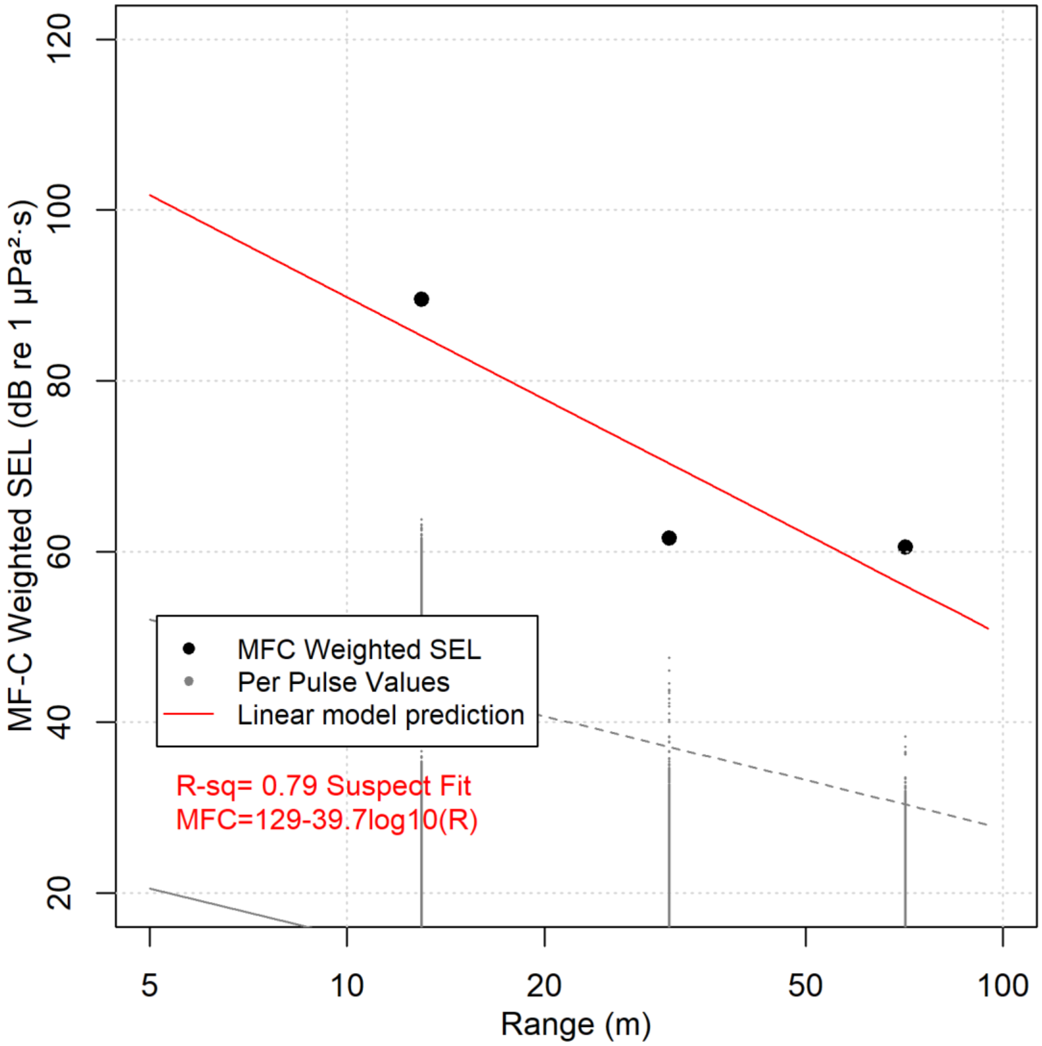

Figure D-29. Mid-frequency cetacean (MFC) weighted per-pulse Sound Exposure Level (SEL) and MFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa²·s (NMFS 2018).

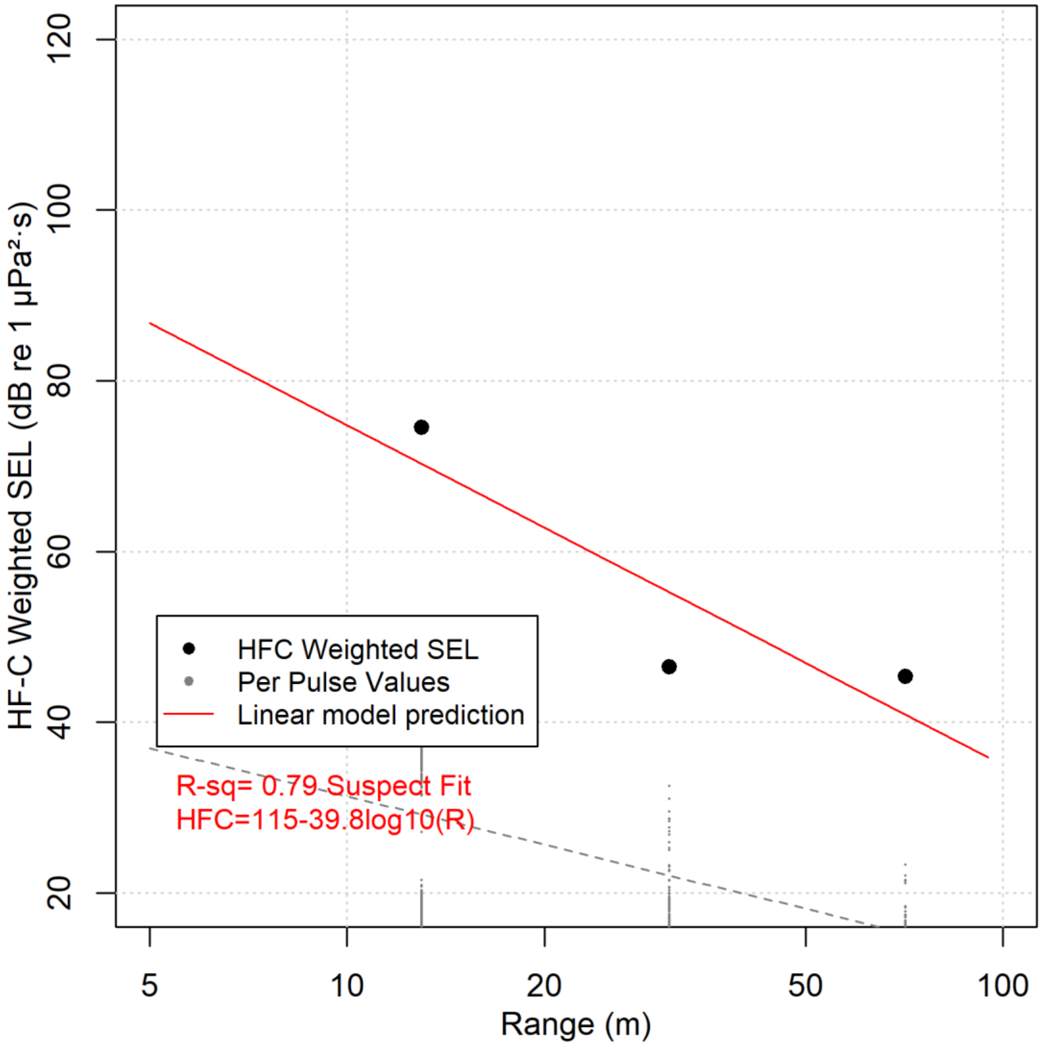

Figure D-30. High-frequency cetacean (HFC) weighted per-pulse Sound Exposure Level (SEL) and HFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 155 dB re 1µPa^2·s (NMFS 2018).

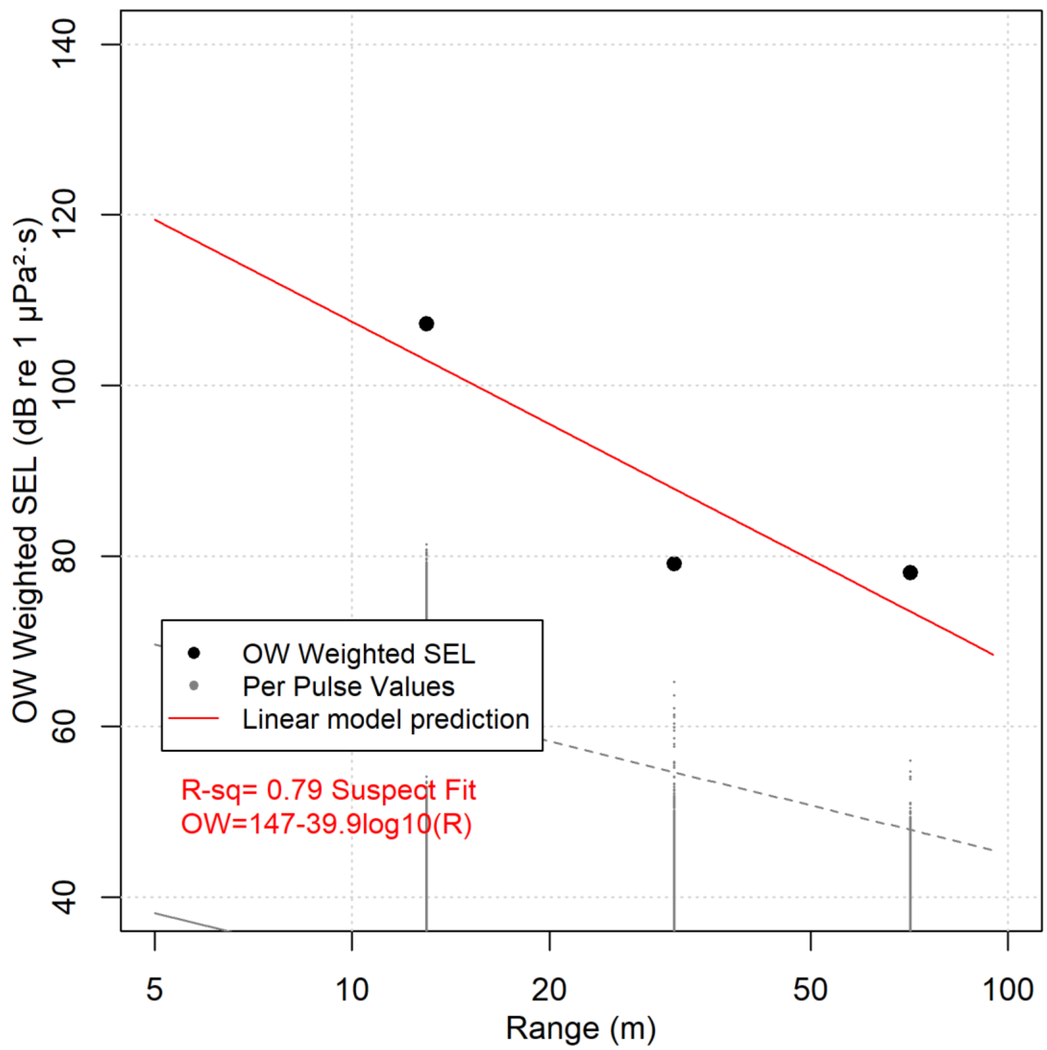

Figure D-31. Otariid underwater (OW) weighted per-pulse Sound Exposure Level (SEL) and OW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 203 dB re 1µPa^2·s (NMFS 2018).

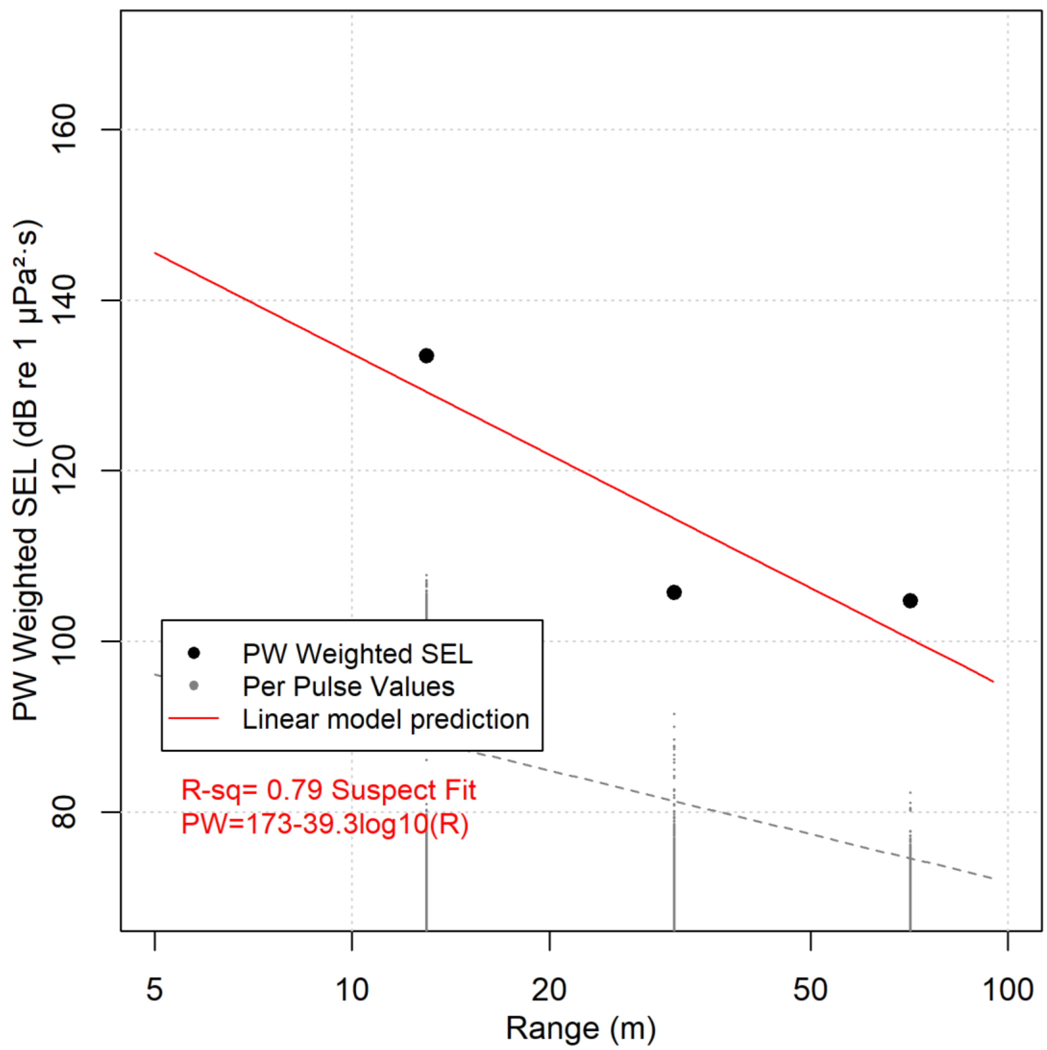

Figure D-32. Phocid underwater (PW) weighted per-pulse Sound Exposure Level (SEL) and PW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa^2·s (NMFS 2018).

D.5. C8P7 (with bubble curtain)

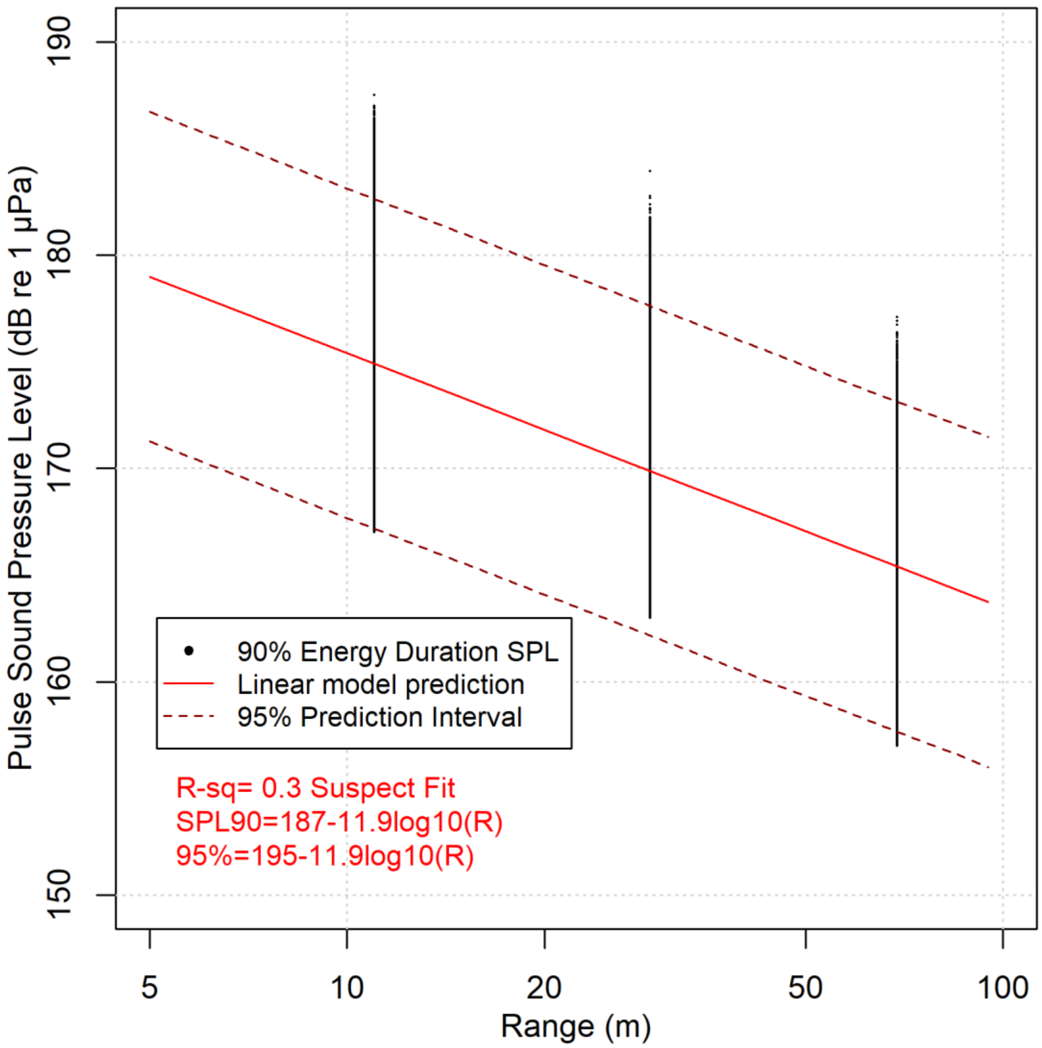

Figure D-33. Sound Pressure Level (SPL) of DTH hammering as a function of range (Stations 1, 2, and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

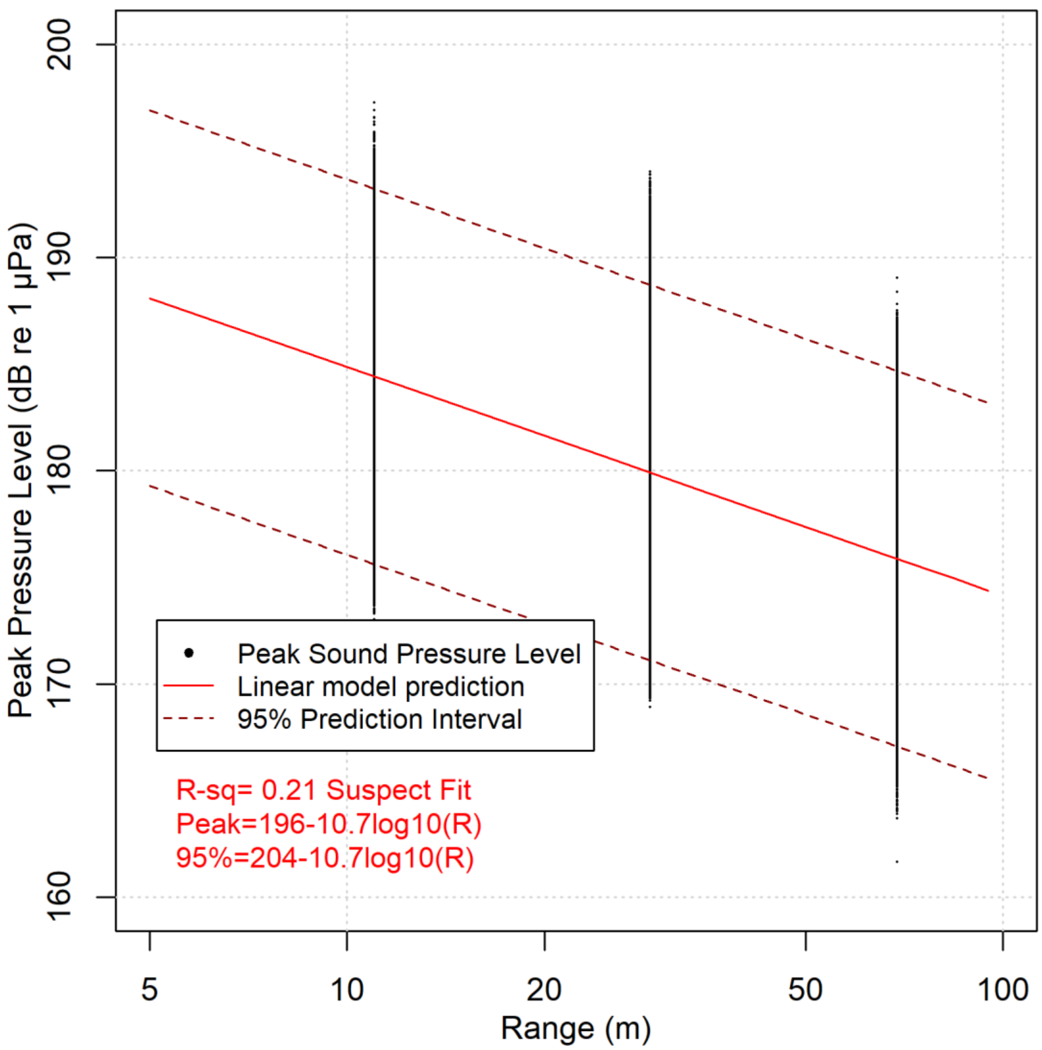

Figure D-34. Peak Sound Pressure (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

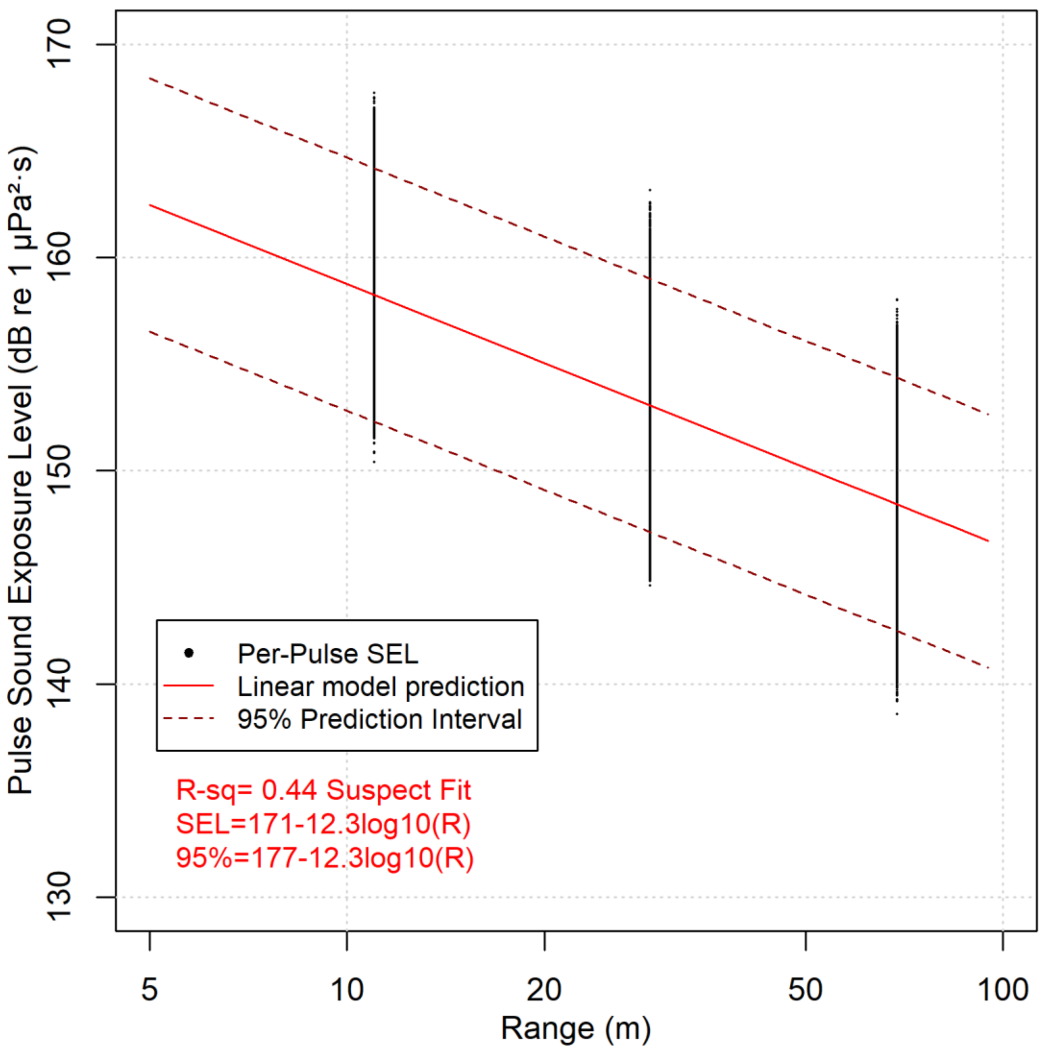

Figure D-35. Per-pulse Sound Exposure Level (SEL) of DTH hammering as a function of range (Stations 1, 2 and 3). Points indicate levels of individual pulses and the red line is the least-squares fit to the individual pulses, with the dashed red lines showing the ±95% confidence interval. Fitting parameters are shown in text.

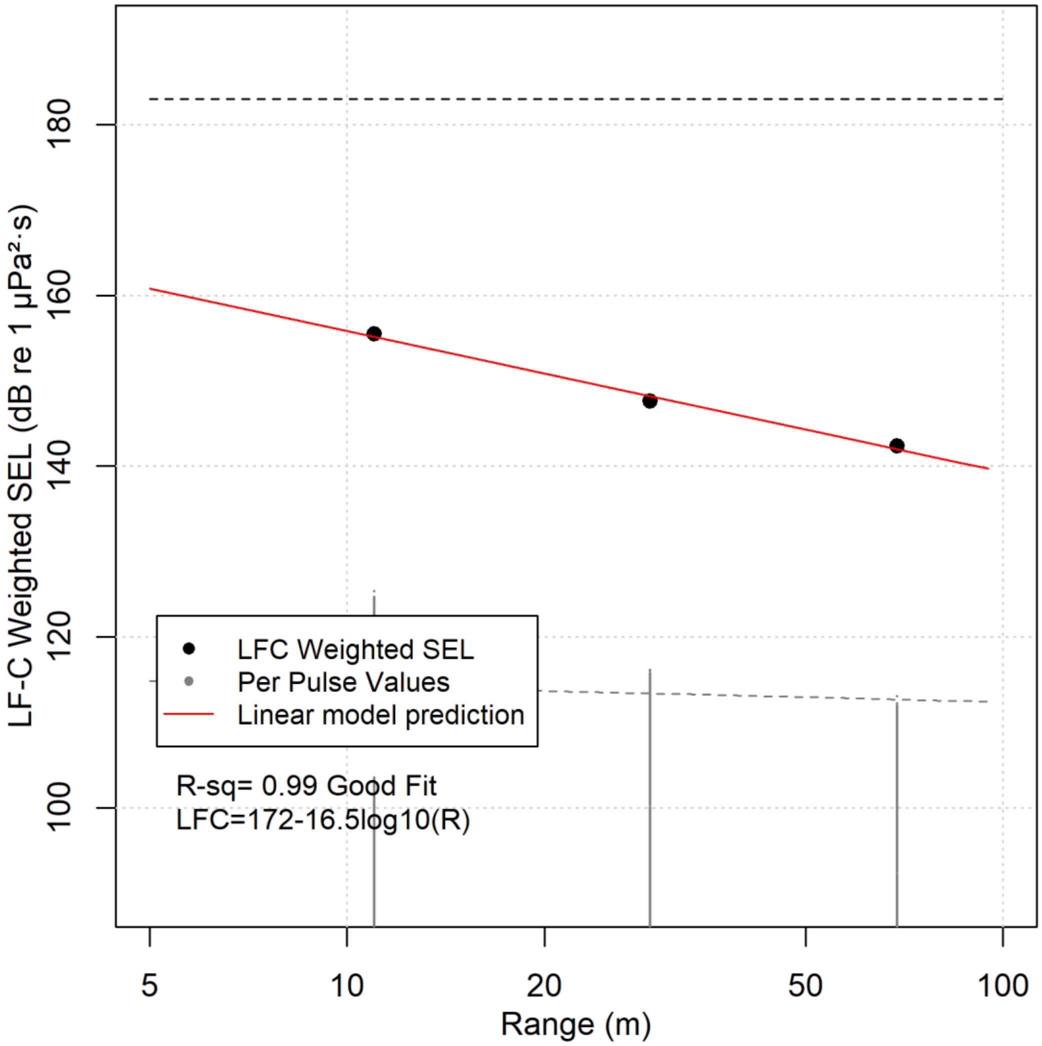

Figure D-36. Low-frequency cetacean (LFC) weighted per-pulse Sound Exposure Level (SEL) and LFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Black dashed line is the threshold for injury at 183 dB re 1µPa^2·s (NMFS 2018).

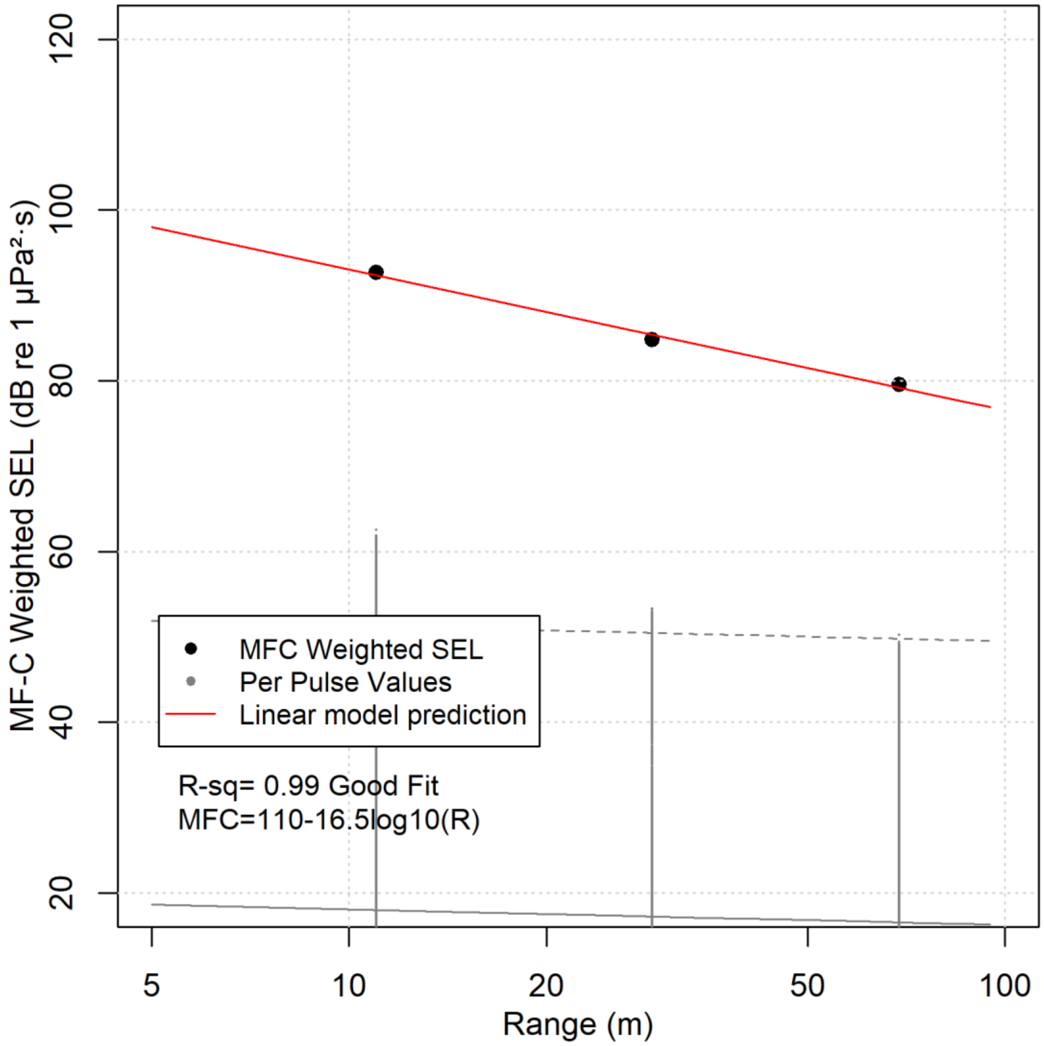

Figure D-37. Mid-frequency cetacean (MFC) weighted per-pulse Sound Exposure Level (SEL) and MFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa^2·s (NMFS 2018).

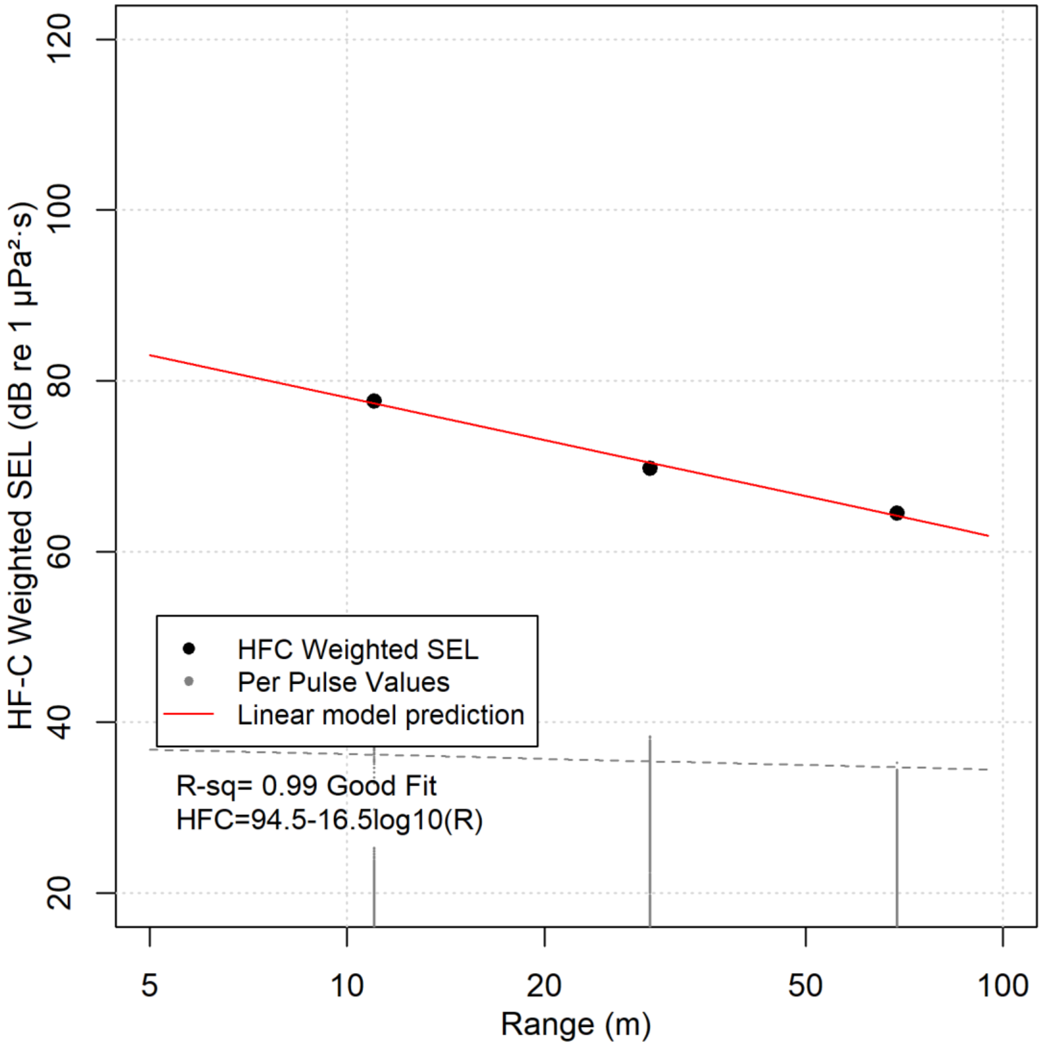

Figure D-38. High-frequency cetacean (HFC) weighted per-pulse Sound Exposure Level (SEL) and HFC-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 155 dB re 1µPa^2·s (NMFS 2018).

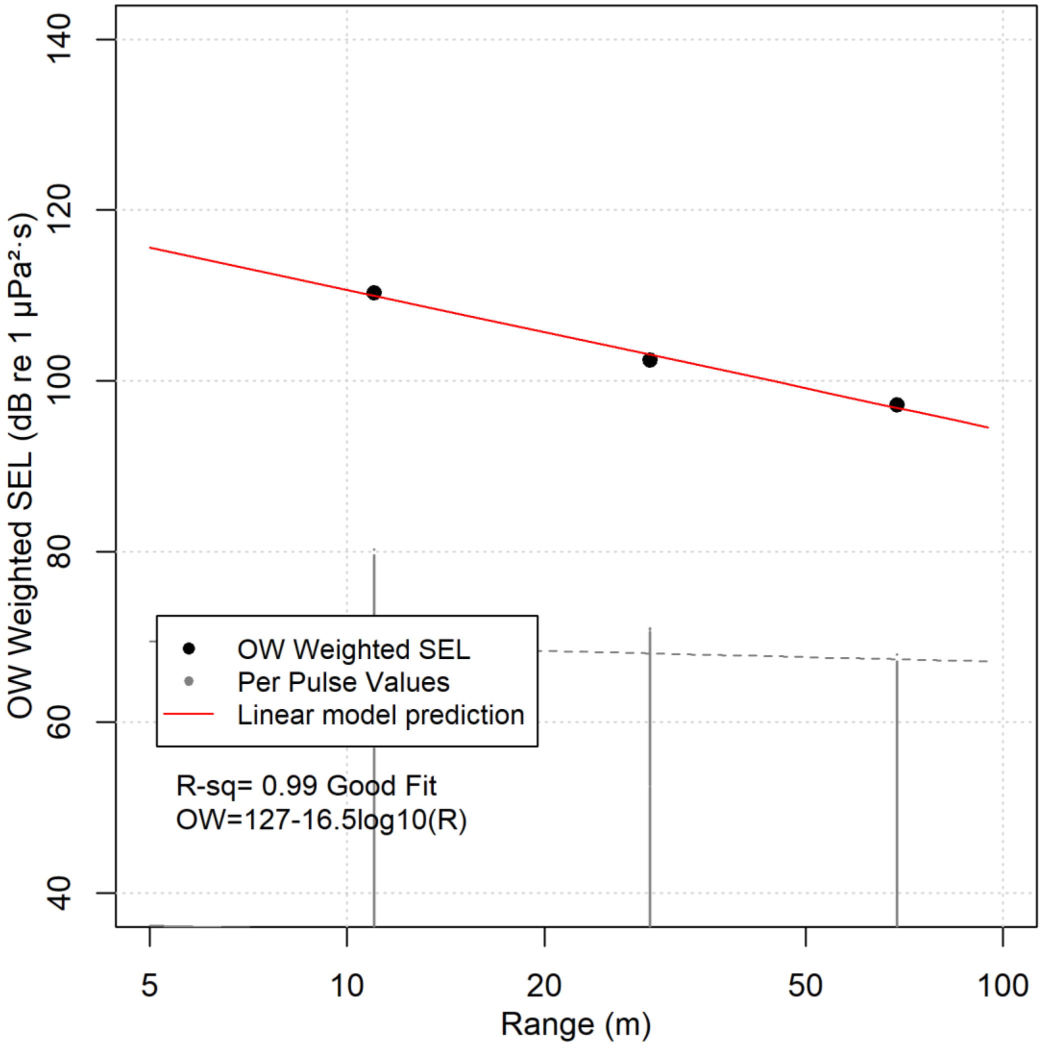

Figure D-39. Otariid underwater (OW) weighted per-pulse Sound Exposure Level (SEL) and OW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 203 dB re 1µPa^2·s (NMFS 2018).

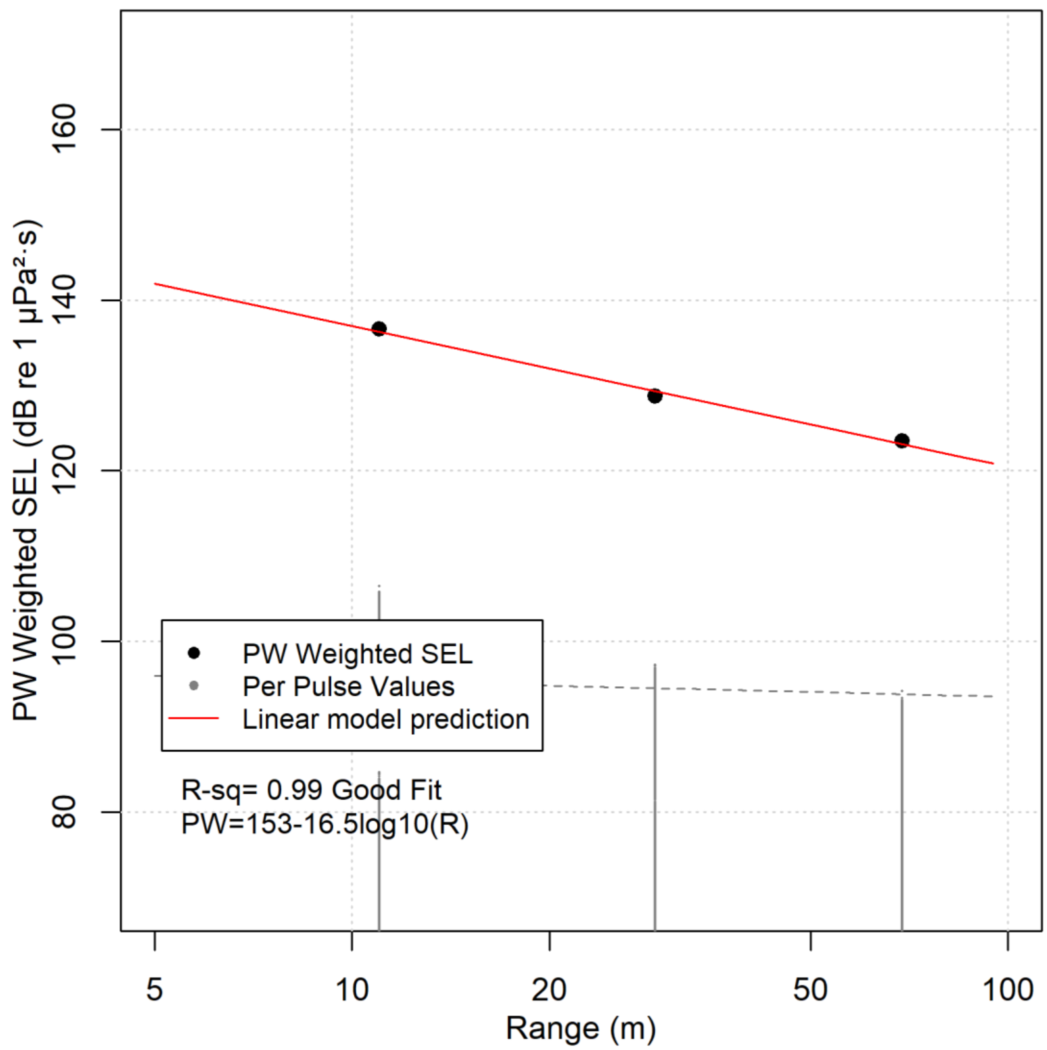

Figure D-40. Phocid underwater (PW) weighted per-pulse Sound Exposure Level (SEL) and PW-weighted accumulated SEL for DTH hammering of a caisson as a function of range (Stations 1, 2 and 3). Gray points indicate levels of individual pulses and the gray line is the least-squares fit to the individual pulses, with the dashed gray lines showing the ±95% confidence interval. Black points show the accumulated SEL for the duration of DTH hammering and the red line is the least-squares fit of the accumulated SEL. Fitting parameters are shown in text. Not shown: the threshold for injury is 185 dB re 1µPa²·s (NMFS 2018).