HYDROACOUSTIC PILE DRIVING NOISE STUDY – COMPREHENSIVE REPORT

Vibratory extraction at the east side of the Kake Ferry terminal (JASCO Applied Sciences, September 2015).

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13. ABSTRACT (Maximum 200 words) Alaska DOT&PF and JASCO Applied Sciences partnered to characterize underwater noise from pile driving activities to inform the assessment of the potential impact of such noise on marine mammals. JASCO measured underwater sounds at the Kake, Auke Bay, Kodiak, and Ketchikan ferry terminals during ferry terminal improvement construction projects and characterized sound levels associated with pile extraction, vibratory pile driving, impact hammer pile driving, and rock socket drilling. Source levels and transmission loss coefficients were determined for each activity at each site. Background sound levels were also characterized at each site for comparison with pile driving sounds. Distances from the piles to behavioral disturbance sound pressure level thresholds were calculated for each source type and compared with source and environmental characteristics. Distances to injurious cumulative sound exposure level thresholds were calculated based on frequency-weighted data to account for hearing sensitivity of marine mammal groups.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	
	mm ft	feet		
	0.305	meters	m yd	
	yards	0.914	meters	m
		AREA		
in^2	square inches	645.2	square millimeters	
	$mm^{2\ ft2}$	square feet		0.093
	square meters	m^2 yd^2	square yard	
	0.836	square meters	m^2	
ac	acres	0.405	hectares	ha
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	
	L ft^3	cubic feet	0.028	
	cubic meters	m^3 yd^3	cubic yards	
	0.765	cubic meters	m^3	
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERAT URE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

AREA

mm^2 square millimeters 0.0016 square inches $in^{2\ m2}$ square meters 10.764 square feet $ft^{2\ m2}$ square meters 1.195 square yards yd^2

ha hectares 2.47 acres ac km^2 square kilometers 0.386 square miles mi^2

Symbol	When You Know	Multiply By	To Find	Symbol
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	$ft^{3\ m3}$
	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERAT URE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Executive Summary

Underwater sound pressure levels were recorded at four sites while hollow steel piles were installed by vibratory and impact pile driving for modernization of the Alaska Marine Highway System ferry terminals. Construction activities were monitored at the Kake, Auke Bay, Kodiak, and Ketchikan ferry terminals in southeast Alaska. JASCO Applied Sciences (JASCO) was contracted to deploy autonomous sound recorders at each location at nominal distances of 10 m and 1 km from each pile. To target data collection at intermediate ranges, a mobile hydrophone recording system drifted during measurements. JASCO collected underwater recordings of noise generated by two methods of pile installation: vibratory pile driving, followed by impact pile driving at Kake, Auke Bay, and Ketchikan, and socket hole drilling followed by vibratory setting at Kodiak. An impact hammer was used for no more than five proofing strikes at Kodiak. JASCO scientists analyzed data recorded when construction activities were not occurring to characterize the ambient sound conditions.

The goal of the sound measurements was to quantify the underwater sound pressure levels (SPL) during vibratory and impact hammer pile driving events. From these data, the sound transmission loss was characterized and distances to marine mammal injury and disturbance thresholds were calculated. After JASCO completed the hydroacoustic monitoring, the National Marine Fisheries Service (NMFS) finalized new rules for marine mammal injury thresholds. Thus, threshold ranges in this report reflect previous and current (new) guidance.

For impact hammering the mean SPL, measured in dB re 1 µPa, normalized to a range of 10 m, was 194.8 at Kake, 191.2 at Auke Bay, 181.3 at Kodiak, and 194.7 at Ketchikan. The less than 4 dB spread for Kake, Auke Bay, and Ketchikan, where similar methods were employed, was consistent for peak and single strike SEL metrics. For vibratory hammering the mean SPL, measured in dB re 1 µPa, at 10 m was 157.9 at Kake, 168.8 at Auke Bay, 155.5 at Kodiak, and 162.5 at Ketchikan. At Kodiak, the mean SPL for drilling was 167.7 dB re 1 µPa. Although lower levels for pile driving were measured at Kodiak compared to the other sites, drilling activities were comparable to the highest vibratory driving levels at Auke Bay.

Computed transmission loss (TL) coefficients, derived from fits of the unweighted received sound level data versus range, varied between sites, ranging from 14.6 to 20.3 for impact pile driving and from 12.0 to 21.9 for vibratory pile driving. For drilling at Kodiak, the TL coefficient was 18.9. Kodiak and Kake had the highest TL coefficients for both impact and continuous sources (vibratory hammer and drill), whereas Auke Bay and Ketchikan had lower TL coefficients. The TL coefficients were combined with the near-source levels to determine the range to marine mammal thresholds. Source levels and transmission loss coefficients were estimated from linear fits computed for recordings that had been frequency weighted for functional hearing group.

Distances to marine mammal disturbance thresholds were derived from regressions of unweighted SPL versus range and weighted SEL versus range. Ketchikan had the greatest computed range (mean levels) to the impact hammering disturbance threshold of 160 dB re 1 µPa at 2703 m. The computed ranges for disturbance from continuous sources (vibratory hammer and drill) varied from less than 1 km at Kake to over 12 km at Ketchikan, with larger ranges resulting from extrapolation beyond the maximum range measured. More realistic ranges to thresholds, especially the low level of 120 dB re 1 µPa, may be obtained from numerical propagation modeling of proposed activities at each site. Ranges to injury, calculated from weighted SEL according to the new guidance, were most often less than 10 m for impact pile driving. The ranges to injury thresholds for low- and high-frequency cetacean functional hearing groups were consistently above 10 m. The greatest ranges to injury, based on mean levels, was 35 m and 82 m, for low- and high-frequency cetaceans respectively, whereas threshold ranges for injury resulting from exposure to continuous sources were greater with the greatest range to injury resulting from vibratory hammering at Ketchikan, estimated at 1288 m for low-frequency cetaceans.

Source levels estimated in this study could apply to other piling activities that are similar in terms of hammer specifications, pile size, and sediment properties, but the TL coefficients are less applicable to other locations. The wide range of TL coefficient estimates for weighted and unweighted metrics underscores the challenge in determining the correct surrogate to use for future proposed actions. Conservative values from these empirical estimates could help determine criteria ranges. Numerical propagation modeling at a proposed action site would provide TL estimates based on the specific

environment, which would generate more realistic estimates of criteria ranges. Regardless of the method of TL estimation, acoustic monitoring with bottom-mounted, autonomous recorders is advised because such recorders collect data that allow researchers to calculate 24 h exposure metrics from all activities used to determine the threshold levels following NMFS 2016 Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (NMFS, 2016).

1. Introduction

Alaska Department of Transportation and Public Facilities (AKDOT&PF, or AKDOT) commissioned a research project to determine empirical distances from various pile driving, pile removal, and drilling sources to relevant sound level thresholds for marine mammal injury and harassment. The project was conducted to inform noise impact assessments and to guide monitoring and mitigation requirements for future AKDOT dock and ferry terminal modernization projects throughout the state.

From September 2015 to July 2016 JASCO Applied Sciences (JASCO) made hydroacoustic measurements of construction activities involving steel cylindrical piles at Kake, Auke Bay, Kodiak, and Ketchikan Alaska (Figure 1). Construction activities included vibratory pile extraction, vibratory pile driving, impact pile driving, and socket hole drilling using a down-hole hammer. Vibratory extraction of existing piles, measured at Kake, was achieved by clamping the vibratory hammer onto the pile and operating the hammer while using a crane to pull the pile upwards. Vibratory pile driving was performed at each site by clamping the vibratory hammer onto the pile wall, operating the hammer, and then lowering the pile with a crane. When vibratory driving could no longer penetrate the substrate, the operator would switch to impact hammering until refusal.

Pile installation at Kodiak was somewhat different than at the other sites because the seabed was composed of a thin (13-18 ft) sediment layer overlying bedrock. The sediment layer did not provide enough structural support for the piles so a 15 ft deep pile socket was drilled into the bedrock. The vibratory driver first set the piles into position in the sediment, and then the drill created a pile socket in the bedrock. The vibratory driver then oscillated the pile into final (plumb) position and the impact hammer operated at low power setting from one to five times to proof the pile in place. Table 1 lists the activities monitored at each site.

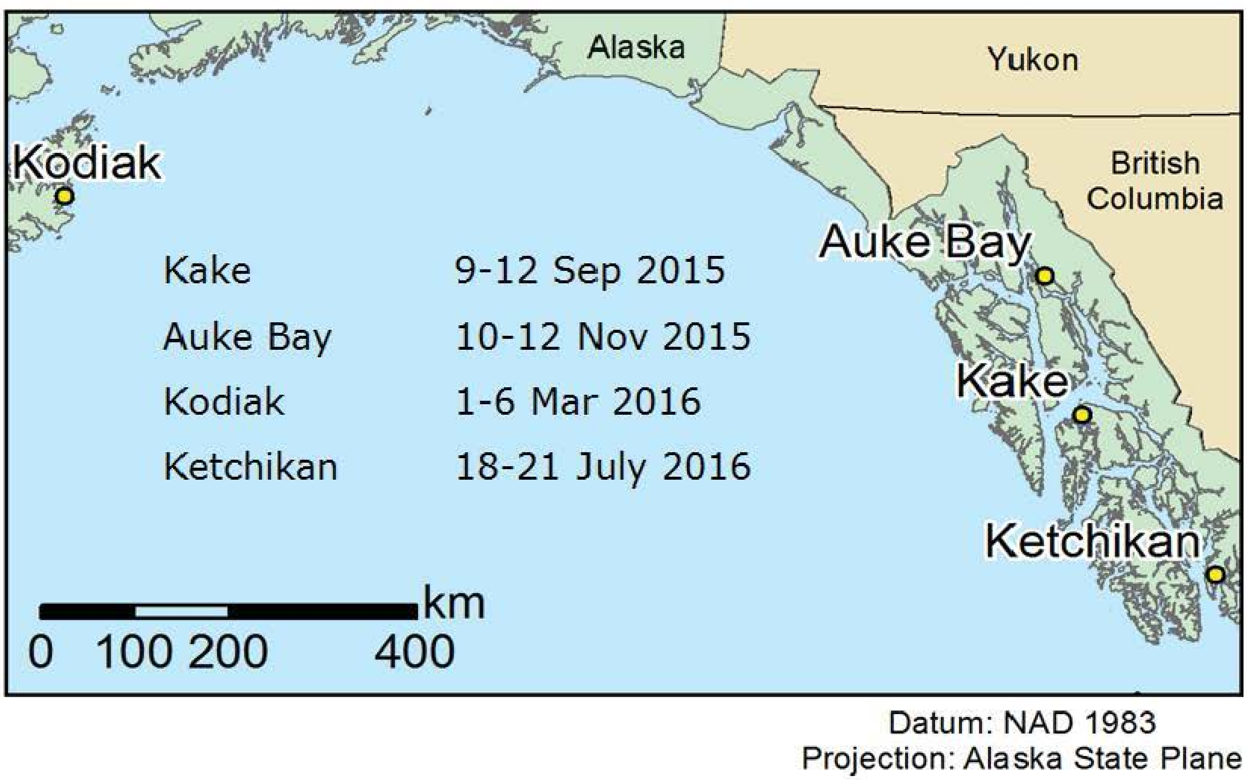

Figure 1. Map of hydroacoustic measurement locations.

Table 1. Monitored pile driving activities at the four measurement locations.

Location	Kake	Auke Bay	Kodiak	Ketchikan
Dates	9-12 Sep 2015	10-12 Nov 2015	1-6 Mar 2016	18-21 Jul 2016
Confined channel	No	No	Yes	Yes
Geotechnical information	Alluvium and till (Thickness 10–15 ft) Bedrock (> 15 ft) Ref: (Dames & Moore 1973)	Silty, gravelly sand (Thickness: 13–23 ft) Clayey silt (Thickness: 15–30 ft) Ref: (AK DOT 1996)	Sand and gravel with silt (Thickness: 15–20 ft) Phyllitic greywacke Bedrock (> 38–40 ft) Ref: (R&M Consultants 2013)	Very soft (0–5 ft) Soft (5–18 ft) Loose (18–31 ft) Medium dense (18–42 ft) Bedrock (42 ft) Ref: (Dames and Moore 1972)
Pile driving activities	Impact driving Vibratory driving Vibratory extraction	Impact driving Vibratory driving	Impact driving Vibratory driving (setting) Vibratory driving (oscillating) Rock socket drilling	Impact driving Vibratory driving
Total number of piles monitored	4*	3	8	3
Pile specifications	Diameter: 30 in* Length: 96 ft* Wall thickness: 0.5 in*	Diameter: 30 in Length: 187.8 ft Wall thickness: 0.75 in	Diameter: 24 in Length: 69 ft Wall thickness: 0.5 in	Diameter: 30 in Length: 145 ft Wall thickness: 0.5 in
Impact hammer	Delmag D19-42 Max energy: 66 kNm Piston weight: 1.82 t Blow rate: 35-52/min	Hydrohammer SC-200 Max energy: 200 kNm Piston weight: 13.6 t Blow rate: 38 blows/min	ICE Model I-36 Energy used: 91.8 kNm Piston weight: 3.6 t Stroke: 8.5 ft	Delmag D46-32 Max energy: 145.5 kNm Piston weight: 4.6 t Stroke: 10.5 ft
Hammer strikes	106-118	262-602	1-5	559-637
Vibratory hammer	HPSI 260 Frequency: 1600 rpm Force: 890 kN Weight: 4853 kg	APE 200-6 Frequency: 0-1650 vpm Force: 2270 kN Weight: 8573 kg	ICE model 44-B with caisson clamp Frequency: 900-1800 vpm Force: 1844 kN Weight: 5647 kg	ICE model 44-B with caisson clamp Frequency: 900-1800 vpm Force: 1844 kN Weight: 5647 kg
Vibratory Duration (min)	5-18	19-30	2-6	72-139
Drill			Power pack: APE 150 Drill bit: Numa Super Jaws Overburden Bit Air compressors (5 total, 3-4 used): IR 1070 CFM (x2), IR 1170 CFM, Sullair 1150 CFM, Sullair 950 CFM	
Drill Duration (hour)			0.75-3.65	

*Two piles were extracted and two were driven with the vibratory and impact hammer. The extracted piles were battered and had a diameter of 18 in with unknown length and thickness.

2. Literature Review and Background

JASCO reviewed literature on pile driving noise and its effects on marine mammals (Appendix H), focusing on construction projects that used smaller piles (15-42 in diameter), which are typical for AKDOT pile driving activities. The document in Appendix H describes sound propagation generally and the specific mechanisms of sound generation from impact and vibratory pile driving and from drilling. The document compiles and summarizes measured sound levels from projects in Alaska, Washington, Oregon, California, and Australia, reported either in journal articles or publicly available technical reports. Impact pile driving sound levels from seven projects were summarized as were sound levels from vibratory pile driving from five projects. Drilling sounds were only discussed in one reference.

The reported sound levels varied with hammer type and energy, pile material and diameter, water depth and bathymetry. The variety of measurement protocols used in the studies complicated cross-project comparisons. Notably, many recordings made from drifting vessels were made with hydrophones suspended into the water column resulting in a variable distance to the sound source throughout piling. Data collection using fixed acoustic recorders that maintain the same depth and distance to the sound source while they record provides a more robust statistical sampling of the emitted sound levels. The monitoring performed for this study made recordings from both fixed and drifting vessels.

Most studies in the literature described and analyzed broadband received sound levels from pile driving, but few referred to the frequency content of the sounds or how marine mammals perceive sounds, likely because regulations concerning underwater sound impacts were, at the time, based on broadband sound pressure level criteria. The United States National Marine Fisheries Service (NMFS) policy and process of assessing marine mammal injuries from sound exposure changed throughout the course of this research project. Prior to August 2016 the guidelines stated that to avoid injuring cetaceans and pinnipeds (Level A harassment), they should not be exposed to sounds that exceed SPLs of 180 and 190 dB re 1 µPa, respectively (NMFS 2000). In August 2016, NMFS issued revised guidance for assessing acoustic injury that included peak pressure level thresholds and SEL thresholds that are accumulated over the shorter of the activity duration or 24 hours (Table 2). The peak pressure level criterion is not frequency weighted whereas the SEL is frequency weighted according to one of five marine mammal species hearing groups: Low-, Mid- and High-Frequency Cetaceans (LFC, MFC, and HFC respectively) and two classes of Pinnipeds in water: phocids (PPW) and otariids (OPW).

The revised criteria (described in more detail in Appendix G) were developed to acknowledge that the potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

In computing threshold ranges, the injury range is conservatively estimated due to the assumption that the marine mammal is stationary at a fixed range for 24 hours or the duration of the activity. This could be appropriate for marine mammals that have strong fidelity to a location (e.g., sea lion aggregation at a fish processing plant near the Kodiak ferry terminal), but not for transient animals whose exclusion zone could encompass animals that are exposed to levels much lower than the thresholds for Level A harassment. Calculating an animal's true sound exposure level would require knowledge of the animal's position as a function of time.

NMFS assumes animals will be behaviorally disturbed (Level B harassment) by impulsive sounds (like impact hammer pile driving) with SPL above 160 dB re 1 µPa and by continuous sounds (like vibropiling and drilling) above 120 dB re 1 µPa. The sound level from vibratory pile driving at any point in time is lower than that generated by impact pile driving, but the exposure is continuous. Therefore, the threshold for Level B harassment—SPL 120 dB instead of 160 dB—is set lower than that for impulses. Due to the 40 dB difference between the two thresholds, behavioral disturbances from vibratory pile driving could occur at much greater distances than from impact driving. Nonetheless, received sound level alone may not be a reliable predictor of behavioral disturbance. Other mediating factors, particularly exposure context, relative background level, and chronic exposure, might be equally important (Ellison et al. 2012). The NMFS Level B harassment criteria does not currently account for these factors.

Table 2 Marine mammal Level A thresholds based on NMFS (2016a) peak pressure level in dB re 1 µPa, and auditory-weighted SEL (24 h) in dB re 1 µPa²·s.

Hearing group	Impulsive source		Non-impulsive source
	Peak pressure level (dB re 1 µPa)	Auditory-weighted SEL_{24h} (dB re 1 µPa²·s)	Auditory-weighted SEL_{24h} (dB re 1 µPa²·s)
Low-frequency cetaceans	219	183	199
Mid-frequency cetaceans	230	185	198
High-frequency cetaceans	202	155	173
Phocid pinnipeds in water	218	185	201
Otariid pinnipeds in water	232	203	219

3. Study Plan

This research study was designed to compile empirical data to assist in establishing observation and shutdown zones for marine mammal monitoring during AKDOT pile driving projects. At each project location, JASCO used two bottom-mounted Autonomous Multichannel Acoustic Recorders (AMARs) to measure underwater sounds over 2-4 days during dock construction activities. The AMARs were placed at nominal distances of 10 m and 1 km from the piles. Background noise was measured during periods between construction activities and overnight when construction had stopped. When possible, additional vessel-based spot sampling was conducted with a hand-deployed hydrophone to constrain transmission loss estimates. Measurements were conducted and analyzed in accordance with NMFS Northeast Region guidelines (NMFS 2016b) and a brief field report was written after each field measurement. This final report summarizes the results from all four sites.

The JASCO field monitoring team's activities consisted of calibrating the recorders, deploying the fixed recorders, collecting CTD measurements, calibrating and collecting acoustic measurements from drifting vessels with the dipping hydrophone, retrieving deployed recorders, and a final recorder calibration. Depending on weather and construction schedules, the order of activities could vary slightly. Detailed monitoring activity tables are included with the supporting data in Appendices A through D of this report.

Acoustic recordings were analyzed to determine received levels for the different types of pile driving as a function of range from the pile. Several sound level metrics were computed for each sound source and, when appropriate, frequency weighting functions were applied for different marine mammal groups. The individual field reports applied audiometric frequency weighting for marine mammals using M-Weighting filters proposed by Southall et al. (2007). Since completion of the field studies, NMFS released different marine mammal weighting functions (Appendix G), which we applied to the data for this comprehensive report.

A linear fit was computed between the logarithm of the range from the pile to the received level for each hammer-pile combination. The resultant function provided insight into the source levels and effects of local environment on the attenuation of sound energy. The derived source levels and attenuation terms were used to determine the range to sound level thresholds for marine mammal injury and disturbance determined by NMFS (2016a).

4. Methods

4.1. Monitoring Locations

Acoustic monitoring of pile driving activities at each site consisted of two measurement processes. First, fixed-position recorders (AMARs) were deployed on bottom moorings with hydrophones positioned 1 m above the sea floor. An AMAR with a low-sensitivity hydrophone was deployed within 10 m of the piles at each site. Another AMAR, with a higher sensitivity hydrophone, was deployed approximately 1 km from the piles. In addition to the two bottom-mounted, fixed-position recorders, a dipping hydrophone was deployed from a vessel at locations between the two AMARs at approximately 6 m below the surface. During recording from the vessel, the engines of the vessel were turned off and the vessel drifted to reduce flow noise on the hydrophone. Ranges from the piles to the recorders were determined through the use of GPS. The subsections that follow detail the AMAR deployment locations at each measurement site.

4.1.1. Kake

Table 3. AMAR deployment locations at Kake, Alaska. Water depths measured using vessel echo sounder.

Monitoring location	Deployment date (UTC)	Deployment time (UTC)	Latitude	Longitude	Water depth (m)
AMAR 1 deployment 1	9-Sep-2015	21:53	56°57.662'N	133°55.280'W	11.8
AMAR 1 deployment 2	11-Sep-2015	16:47	56°57.662'N	133°55.280'W	11.8
AMAR 2 deployment 1	10-Sep-2015	17:05	56° 57.377' N	133° 56.278' W	33.6
AMAR 2 deployment 2	12-Sep-2015	22:50	56° 57.365' N	133° 56.195' W	33.6

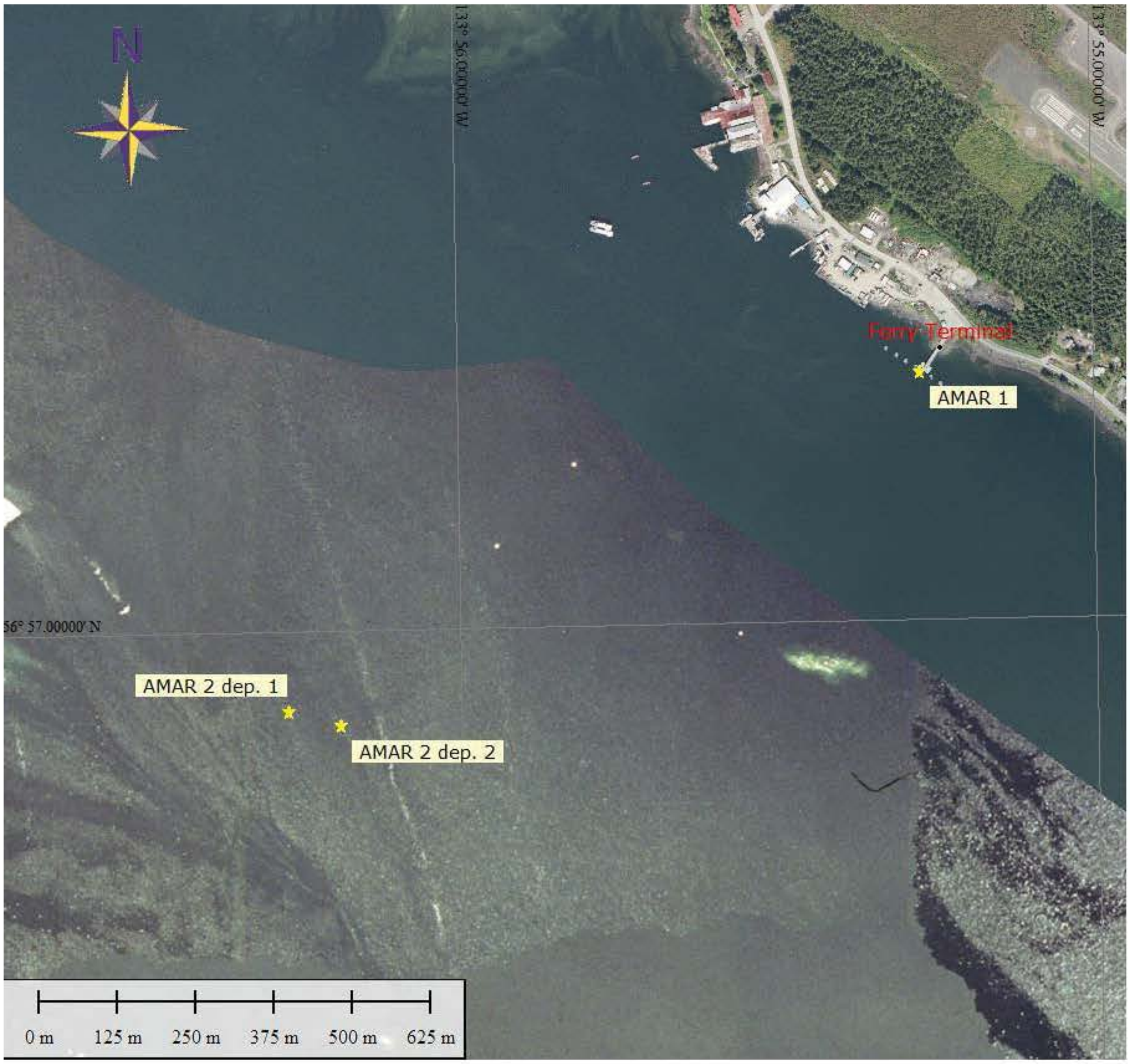

Figure 2. AMAR deployment locations during hydroacoustic monitoring at Kake, Alaska. Aerial orthophotos obtained from USGS.

4.1.2. Auke Bay

Table 4. AMAR deployment locations at Auke Bay, Alaska. Water depths measured using vessel echo sounder.

Monitoring location	Deployment date (UTC)	Deployment time (UTC)	Latitude	Longitude	Water depth (m)
AMAR 1	2015-Nov-10	01:12	56°57.662'N	133°55.280'W	18.9
AMAR 2	2015-Nov-10	01:51	56°57.377'N	133° 56.278'W	47.9

Figure 3. AMAR deployment locations during hydroacoustic monitoring at Auke Bay, Alaska. Aerial orthophotos obtained from USGS.

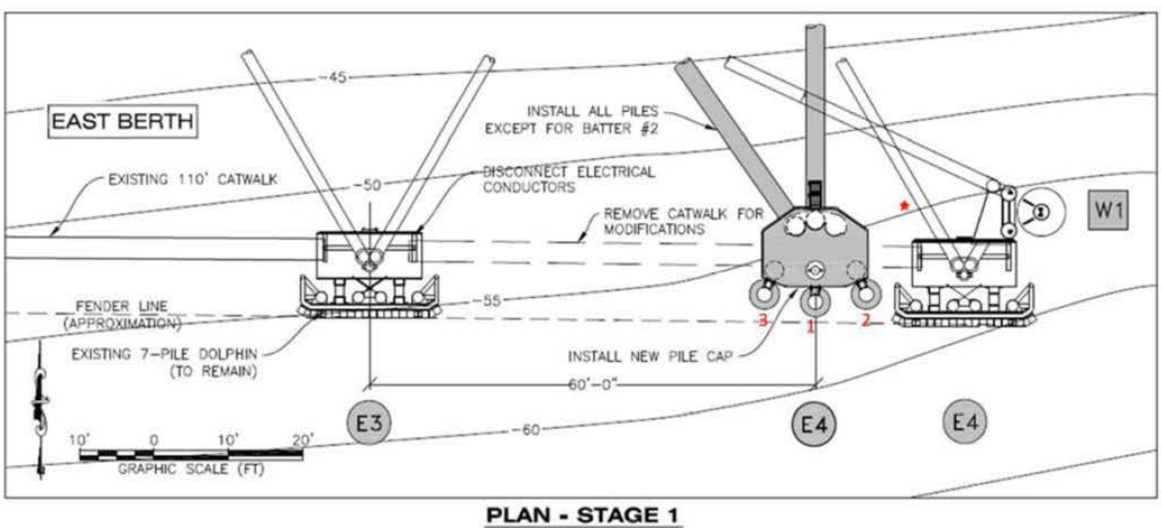

Figure 4. Position of AMAR 1 (red star) at Pier E4 in relation to Piles 1-3. Piles 1-3 were not in place at the time of AMAR 1 deployment, therefore the range from the hydrophone to the piles was calculated from the engineering plans. An uncertainty of ±1 m was included the range to AMAR, based on the logged deployment coordinates.

4.1.3. Kodiak

Table 5. AMAR deployment locations at Kodiak, Alaska. Water depths measured using vessel echo sounder.

Monitoring location	Deployment date (UTC)	Deployment time (UTC)	Latitude	Longitude	Water depth (m)
AMAR 1	2016-Mar-02	01:44	57°47.235'N	152°24.134'W	5.0
AMAR 2	2016-Mar-02	02:34	57°47.501'N	152° 23.133'W	15.2

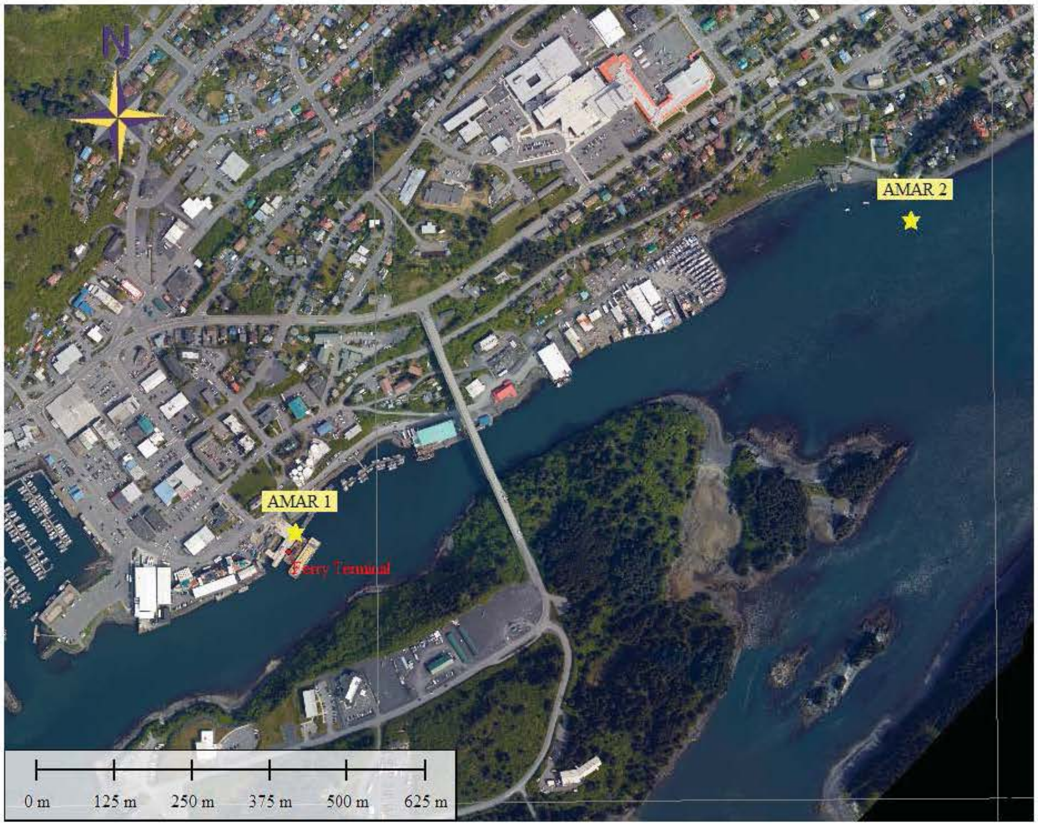

Figure 5. AMAR deployment locations during hydroacoustic monitoring at Kodiak, Alaska. Aerial orthophotos obtained from NOAA Office for Coastal Management (2016a).

4.1.4. Ketchikan

Table 6. AMAR deployment locations at Ketchikan, Alaska. Water depths measured using vessel echo sounder.

Monitoring location	Deployment date (UTC)	Deployment time (UTC)	Latitude	Longitude	Water depth (m)
AMAR 1	2016-Jul-18	02:42	55°21.228'N	131°41.736'W	13.9
AMAR 2	2016-Jul-18	02:56	55°20.782'N	131°41.334'W	32.3

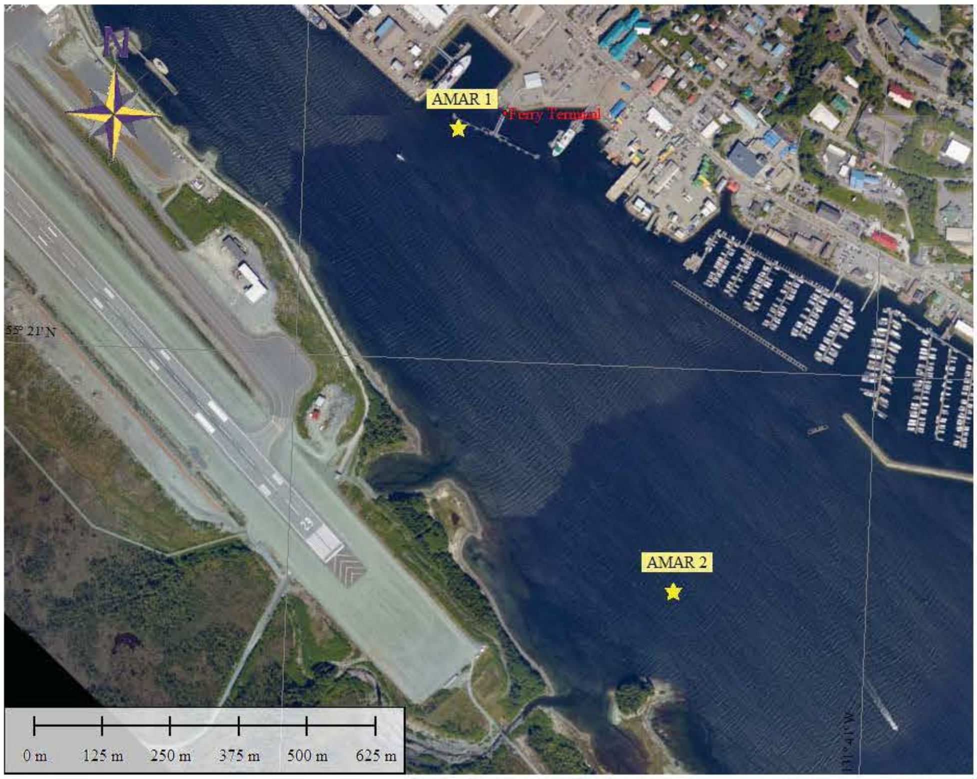

Figure 6. AMAR deployment locations during hydroacoustic monitoring at Ketchikan, Alaska. Aerial orthophotos obtained from NOAA Office for Coastal Management (2016b).

4.2. Data Acquisition

The following subsections contain the monitoring activity details for each site. Detailed AMAR parameters used for the recording are provided in Appendix F.

4.2.1. Kake

Table 7. Acoustic monitoring activity details at Kake, Alaska.

Recorders	2 AMAR, 1 dipping hydrophone
Vessel	Kalyn Ann
Recording times (UTC)	AMAR 1: 2015-09-09 21:09–2015-09-11 01:03 AMAR 1: 2015-09-11 16:36–2015-09-13 02:55 AMAR 2: 2015-09-10 14:13–2015-09-12 03:19 AMAR 2: 2015-09-12 21:57–2015-09-13 03:02
Monitoring ranges	AMAR 1: 7-17 m AMAR 2: 1098-1161 m
Dipping hydrophone ranges	61-69 m, 146-166 m, and 130-204 m
CTD casts performed	3

4.2.2. Auke Bay

Table 8. Acoustic monitoring activity details at Auke Bay, Alaska.

Recorders	**2 AMAR, 1 dipping hydrophone**
Vessel	Eclipse
Recording times (UTC)	AMAR 1: 2015-11-09 00:52–2015-11-12 01:06 AMAR 2: 2015-11-10 01:27–2015-11-12 00:16 Dipping, non-continuous: 2015-11-10 00:33–2015-11-12 00:22
Monitoring ranges	AMAR 1: 4.0–6.8 m AMAR 2: 1184–1187 m
Dipping hydrophone ranges	215–430 m
CTD casts performed	4

4.2.3. Kodiak

Table 9. Acoustic monitoring activity details at Kodiak, Alaska.

Recorders	**2 AMAR, 1 dipping hydrophone**
Vessel	Bella-G
Recording times (UTC):	AMAR 1: 2016-03-01 23:22–2016-03-06 03:10 AMAR 2: 2016-03-01 23:20–2016-03-06 03:07 Dipping, non-continuous: 2016-03-04 22:13–2016-03-04 23:28
Monitoring ranges	AMAR 1: 9.9–31.1 m AMAR 2: 1117–1136 m
Dipping hydrophone ranges	69–234 m
CTD casts performed	2

4.2.4. Ketchikan

Table 10. Acoustic monitoring activity details at Ketchikan, Alaska.

Recorders	**2 AMAR, 1 dipping hydrophone**
Vessel	Aluminum outboard cabin cruisers from Baranof Fishing Excursions
Recording times (UTC):	AMAR 1: 2016-07-18 01:28–2016-07-21 02:00 AMAR 2: 2016-07-18 01:25–2016-07-21 01:58 Dipping, non-continuous: 2016-07-19 23:21–2016-07-20 00:04Dipping, non-continuous: 2016-07-21 00:15–2016-07-21 00:47
Monitoring ranges	AMAR 1: 16.3–18.4 m AMAR 2: 947–949 m
Dipping hydrophone ranges	66–248 m
CTD casts performed	2

4.2.5. Calibration

A 42AC pistonphone calibrator (G.R.A.S. Sound & Vibration A/S; Auke Bay, Kake, and Kodiak s/n 85462; Ketchikan s/n 201839) verified the sensitivity of the whole recording apparatus of both the AMAR and the OSM systems. The pressure response of the recording system was verified by placing the pistonphone and its adapter over each hydrophone independently while the pistonphone produced a known pressure signal on the hydrophone element (a 250 Hz sinusoid at 152.2 dB re 1 µPa). Calibrations were performed in JASCO's warehouse before the recorders were shipped and again immediately before and after each deployment to confirm consistency of the system sensitivity throughout the project. Readings were verified between each deployment and before data analysis was performed.

4.2.6. Environment

Weather, specifically wind and precipitation, can impact underwater ambient noise conditions. Weather data for the periods of acoustic monitoring were obtained from NOAA (National Weather Service) weather stations located near the construction sites. If there was no precipitation during the deployment period, the data only included wind speed. The weather data for each site are in the respective Appendices of supporting data.

The conductivity, temperature, and depth of the water column were measured with a Minos X (AML Oceanographic, s/n 8413) at each site. CTD profiles were measured and the sound speed profile of the water column was derived from the average of the profiles. At Auke Bay, four CTD profiles were measured. At Kake, three CTD profiles were measured. At both Ketchikan and Kodiak, two CTD profiles were measured. These data are also provided in the site-relevant Appendices of supporting data.

4.3. Pile Driving Activities

The subsections that follow detail the pile driving activities that were monitored at each site. Pile driving logs received from the construction contractors at each site are provided in Appendix E.

4.3.1. Kake

Table 11. Log of pile driving activities at Kake, Alaska.

Date (UTC)	Time (UTC)	Activity
2015-09-10	18:05-18:20	Vibratory extraction of 18" batter pile at west side of ramp.
2015-09-10	19:20-20:20	Vibratory piling of 30" west restraint pile. Installation aborted after pile toe hit sub-bottom obstruction.
2015-09-10	22:20-23:10	Vibratory piling of 30" west restraint pile at temporary location.
2015-09-11	17:05-17:20	Vibratory extraction of 18" batter pile at east side of ramp.
2015-09-11	18:10-18:50	Vibratory piling of 30" east restraint pile. Installation aborted after pile toe hit sub-bottom obstruction.
2015-09-11	22:30-22:50	Vibratory piling of 30" east restraint pile at temporary location.
2015-09-11	23:15-23:30	Vibratory piling of 30" east restraint pile at final location.
2015-09-12	16:15-17:40	Vibratory piling of 30" west restraint pile at final location.
2015-09-12	21:29-21:33	Impact hammering of 30" west restraint pile.
2015-09-13	00:44-00:48	Impact hammering of 30" east restraint pile.

4.3.2. Auke Bay

Table 12. Log of pile driving activities at Auke Bay, Alaska.

Pile	Activity	Date (UTC)	Time (UTC)
1	Vibratory driving	2015-11-11	01:45:10
3		2015-11-11	16:55:55
2		2015-11-11	19:30:36
3	Impact hammering	2015-11-11	22:53:44
1		2015-11-12	00:00:55
2		2015-11-12	0:05:15

4.3.3. Kodiak

Table 13. Log of pile driving activities at Kodiak, Alaska.

Pile	Activity	Date (UTC)	Time (UTC)
D22	Drilling	3/2/2016	18:11
D20		3/4/2016	18:29
D18		3/4/2016	20:22
D16		3/4/2016	22:07
D15		3/5/2016	19:38
D14		3/5/2016	21:44
D13		3/5/2016	23:38
D12		3/6/2016	0:30
D20	Vibratory driving (setting)	3/4/2016	2:00
D14		3/5/2016	17:43
D15		3/5/2016	17:49
D13		3/5/2016	17:55
D12		3/5/2016	18:01
D22	Vibratory driving (oscillating)	3/4/2016	2:12
D16		3/4/2016	23:50
D18	Impact hammering	3/5/2016	0:13
D16		3/5/2016	0:22
D22		3/5/2016	0:07

Pile	Activity	Date (UTC)	Time (UTC)
D20		3/5/2016	0:09

4.3.4. Ketchikan

Table 14. Log of pile driving activities at Ketchikan, Alaska.

Pile	Activity	Date (UTC)	Time (UTC)
2	Vibratory driving	2016-07-19	18:40
1		2016-07-19	23:19
3		2016-07-20	17:03
3	Impact hammering	2016-07-21	00:16
2		2016-07-21	01:01
1		2016-07-21	01:25

4.4. Data Analysis

Analysts used the proprietary software PAMlab to calculate calibrated metrics. Metrics were computed over 1 s windows for vibratory driving. For impact pile driving, individual strike records were detected using PAMlab's Impulse detection algorithm. The detector computed the Teager-Kaiser (TK) energy of the acoustic file, and triggered detections when the value of the TK energy exceeded a threshold. TK energy is useful for detection of impulsive sounds as it amplifies the effect of big changes between subsequent samples within the acoustic record. The 90% energy window was determined from the detection period. SPL metrics were computed over the 90% energy window. Detections were limited to intervals greater than 0.5 s to prevent detecting multiple path arrivals as distinct pulses. Computed acoustic metrics (Appendix G) included 90% sound pressure level (SPL), sound exposure level (SEL), and peak sound level (peak level). Single-strike SELs from pile driving impulses received on the fixed AMARs were summed, in pressure units, to yield SELs for each pile. Data from the fixed AMARs and dipping hydrophone system were processed using this procedure.

PAMlab outputs were synthesized with the ranges of the recorders, fixed and drifting, to the pile. A linear fit was computed between the SPL and the logarithm of the ranges to determine the transmission loss (TL) coefficient, *n*, according to Equation 1.

$$RL = SL - n \log R \qquad \text{Equation (1)}$$

The regressions were performed for a sub-set of the recordings when pile driving levels received simultaneously at all three recorders sufficiently exceeded background levels, determined by visually examining the spectrograms of the recorded data. A sub-set of the data were used to avoid biasing the empirical fit which could happen if more data were used from the AMARs than the dipping hydrophone system. Saturated signals, which occurred when the received level exceeded the maximum level that can be digitized by the recording system were excluded from analysis as were periods that were contaminated by noise from vessels or other sources. Notes are added in the Results section where such data were excluded since this has the potential to bias the analysis. The TL coefficients thus calculated for each pile were then used in Equation 1 to back-calculate the source level (*SL*) statistics based on the mean, median, and 90th percentile received levels (*RL*) computed from the full record of data from AMAR 1 at range *R*. The ranges to marine mammal impact threshold levels were computed from the source level statistics and transmission loss coefficients for each pile, using Equation 1.

For each pile we present the following results:

- A representative waveform (sound pressure versus time) and spectral density curve (sound pressure level as a function of frequency, at a resolution of 1 Hz) received on each recorder for impact and vibratory installation of each pile.
- A spectrogram plot (sound intensity as a function of time and frequency, 10 s window) for a few representative pulses received at each recorder during impact installation of each pile.
- A spectrogram plot (sound intensity as a function of time and frequency, 10 s window) for data received at each recorder during vibratory installation of each pile.
- Received sound pressure levels versus time for peak level, SPL, single-strike SEL (SELss), and accumulated SEL (SEL), received on each recorder for impact and vibratory installation of each pile.
- Received sound pressure levels (SPL) versus range for a subset of data recorded on each recorder during impact and vibratory installation of each pile.
- Marine mammal auditory weighting functions are covered in Appendix G.2. Frequency-weighting was applied following the specific methods and thresholds for injury summarized by NMFS criteria for injury (NMFS 2016a). The frequency-weighting filters were applied to the pile driving data. The SPL and SEL values were computed as per Equation 1. The Medium and High Frequency Cetacean functional hearing groups represent species with nominal hearing ranges of 150 Hz to 160 kHz and 275 Hz to 160 kHz, respectively (NMFS 2016a). While the predominant frequencies of noise in pile driving activity are below 10 kHz, the signals are broadband and contain acoustic energy in higher frequencies (Appendices A.5, B.5, C.5, and D.5). The frequencies of best hearing for these functional hearing groups extend beyond the highest frequency characterized by the AMAR data (32 kHz) and the weighted levels computed for these species may be underestimated in these data. Measurements should be made at higher sampling rates so that accurate weighted SEL can be computed for these hearing groups.
- 1/3-octave band level box plots for vibratory and impact installation of each pile are provided in figures in site-relevant Appendices of supporting data.

NMFS (2016a) criteria are based on peak pressure levels and 24 hour SEL. The SEL was calculated for each 24 h day (24 hours, local time) in which pile driving occurred. If more than one pile was installed or extracted, the SELs were calculated for all piles in that period. Impact and continuous sources–vibratory hammer and drilling–were considered separately.

4.4.1. Weighting Function Adjustments

NMFS released an Optional User Spreadsheet when they issued the revised acoustic injury guidance (NMFS 2016a). The User Spreadsheet provides Weighting Function Adjustments (WFA) to estimate weighted SEL from unweighted SEL. The WFA depend on the marine mammal hearing group and the 90th percentile frequency of the source sound spectrum. The WFA frequencies for impact and vibratory piling suggested by NMFS are 2 and 2.5 kHz, respectively. Table 15 lists the WFA for impact and vibratory piling for each marine mammal group.

Table 15. Weighting Function Adjustments for impact and vibratory piling assuming the source-dependent 90th percentile frequency recommended in the NMFS Spreadsheet.

Functional Hearing Group	Impact Hammering (@ 2 kHz)	Vibratory Piling (@ 2.5 kHz)
LFC	-0.01	-0.05
MFC	-19.74	-16.83
HFC	-26.87	-23.50
PPW	-2.08	-1.29
OPW	-1.15	-0.60

NMFS acknowledges the WFA likely result in conservative estimates of weighted SEL. In the site-relevant Appendices of supporting data we provide the difference between the broadband-discounted SEL and weighted SEL (i.e., (unweighted SEL + WFA) – weighted SEL) to assess this claim. For our analysis, we assumed vibratory extraction had the same WFA as for vibratory piling.

The broadband-discounted SEL was calculated from the unweighted SEL by adding the WFA to the broadband SEL. This value was used as the source level input in the NMFS Optional User Spreadsheet to determine distance to threshold ranges.

The ranges to thresholds based on NMFS 2016 criteria were determined by two separate processes:

1. The Optional User Spreadsheet, included in NMFS (2016), was completed based on source levels and numbers of strikes determined by analyzing the recordings. The WFA were selected based on spreadsheet instructions.
2. Similar to the procedure used for solving Equation 1 for the unweighted levels, Equation 1 was solved using 24 h SEL from weighted pulse levels with ranges calculated for thresholds specified in NMFS (2016) according to the following process, we calculated:
   - Weighted SEL for each pile at each AMAR (mean weighted value + 10*log(N)).
   - Weighted-level spreading loss for each pile and weighting function.
   - Range at which the total SEL for all piles reached the threshold by applying the appropriate spreading loss terms to the AMAR measurements.
   - Ranges as distances to Level A harassment thresholds for a fixed receiver.

4.4.2. Ambient Data Analysis

Ambient noise levels at each recording station were measured as:

- Broadband and approximate decade band sound pressure levels (SPLs) over time for these frequency bands: 10 Hz to 64 kHz, 10–100 Hz, 100 Hz to 1 kHz, 1–10 kHz, and 10–64 kHz.
- Spectrograms: Ambient noise at each station was analyzed by Hamming-windowed fast Fourier transforms (FFTs), with 1 Hz resolution and 50% window overlap.
- Statistical distribution of sound pressure levels (exceedance levels) in each 1/3-octave band and for the power spectral density.

5. Results

Received levels for pile driving activity sounds were analyzed at each recorder. A linear fit was computed between the levels and the range to the piles to determine the source levels and transmission loss coefficients. Received levels and empirical ranges to threshold distances are presented for each construction site. All dates and times are reported in UTC. Spectrograms representing the entire monitoring period, band-limited time histories, time histories of pile driving sound levels, and ambient noise characteristics are provided in the appendices as supporting data.

5.1. Kake

JASCO field staff monitored pile driving activities at the Kake ferry terminal facility from 9–13 Sep 2015. Activities monitored included extracting two batter piles and installing two restraint piles. Vibratory extractions occurred on the east and west sides of the project location, as did installations.

Each vibratory extraction took 15 min. Vibratory driving of the east restraint at the final position took 15 min; impact hammering occurred over 4 min with 106 strikes. Vibratory driving of the west restraint occurred over 95 min; impact piling occurred for 4 min and included 118 strikes. Periods without construction activity were analyzed to estimate the background noise levels at the Kake ferry terminal. Pile installation was monitored at two fixed distances from each pile (west restraint: 9.5 m and 1098 m; east restraint: 14 m and 1161 m). Pile extraction was monitored from two fixed distances for each pile (west restraint: 7 m and 1149 m; east restraint: 17 m and 1157 m).

5.1.1. Impact Driving Noise Levels

A spectrogram showing multiple strikes of the impact hammer on the east restraint pile at a range of 14 m displays the broadband frequency content of the impacts (Figure 7). The received levels at the recorders decreased with range, whereas the durations of the signals increased with range (Figure 8). The SPLs were relatively stable, within a few dB, over the course of the hammering. During the last impacts, the AMAR at 1098 m from the east restraint pile did not record the entire signal because it was saturated, meaning that the signal exceeded the recording system's capabilities.

A linear regression between the SPL and the logarithm of the range to the recorders is presented in Figure 9. This regression provides estimates of the source level and transmission loss coefficient in Equation 1. The strikes that saturated the AMAR were excluded from this analysis. The estimated source level from this regression is 212.8 dB re 1 µPa, with a transmission loss estimate of 19.6 (*n* in Equation 1). The maximum SPL for all of the impacts recorded was 199.1 dB 9.5 m from the west restraint. The mean, median, max, and 90% received levels for SPL, peak pressure, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) are provided in Table 16.

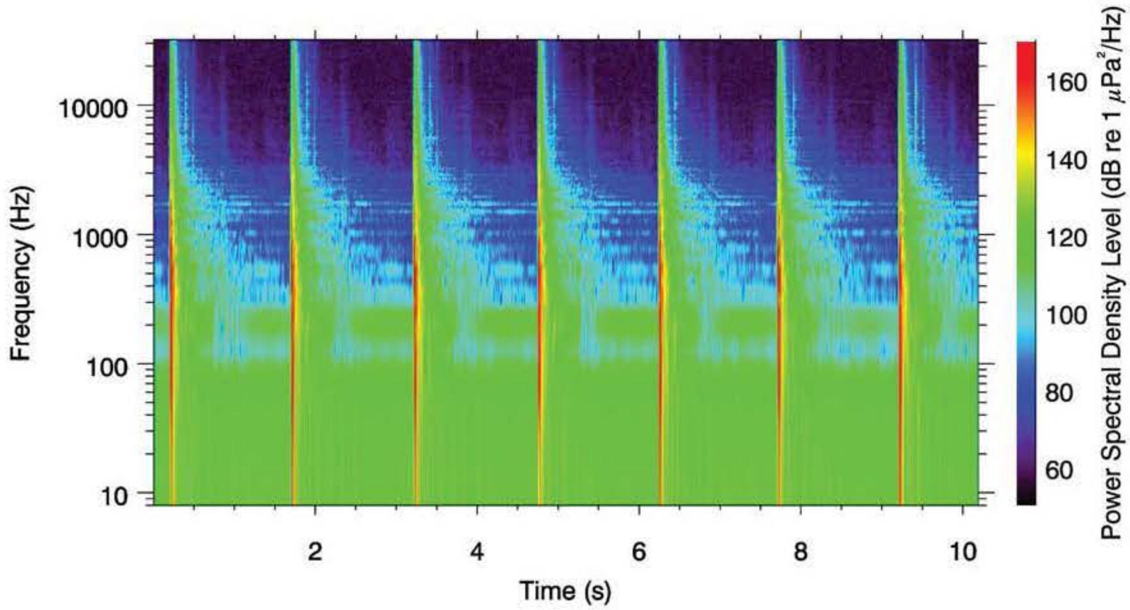

Figure 7. Spectrogram of multiple strikes by the impact hammer on the 30" diameter east restraint pile measured at 14 m range on AMAR 1.

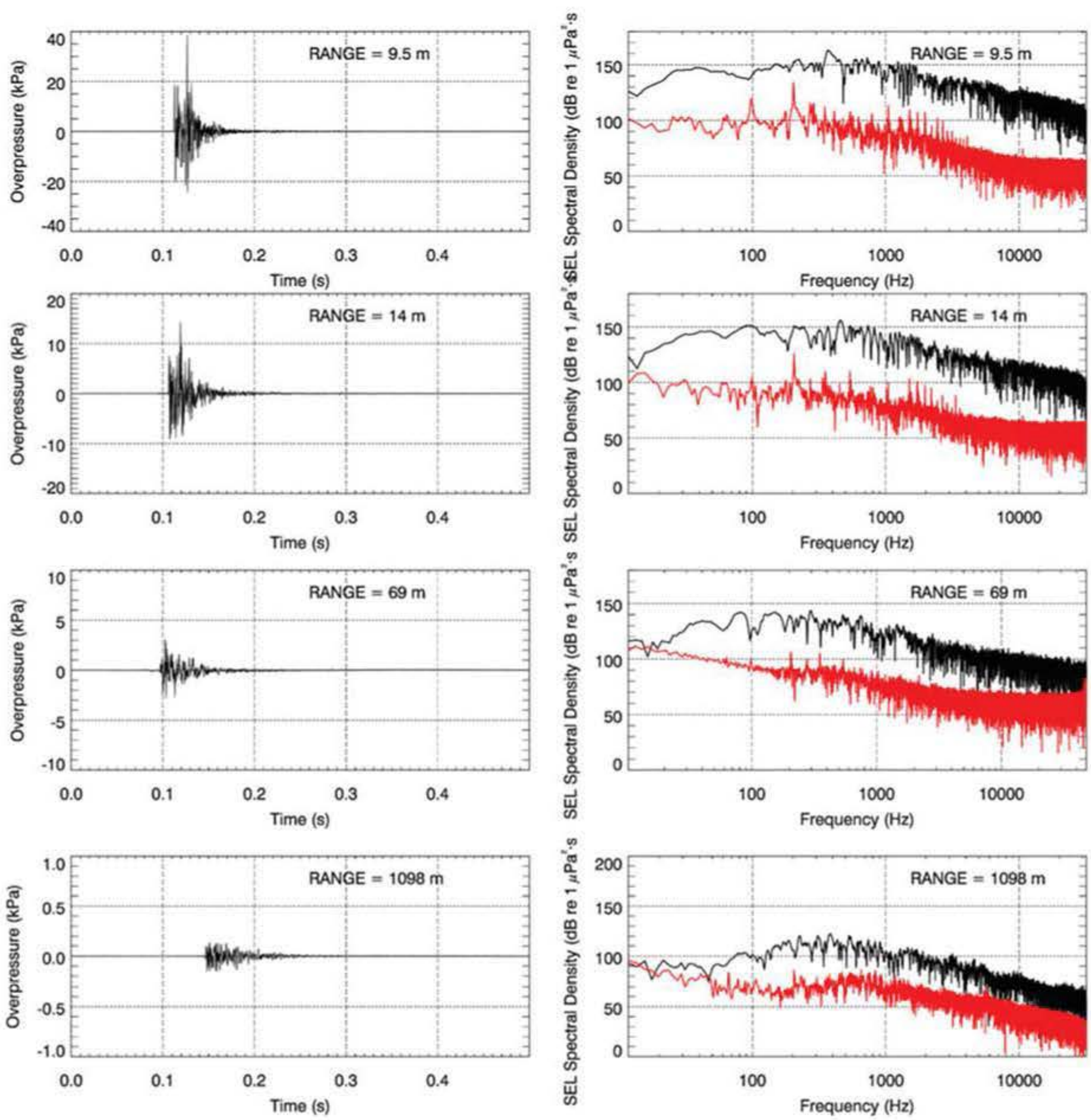

Figure 8. Waveforms (left) and spectra (right) for impact hammering of the east and west restraint piles measured at various distances from the pile. Background noise spectrum from the 0.5 s window preceding the pulse is shown in red.

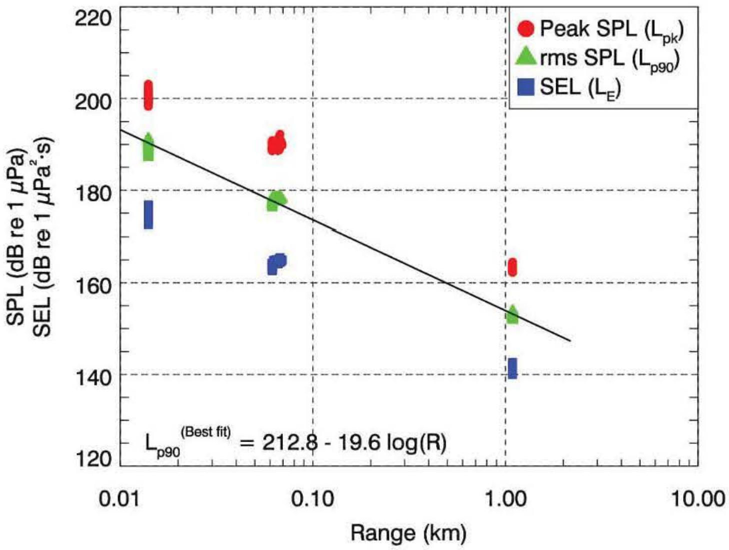

Figure 9. Peak level, SPL, and SEL versus range for impact driving of the 30" diameter east restraint pile. Line shows best-fit transmission loss curve to SPL data. Levels included in this plot are from the 50 strikes that were recorded on both AMARs and the dipping hydrophone.

Table 16. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving 30" diameter steel piles. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level	Weighting	Mean	Median	Max	90th percentile
West Restraint					
AMAR 1–9.5 m range (n = 118)					
peak level (dB re 1 µPa)	Unw	208.9	208.4	212.2	211.5
SPL (dB re 1 µPa)	Unw	196.1	195.3	199.1	198.4
single-strike SEL (dB re 1 µPa²s)	Unw	181.0	180.3	183.7	183.1
	LFC	180.3	179.5	183.0	182.4
	MFC	160.3	160.1	163.0	162.5
	HFC	157.3	157.2	159.8	159.3
	PPW	173.3	172.7	176.1	175.4
	OPW	173.6	173.2	176.4	175.8
East Restraint					
AMAR 1–14 m range (n = 106)					
peak level (dB re 1 µPa)	Unw	201.7	201.8	204.3	203.4
SPL (dB re 1 µPa)	Unw	190.9	191.0	192.6	192.3
single-strike SEL (dB re 1 µPa²s)	Unw	176.3	176.4	178.1	177.7
	LFC	175.4	175.3	177.2	176.8
	MFC	153.6	153.5	155.6	155.1
	HFC	150.3	150.3	152.5	151.8

Sound level	Weighting	Mean	Median	Max	90th percentile
	PPW	168.1	168.1	170.3	169.5
	OPW	168.5	168.3	170.7	169.9
AMAR 2–1098 m range (n = 106)					
peak level (dB re 1 µPa)	Unw	164.5	164.0	166.5	166.4
SPL (dB re 1 µPa)	Unw	154.1	154.0	155.7	155.2
single-strike SEL (dB re 1 µPa²s)	Unw	142.2	142.2	144.1	143.6
	LFC	141.4	141.3	143.3	142.8
	MFC	117.0	117.3	118.9	118.4
	HFC	112.9	113.1	115.0	114.6
	PPW	133.0	133.1	134.7	134.1
	OPW	133.0	133.2	134.6	134.1

5.1.2. Vibratory Driving Noise Levels

A spectrogram showing over 3 min of the vibratory hammer on the east restraint pile at a range of 14 m displays the broadband frequency content of the vibratory hammering over time (Figure 10). The received levels at the recorders decreased with range (Figure 11). Close to the piles, the SPLs clearly exceeded the background levels, while at 1 km the levels did not exceed the background by the same margins.

A linear regression between the SPL and the logarithm of the range to the recorders is presented in Figure 11. The estimated source level at 1 m from this regression is 174.9 dB re 1 µPa, with a transmission loss estimate of 20.6 (*n* in Equation 1). The mean, median, max, and 90% received levels for 1 s SPLs (equivalent to SEL) and statistics of SPLs weighted according to the 2016 NMFS guidelines are presented in Table 17 and Table 18. The maximum 1 s SPL was 170.6 dB, 9.5 m from the west restraint.

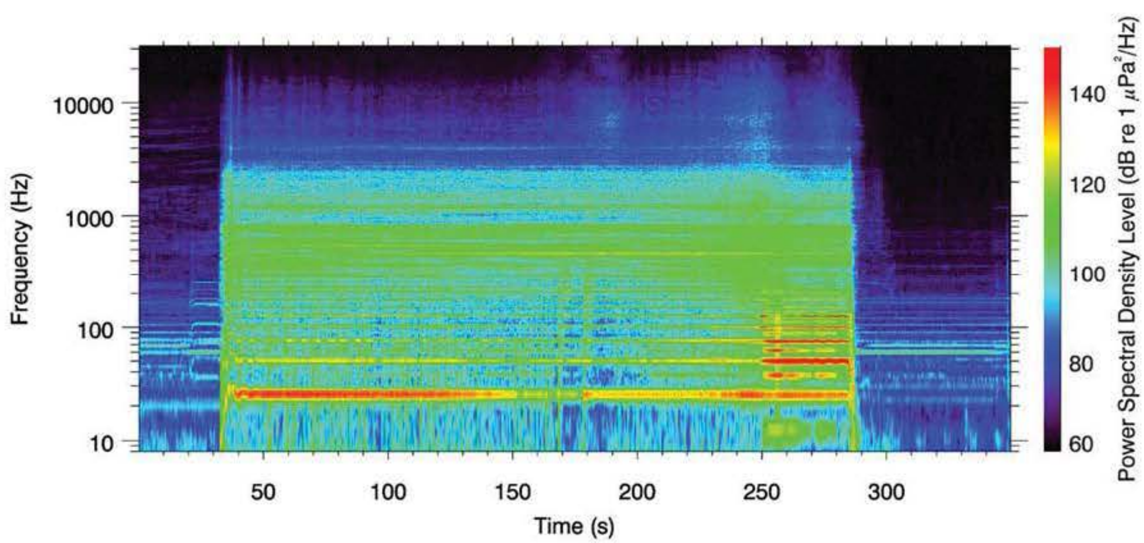

Figure 10. Spectrogram of vibratory driving of the 30" diameter east restraint pile measured at 14 m range on AMAR 1.

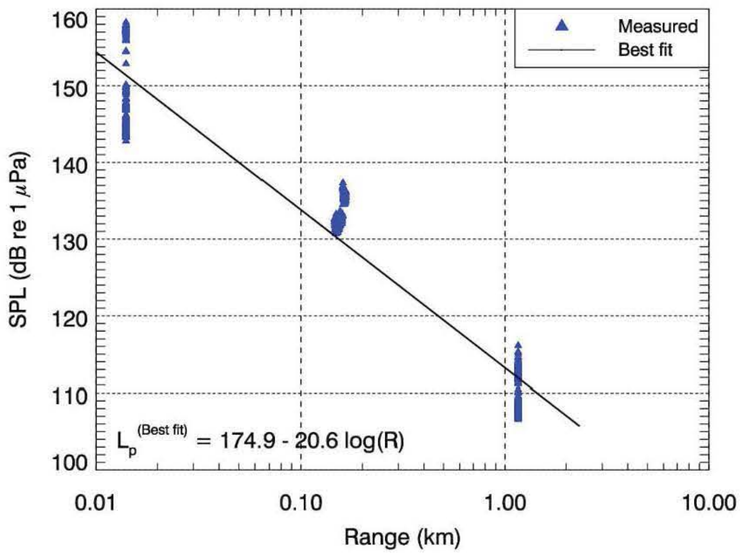

Figure 11. Plot of SPL versus range for vibratory driving of the 30” diameter east restraint pile. Line shows best-fit transmission loss curve to SPL data from AMARs 1 and 2 and the dipping hydrophone.

Table 17. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving of the 30” diameter east restraint pile. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level	Weighting	Mean	Median	Max	90th percentile
AMAR 1–14 m range (295 s)					
SPL (dB re 1 µPa)	Unw	150.8	147.5	158.2	156.9
	LFC	144.6	142.2	151.8	148.8
	MFC	122.2	117.4	139.9	124.5
	HFC	119.3	113.3	137.9	121.4
	PPW	135.7	134.9	145.5	137.5
	OPW	135.9	135.2	145.6	137.5
AMAR 2–1161 m range (290 s)					
SPL (dB re 1 µPa)	Unw	110.1	108.2	118.8	113.4
	LFC	107.8	106.7	117.1	109.9
	MFC	88.3	87.3	103.2	90.1
	HFC	85.5	84.5	100.5	87.3
	PPW	99.3	98.7	111.0	100.3
	OPW	99.2	98.5	111.1	100.0

Table 18. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving of the 30” diameter west restraint pile. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level	Weighting	Mean	Median	Max	90th percentile
AMAR 1–9.5 m range (1098 s)					
SPL (dB re 1 µPa)	Unw	160.4	158.6	170.6	163.8
	LFC	151.9	149.2	166.7	154.7
	MFC	124.5	120.9	140.4	124.5
	HFC	121.1	115.7	138.5	120.1
	PPW	140.3	139.1	152.1	140.8
	OPW	139.8	138.8	152.5	140.3

5.1.3. Vibratory Extraction Noise Levels

Vibratory extraction of two existing 18” restraint piles were monitored to determine the level of noise generated by this activity. The regression of recorded levels and logarithm to range provided a source level estimate of 168.2 dB, with a transmission loss coefficient of 19.2 (Figure 12). Statistics of the broadband and functional hearing group weighted SPLs are provided in Table 19.

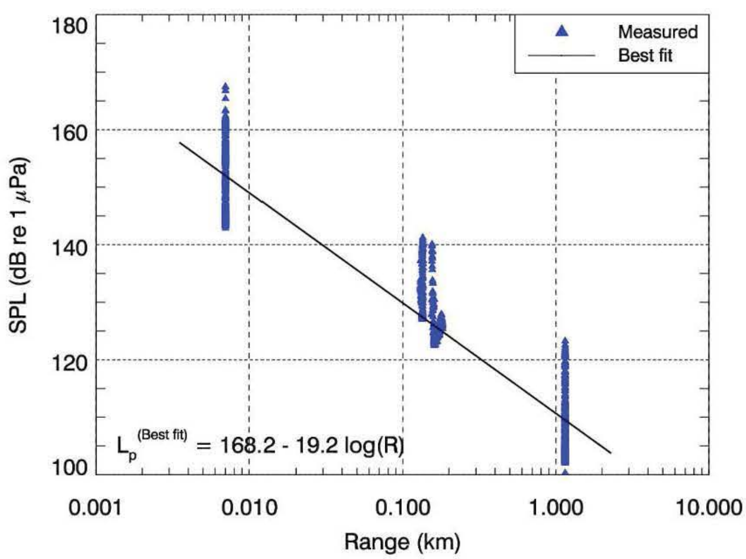

Figure 12. SPL versus range for vibratory extraction of the 18” diameter west restraint pile. Line shows best-fit transmission loss curve to SPL data from AMARs 1 and 2 and the dipping hydrophone.

Table 19. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory extraction of the 18” diameter west restraint steel pile. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level	Weighting	Mean	Median	Max	90th percentile
AMAR 1–7 m range (n = 222)					
SPL (dB re 1 µPa)	Unw	156.2	151.0	167.3	161.1
	LFC	152.4	145.1	165.5	156.5
	MFC	137.4	119.3	155.7	136.9
	HFC	134.4	115.2	152.5	132.9
	PPW	146.5	136.0	163.2	149.3
	OPW	146.8	135.8	163.6	149.3
AMAR 2–1149 m range (n = 222)					
SPL (dB re 1 µPa)	Unw	113.9	106.7	126.8	118.9
	LFC	112.6	104.9	126.2	117.5
	MFC	99.1	90.2	118.2	99.5
	HFC	95.8	88.7	115.1	94.7
	PPW	108.9	97.8	125.2	111.4
	OPW	109.3	97.9	125.5	111.9

Table 20. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory extraction of the 18” diameter east restraint steel pile. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level	Weighting	Mean	Median	Max	90th percentile
AMAR 1–17 m range (n = 320)					
SPL (dB re 1 µPa)	Unw	152.4	147.7	162.8	154.9
	LFC	149.0	141.7	159.7	152.5
	MFC	127.4	113.6	144.2	129.2
	HFC	124.6	109.4	142.0	125.8
	PPW	140.3	131.0	152.5	144.7
	OPW	140.4	130.9	152.7	145.0
AMAR 2–1157 m range (n = 321)					
	Unw	115.6	110.2	126.4	119.3
	LFC	114.0	108.3	125.0	117.9
	MFC	94.0	81.8	109.1	98.0
	HFC	90.0	78.2	105.6	92.8
	PPW	107.5	97.8	120.3	112.0
	OPW	107.9	97.1	120.9	112.5

5.1.4. Threshold Distances

Equation 1 was solved for the threshold criteria provided in Section 2, using the regressions and statistical measures of source levels and transmission loss from Sections 5.1.1 through 5.1.3. For impact pile driving, vibratory pile driving, and vibratory pile extraction, the ranges to the different thresholds are in Table 21. Injury ranges were less than 86 m, and behavioral disturbance range was less than 1300 m.

Table 21. Distance to SPL thresholds determined from best-fit transmission loss coefficient and SPLs on AMAR 1 (90th percentile and mean). Threshold distances are maximized over the levels from the east and west restraint piles.

Threshold (SPL, dB re 1 µPa)	90th Percentile Distance (m)	Mean Distance (m)	Transmission Loss Coefficient
Impact driving 30" piles			
190	27	20	19.6
180	86	66	19.6
160	897	685	19.6
Vibratory driving 30" piles			
120	1207*	825	20.6
Vibratory extraction 18" piles			
120	1269*	940	19.2

*Extrapolated beyond maximum measurement range.

5.1.5. Weighted Transmission Loss Coefficients

NMFS 2016 functional hearing group weighting functions were applied to the received signals and when possible, regressions between the weighted levels and the logarithm of the ranges were computed to determine the transmission loss coefficient for each functional hearing group (Table 22–Table 24). Transmission loss estimates ranged from 16.9 for the extraction of the west pile with OPW weighting to 19.7 for impact hammering of the east restraint for HFC.

Table 22. Transmission loss coefficients from mean AMAR measurements for impact hammering. N/A = data excluded from analysis. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	West Restraint	East Restraint
LFC	N/A	17.9
MFC	N/A	19.3
HFC	N/A	19.7
PPW	N/A	18.5
OPW	N/A	18.7

Table 23. Transmission loss coefficients from mean AMAR measurements for vibratory driving. N/A = data excluded from analysis. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	West Restraint	East Restraint
LFC	N/A	19.2

Weighting	West Restraint	East Restraint
MFC	N/A	17.7
HFC	N/A	17.7
PPW	N/A	19.0
OPW	N/A	19.2

Table 24. Transmission loss coefficients from mean AMAR measurements for vibratory extraction. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	West pile	East pile
LFC	18.0	19.1
MFC	17.3	18.2
HFC	17.4	18.9
PPW	17.0	17.9
OPW	16.9	17.7

5.1.6. Weighted-Level Threshold Distances

For AMAR 1, peak levels were calculated from maximum peak measurements and back-propagated using spherical spreading when measurements did not reach a peak threshold, and forward-propagated using the practical spreading loss model when measurements exceeded a peak threshold (Table 25). The peak threshold distances are less than the SEL-based threshold ranges for all hearing groups.

Table 25. Range in meters to onset of hearing injury based on NMFS 2016 criteria (Section 2) for pile driving at Kake ferry terminal. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	Impact		Vibratory
	SEL 24h	Peak	SEL 24h
LFC	124	4	2
MFC	7	1	0
HFC	164	31	2
PPW	37	5	0
OPW	4	1	0

5.2. Auke Bay

Pile driving activities at the Auke Bay ferry terminal were monitored by JASCO field staff from 9-12 Nov 2015. Activities monitored included installation of three piles. Vibratory driving of each pile took about 30 min. Impact hammering occurred for less than 15 min for each pile. Periods without construction activity were analyzed to estimate the background noise levels at the Auke Bay ferry terminal. Pile installation was monitored at two fixed distances from each pile (Pile 1: 5.3 m and 1188 m; Pile 2: 4.0 m and 1187 m; Pile 3: 6.8 m and 1184 m).

5.2.1. Impact Driving Noise Levels

Examples of signals recorded on each AMAR are provided in Figure 13. The spectrum from AMAR 1, at 6.8 m from the pile is more clearly above the background noise level, throughout the frequency range, compared with the signal recorded at AMAR 2. The peak level of the signal at AMAR 1 was over 100 times that at AMAR 2 in Figure 13. A spectrogram showing multiple strikes of the impact hammer on Pile 3 at a range of 6.8 m displays the broadband frequency content of the impacts (Figure 14). Received levels were relatively stable, within a few dB, over the course of the hammering.

A linear regression between the SPL and the logarithm of the range to the recorders is presented in Figure 15. Only pulses recorded simultaneously on each system were included in the regression. The whiskers and dashed lines represent the variability due to GPS accuracy. The estimated source level at 1 m from this regression is 206.6 dB re 1 µPa, with a transmission loss estimate of 14.6 (*n* in Equation 1). The mean, median, max, and 90% received levels for SPL, peak pressure, and single-strike SEL (unweighted and weighted according to the 2016 NMFS guidance) are provided in Table 26 through Table 28. The maximum SPL for all of the impacts recorded was 203.8 dB 6.8 m from Pile 3.

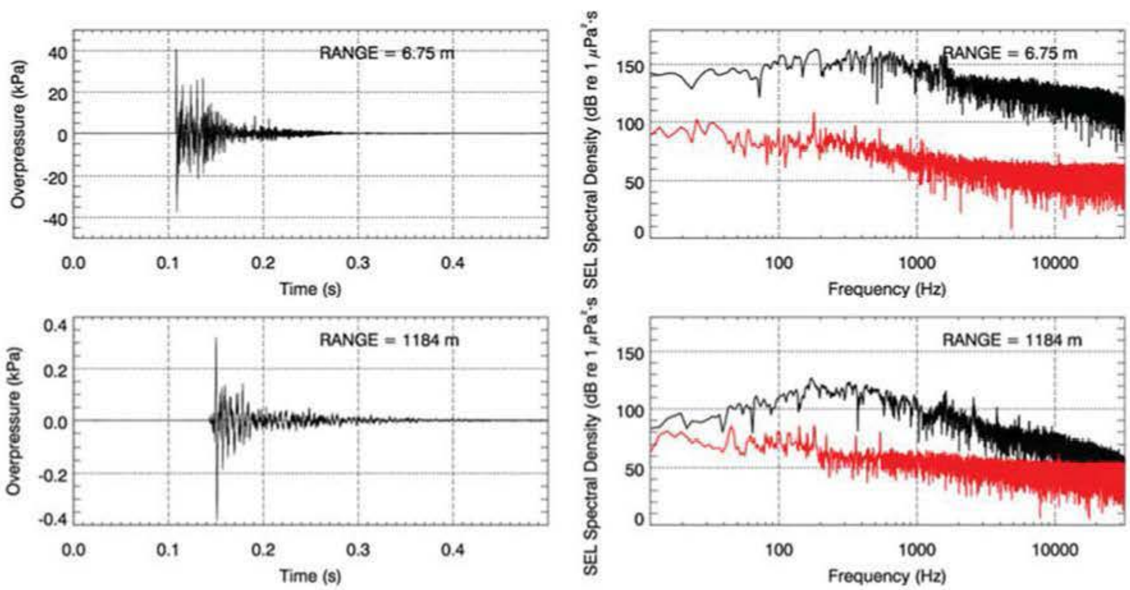

Figure 13. Waveforms (left) and spectra (right) for impact hammering of 30" steel piles recorded at AMAR 1 (top) and AMAR 2 (bottom). Background noise spectrum from the 0.5 s window preceding the pulse is shown in red.

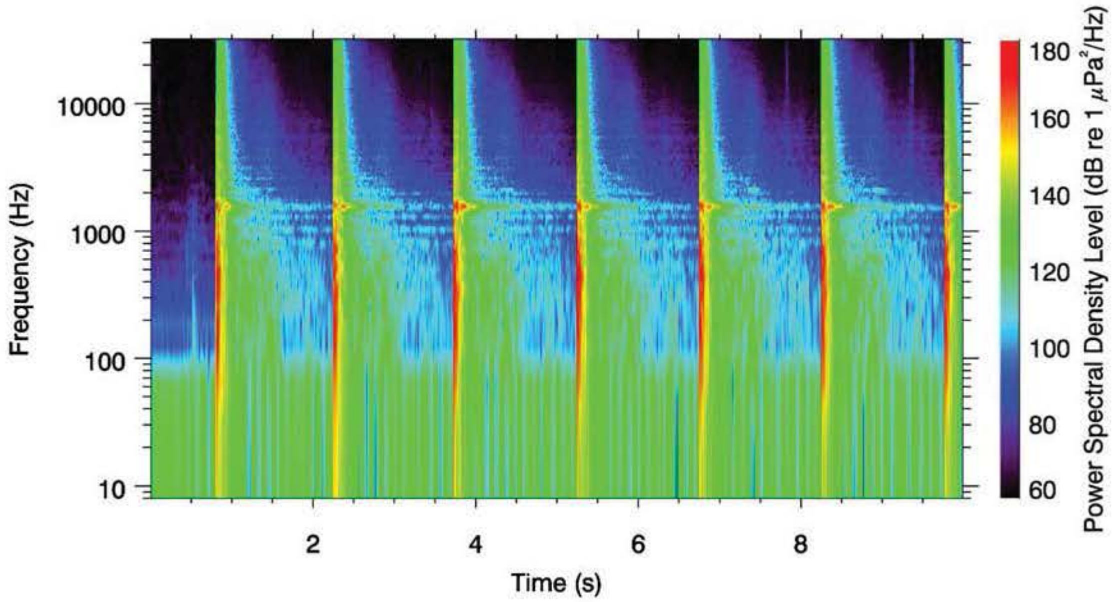

Figure 14. Spectrogram of multiple strikes by the impact hammer on Pile 3 measured at 6.8±1 m range on AMAR 1.

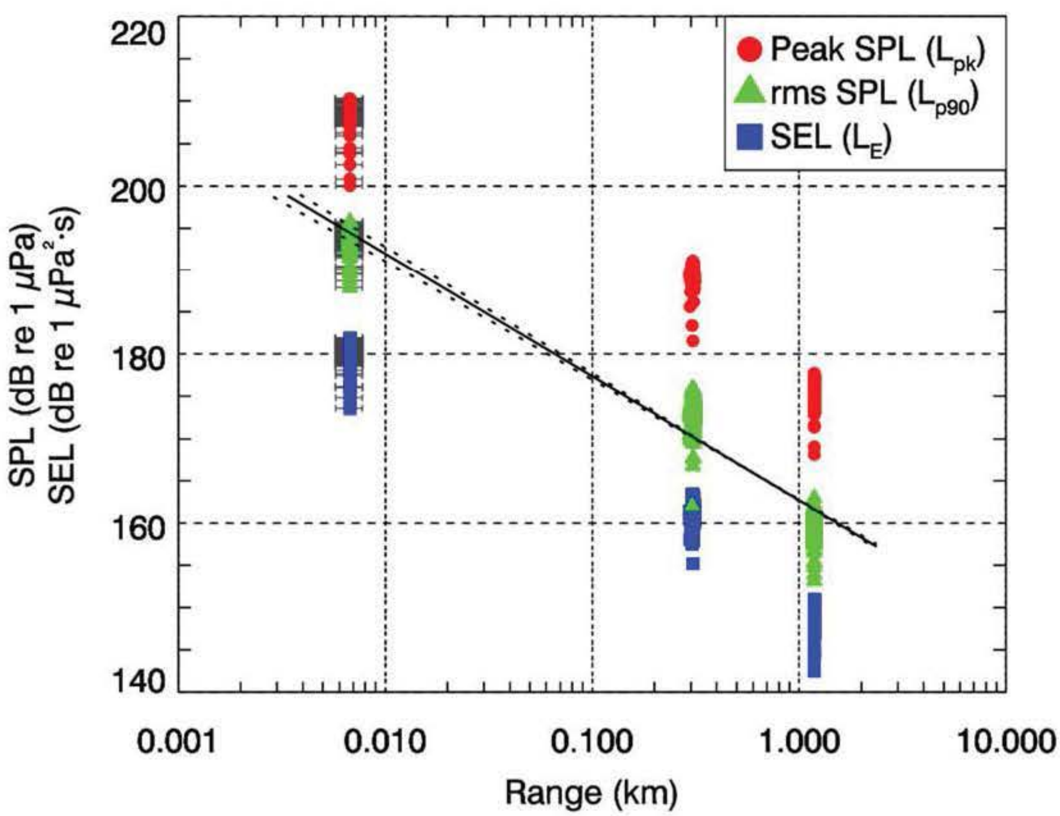

Figure 15. Peak level, SPL, and SEL versus range measured during impact driving of Pile 3. Horizontal whiskers show estimated uncertainty in AMAR 1 range. Solid line shows best-fit transmission loss curve to SPL data ($SPL = 206.6–14.6\times \log R$). Dashed lines show best fit curves incorporating uncertainty in AMAR 1 range. Only levels from pulses recorded simultaneously on both AMARs and the dipping hydrophone were used to estimate transmission loss (n = 336 at each location).

Table 26. Pile 1: Impact driving statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water. Note that AMAR 1 data were clipped and are not presented.

Sound level	Weighting	Mean	Median	Max	90th percentile
AMAR 2 –1188 m range (n = 22)					
peak level (dB re 1 µPa)	Unw	180.4	181.1	181.5	181.5
SPL (dB re 1 µPa)	Unw	163.7	164.4	164.8	164.7
single-strike SEL (dB re 1 µPa^{2}s)	Unw	153.6	154.3	154.6	154.5
	LFC	152.1	152.8	153.2	153.0
	MFC	126.6	127.4	128.1	128.0
	HFC	123.5	124.3	125.0	124.8
	PPW	142.2	142.9	143.6	143.4
	OPW	141.9	142.7	143.4	143.1

Table 27. Pile 2: Impact driving statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water. Note that AMAR 1 data were clipped and are not presented.

Sound level	Weighting	Mean	Median	Max	90th percentile
AMAR 2–1187 m range (n = 262)					
peak level (dB re 1 µPa)	Unw	181.6	181.7	182.5	182.1
SPL (dB re 1 µPa)	Unw	164.6	164.6	166.3	165.2
single-strike SEL (dB re 1 µPa^{2}s)	Unw	154.2	154.1	155.9	154.9
	LFC	153.0	153.0	154.7	153.6
	MFC	125.7	125.5	128.3	126.7
	HFC	122.1	122.0	125.0	123.3
	PPW	143.4	143.4	145.0	144.1
	OPW	143.2	143.2	144.9	143.9

Table 28. Pile 3 Impact driving statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level	Weighting	Mean	Median	Max	90th percentile
AMAR 1–6.8± 1 m range (n = 535)					
peak level (dB re 1 µPa)	Unw	208.3	208.4	210.3	209.3
SPL (dB re 1 µPa)	Unw	193.6	193.7	203.8	194.6
single-strike SEL (dB re 1 µPa^{2}s)	Unw	179.7	179.8	181.9	180.7
	LFC	178.8	178.9	181.0	179.9

Sound level	Weighting	Mean	Median	Max	90th percentile
	MFC	157.4	157.3	160.9	159.1
	HFC	154.8	154.7	158.5	156.5
	PPW	171.3	171.3	173.8	172.6
	OPW	171.7	171.7	174.3	173.1
AMAR 2–1184 m range (n = 602)					
peak level (dB re 1 µPa)	Unw	177	175.1	183.2	181.2
SPL (dB re 1 µPa)	Unw	161.1	159	168.1	164.8
single-strike SEL (dB re 1 µPa^{2}s)	Unw	150.4	148.4	157.4	154.6
	LFC	149.1	147.2	156.1	153.2
	MFC	122.2	119.1	131.1	126.5
	HFC	118.5	115.2	127.7	122.8
	PPW	139.5	137.5	146.7	143.6
	OPW	139.3	137.3	146.6	143.4

5.2.2. Vibratory Driving Noise Levels

A spectrogram showing over 25 min of the vibratory hammer on Pile 1 at a range of 5.3 m displays the broadband frequency content of the vibratory hammering over time (Figure 16). The received level at the recorders decreased with range (Figure 17). Close to the piles, the SPLs clearly exceeded the background levels, while at 1 km the levels did not exceed the background by the same margins.

A linear regression between the SPL and the logarithm of the range to the recorders is presented in Figure 17. The estimated source level at 1 m from this regression is 178.2 dB re 1 µPa, with a transmission loss estimate of 16.4 (*n* in Equation 1). The mean, median, max, and 90% received levels for 1 s SPLs (equivalent to SEL) are provided in Table 29 through Table 31. The maximum 1 s SPL for was 183.5 dB, 6.8 m from Pile 3. Statistics of SPLs weighted according to the 2016 NMFS guidelines are also included.

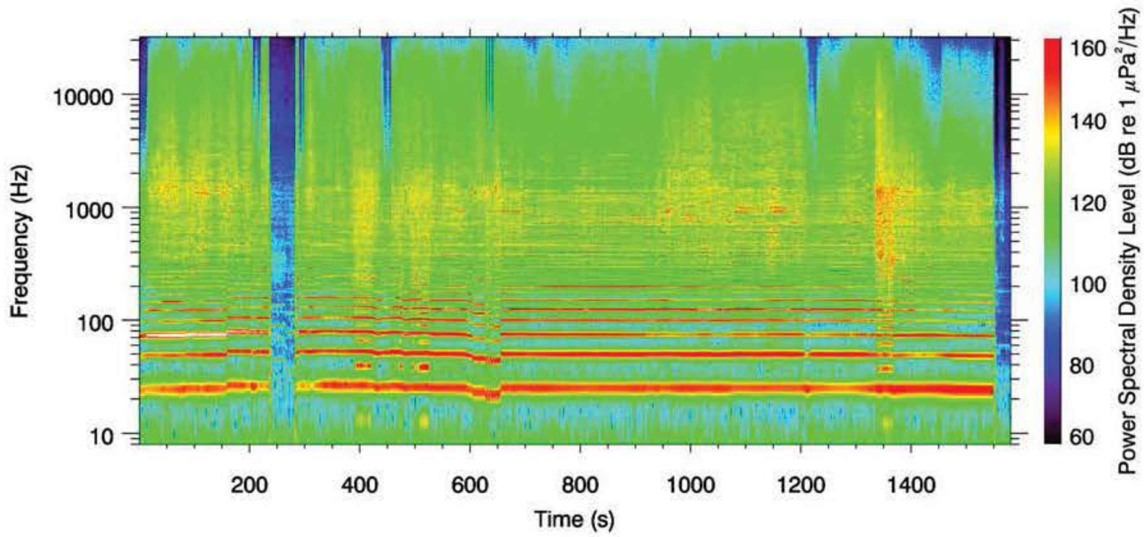

Figure 16. Spectrogram of vibratory driving of Pile 1 measured on AMAR 1.

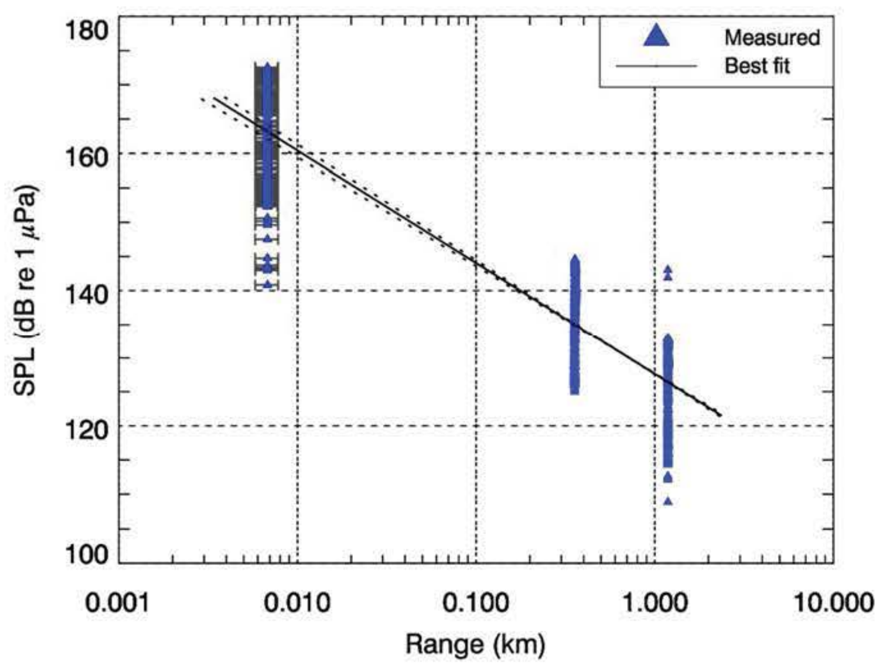

Figure 17. SPL (1 s average) versus range measured during vibratory driving of Pile 3. Horizontal whiskers show the uncertainty of the range to AMAR 1. Solid line shows best-fit transmission loss curve to SPL data ($SPL = 178.2 – 16.4 \times \log R$). Dashed lines show best fit curves incorporating uncertainty in AMAR 1 range. Only levels from vibratory driving recorded simultaneously on both AMARs and the dipping hydrophone were used to estimate transmission loss (341 s at each location).

Table 29. Pile 1: Vibratory driving statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (dB re 1 µPa)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–5.3±1 m range (1799 s)					

Sound level (dB re 1 µPa)	Weighting	Mean	Median	Max	90th percentile
SPL	Unw	173.9	173.1	181.6	176.5
	LFC	172.2	171.1	180.6	174.7
	MFC	163.3	159.9	175.0	167.3
	HFC	161.2	157.5	173.1	165.2
	PPW	169.1	167.1	179.1	172.4
	OPW	169.4	167.5	179.1	172.7
AMAR 2–1188 m range (2000 s)					
SPL	Unw	137.8	138.2	141.6	140.3
	LFC	133.9	133.7	140.8	136.6
	MFC	122.4	119.3	133.3	126.0
	HFC	119.5	116.4	130.8	123.2
	PPW	129.6	127.2	139.5	132.9
	OPW	129.8	127.4	139.8	133.1

Table 30. Pile 2: Vibratory driving statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (dB re 1 µPa)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–4.0± 1 m range (1156 s)					
SPL	Unw	174.0	173.2	180.1	177.0
	LFC	172.0	170.6	179.2	175.9
	MFC	163.9	161.7	172.0	168.1
	HFC	161.6	159.3	169.8	165.8
	PPW	169.7	167.9	177.5	173.6
	OPW	169.9	168.2	177.8	173.9
AMAR 2–1187 m range (1233 s)					
SPL	Unw	136.5	136.3	141.0	139.3
	LFC	133.7	132.8	139.6	137.4
	MFC	122.8	120.5	130.4	127.4
	HFC	119.9	117.5	127.9	124.6
	PPW	130.1	128.3	137.2	134.4
	OPW	130.4	128.5	137.4	134.6

Table 31. Pile 3: Vibratory driving statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (dB re 1 µPa)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–6.8± 1 m range (1589 s)					
SPL	Unw	172.1	171.2	183.5	175.4
	LFC	170.2	168.9	182.7	174.0
	MFC	159.7	154.6	175.8	164.3
	HFC	157.4	152.1	173.7	162.2
	PPW	166.5	163.6	180.3	170.7
	OPW	166.9	163.9	180.4	171.0
AMAR 2–1184 m range (1558 s)					
SPL	Unw	139.1	133.8	144.8	143.2
	LFC	134.2	131.1	142.6	137.7
	MFC	119.7	113.8	133.7	124.5
	HFC	116.7	110.2	130.7	121.4
	PPW	127.8	125.2	140.8	132.2
	OPW	128.0	125.2	141.1	132.5

5.2.3. Threshold Distances

Equation 1 was solved for the threshold criteria provided in Section 2. Using the regressions and statistical measures of source levels and transmission loss from Sections 5.2.1 and 5.2.2. Ranges to the different thresholds are in Table 32 for both impact and vibratory pile driving. Injury ranges were less than 67 m, and behavioral disturbance range was less than 1600 m for impact pile driving. Behavioral disturbance ranges for vibratory driving were extrapolated out to 16 km but there is significant uncertainty with a value extrapolated to such an extent based on measurements at a maximum distance of 1188 m.

Table 32. Distance to SPL thresholds determined from best-fit transmission loss coefficient and SPLs on AMAR 1 (90th percentile and mean). Distances for impact pile driving were calculated for Pile 3 data only, due to clipping of Pile 1 and 2 measurements.

Threshold (SPL, dB re 1 µPa)	90th Percentile Distance (m)	Mean Distance (m)	Transmission Loss Coefficient	90th Percentile SL (dB re 1 µPa @ 1 m)	Mean SL (dB re 1 µPa @ 1 m)
Impact driving 30" piles					
190	14±2	12±2	14.6±0.5	206.7±1.3	205.7±1.3
180	67±5	57±5	14.6±0.5	206.7±1.3	205.7±1.3
160	1567‡±44	1338‡±31	14.6±0.5	206.7±1.3	205.7±1.3
Vibratory driving 30" piles					
120	16,126^± 1507	10,257^±455	16.4±0.5	180.9±1.5	185.8±1.7

* Transmission loss coefficient was based on regression analysis of SPL vs range data for Pile 3 (Figure 17).

‡ Extrapolated beyond maximum measurement range.

^ Extrapolated far beyond maximum measurement range. These values are unrealistic, see Discussion section 6.3.

5.2.4. Weighted Transmission Loss Coefficients

NMFS 2016 functional hearing group weighting functions were applied to the received signals and when possible, regressions between the weighted levels and the logarithm of the ranges were computed to determine the transmission loss coefficient for each functional hearing group (Table 33 and Table 34). Transmission loss estimates ranged from 13.3 for the impact hammering of Pile 3 with LFC weighting to 18.2 for vibratory driving of Pile 3 for HFC.

Table 33. Transmission loss coefficients from mean AMAR measurements for impact hammering of Pile 3 (using nominal source-receiver ranges). LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water. N/A = data excluded from analysis.

Weighting	Pile 3*
LFC	13.3
MFC	15.7
HFC	16.2
PPW	14.2
OPW	14.5

*AMAR 1 measurements were clipped near the end of piling so the mean levels from AMAR 1 may be somewhat low relative to AMAR 2 measurements (which included the higher-level pulses near the end of piling). This may result in underestimated transmission loss coefficients.
† N/A represents data excluded from analyses.

Table 34. Transmission loss coefficients from mean AMAR measurements for vibratory driving (using nominal source-receiver ranges). LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	Pile 1	Pile 2	Pile 3
LFC	16.3	15.4	16.1
MFC	17.4	16.5	17.9
HFC	17.7	16.8	18.2
PPW	16.8	15.9	17.3
OPW	16.8	15.9	17.4

5.2.5. Weighted-Level Threshold Distances

Peak levels were calculated from max peak measurements and back-propagated using spherical spreading for AMAR 1 measurements lower than the peak threshold and forward-propagated using 15log*R* for AMAR 1 measurements higher than the peak threshold (Table 35). The peak threshold distances are less than the SEL-based threshold ranges for all hearing groups.

Table 35. Range in meters to onset of injury based on NMFS 2016 criteria (Section 2) for pile driving at Auke Bay ferry terminal. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	Impact		Vibratory
	SEL 24h	Peak	SEL 24h
LFC	740	1	15
MFC	13	0	6
HFC	557	6	82
PPW	122	1	9
OPW	8	0	1

5.3. Kodiak

Installation of piles at the Kodiak ferry terminal utilized different methods. Rock sockets were drilled and the piles were set in the sockets with vibratory hammer. Drilling occurred over a range of 40 min to 4 h depending on the pile. The vibratory hammer was used for up to 6 min per pile. The impact hammer struck the piles from 1 to 5 times. Drilling occurred for 45 min to 3 h 40 min. Periods of time without construction activity were analyzed to estimate the background noise levels at the Kodiak ferry terminal. Pile installation was monitored at nominal distances of 10 m and 1 km (Table 36).

Table 36. Range from piles to AMARs.

Pile	AMAR 1 range (m)	AMAR 2 range (m)
D12	31.1	1136
D13	28.1	1133
D14	25.1	1130
D15	22.0	1127
D16	19.0	1125
D18	16.0	1122
D20	12.9	1119
D22	9.9	1117

5.3.1. Impact Driving Noise Levels

Examples of signals recorded on each AMAR are provided in Figure 18. The spectrum from AMAR 1, at 9.9 m from the pile is more clearly above the background noise level, throughout the frequency range, compared with the signal recorded at AMAR 2. The peak level of the signal at AMAR 1 was over 100 times that at AMAR 2 in Figure 18. Spectrograms showing individual strikes of the impact hammer on Piles D22, D20, D18, and D16 at distances ranging from 9.9 to 19 m displays the broadband frequency content of the impacts (Figure 19–Figure 22).

A linear fit between the SPL and the logarithm of the range to the recorders is presented in Figure 23. Only pulses recorded simultaneously on each system were included in the regression. The impact from Pile D16 was excluded because the dipping hydrophone was not deployed for that impact. The estimated source level at 1 m from this regression is 200.1 dB re 1 µPa, with a transmission loss estimate of 20.3 (*n* in Equation 1). The mean, median, max, and 90% received levels for SPL, single-strike SEL, and peak pressure are provided in Table 37 through Table 40. The maximum SPL for all of the impacts recorded was 183.4 dB 12.9 m from D20. Statistics of SELs weighted according to the 2016 NMFS guidelines are also included.

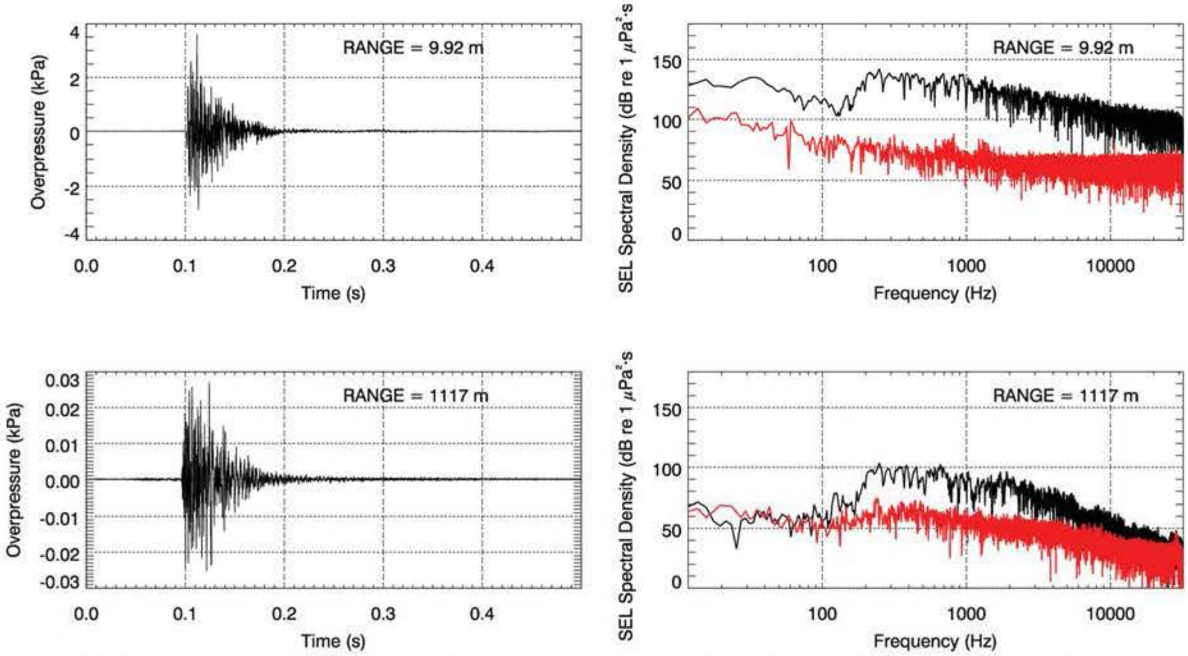

Figure 18. Waveforms (left) and spectra (right) for impact hammering of 24" steel piles recorded at AMAR 1 (top) and AMAR 2 (bottom). Background noise spectrum from the 0.5 s window preceding the pulse is shown in red.

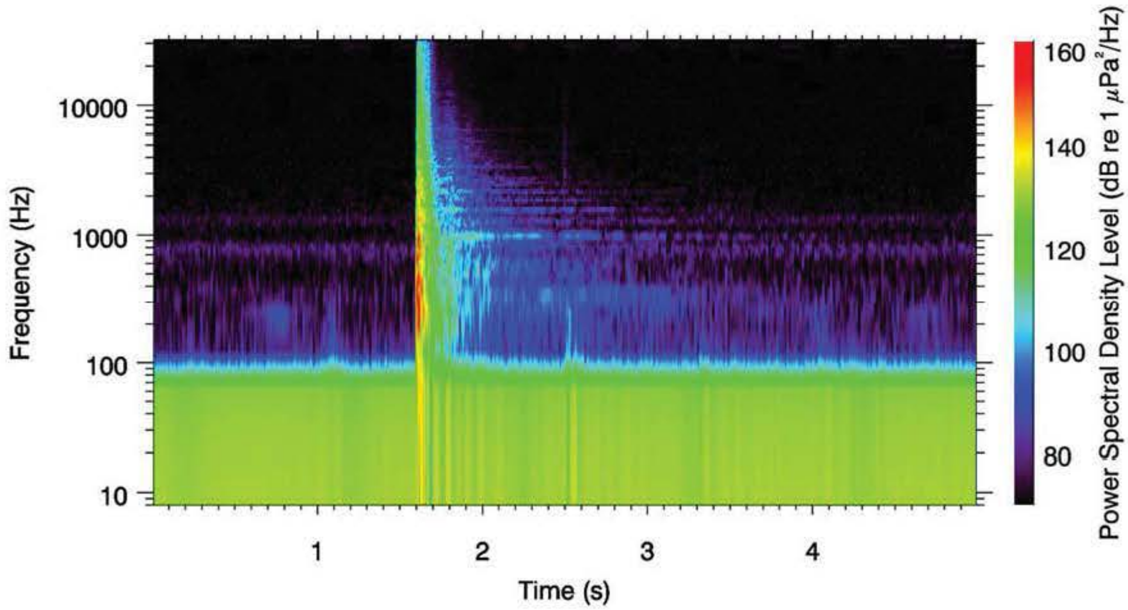

Figure 19. Spectrogram of the only strike by the impact hammer on Pile D22 measured at 9.9 m range on AMAR 1.

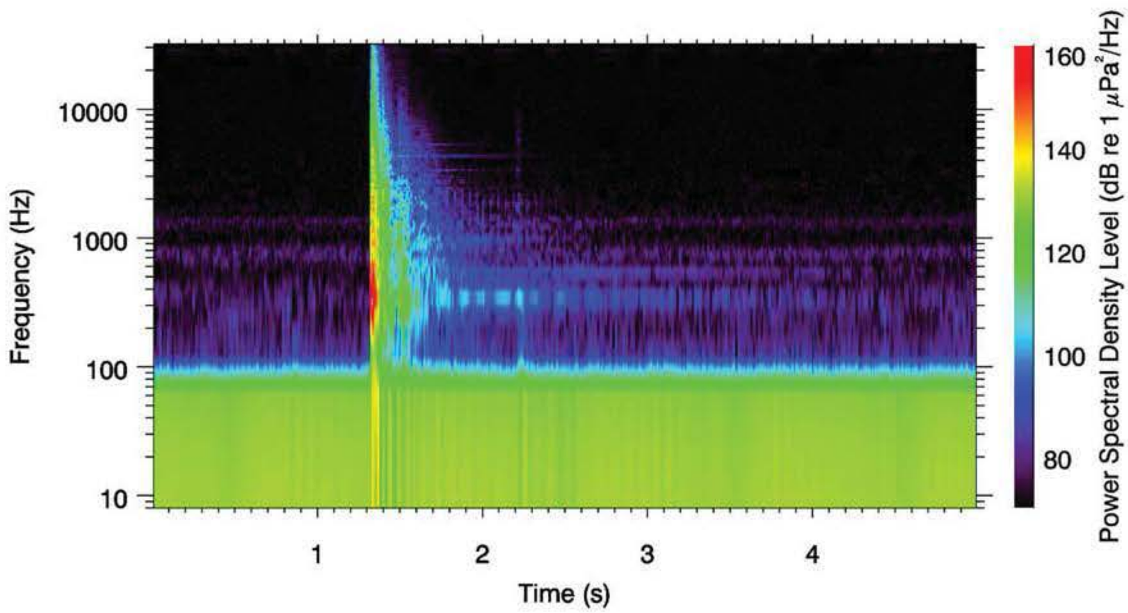

Figure 20. Spectrogram of one strike by the impact hammer on Pile D20 measured at 12.9 m range on AMAR 1.

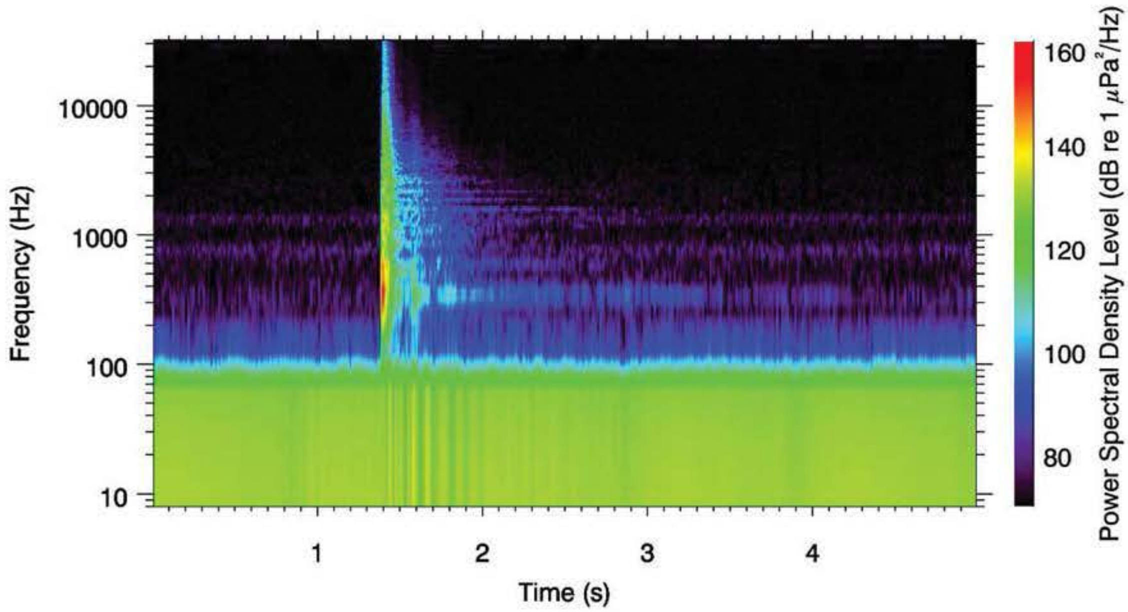

Figure 21. Spectrogram of one strike by the impact hammer on Pile D18 measured at 16.0 m range on AMAR 1.

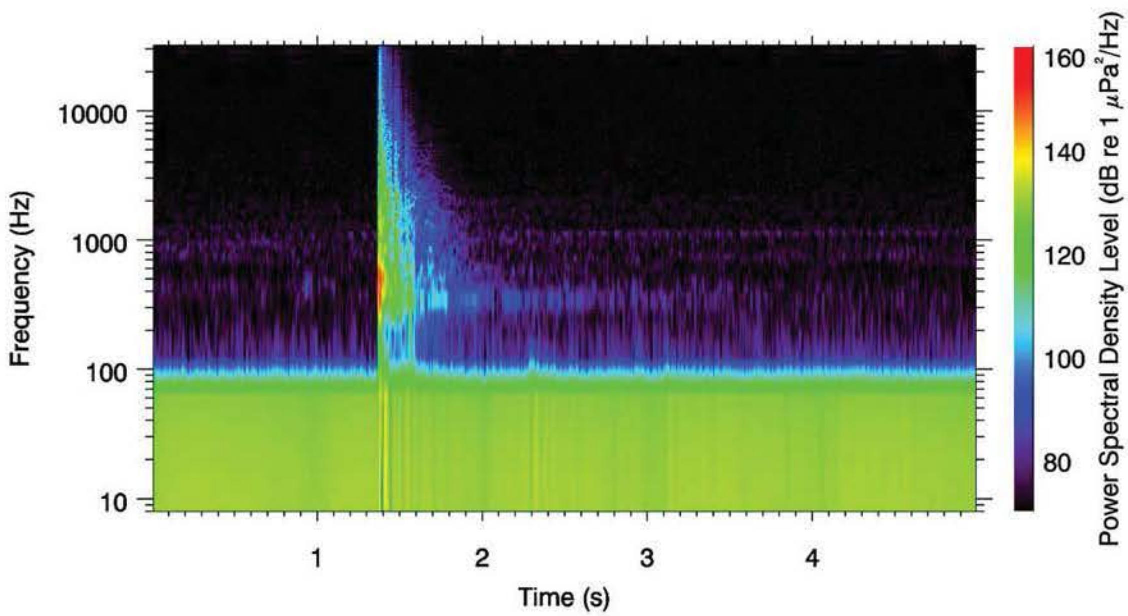

Figure 22. Spectrogram of the only strike by the impact hammer on Pile D16 measured at 19.0 m range on AMAR 1.

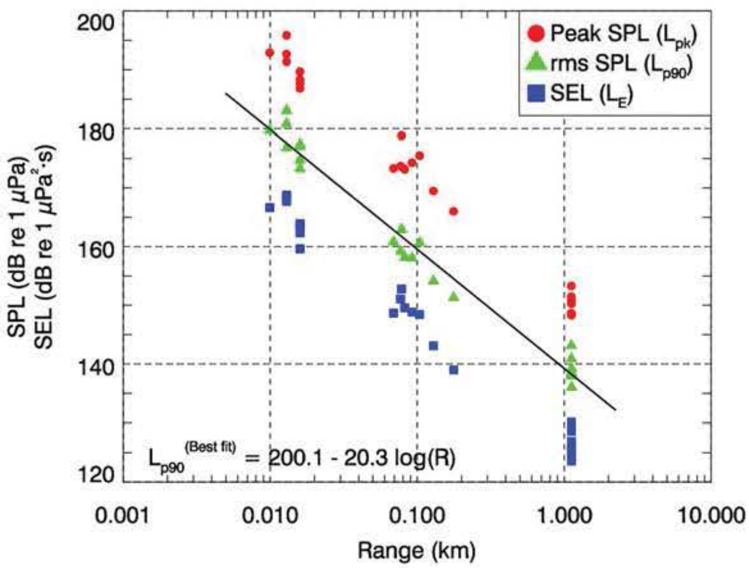

Figure 23. Peak level, SPL, and SEL versus range measured during impact driving of Piles D22, D20, and D18 (sound levels from the single strike on Pile D16 were not included in this analysis because the dipping hydrophone was not deployed during the strike). Solid line shows best-fit transmission loss curve to SPL data. Only levels from pulses recorded simultaneously on both AMARs and the dipping hydrophone were used to estimate transmission loss (n = 8 at each location).

Table 37. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving of Pile D22 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D22)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–9.9 m range (n = 1)					
peak level (dB re 1 µPa)	Unw	192.9	192.9	192.9	192.9
SPL (dB re 1 µPa)	Unw	180.1	180.1	180.1	180.1
single-strike SEL (dB re 1 µPa²s)	Unw	167.0	167.0	167.0	167.0
	LFC	166.2	166.2	166.2	166.2
	MFC	151.2	151.2	151.2	151.2
	HFC	148.8	148.8	148.8	148.8
	PPW	160.7	160.7	160.7	160.7
	OPW	161.2	161.2	161.2	161.2
AMAR 2–1117 m range (n = 1)					
peak level (dB re 1 µPa)	Unw	148.6	148.6	148.6	148.6
SPL (dB re 1 µPa)	Unw	138.1	138.1	138.1	138.1
single-strike SEL (dB re 1 µPa²s)	Unw	125.6	125.6	125.6	125.6
	LFC	125.0	125.0	125.0	125.0
	MFC	102.6	102.6	102.6	102.6
	HFC	97.0	97.0	97.0	97.0
	PPW	119.0	119.0	119.0	119.0

Sound level (Pile D22)	Weighting	Mean	Median	Max	90th percentile
	OPW	119.5	119.5	119.5	119.5

Table 38. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving of Pile D20 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D20)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–12.9 m range (n = 3)					
peak level (dB re 1 µPa)	Unw	193.7	192.6	195.9	195.9
SPL (dB re 1 µPa)	Unw	181.3	181.2	183.4	183.4
single-strike SEL (dB re 1 µPa²s)	Unw	168.6	168.7	169.1	169.1
	LFC	167.8	168.0	168.2	168.2
	MFC	150.3	151.0	151.3	151.3
	HFC	147.7	148.3	148.8	148.8
	PPW	161.0	161.6	161.9	161.9
	OPW	161.2	161.8	162.2	162.2
AMAR 2–1119 m range (n = 3)					
peak level (dB re 1 µPa)	Unw	152.0	151.4	153.3	153.3
SPL (dB re 1 µPa)	Unw	141.9	142.8	143.1	143.1
single-strike SEL (dB re 1 µPa²s)	Unw	128.7	129.9	130.1	130.1
	LFC	128.0	129.2	129.4	129.4
	MFC	103.0	103.9	105.1	105.1
	HFC	97.1	97.9	99.2	99.2
	PPW	120.6	121.7	122.4	122.4
	OPW	120.9	122.0	122.7	122.7

Table 39. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving of Pile D18 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D18)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–16.0 m range (n = 5)					
peak level (dB re 1 µPa)	Unw	187.9	187.7	189.7	189.7
SPL (dB re 1 µPa)	Unw	176.1	175.2	177.9	177.9
single-strike SEL (dB re 1 µPa²s)	Unw	162.7	162.7	164.3	164.3
	LFC	162.0	162.1	163.6	163.6
	MFC	146.5	147.0	148.7	148.7

Sound level (Pile D18)	Weighting	Mean	Median	Max	90th percentile
	HFC	143.8	144.3	145.8	145.8
	PPW	156.4	156.6	158.7	158.7
	OPW	156.6	156.7	159.0	159.0
AMAR 2–1122 m range (n = 5)					
peak level (dB re 1 µPa)	Unw	149.3	148.6	150.5	150.5
SPL (dB re 1 µPa)	Unw	138.1	138.1	139.2	139.2
single-strike SEL (dB re 1 µPa^{2}s)	Unw	125.2	124.7	126.8	126.8
	LFC	124.6	124.1	126.2	126.2
	MFC	103.2	103.7	105.6	105.6
	HFC	97.7	98.3	99.8	99.8
	PPW	118.7	118.7	121.3	121.3
	OPW	119.2	119.2	121.9	121.9

Table 40. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving of Pile D16 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D16)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–19.0 m range (n = 1)					
peak level (dB re 1 µPa)	Unw	184.9	184.9	184.9	184.9
SPL (dB re 1 µPa)	Unw	174.8	174.8	174.8	174.8
single-strike SEL (dB re 1 µPa^{2}s)	Unw	161.0	161.0	161.0	161.0
	LFC	160.3	160.3	160.3	160.3
	MFC	140.3	140.3	140.3	140.3
	HFC	137.7	137.7	137.7	137.7
	PPW	152.3	152.3	152.3	152.3
	OPW	152.2	152.2	152.2	152.2
AMAR 2–1125 m range (n = 1)					
peak level (dB re 1 µPa)	Unw	147.7	147.7	147.7	147.7
SPL (dB re 1 µPa)	Unw	138.4	138.4	138.4	138.4
single-strike SEL (dB re 1 µPa^{2}s)	Unw	124.8	124.8	124.8	124.8
	LFC	124.2	124.2	124.2	124.2
	MFC	96.5	96.5	96.5	96.5
	HFC	90.6	90.6	90.6	90.6
	PPW	115.7	115.7	115.7	115.7
	OPW	115.8	115.8	115.8	115.8

5.3.2. Vibratory Setting Driving Noise Levels

Vibratory setting was monitored at two nominal distances and also from a mobile platform for piles D12, D13, D14, D15, and D20. A spectrogram showing over 3 min of the vibratory hammer on Pile D20 at a range of 12.9 m displays the broadband frequency content of the vibratory hammering over time (Figure 24). One-second SPLs of vibratory driving are plotted against time in Figure C-7 and Figure C-8. Close to the piles, the SPLs clearly exceeded the background levels, while at 1 km the levels did not exceed background by the same margins.

The mean, median, max, and 90% received levels for 1 s SPLs (equivalent to SEL) are provided in Table 41 through Table 45. The maximum 1 s SPL for was 161.8 dB, 12.9 m from Pile D20. Statistics of SPLs weighted according to the 2016 NMFS guidelines are also included.

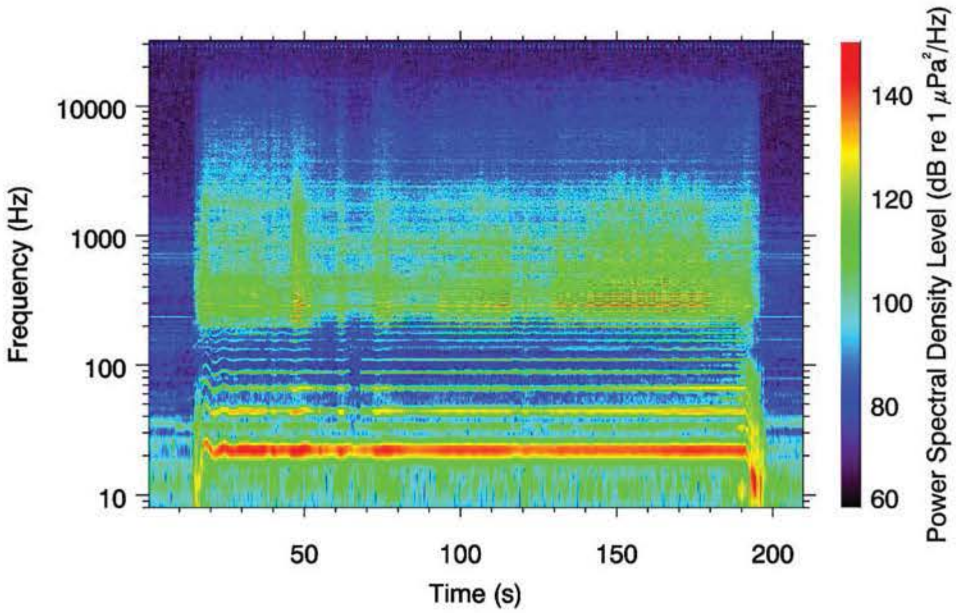

Figure 24. Spectrogram of setting Pile D20 into the sediment with the vibratory driver (measured on AMAR 1).

Table 41. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (setting) of Pile D20 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D20)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–12.9 m range (292 s)					
SPL (dB re 1 µPa)	Unw	154.6	151.5	161.8	159.5
	LFC	152.4	145.1	160.5	158.1
	MFC	128.3	128.3	135.1	131.0
	HFC	127.7	127.6	134.9	130.5
	PPW	140.8	135.4	148.6	146.1
	OPW	139.2	134.7	148.2	144.1
AMAR 2–1119 m range (292 s)					
SPL (dB re 1 µPa)	Unw	114.8	108.8	123.0	120.2
	LFC	113.7	107.7	122.4	119.0

Sound level (Pile D20)	Weighting	Mean	Median	Max	90th percentile
	MFC	87.4	84.5	106.1	88.4
	HFC	83.1	81.1	100.9	84.1
	PPW	103.9	99.8	119.2	107.9
	OPW	103.4	99.8	119.7	106.8

Table 42. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (setting) of Pile D15 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D15)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–22.0 m range (133 s)					
SPL (dB re 1 µPa)	Unw	146.7	144.7	154.1	150.4
	LFC	143.1	139.6	151.9	146.9
	MFC	119.2	118.9	122.9	120.3
	HFC	117.1	117.0	119.0	117.9
	PPW	132.9	129.5	142.2	136.0
	OPW	132.3	128.7	142.1	134.8
AMAR 2–1127 m range (133 s)					
SPL (dB re 1 µPa)	Unw	113.8	109.0	122.2	117.8
	LFC	112.9	108.0	121.4	116.7
	MFC	86.0	84.7	93.2	88.6
	HFC	82.4	81.8	87.4	84.0
	PPW	103.7	99.6	113.6	107.2
	OPW	103.6	99.6	114.0	107.2

Table 43. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (setting) of Pile D14 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D14)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–25.1 m range (194 s)					
SPL (dB re 1 µPa)	Unw	147.9	143.7	158.2	152.9
	LFC	146.6	141.7	157.4	151.9
	MFC	132.1	118.6	144.5	137.0
	HFC	129.0	116.2	141.9	133.2
	PPW	142.0	132.2	153.3	148.3
	OPW	142.4	131.8	153.7	148.9
AMAR 2–1130 m range (194 s)					
SPL (dB re 1 µPa)	Unw	117.3	113.6	127.2	122.2

Sound level (Pile D14)	Weighting	Mean	Median	Max	90th percentile
	LFC	116.2	112.3	126.4	121.2
	MFC	97.6	85.5	109.3	104.0
	HFC	93.2	82.2	105.1	99.5
	PPW	110.2	102.5	120.7	116.2
	OPW	110.6	101.9	121.2	116.8

Table 44. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (setting) of Pile D13 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D13)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–28.1 m range (153 s)					
SPL (dB re 1 µPa)	Unw	145.0	143.4	150.8	148.9
	LFC	143.5	141.4	149.9	148.1
	MFC	129.0	120.3	139.8	134.1
	HFC	126.1	117.3	137.2	130.5
	PPW	139.5	133.6	148.0	144.7
	OPW	140.0	133.6	148.5	145.1
AMAR 2–1133 m range (153 s)					
SPL (dB re 1 µPa)	Unw	115.3	113.1	122.3	119.8
	LFC	114.7	111.9	121.9	119.3
	MFC	96.6	90.0	108.2	101.2
	HFC	92.3	87.7	104.1	96.0
	PPW	110.1	103.1	119.0	115.2
	OPW	110.8	102.9	119.5	116.0

Table 45. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (setting) of Pile D12 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water. AMAR 2 data are not shown because noise from numerous nearby vessels contaminated vibratory driving measurements.

Sound level (Pile D12)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–31.1 m range (343 s)					
SPL (dB re 1 µPa)	Unw	142.8	135.4	156.0	146.7
	LFC	140.2	133.2	154.7	143.6
	MFC	128.5	116.2	147.3	126.7
	HFC	126.4	115.0	145.3	124.0
	PPW	134.8	122.8	152.5	135.9
	OPW	134.8	121.7	152.7	135.8

5.3.3. Vibratory Oscillation Driving Noise Levels

Vibratory oscillation driving was monitored at two nominal distances and also from a mobile platform for piles D16 and D22. A spectrogram showing over 2 min of the vibratory hammer on Pile D22 at a range of 9.9 m displays the broadband frequency content, with most of the energy below 1 kHz, of the vibratory hammering over time (Figure 25). The received level at the recorders decreased with range (Figure 26). Close to the piles, the SPLs clearly exceeded the background levels, while at 1 km the levels did not exceed background by the same margins.

A linear fit between the SPL and the logarithm of the range to the recorders for Pile D16 is presented in Figure 26. The estimated source level at 1 m from this regression is 178.2 dB re 1 µPa, with a transmission loss estimate of 21.9 (*n* in Equation 1). The mean, median, max, and 90% received levels for 1 s SPLs (equivalent to SEL) are provided in Table 46, and Table 47. The maximum 1 s SPL for was 160.6 dB, 9.9 m from Pile D22. Statistics of SPLs weighted according to the 2016 NMFS guidelines are also included.

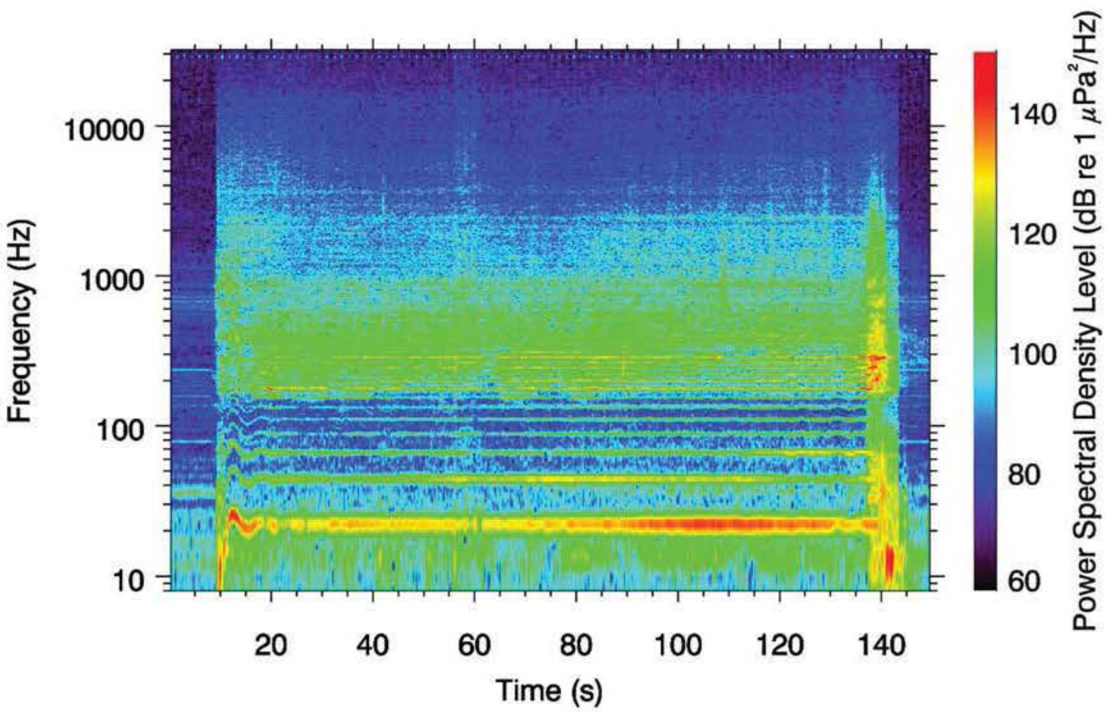

Figure 25. Spectrogram of oscillating Pile D22 into its socket with the vibratory driver (measured on AMAR 1).

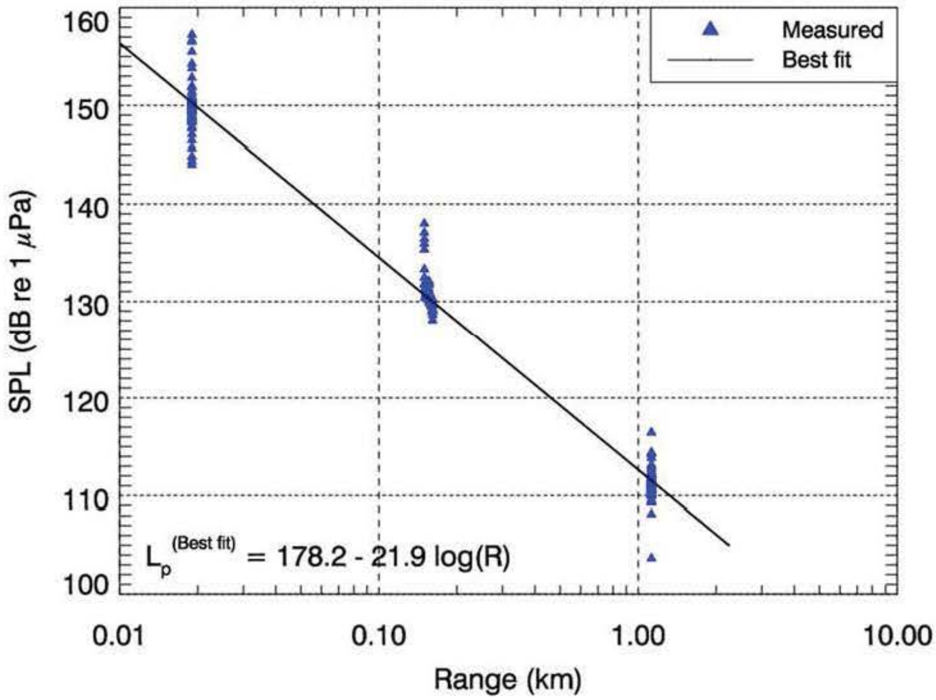

Figure 26. SPL (1 s average) versus range measured during vibratory driving (oscillating) of Pile D16. Solid line shows best-fit transmission loss curve to SPL data. Only levels from vibratory driving recorded simultaneously on both AMARs and the dipping hydrophone were used to estimate transmission loss (75 s at each location).

Table 46. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (oscillating) of Pile D22 24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D22)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–9.9 m range (135 s)					
SPL (dB re 1 µPa)	Unw	149.6	148.1	160.6	151.1
	LFC	146.1	143.2	158.8	147.3
	MFC	128.3	128.0	133.7	131.4
	HFC	127.7	127.4	133.5	130.9
	PPW	135.7	133.2	149.0	136.2
	OPW	135.0	132.6	148.9	135.1
AMAR 2–1117 m range (135 s)					
SPL (dB re 1 µPa)	Unw	107.9	105.6	119.4	110.2
	LFC	106.6	104.2	118.1	108.9
	MFC	85.6	83.0	97.0	88.5
	HFC	81.5	80.2	91.1	83.7
	PPW	99.4	96.3	111.3	102.7
	OPW	99.5	96.0	111.9	103.1

Table 47. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (oscillating) of Pile D16 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D16)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–19.0 m range (208 s)					
SPL (dB re 1 µPa)	Unw	145.2	140.0	157.0	150.2
	LFC	143.3	136.4	153.8	149.6
	MFC	127.9	118.8	142.3	133.6
	HFC	123.9	117.0	139.2	129.0
	PPW	140.2	127.4	151.9	147.2
	OPW	140.8	126.7	152.4	148.0
AMAR 2–1125 m range (212 s)					
SPL (dB re 1 µPa)	Unw	107.8	106.4	115.2	111.4
	LFC	107.2	105.5	114.8	111.0
	MFC	88.4	85.9	97.0	92.2
	HFC	83.8	81.9	92.6	86.8
	PPW	102.5	99.7	110.8	106.9
	OPW	103.1	100.2	111.5	107.6

5.3.4. Drilling Noise Levels

Drilling of rock sockets was monitored at two nominal distances for each pile, and also from a mobile platform. A spectrogram showing over 25 min of the drilling for Pile D22 at a range of 9.9 m displays the broadband frequency content, with energy up to 10 kHz, over time (Figure 27). The received level at the recorders decreased with range (Figure 28). Noise levels from drilling clearly exceeded the background levels up to 1 km away.

A linear fit between the SPL and the logarithm of the range to the recorders for Pile D16 is presented in Figure 28. The estimated source level at 1 m from this regression is 189.8 dB re 1 µPa, with a transmission loss estimate of 18.9 (*n* in Equation 1). The mean, median, max, and 90% received levels for 1 s SPLs (equivalent to SEL) are provided in Table 48 through Table 55. The maximum 1 s SPL for was 174.3 dB, 12.9 m from Pile D20. Statistics of SPLs weighted according to the 2016 NMFS guidelines are also included.

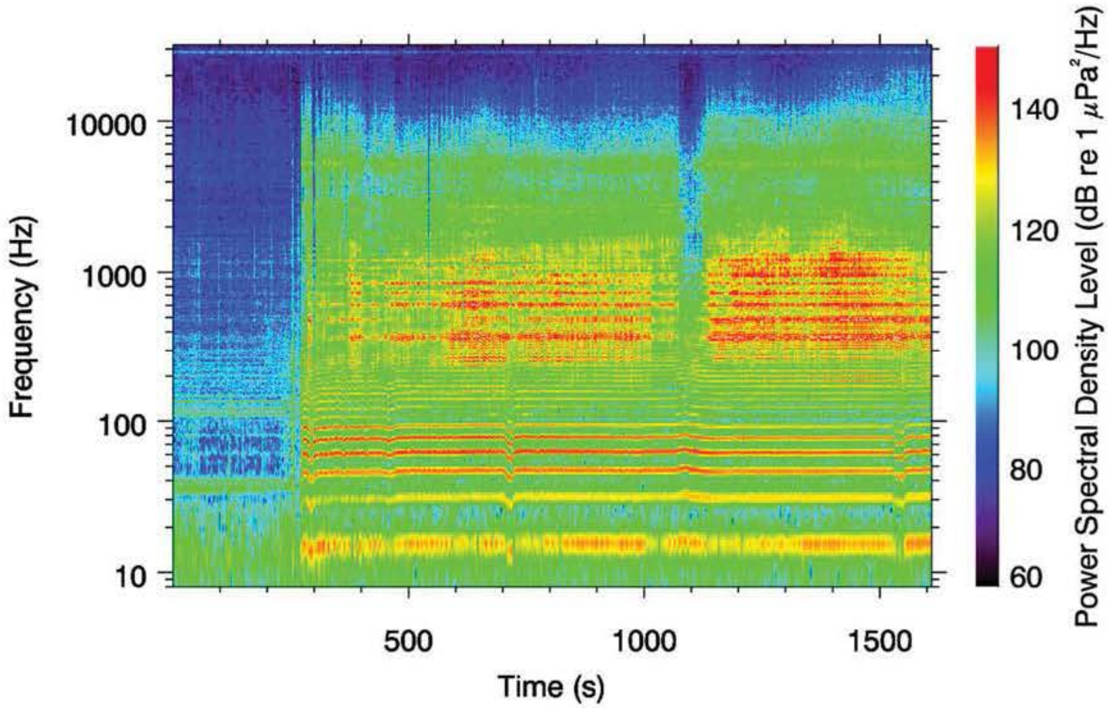

Figure 27. Spectrogram of drilling of Pile D22 measured on AMAR 1.

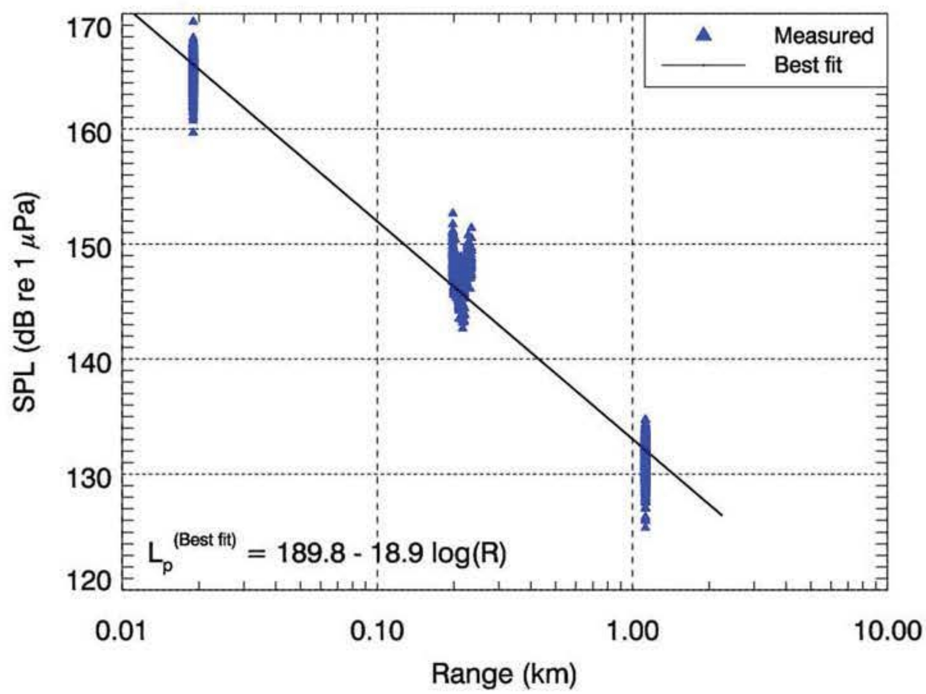

Figure 28. Plot of SPL (1 s average) versus range measured during drilling of Pile D16. Solid line shows best-fit transmission loss curve to SPL data. Only levels from drilling recorded simultaneously on both AMARs and the dipping hydrophone were used to estimate transmission loss (367 s at each location).

Table 48. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for drilling of Pile D22 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water. This pile socket was particularly difficult to drill and took much longer than the others. Sound levels are also significantly lower than for other piles so these measurements may not be representative of typical drilling levels.

Sound level (Pile D22)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–9.9 m range (13163 s)					
SPL (dB re 1 µPa)	Unw	148.9	146.5	160.9	151.9
	LFC	146.9	142.8	160.4	150.6
	MFC	135.8	128.8	152.9	139.9
	HFC	131.7	124.8	149.1	135.8
	PPW	144.4	138.6	159.7	148.5
	OPW	144.7	139.0	159.8	148.8
AMAR 2–1117 m range (13185 s)					
SPL (dB re 1 µPa)	Unw	121.7	114.8	142.5	123.3
	LFC	120.6	113.9	141.3	122.2
	MFC	106.9	97.3	127.9	107.6
	HFC	104.3	93.2	127.3	104.2
	PPW	116.0	108.9	137.3	117.9
	OPW	116.4	109.3	137.6	118.3

Table 49. Statistics of SPL for drilling (unweighted and frequency-weighted according to the 2016 NMFS guidance) of Pile D20 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D20)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–12.9 m range (3215 s)					
SPL (dB re 1 µPa)	Unw	169.0	168.9	174.3	171.5
	LFC	168.6	168.4	173.9	171.2
	MFC	145.2	144.5	152.1	148.3
	HFC	140.8	140.0	147.9	144.1
	PPW	161.5	161.2	167.4	164.2
	OPW	162.0	161.5	168.1	164.9
AMAR 2–1119 m range (3219 s)					
SPL (dB re 1 µPa)	Unw	132.1	131.8	138.3	134.6
	LFC	131.7	131.4	137.9	134.2
	MFC	104.0	103.4	114.7	106.2
	HFC	98.6	97.5	112.1	100.7
	PPW	123.7	123.3	130.1	126.3
	OPW	124.0	123.5	130.7	126.7

Table 50. Statistics of SPL for drilling (unweighted and frequency-weighted according to the 2016 NMFS guidance) of Pile D18 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D18)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–16.0 m range (2766 s)					
SPL (dB re 1 µPa)	Unw	167.1	167.0	172.3	169.2
	LFC	166.5	166.4	172.0	168.7
	MFC	147.8	144.3	156.9	152.3
	HFC	143.9	139.9	153.0	148.6
	PPW	159.6	158.5	166.3	162.6
	OPW	159.8	158.6	166.9	162.9
AMAR 2–1122 m range (2767 s)					
SPL (dB re 1 µPa)	Unw	131.2	130.8	138.2	133.6
	LFC	130.6	130.2	137.5	133.0
	MFC	106.0	102.9	123.6	108.5
	HFC	102.2	97.8	122.6	103.7
	PPW	122.4	121.4	131.4	125.1
	OPW	122.6	121.3	131.9	125.4

Table 51. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for drilling of Pile D16 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D16)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–19.0 m range (2711 s)					
SPL (dB re 1 µPa)	Unw	164.2	161.3	171.1	168.2
	LFC	163.5	160.7	170.5	167.6
	MFC	146.6	144.4	154.3	150.9
	HFC	142.6	140.1	150.2	147.0
	PPW	157.0	154.9	163.5	161.0
	OPW	157.1	155.1	163.3	161.0
AMAR 2–1125 m range (2713 s)					
SPL (dB re 1 µPa)	Unw	130.3	127.5	137.2	134.4
	LFC	129.8	127.0	136.8	134.0
	MFC	105.4	103.2	114.3	109.4
	HFC	100.4	98.0	111.3	104.4
	PPW	122.2	119.1	128.9	126.4
	OPW	122.6	119.4	129.2	126.7

Table 52. Statistics of SPL for drilling of Pile D15 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D15)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–22.0 m range (3924 s)					
SPL (dB re 1 µPa)	Unw	159.3	151.9	169.3	164.1
	LFC	158.8	150.0	169.0	163.7
	MFC	134.9	127.7	145.4	139.4
	HFC	130.1	123.3	141.3	134.4
	PPW	151.9	141.0	162.6	156.8
	OPW	152.5	140.9	163.3	157.4
AMAR 2–1127 m range (3929 s)					
SPL (dB re 1 µPa)	Unw	129.4	126.9	144.1	133.4
	LFC	128.8	126.0	143.3	132.9
	MFC	107.9	101.1	133.7	107.8
	HFC	104.6	95.6	130.8	103.8
	PPW	121.3	118.6	141.5	125.2
	OPW	121.5	118.7	141.8	125.4

Table 53. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for drilling of Pile D14 (24” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D14)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–25.1 m range (4075 s)					
SPL (dB re 1 µPa)	Unw	157.1	148.4	168.3	162.2
	LFC	156.6	147.1	167.8	161.8
	MFC	134.9	129.0	145.9	139.8
	HFC	130.7	125.0	142.2	135.4
	PPW	149.5	140.6	160.0	154.7
	OPW	149.8	140.8	160.3	155.1
AMAR 2–1130 m range (4082 s)					
SPL (dB re 1 µPa)	Unw	128.4	123.4	139.4	133.1
	LFC	127.7	122.7	138.1	132.5
	MFC	110.0	101.3	128.3	111.1
	HFC	107.4	98.0	126.8	107.9
	PPW	121.1	116.2	134.7	125.3
	OPW	121.4	116.5	135.0	125.6

Table 54. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for drilling of Pile D13 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D13)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–28.1 m range (2890 s)					
SPL (dB re 1 µPa)	Unw	156.1	152.5	165.5	160.3
	LFC	155.7	151.8	165.1	160.0
	MFC	138.1	133.6	146.5	142.9
	HFC	133.8	129.4	142.2	138.6
	PPW	150.6	146.0	159.6	155.0
	OPW	151.1	146.4	160.3	155.7
AMAR 2–1133 m range (2894 s)					
SPL (dB re 1 µPa)	Unw	127.6	124.6	135.6	131.7
	LFC	127.1	124.1	135.2	131.3
	MFC	106.8	104.1	120.4	109.9
	HFC	102.6	99.2	118.1	105.1
	PPW	120.6	117.8	128.5	124.8
	OPW	121.0	118.2	129.0	125.3

Table 55. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for drilling of Pile D12 (24" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile D12)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–31.1 m range (3161 s)					
SPL (dB re 1 µPa)	Unw	155.7	153.0	165.2	159.7
	LFC	155.4	152.4	165.1	159.6
	MFC	138.1	135.4	147.6	142.3
	HFC	133.7	130.9	143.4	137.9
	PPW	150.7	147.8	160.2	155.2
	OPW	151.4	148.3	161.2	156.0
AMAR 2–1136 m range (3167 s)					
SPL (dB re 1 µPa)	Unw	126.1	124.8	139.0	129.0
	LFC	125.4	124.3	135.8	128.6
	MFC	113.7	104.1	136.3	110.3
	HFC	112.9	99.6	136.0	106.0
	PPW	119.8	118.2	133.2	122.6
	OPW	120.1	118.6	132.8	123.2

5.3.5. Threshold Distances

Equation 1 was solved for the threshold criteria provided in Section 2 using the regressions and statistical measures of source levels and transmission loss from Sections 5.3.1, 5.3.2, 5.3.3, and 5.3.4. The ranges for thresholds for each source are in Table 56.

Injury ranges were less than 19 m, and behavioral disturbance range was 183 m for impact hammering. For continuous sources, vibratory setting and oscillation, and drilling the behavioral disturbance range was varied from 455 m to almost 7 km for drilling.

Table 56. Distance to SPL thresholds determined from best-fit transmission loss coefficient and SPLs on AMAR 1 (90th percentile and mean). Threshold distances and source levels are maximized over data from all piles monitored for each activity.

Threshold (SPL, dB re 1 µPa)	90th Percentile Distance (m)	Mean Distance (m)	Transmission Loss Coefficient	90th Percentile SL (dB re 1 µPa @ 1 m)	Mean SL (dB re 1 µPa @ 1 m)
Impact driving 24" piles					
190 dB re 1 µPa	6.1	4.8	20.3	205.9	203.8
180 dB re 1 µPa	19	15	20.3	205.9	203.8
160 dB re 1 µPa	183	145	20.3	205.9	203.8
Vibratory driving (setting) 24" piles					
120 dB re 1 µPa	821	490	21.9*	183.8	178.9
Vibratory driving (oscillating) 24" piles					
120 dB re 1 µPa	455	269	21.9	178.2	173.2
Drilling 24" piles					
120 dB re 1 µPa	6846‡	5049‡	18.9	192.5	190.0

* Transmission loss coefficient was based on regression analysis of SPL vs range data for vibratory driving (oscillating) Pile D16 (Figure 17) because no dipping hydrophone measurements of vibratory driving (setting) were made.
‡ Extrapolated beyond maximum measurement range.

5.3.6. Weighted Transmission Loss Coefficients

NMFS 2016 functional hearing group weighting functions were applied to the received signals and when possible, regressions between the weighted levels and the logarithm of the ranges were computed to determine the transmission loss coefficient for each functional hearing group (Table 57–Table 60). Transmission loss estimates ranged from 13.3 for the drilling of Pile D12 with HFC weighting to 26.1 for impact hammering of Pile D20 for HFC.

Table 57. Transmission loss coefficients from mean AMAR measurements for impact hammering. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	D22	D20	D18	D16
LFC	20.1	20.5	20.3	20.0

Weighting	D22	D20	D18	D16
MFC	23.7	24.4	23.5	24.2
HFC	25.2	26.1	25.0	26.0
PPW	20.3	20.8	20.4	20.2
OPW	20.3	20.8	20.3	20.1

Table 58. Transmission loss coefficients from mean AMAR measurements for vibratory setting of 24" diameter steel piles. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	D20	D15	D14	D13	D12
LFC	20.0	17.7	18.4	17.9	N/A
MFC	21.1	19.4	20.9	20.2	N/A
HFC	23.0	20.3	21.7	21.1	N/A
PPW	19.0	17.1	19.2	18.3	N/A
OPW	18.5	16.8	19.2	18.2	N/A

Table 59. Transmission loss coefficients from mean AMAR measurements for vibratory oscillation of 24" diameter steel piles. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	D22	D16
LFC	19.2	20.3
MFC	20.8	22.2
HFC	22.5	22.6
PPW	17.7	21.2
OPW	17.3	21.2

Table 60. Transmission loss coefficients from mean AMAR measurements for drilling. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	D22*	D20	D18	D16	D15	D14	D13	D12
LFC	12.8	19.0	19.4	19.0	17.5	17.5	17.8	19.2
MFC	14.1	21.3	22.6	23.2	15.8	15.1	19.5	15.6
HFC	13.3	21.8	22.6	23.8	14.9	14.1	19.4	13.3
PPW	13.8	19.5	20.2	19.6	17.9	17.2	18.7	19.8
OPW	13.8	19.6	20.2	19.5	18.1	17.2	18.7	20.0

*Several vessels passed close to AMAR 2 during these measurements which elevated the mean levels for that recorder. Transmission loss coefficients may therefore be underestimated here.

5.3.7. Weighted-Level Threshold Distances

Peak levels were calculated from max peak measurements and back-propagated using spherical spreading for AMAR 1 measurements lower than the peak threshold and forward-propagated using 15log*R* for AMAR 1 measurements higher than the peak threshold (Table 61). The peak threshold distances are less than the SEL-based threshold ranges for all hearing groups.

Table 61. Range in meters to onset of injury based on NMFS 2016 criteria (Section 2) for pile driving at Kodiak ferry terminal. Drilling and vibratory hammer setting were considered together for exposure estimates within the continuous category. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	Impact		Continuous		
	SEL 24h	Peak	Day1	Day 2	Day 3
LFC	5	1	3	35	24
MFC	1	0	1	4	2
HFC	15	6	10	40	30
PPW	2	1	2	12	9
OPW	0	0	0	2	1

5.4. Ketchikan

Pile driving activities at the Ketchikan Ferry Terminal facility were monitored by JASCO field staff from 2016-07-13 to 2016-07-14 (UTC). Activities monitored included installation of three piles. Vibratory driving of each pile took from 72 to 138 min. Impact hammering occurred for less than 15 min for each pile. Periods of time without construction activity were analyzed to estimate the background noise levels at the Ketchikan Ferry Terminal. Pile installation was monitored at two fixed distances from each pile (west restraint: 9.5 m and 1098 m; east restraint: 14 m and 1161 m). Pile extraction was monitored from two fixed distances for each pile (Pile 1: 18.4 m and 949 m; Pile 2: 17.3 m and 948 m; Pile 3: 16.3 m and 947 m).

5.4.1. Impact Driving Noise Levels

Examples of signals recorded on each AMAR are provided in Figure 29. The spectrum from AMAR 1, at 16.3 m from the pile exceeded the background noise at low frequencies, compared with the signal recorded at AMAR 2. The peak level of the signal at AMAR 1 was over 30 times that at AMAR 2 in Figure 29. A spectrogram showing multiple strikes of the impact hammer on Pile 3 at a range of 16.3 m displays the broadband frequency content of the impacts (Figure 30).

A linear regression between the SPL and the logarithm of the range to the recorders is presented in Figure 31. Only pulses recorded simultaneously on each system were included in the regression. The estimated source level at 1 m from this regression is 210.4 dB re 1 µPa, with a transmission loss estimate of 15.0 (*n* in Equation 1). The mean, median, max, and 90% received levels for SPL, peak pressure, and single-strike SEL (unweighted and weighted according to the 2016 NMFS guidance) are provided in Table 62 through Table 64. The maximum SPL for all of the impacts recorded was 193.6 dB 18.4 m from Pile 1 and 16.3 m from Pile 3.

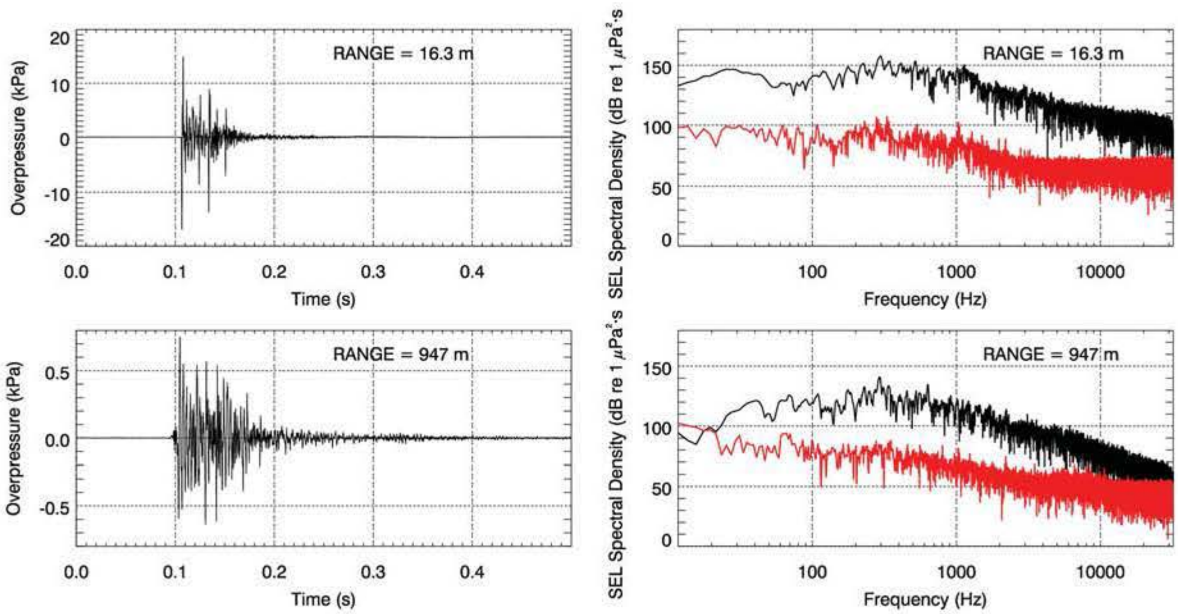

Figure 29. Waveforms (left) and spectra (right) for impact hammering of Pile 3 (30" diameter steel pile) recorded at AMAR 1 (top) and AMAR 2 (bottom). Background noise spectrum from the 0.5 s window preceding the pulse is shown in red.

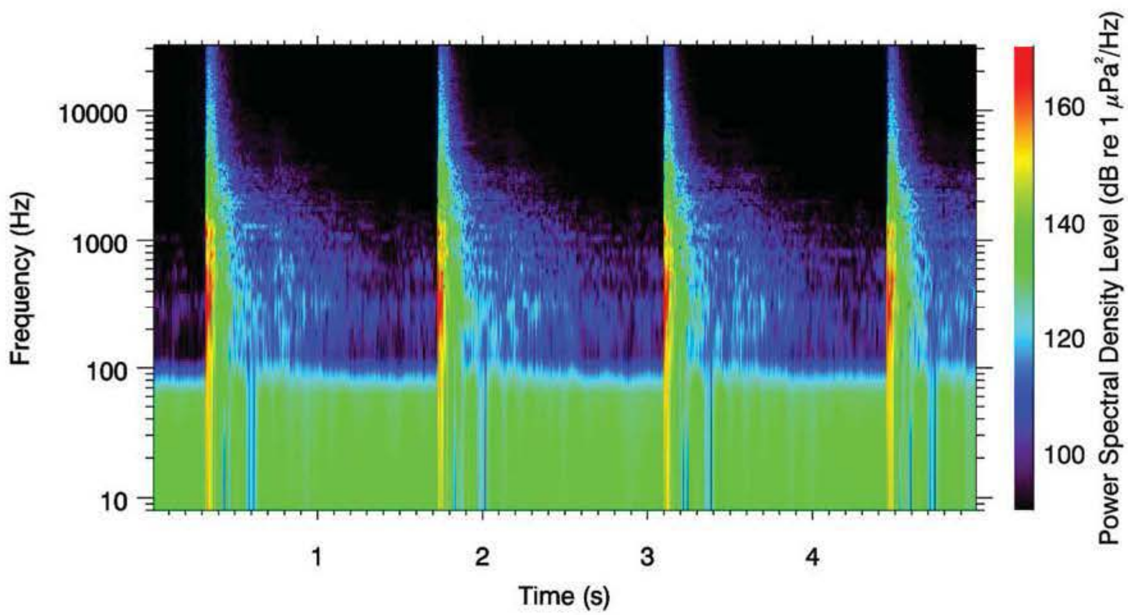

Figure 30. Spectrogram of four strikes by the impact hammer on Pile 3 measured at 16.3 m range on AMAR 1.

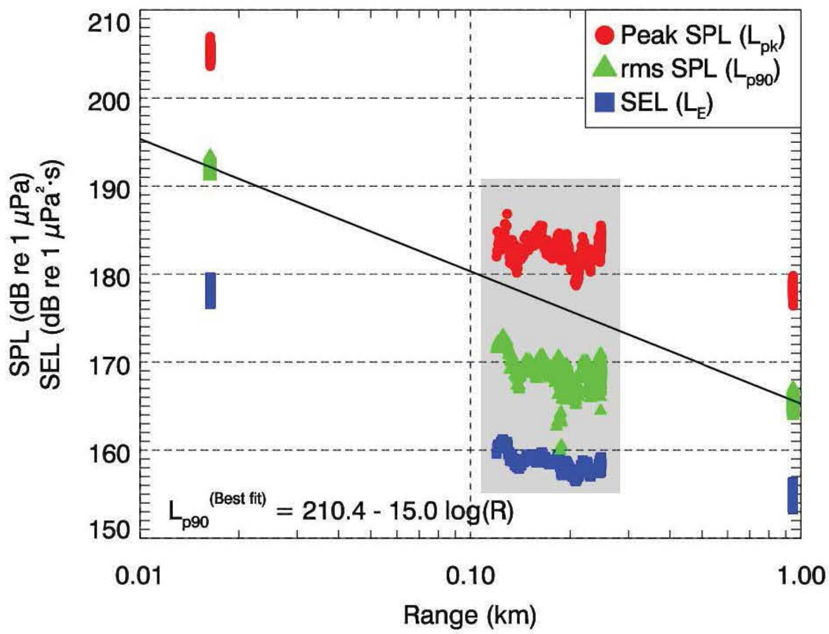

Figure 31. Peak level, SPL, and SEL versus range measured during impact driving of Pile 3. Shaded region indicates dipping hydrophone measurements which were not used to estimate transmission loss because of a close-range, near-surface acoustic shadow zone (see Discussion Section 6.2). Solid line shows best-fit transmission loss curve to AMAR-based SPL data. Only levels from pulses recorded simultaneously on both AMARs and the dipping hydrophone are shown (n = 392 at each location).

Table 62. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving of Pile 3 (30" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile 3)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–16.3 m range (n = 582)					
peak level (dB re 1 µPa)	Unw	204.8	204.8	207.0	205.8
SPL (dB re 1 µPa)	Unw	191.5	191.8	193.6	193.0
single-strike SEL (dB re 1 µPa²s)	Unw	177.6	177.6	179.6	179.0
	LFC	176.8	176.7	178.9	178.2
	MFC	154.4	154.5	158.2	156.4
	HFC	151.8	151.7	155.7	153.9
	PPW	168.7	168.7	171.4	170.6
	OPW	169.0	168.9	171.9	171.0
AMAR 2–947 m range (n = 582)					
peak level (dB re 1 µPa)	Unw	178.0	178.1	179.8	179.2
SPL (dB re 1 µPa)	Unw	165.4	165.5	167.3	166.5
single-strike SEL (dB re 1 µPa²s)	Unw	154.5	154.6	156.4	155.7
	LFC	153.4	153.5	155.5	154.7
	MFC	126.3	126.0	129.5	128.5

Sound level (Pile 3)	Weighting	Mean	Median	Max	90th percentile
	HFC	121.8	121.4	125.1	124.0
	PPW	144.0	144.0	146.9	145.6
	OPW	143.8	143.7	146.9	145.5

Table 63. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving of Pile 2 (30" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile 2)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–17.3 m range (n = 559)					
peak level (dB re 1 µPa)	Unw	204.9	204.7	208.4	206.9
SPL (dB re 1 µPa)	Unw	190.5	190.8	192.9	192.1
single-strike SEL (dB re 1 µPa^{2}s)	Unw	177.2	177.1	179.7	178.9
	LFC	176.4	176.2	179.0	178.3
	MFC	154.9	155.3	158.5	156.5
	HFC	152.3	152.5	156.4	154.0
	PPW	169.2	168.8	172.2	171.3
	OPW	169.6	169.3	172.8	171.9
AMAR 2–947.9 m range (n = 559)					
peak level (dB re 1 µPa)	Unw	177.7	177.7	180.6	179.5
SPL (dB re 1 µPa)	Unw	164.0	163.9	166.5	165.7
single-strike SEL (dB re 1 µPa^{2}s)	Unw	153.5	153.2	156.1	155.2
	LFC	152.5	152.0	155.2	154.3
	MFC	126.2	126.0	129.9	128.4
	HFC	121.6	121.6	124.9	123.4
	PPW	143.4	142.7	146.6	145.7
	OPW	143.3	142.6	146.6	145.7

Table 64. Statistics of peak level, SPL, and single-strike SEL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for impact driving of Pile 1 (30" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile 1)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–18.4 m range (n = 637)					
peak level (dB re 1 µPa)	Unw	205.2	205.3	207.4	205.8
SPL (dB re 1 µPa)	Unw	191.4	191.7	193.6	192.6
single-strike SEL (dB re 1 µPa^{2}s)	Unw	176.7	176.7	179.5	177.7

Sound level (Pile 1)	Weighting	Mean	Median	Max	90th percentile
	LFC	176.0	175.9	178.9	177.0
	MFC	153.9	153.6	159.9	155.8
	HFC	151.1	150.6	158.1	153.1
	PPW	169.0	168.9	173.1	170.3
	OPW	169.6	169.5	173.9	170.9
AMAR 2–949 m range (n = 635)					
peak level (dB re 1 µPa)	Unw	178.6	178.8	180.2	179.4
SPL (dB re 1 µPa)	Unw	162.3	162.3	164.8	163.3
single-strike SEL (dB re 1 µPa^{2}s)	Unw	151.8	151.6	154.4	152.9
	LFC	150.7	150.5	153.6	152.1
	MFC	122.7	122.0	127.7	125.4
	HFC	117.9	117.1	124.6	120.1
	PPW	141.8	141.4	145.5	143.4
	OPW	141.8	141.4	145.9	143.5

5.4.2. Vibratory Driving Noise Levels

A spectrogram showing over 8 min of the vibratory hammer on Pile 2 at a range of 17.3 m displays the broadband frequency content, with most of the energy below 2 kHz, of the vibratory hammering over time (Figure 32). The received level at the recorders decreased with range (Figure 33). Close to the piles, the SPLs clearly exceeded the background levels, while at 1 km the levels did not exceed background by the same margins.

A linear regression between the SPL and the logarithm of the range to the recorders is presented in Figure 33. The estimated source level at 1 m from this regression is 172.5 dB re 1 µPa, with a transmission loss estimate of 12.0 (*n* in Equation 1). The mean, median, max, and 90% received levels for 1 s SPLs (equivalent to SEL) are provided in Table 65 through Table 67. The maximum 1 s SPL for was 169.0 dB, 17.3 m from Pile 2. Statistics of SPLs weighted according to the 2016 NMFS guidelines are also included.

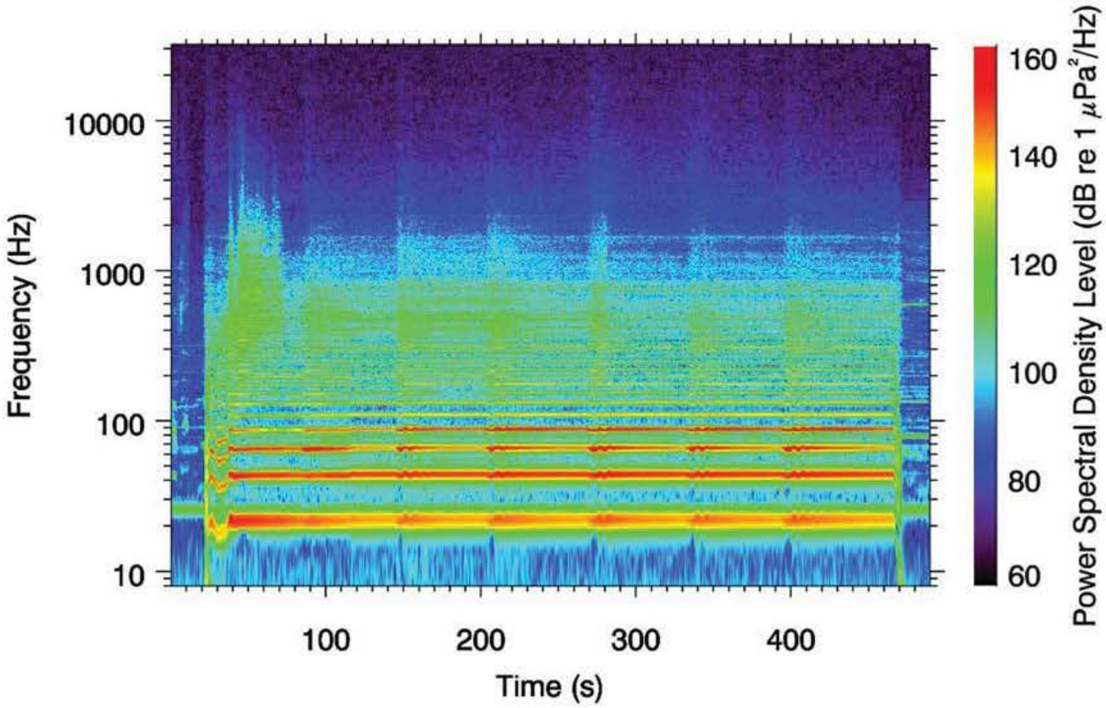

Figure 32. Spectrogram of vibratory driving of Pile 2 (measured on AMAR 1).

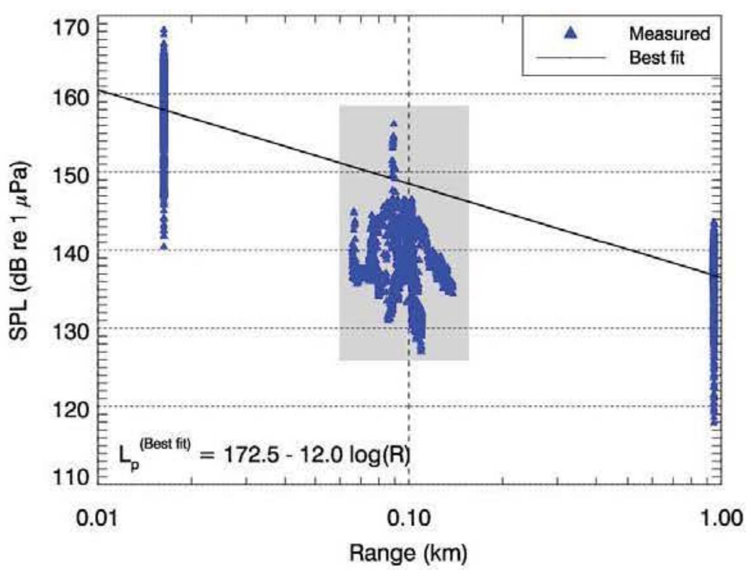

Figure 33. SPL (1 s average) versus range measured during vibratory driving of Pile 1. Shaded region indicates dipping hydrophone measurements which were not used to estimate transmission loss because of a close-range, near-surface acoustic shadow zone (see Section 6.2. Discussion). Solid line shows best-fit transmission loss curve to AMAR-based SPL data. Only levels from vibratory driving recorded simultaneously on both AMARs and the dipping hydrophone are shown (1294 s at each location).

Table 65. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (oscillating) of Pile 2 (30" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile 2)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–17.3 m range (6960 s)					
SPL (dB re 1 µPa)	Unw	162.6	162.4	169.0	166.1
	LFC	153.8	152.4	165.2	156.4
	MFC	130.8	119.6	153.2	125.4
	HFC	128.2	117.8	151.5	122.5
	PPW	143.5	136.4	160.4	144.2
	OPW	143.5	132.6	161.1	142.9
AMAR 2–948 m range (5251 s)					
SPL (dB re 1 µPa)	Unw	143.2	142.4	150.0	146.2
	LFC	134.2	133.3	142.0	137.4
	MFC	107.4	102.2	124.0	110.3
	HFC	104.9	100.1	120.1	107.3
	PPW	120.7	117.6	137.0	123.0
	OPW	119.6	112.8	137.5	121.7

Table 66. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (oscillating) of Pile 1 (30" ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile 1)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–18.4 m range (4374 s)					
SPL (dB re 1 µPa)	Unw	157.8	156.8	167.6	161.7
	LFC	149.6	147.7	166.1	151.9
	MFC	130.2	120.5	159.6	125.4
	HFC	127.9	118.5	158.0	123.2
	PPW	140.9	134.0	163.8	139.7
	OPW	141.1	132.2	163.9	139.2
AMAR 2–949 m range (1919 s)					
SPL (dB re 1 µPa)	Unw	140.0	139.4	145.2	142.8
	LFC	133.1	130.7	140.8	138.1
	MFC	107.0	104.7	119.1	110.3
	HFC	104.1	102.6	114.5	106.7
	PPW	120.8	116.7	133.8	126.4
	OPW	120.0	114.7	134.3	125.2

Table 67. Statistics of SPL (unweighted and frequency-weighted according to the 2016 NMFS guidance) for vibratory driving (oscillating) of Pile 3 (30” ø). Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Sound level (Pile 3)	Weighting	Mean	Median	Max	90th percentile
AMAR 1–16.3 m range (8337 s)					
SPL (dB re 1 µPa)	Unw	154.7	151.7	164.4	159.1
	LFC	148.2	143.9	161.4	152.9
	MFC	121.9	116.8	143.6	122.1
	HFC	118.9	115.1	141.4	118.8
	PPW	137.3	130.2	154.7	140.7
	OPW	136.9	128.3	155.2	139.6
AMAR 2–947 m range (5356 s)					
SPL (dB re 1 µPa)	Unw	135.6	132.7	147.3	138.3
	LFC	128.9	126.4	140.1	132.4
	MFC	102.4	98.6	119.3	105.2
	HFC	99.6	95.3	117.4	102.3
	PPW	116.3	113.9	130.0	119.5
	OPW	115.3	112.5	130.5	118.3

5.4.3. Threshold Distances

Equation 1 was solved for the threshold criteria provided in Section 2 using the regressions and statistical measures of source levels and transmission loss from Sections 5.4.1 and 5.4.2. The ranges for thresholds for each source are in Table 68. Injury ranges were less than 130 m, and behavioral disturbance range was 2703 m for impact hammering. For vibratory driving, the behavioral disturbance range was up to 120 km. Both of the distances for behavioral disturbance were extrapolated past the range measured. Section 6.3 discusses the extrapolation past measurement range.

Table 68. Distance to SPL thresholds determined from best-fit transmission loss coefficient and SPLs on AMAR 1 (90th percentile and mean). Threshold distances and source levels are maximized over data from all piles monitored for each activity.

Threshold (SPL, dB re 1 µPa)	90th Percentile Distance (m)	Mean Distance (m)	Transmission Loss Coefficient	90th Percentile SL (dB re 1 µPa @ 1 m)	Mean SL (dB re 1 µPa @ 1 m)
Impact driving 30” piles					
190	27.4	22.8	15.0	211.6	210.4
180	127	105	15.0	211.6	210.4
160	2703*	2250*	15.0	211.6	210.4
Vibratory driving 30” piles					
120	120,147*	61,383*	12.0	181.0	177.5

*Extrapolated far beyond maximum measurement range. These values are unrealistic, see Discussion section 6.3.

5.4.4. Weighted Transmission Loss Coefficients

NMFS 2016 functional hearing group weighting functions were applied to the received signals and when possible, regressions between the weighted levels and the logarithm of the ranges were computed to determine the transmission loss coefficient for each functional hearing group (Table 69 and Table 70). Transmission loss estimates ranged from 10.7 for the vibratory driving of Pile 1 with LFC weighting to 19.4 for impact hammering of Pile 1 for HFC.

Table 69. Transmission loss coefficients from mean AMAR measurements for impact hammering. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	Pile 1	Pile 2	Pile 3
LFC	14.8	13.7	13.3
MFC	18.2	16.5	15.9
HFC	19.4	17.7	17.0
PPW	15.9	14.8	14.0
OPW	16.2	15.1	14.3

Table 70. Transmission loss coefficients from mean AMAR measurements for vibratory driving. The coefficients were calculated after accounting for fewer measurements from AMAR 2 (due to contaminating non-piling noise sources) by assuming levels for the masked times corresponded to the 75th percentile levels. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	Pile 1	Pile 2	Pile 3
LFC	10.7	11.7	11.6
MFC	14.7	14.1	12.0
HFC	14.8	14.0	11.9
PPW	13.3	13.6	12.6
OPW	14.0	14.3	13.1

5.4.5. Weighted-Level Threshold Distances

Peak levels were calculated from max peak measurements and back-propagated using spherical spreading for AMAR 1 measurements lower than the peak threshold and forward-propagated using 15log*R* for AMAR 1 measurements higher than the peak threshold (Table 71). The peak threshold distances are less than the SEL-based threshold ranges for all hearing groups.

Table 71. Range in meters to onset of injury based on NMFS 2016 criteria (Section 2) for pile driving at Ketchikan Ferry Terminal. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Weighting	Impact		Vibratory
	SEL 24h	Peak	SEL 24h
LFC	1288*	< 10	10
MFC	21	< 10	< 10

Weighting	Impact		Vibratory
	SEL 24h	Peak	SEL 24h
HFC	746	46	11
PPW	212	< 10	< 10
OPW	13	< 10	< 10

*Extrapolated beyond maximum measurement range. See Discussion section 6.3.

6. Discussion

The goal of this measurement program was to quantify sound levels and transmission loss from typical piling activities associated with AKDOT&PF construction projects to use in environmental impact assessments of future piling projects in Alaska. Results from one of the four measurement sites could apply to other locations; however, there are many factors to consider when selecting surrogate measurements: construction activity and duration, hammer size/energy, pile dimensions, sediment characteristics, bathymetry, and water sound speed profile. Effects from some of these factors were observed in the measurements and are discussed at greater length in the subsections that follow.

The pile installation at Kodiak resulted in atypically low sound levels for both vibratory and impact hammers that should only be used as surrogates for hammer operations associated with rock socket pile installation. Due to the drilling of rock socket holes, vibratory and impact hammering source levels were lower, and durations of hammer operations were reduced. These reductions in level and duration meant relatively small harassment zones for impact and vibratory pile driving (less than 183 m and 821 m, respectively). These measurements of impact and vibratory pile driving at Kodiak could be used as surrogate only at sites with similar sediment types and drilling operations.

At Kake, Auke Bay, and Ketchikan, hammer size/energy and vibratory source level measurements were correlated, but impact hammering source levels did not vary much. Thus, vibratory hammer size/energy must be considered when surrogate source levels are selected. The connection between impact hammer energy and source levels, although supported both in theory and in the literature (Laughlin 2005), can be affected by other factors either alone or in combination. In this study, sediment characteristics and pile dimensions were confounding factors. Harder sediments are typically more difficult to drive into which may result in relatively higher sound levels and longer piling duration.

The unweighted and weighted-level transmission loss coefficients depend on the source spectra and frequency-dependent transmission loss at each site. Kake and Kodiak, the shallower sites, had higher unweighted TL coefficients (approximately 20) relative to Auke Bay and Ketchikan, the deeper sites, which had lower unweighted TL coefficients (approximately 15). Sediment characteristics could have contributed to this discrepancy, but it is difficult to assess the relative significance given their uncertainty along the propagation path.

Geometric transmission loss coefficients of 10 and 20 correspond to cylindrical and spherical spreading loss, respectively. Both values assume ideal environments, however in reality, the measured transmission losses usually vary between these two values. Occasionally, the transmission loss can be closer to 10 log$R$, and in some situations greater than 20 log$R$. Often, 15 log$R$ is used as an estimate of transmission loss when empirical measurements are not available. Because estimates depend on sediment types, bathymetry, and other environmental characteristics, and are affected by the frequency-weighting functions for the various functional hearing groups and source spectrum, selecting an appropriate transmission loss coefficient for a given environment can be challenging without empirical data for the location.

Numerical propagation modeling could be used to determine the relative importance of bathymetry and sediment characteristics for a given source spectrum. Despite the observed decrease in TL coefficients with water depth, this decrease is not likely appropriate for deeper water. In very deep water, spherical spreading (TL coefficient of 20) is expected.

The weighted-level TL coefficients showed much more variability, from 11.6 to 26.0. The frequency-dependent weighting functions greatly complicate establishing correlations between weighted-level TL coefficient observations and source/environmental features. Numerical propagation modeling could be used to predict weighted levels and their decay with range given the source spectrum and environmental parameters.

The source levels estimated in this study could apply to similar piling activities (in terms of piling operation, source, pile size, and sediment properties), but the TL coefficients are much more difficult to predict using empirical data given their dependence on source spectra and environmental properties. Weighted-level TL coefficients are especially difficult to predict using empirical data given the additional complexity of frequency weighting.

6.1. Comparing Sound Levels Across Sites

The broadband sound levels for impact hammering could be grouped by location with Kodiak separated from the other sites due to the different site conditions and pile installation techniques used there. At Kodiak, there were 1-5 impacts per pile, whereas at the other sites, the number of impacts varied from 106 to 637. The goal of hammering at sites differed by site. Impact hammering at Kodiak was for pile load testing ("proofing"), whereas at Kake, Auke Bay, and Ketchikan, it was used for driving the piles into the sediments and proofing the piles upon refusal. At Kake, Auke Bay, and Ketchikan, impact hammering SPL and single-strike SEL were consistently within 3 dB when standardized to a range of 10 m from the pile (Table 72). At Kodiak, the levels were consistently lower. The function of the impact hammering, and consequently the number of strikes, coupled with sound levels more than 10 dB greater at Kake, Auke Bay, and Ketchikan resulted in much higher cumulative levels and greater range to criteria thresholds compared to impact hammer sounds at Kodiak.

The 1/3-octave band levels measured at AMAR 1 for impact pile driving are similar at Kake, Auke Bay, and Ketchikan (Figure 34). At Kodiak, the 1/3-octave band levels above 50 Hz are lower than the levels at the same frequencies at the other sites, particularly for frequencies between 50 and 300 Hz. The levels in Figure 34 were not corrected for range from the pile, which accounts for some of the differences.

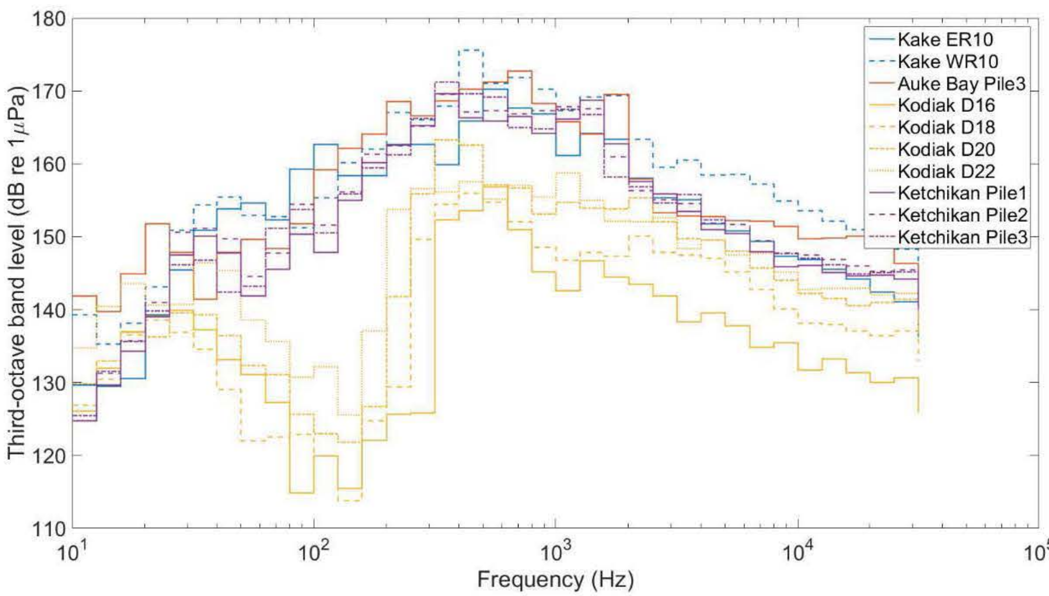

Figure 34. The mean 1/3-octave band levels from all sites at AMAR 1. The levels were not corrected for range from the pile, which accounts for some of the differences.

The broadband sound levels generated by vibratory hammering varied across all sites, even when standardized to a common range of 10 m from the pile (Table 72). Kodiak had the lowest levels, followed by Kake, Ketchikan, and Auke Bay. The 1/3-octave band levels at Auke Bay were consistently higher than at other sites (Figure 35). The levels in Figure 35 were not corrected for range from the pile, which accounts for some of the differences. AMAR 1 was closer to the piles at Auke Bay than at other sites. The rock socket installation at Kodiak might have contributed to the lower broadband levels, but the 1/3-octave band levels for vibropiling showed a trend consistent with the impact hammering from Kodiak with reduced energy from 50 to 300 Hz (Figure 34 and Figure 35), which is part due to the fact that the shallow water at Kodiak that does not support propagation of sound at these frequencies. The 1/3-octave band levels at Kake for extracting and installing piles with the vibratory hammer were similar.

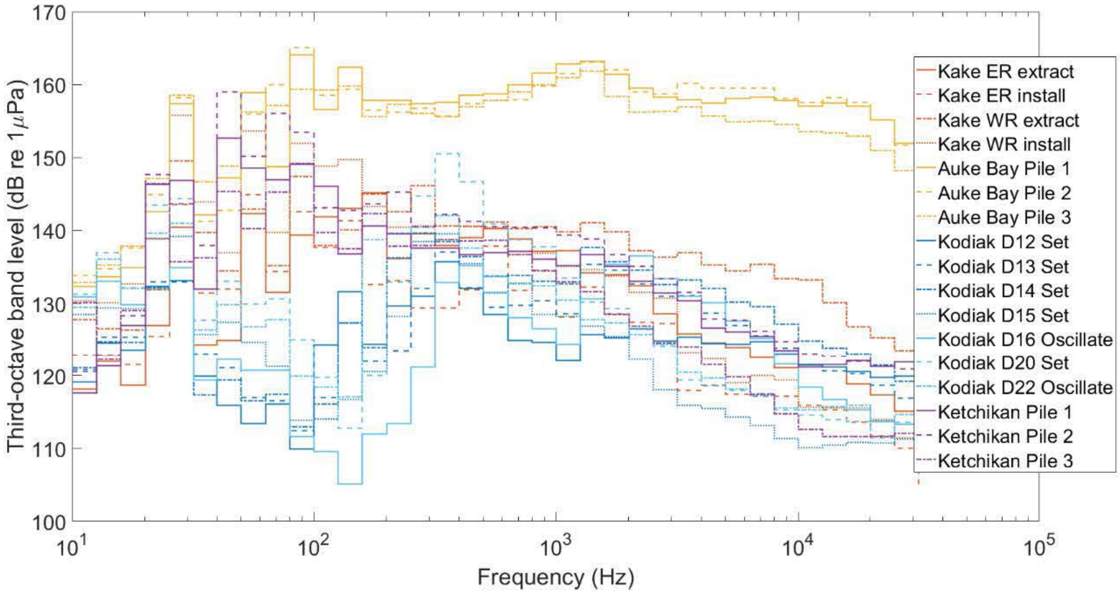

Figure 35. Mean 1/3-octave band levels recorded on AMAR 1 at each of the ferry terminals for the vibratory hammer. Kake data includes extraction and installation. Kodiak data includes setting and oscillating. The levels were not corrected for range from the pile, which accounts for some of the differences.

The mean drilling sound level at 10 m range measured at Kodiak was 168 dB, approximately 12 dB greater than that generated by the vibratory hammer at Kodiak (Table 72). The 1/3-octave band levels for drilling showed that most of the energy was between 200 Hz and 2 kHz (Figure 36). Unlike the impact and vibratory hammer at Kodiak (Figure 34 and Figure 35), the spectral levels were higher—between 50 and 300 Hz—for drilling. The 1/3-octave band levels in Figure 36 were not corrected for range of the recorder from the pile.

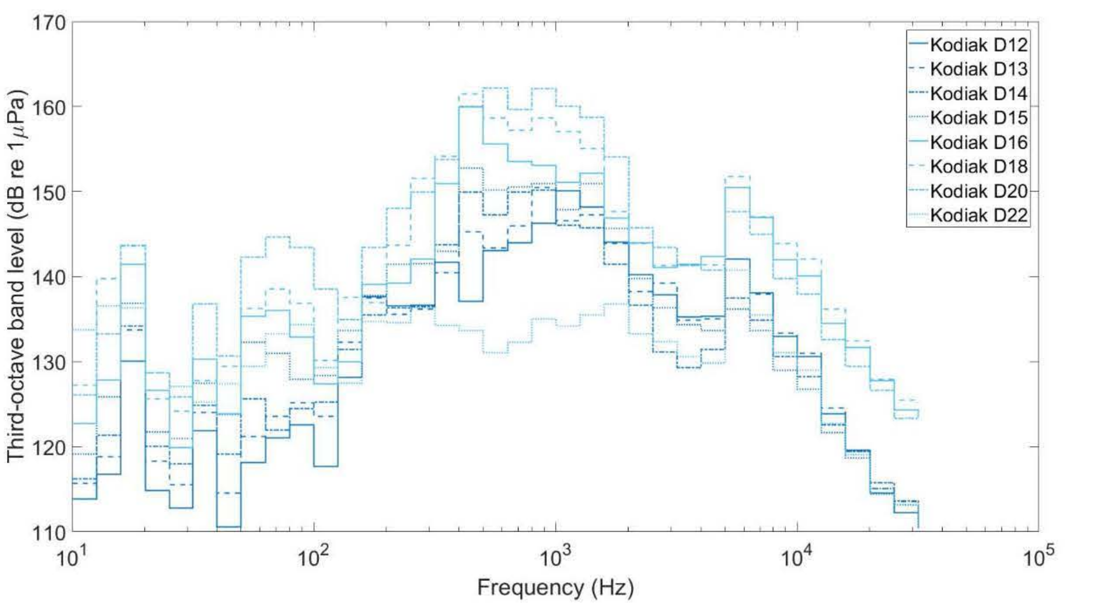

Figure 36. Mean 1/3-octave band levels generated by drilling activity, recorded on AMAR 1 at Kodiak ferry terminal. Spectral levels were not corrected for range from pile.

The size and energy of the hammers used to install the piles varied between locations. The same model vibratory hammer was used at Kodiak and Ketchikan, with different models being used at both Kake and

Auke Bay. Impact hammers differed at all sites (Table 1). Sound levels from impact hammering at all sites did not correlate to the weight or energy of the impact hammers. Mean SPL for vibratory hammering was correlated with force, which is intrinsically related to weight, at all sites where vibratory hammering occurred (i.e. all sites except Kodiak). Higher sound levels were recorded when higher forces and weights were imparted (Figure 37). Because the sample size was small, and there were multiple confounding environmental factors—sediment, bedrock, sound speed, bathymetry—other than to state a larger vibratory hammer likely generates higher levels, it is specious to make predictions solely on hammer specifications.

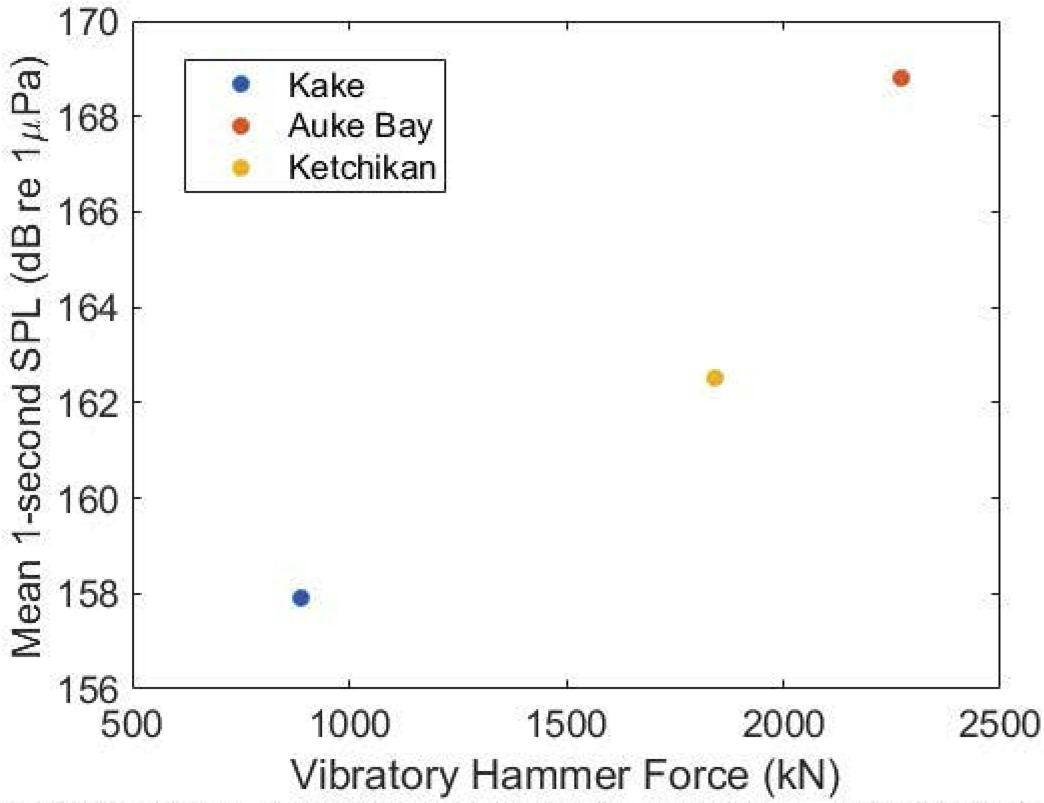

Figure 37. Mean 1 s SPL (dB re 1 µPa @ 10 m) as a function of vibratory hammer force (kN). Higher mean source levels were associated with higher hammer forces.

Environmental factors that affect sound propagation—subbottom properties, water column sound speed profile, and bathymetry—are the dominant factors that influence variability of the ranges to thresholds for Level A and Level B harassment among locations (summarized in Table 73).

Measurement of sound speed profiles during monitoring of test pile installations (plotted in the site-relevant appendices of supporting data) indicated both upwards and downwards refracting environments, as well as iso-velocity profiles. However, none of the profiles were strong enough, given the shallow water, to strongly influence acoustic propagation.

Sound propagation is also influence by sediment type and the subbottom, particularly the depth of sediment through which a pile must be driven and the length of time and number of impacts required to drive the pile. Excluding Kodiak, the site with the least amount of sediment overlying bedrock, Kake, had shorter vibratory driving and fewer impact strikes than either Auke Bay or Ketchikan. The overburden, sediment overlying bedrock, was approximately 15 ft at Kake, 45 ft at Auke Bay, and 42 ft at Ketchikan (see Table 1). The duration of vibratory hammering lasted 15 min at Kake, 30 min at Auke Bay, and over an hour at Ketchikan. The depth and density of the overburden could help determine exposure levels due to pile driving. Sediment type also affects the amount of sound energy that is radiated into the water column. Highly-reflective sediments typically result in higher in-water sound levels.

The ferry terminals that were monitored were either within a confined channel (Kodiak and Ketchikan), or facing open water (Kake and Auke Bay). The bathymetric profiles between AMARs show that Ketchikan has the steepest slope and deepest channel (Figure 38), which contributed to discrepancies between levels measured on bottom mounted and drifting recorders at that location (Section 6.2). The very shallow water in Kodiak inhibited propagation of lower frequency sounds.

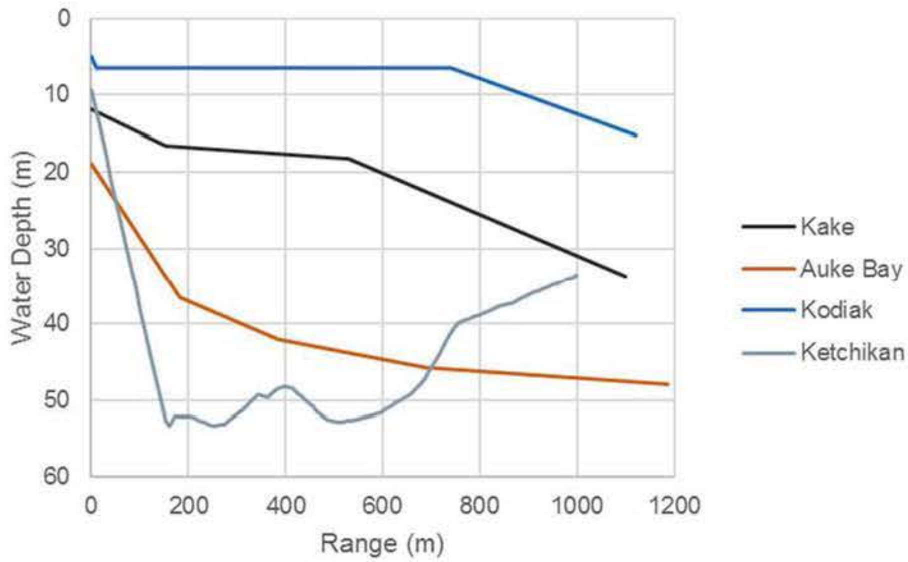

Figure 38. Bathymetric profile showing depth as a function of range between the pile and AMAR 2 at each of the ferry terminals.

6.2. Importance of Hydrophone Placement

Hydroacoustic pile driving measurements are typically conducted using a few hydrophones to sample the underwater acoustic field. The hydrophone position in range and depth (and potentially azimuth) is especially important for pile driving measurements due to propagation effects. At Ketchikan, effects in the measured levels due to hydrophone placement were observed. Sound levels from both impact and vibratory pile driving measured using the dipping hydrophone between AMARs 1 and 2 were lower than the linear trend formed between the AMAR data (Figure 31 and Figure 33). The mismatch between the AMAR and dipping hydrophone data is a result of the directionality of the pile as an acoustic source, bathymetry, and measurement locations.

When a hammer imparts a force on the top of a pile, it generates a stress wave that travels down the pile. This wave deforms the pile wall, which generates sound waves propagating into the surrounding water. The stress wave speed (~5000 m/s) is much faster than that of water (~1495 m/s in this study) so the displacement creates an acoustic field that has a planar wavefront angled downwards at approximately 17.5° from horizontal. This wavefront is symmetric in all azimuthal directions, creating a "Mach cone" propagating from the pile that dominates the acoustic field (Reinhall and Dahl 2011).

The Mach cone reflects off the seafloor and surface as it propagates and can be modeled using a ray-tracing propagation model. Figure 39 shows a ray-trace diagram of the sound paths (black lines) that emanate from the pile and travel through the water, using the Ketchikan environment as an example. Sound levels are higher in areas where there are many ray paths compared with areas with few ray paths. The sound rays were computed using the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994) for 9 point sources spanning the water column (between 0.5 and 8.5 m depth) for angles between 17 and 18° below horizontal to illustrate the range and depth coverage of the Mach cone.

The bathymetry was obtained from water depth measurements during AMAR deployments at Ketchikan and echosounder measurements along the track from AMAR 1 to 2. The bathymetry was interpolated between 17 and 150 m range and extrapolated to 0 m. The downwards-refracting measured sound speed profile from 20 Jul was modeled. The steep near-source bathymetry allows the Mach cone to propagate downwards to ~50 m depth at 150 m range before it is reflected upwards. This creates a significant depth-dependent acoustic shadow zone for the Mach cone at ranges less than ~270 m. The dipping hydrophone measurements at Ketchikan were made in this shadow zone (10 m depth between 120 and 248 m range), where there are few ray arrivals, whereas the AMAR measurements were made in the path of the Mach cone (10 m depth at 17 m range for AMAR 1 and 28 m depth at 948 m range for AMAR 2) with many ray arrivals and, thus, more sound energy. The difference in the number of ray arrivals explains why the dipping hydrophone sound levels were lower than the trend between the AMARs. Because the dipping hydrophone measurements do not represent maximum sound levels throughout the water column, they were therefore excluded from the fits in the sound level versus range plots (see Figure 17 and Figure 31).

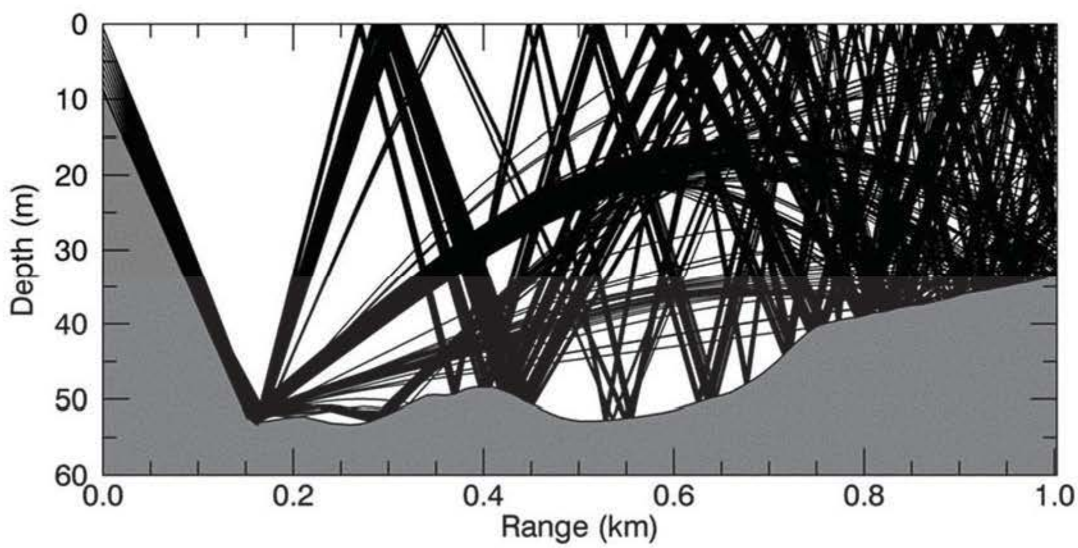

Figure 39. Ray trace diagram for propagation of the Mach cone (between 17 and 18 degrees below horizontal) for sources spanning the water column. Grey region indicates subbottom. Ray coverage indicates a significant depth-dependent acoustic shadow zone for the Mach cone at ranges less than approximately 270 m.

6.3. Extrapolated Ranges

Distances to threshold levels were determined using levels measured on AMAR 1 and TL coefficients derived from both AMAR 1 and 2. In some cases, threshold distances were calculated by extrapolating measurements beyond the maximum measurement range (nominally 1 km). Extrapolated threshold distances can be highly uncertain because the TL coefficient determined between AMARs 1 and 2 might be inappropriate for long-range propagation beyond AMAR 2.

Table 68 lists the distances to the 120 dB SPL threshold for vibratory piling at Ketchikan as approximately 120 and 61 km for the 90th percentile and mean levels, respectively. These distances were extrapolated from the empirical transmission loss fit (Figure 17) well beyond the maximum measurement range of approximately 950 m. These ranges are overestimated for the measurement location given that land blocks acoustic propagation beyond (at most) 12 km, and are likely overestimated even for the same pile driver/pile combination in an open-water environment.

We modeled the vibratory driving levels in an open-water environment so we could compare the long-range modeled sound levels to the empirical fit predictions. Sound propagation was modeled using JASCO's Marine Operations Noise Model (MONM). MONM computes acoustic propagation via a wideangle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a an elastic seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996).

For the simulated open-water environment, we used the measured bathymetry to 1 km range (described and shown in Section 6.2 and Figure 39) and extended it to 100 km range with a constant water depth. The measured sound speed profile (Appendix D.2) and a very fine sand sediment model were used for the environmental properties (a less-reflective silt sediment model resulted in a poor fit to AMAR 2 measurements). The source levels were derived by back-propagating the 90th percentile 1/3-octave band levels for Pile 2 assuming spherical spreading, i.e., 20 log*R*. The pile was approximated as a point source at mid-water column and the receiver followed the seafloor to simulate a bottom-mounted recorder.

Although the pile is simplified as a point source and the sediment model might not be accurate, the modeled levels agree well with measurements. Beyond the maximum measurement range, the extrapolated empirical levels deviate from modeled levels. Although the long-range flat bathymetry might not be realistic, the qualitative curve in SPL at long ranges is typical because energy is lost from numerous interactions between sound waves and the seabed. Pulses measured at relatively close range (less than 1 km) do not have significant bottom loss so the empirical fit has a low transmission loss coefficient (12.0). This coefficient is appropriate between the AMARs, but is likely underestimated beyond AMAR 2, which can lead to overestimated distances to the 120 dB threshold from extrapolating from the empirical fit.

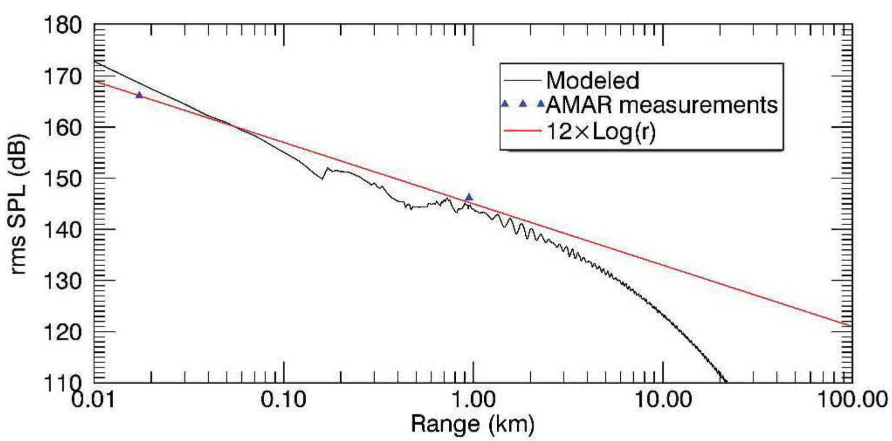

Figure 40. Modeled and measured SPL (90th percentile) for vibratory piling of Pile 2 at Ketchikan. Black line is modeled using MONM.

NMFS behavioral disturbance threshold level, Level B harassment, for continuous sounds (vibratory driving and drilling) is 120 dB. At two of the four sites, Auke Bay and Ketchikan, the received levels at the AMAR 1 km from the piles exceeded this threshold. Using these received levels, the calculated range to this threshold was much greater than the ranges at which recorders were placed. Extrapolation beyond the maximum range sampled could lead to extremely high, and most likely conservative, threshold ranges. More accurate ranges can be calculated with measurements at ranges greater than 1 km. While some extrapolation might be necessary, additional sample points could indicate greater transmission loss. The greater transmission loss at longer ranges could also be predicted and/or confirmed with numerical sound propagation models.

6.4. Drilling Sound Levels

Drilling source levels at the Kodiak ferry terminal were higher than the vibratory hammering source levels at all sites except Auke Bay (Table 72). The recording signals were dominated by sounds produced by the drill's hammer at the pile toe. The hammer struck the pile toe at a frequency of approximately 15.5 Hz. Due to the relatively high rate of impact and overlapping pulse waveforms, drilling sounds were treated as a continuous noise (Figures 41 and 42). The threshold distance is relatively large because the disturbance criteria threshold for continuous noise is 120 dB re 1 µPa (Table 56).

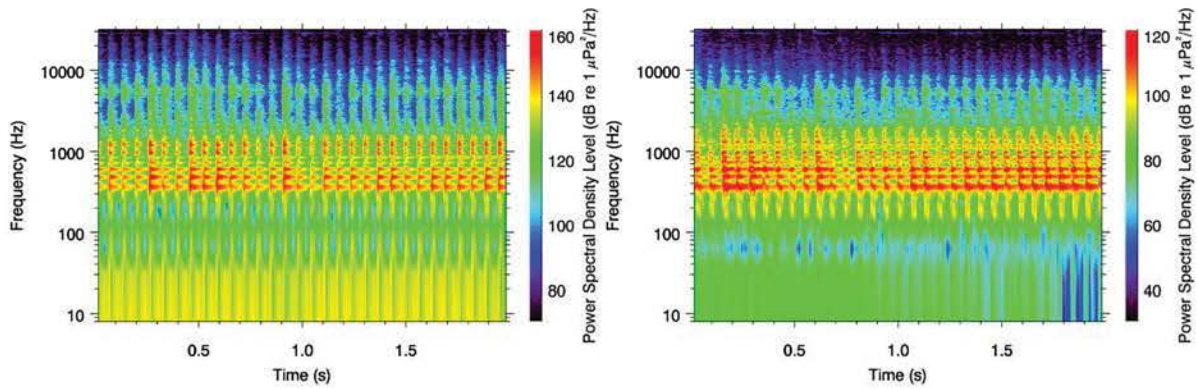

Figure 41. Spectrograms of down-the-hole drilling Pile D20 measured on AMAR 1 at 12.9 m (left) and AMAR 2 at 1119 m (right).

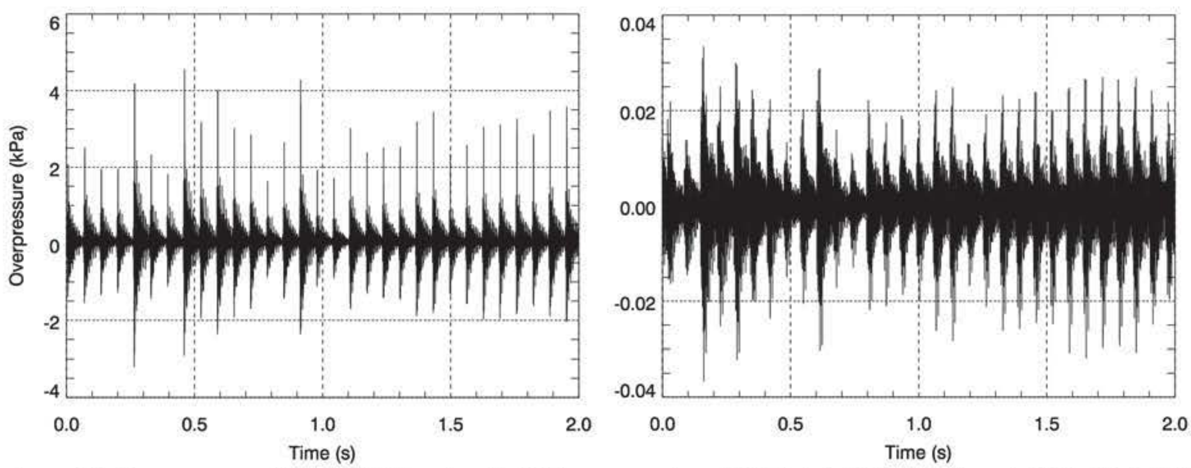

Figure 42. Pressure waveforms of drilling for pile D20 measured on AMAR 1 at 12.9 m (left) and AMAR 2 at 1119 m (right).

6.5. Suitability of Weighting Function Adjustments

The Weighting Function Adjustments (WFA) provided by NMFS for estimating frequency-weighted SEL from broadband SEL measurements generally provide conservative estimates; however, when the WFA were used for near-source impact hammering High-frequency cetacean (HFC)-weighted levels, all levels were underestimated at all four measurement sites. This indicates impact piling contains significant high-frequency energy that the WFA process underestimates. To be conservative, proponents would likely need to use a higher percentile frequency for impact hammering above 2 kHz to estimate HFC-weighted levels from broadband measurements.

Using the WFA method at the longer-range AMAR 2 measurements did not result in underestimated levels as was the case in the near-source measurements. The high frequencies in the passband of the HFC weighting function typically experience greater transmission loss so at long ranges, impact piling sounds contain less high-frequency energy. The increased transmission loss reduces the true 90th percentile frequency with range, and by approximately 1 km, the WFA method resulted in conservative estimates for HFC-weighted impact hammering levels, but this phenomenon might not occur in all environments.

7. Conclusion

Received levels standardized to 10 m range are summarized for each source type at each location (Table 72). These values are averaged over all measured piles at each site. The resulting ranges to thresholds at each site grouped by impact and continuous source type are in Table 73. Criteria ranges are summarized from results sections for each location (Kake: Sections 5.1.4 and 5.1.6; Auke Bay: Sections 5.2.3 and 5.2.5; Kodiak: 5.3.5 and 5.3.7; Ketchikan: 5.4.3 and 5.4.5). Transmission loss coefficients (*n* in Equation 1) were calculated in linear regressions for each source type at each location (Table 74).

Table 72. Summary of received levels at 10 m range. Values are computed as the linear average of the metrics for each pile at a given site.

Hammer	Site	Metric	Mean	Median	Max	90th percentile
Impact	Kake	peak level (dB re 1 µPa)	206.9	206.6	210.0	209.3
	Auke Bay		205.9	206.0	207.9	206.9
	Kodiak		193.3	192.8	194.8	194.8
	Ketchikan		208.6	208.5	211.2	209.8
Impact	Kake	SPL (dB re 1 µPa)	194.8	194.4	197.4	196.8
	Auke Bay		191.2	191.3	201.4	192.2
	Kodiak		181.3	181.1	182.7	182.7
	Ketchikan		194.7	195.0	197.0	196.2
Impact	Kake	single-strike SEL (dB re 1 µPa2s)	179.9	179.6	182.3	181.7
	Auke Bay		177.3	177.4	179.5	178.3
	Kodiak		168.2	168.3	168.8	168.8
	Ketchikan		180.7	180.7	183.2	182.1
Vibro	Kake	SPL (dB re 1 µPa)	157.9	155.8	167.7	162.0
	Auke Bay		168.8	168.0	178.1	171.8
	Kodiak		155.5	152.3	164.8	160.0
	Ketchikan		162.5	161.9	170.3	166.2
Drilling	Kodiak	SPL (dB re 1 µPa)	167.7	166.2	175.1	171.0

Table 73. Summary table of range to threshold based on Level B or behavioral (NMFS 2016b) and Level A or injury (NMFS 2016a) harassment criteria. All ranges are in meters. For Kodiak, drilling and vibratory hammer were combined for Level A harassment, and kept separate for Level B harassment. Drilling ranges are in parentheses for Kodiak Level B ranges. LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Noise Type	Harassment Criteria by Hearing Group	Kake		Auke Bay		Kodiak		Ketchikan	
		Mean	90th Percentile	Mean	90th Percentile	Mean	90th Percentile	Mean	90th Percentile
Continuous	Level B (120 dB)	825	1207*	10,257^	16,126^	490 (5049*)	821 (6846*)	61,383^	120,147^
	Level A LFC	< 10	< 10	15	23	35	50	10	14
	Level A MFC	< 10	< 10	< 10	10	< 10	< 10	< 10	< 10
	Level A HFC	< 10	< 10	82	134	40	59	11	13
	Level A PPW	< 10	< 10	< 10	13	12	18	< 10	< 10
	Level A OPW	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Impact	Level B (160 dB)	685	897	1338*	1567*	145	183	2250*	2703*
	Level A LFC	124	157	740	1157*	< 10	< 10	1288*	1641*
	Level A MFC	< 10	< 10	13	13	< 10	< 10	21	29
	Level A HFC	164	207	557	807	15	17	746	977
	Level A PPW	37	46	122	153	< 10	< 10	212	293
	Level A OPW	< 10	< 10	< 10	< 10	< 10	< 10	13	20

*Extrapolated beyond maximum measurement range.

^ Extrapolated far beyond maximum measurement range. These values are unrealistic, see Discussion section 6.3.

Table 74. Summary of unweighted transmission loss coefficients calculated for each source activity and site.

Activity	Site	Transmission Loss Coefficient
Impact Driving	Kake	19.6
	Auke Bay	14.6
	Kodiak	20.3
	Ketchikan	15.0
Vibratory Driving	Kake	20.6
	Auke Bay	16.4
	Kodiak	21.9
	Ketchikan	12.0
Vibratory Extraction	Kake	19.2
Drilling	Kodiak	18.9

Glossary

1/3-octave band
Non-overlapping passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave bands comprise one octave. One-third-octave bands become wider with increasing frequency. Also see octave.

A-weighting
Frequency-selective weighting for human hearing in air that is derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies.

absorption
The conversion of acoustic energy into heat, which is captured by insulation.

ambient noise
All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 R2004), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation
The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

audiogram
A graph of hearing threshold level (sound pressure levels) as a function of frequency, which describes the hearing sensitivity of an animal over its hearing range.

auditory weighting function (frequency-weighting function)
Auditory weighting functions account for marine mammal hearing sensitivity. They are applied to sound measurements to emphasize frequencies that an animal hears well and de-emphasize frequencies they hear less well or not at all (Southall et al. 2007, Finneran and Jenkins 2012, NOAA 2013).

background noise
Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI S1.1-1994 R2004). Ambient noise detected, measured, or recorded with a signal is part of the background noise.

bandwidth
The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., pile driving hammers, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI/ASA S1.13-2005 R2010).

bar
Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to 10^6 Pa or 10^{11} µPa.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

compressional wave
A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

continuous sound
A sound whose sound pressure level remains above ambient sound during the observation period (ANSI/ASA S1.13-2005 R2010). A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

equal-loudness contour
A curve or curves that show, as a function of frequency, the sound pressure level required to cause a given loudness for a listener having normal hearing, listening to a specified kind of sound in a specified manner (ANSI S1.1-1994 R2004).

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: *f*. 1 Hz is equal to 1 cycle per second.

functional hearing group
Grouping of marine mammal species with similar hearing ranges. Commonly defined functional hearing groups include low-, mid-, and high-frequency cetaceans, pinnipeds in water, and pinnipeds in air.

Global Positioning System (GPS)
A satellite based navigation system providing accurate worldwide location and time information.

hearing threshold
The sound pressure level that is barely audible for a given individual in the absence of significant background noise during a specific percentage of experimental trials.

hertz (Hz)
A unit of frequency defined as one cycle per second.

high-frequency cetacean (HFC)
The functional hearing group that represents odontocetes specialized for using high frequencies.

hydrophone
An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

impulsive sound
Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA 2013, ANSI S12.7-1986 R2006). For example, seismic airguns and impact pile driving.

low-frequency cetacean (LFC)
The functional hearing group that represents mysticetes (baleen whales).

median
The 50th percentile of a statistical distribution.

mid-frequency cetacean (MFC)
The functional hearing group that represents some odontocetes (dolphins, toothed whales, beaked whales, and bottlenose whales).

M-weighting
The process of band-pass filtering loud sounds to reduce the importance of inaudible or less-audible frequencies for broad classes of marine mammals. "Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds" (Southall et al. 2007).

mysticete
Mysticeti, a suborder of cetaceans, use their baleen plates, rather than teeth, to filter food from water. They are not known to echolocate, but use sound for communication. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and the gray whale (*Eschrichtius robustus*).

non-impulsive sound
Sound that is broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and typically does not have a high peak pressure with rapid rise time (typically only small fluctuations in decibel level) that impulsive signals have (ANSI/ASA S3.20-1995 R2008). For example, marine vessels, aircraft, machinery, construction, and vibratory pile driving (NIOSH 1998, NOAA 2015).

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete
The presence of teeth, rather than baleen, characterizes these whales. Members of the Odontoceti are a suborder of cetaceans, a group comprised of whales, dolphins, and porpoises. The toothed whales' skulls are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

otariid
A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus.

parabolic equation method
A computationally-efficient solution to the acoustic wave equation that is used to model transmission loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of transmission loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

peak level
The maximum instantaneous sound pressure level, in a stated frequency band, within a stated period. Also called zero-to-peak pressure level. Unit: decibel (dB).

peak-to-peak level
The difference between the maximum and minimum instantaneous sound pressure levels. Unit: decibel (dB).

percentile level, exceedance
The sound level exceeded *n*% of the time during a measurement.

permanent threshold shift (PTS)
A permanent loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

phocid
A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

pinniped
A common term used to describe all three groups that form the superfamily Pinnipedia: phocids (true seals or earless seals), otariids (eared seals or fur seals and sea lions), and walrus.

point source
A source that radiates sound as if from a single point (ANSI S1.1-1994 R2004).

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: $\mu Pa^2/Hz$, or $\mu Pa^2 \cdot s$.

power spectral density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 $\mu Pa^2/Hz$.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: *p*.

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

received level
The sound level measured at a receiver.

rms
root-mean-square.

signature
Pressure signal generated by a source.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound exposure
Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second ($Pa^2 \cdot s$) (ANSI S1.1-1994 R2004).

sound exposure level (SEL)
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound field
Region containing sound waves (ANSI S1.1-1994 R2004).

sound intensity
Sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 µPa:

$$\mathrm{SPL} = 10\log_{10}\left(p^2 / p_0^2\right) = 20\log_{10}\left(p / p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level. See also 90% sound pressure level and fast-average sound pressure level.

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 µPa @ 1 m (sound pressure level) or dB re 1 $\mu Pa^2 \cdot s$ (sound exposure level).

spectrogram
A visual representation of acoustic amplitude compared with time and frequency.

spectrum
An acoustic signal represented in terms of its power (or energy) distribution compared with frequency.

temporary threshold shift (TTS)
Temporary loss of hearing sensitivity caused by excessive noise exposure.

transmission loss (TL)
The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called propagation loss.

wavelength
Distance over which a wave completes one oscillation cycle. Unit: meter (m). Symbol: λ.

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Appendix A. Supporting Data for Kake

A.1. Monitoring Activities

The activities of the JASCO field monitoring team during the Kake pile driving and extraction are provided in Table A-1. The AMARs were deployed to different locations for extraction and installation of piles, thus adding additional retrieval and deployment of AMARs.

Table A-1. Log of hydroacoustic monitoring of pile driving at Kake, Alaska.

Date (UTC)	Time (UTC)	Activity
2015-09-09	18:19	AMAR 2: Calibrated
2015-09-09	18:27	AMAR 1: Calibrated
2015-09-09	21:53	AMAR 1: Deployed at ferry terminal
2015-09-10	17:05	AMAR 2: Deployed in Keku Strait
2015-09-10	18:07	Dipping hydrophone measured vibratory pile extraction
2015-09-10	21:49	CTD cast in Keku Strait
2015-09-11	0:21	AMAR 1: Retrieved before ferry docked at terminal
2015-09-11	1:50	AMAR 2: Retrieved
2015-09-11	2:29	AMAR 2: Calibrated
2015-09-11	16:47	AMAR 1: Deployed at ferry terminal
2015-09-11	22:59	CTD cast in Keku Strait
2015-09-11	23:21	Dipping hydrophone measured vibratory pile driving
2015-09-12	22:50	AMAR 2: Deployed in Keku Strait
2015-09-12	23:08	CTD cast in Keku Strait
2015-09-13	0:45	Dipping hydrophone measured impact pile driving
2015-09-13	1:15	AMAR 2: Retrieved
2015-09-13	2:06	AMAR 1: Retrieved
2015-09-13	2:52	AMAR 1: Calibrated

A.2. Weather Data

Over the course of the period of acoustic monitoring of construction activity at the Kake ferry terminal, there was no recorded precipitation. Wind speeds varied between calm and 20 mph (Figure A-1). The high winds began during daytime 10 Sep. Around midnight 11 Sep gusts were upwards of 30 mph.

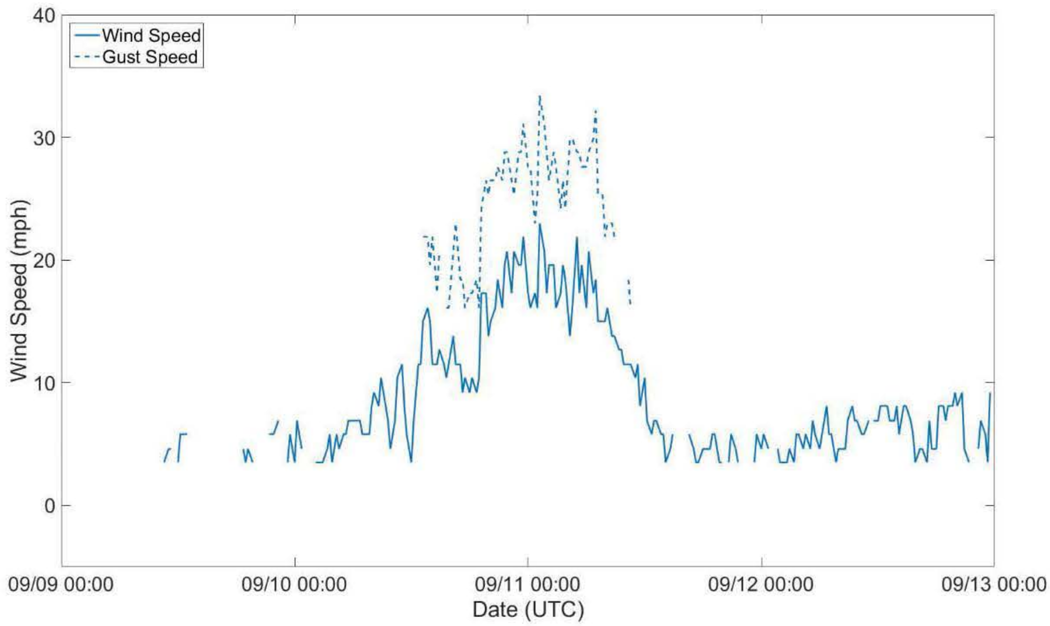

Figure A-1. Wind and gust speed recorded at weather at Kake airport (AFE). No precipitation was recorded during this period.

At Kake, the sound speed profiles calculated from CTD casts made between the deployed AMARs on three consecutive days, from 10-12 Sep 2015, were relatively constant with depth varying by no more than 5 m/s over the entire depth of the water (Figure A-2). Although the maximum variation in the sound speed profiles was limited, the trends from each of the three casts were different. On 10 Sep, there was a sharp shift to a slower sound speed at about 10 m below the wind-mixed surface layer. On 11 Sep, the velocity was relatively constant due to mixing from the high winds, but increased slightly with depth. On 12 Sep, there was a downward refracting profile characterized by a decrease in sound speed 2 m below the surface, and then the profile followed that from 11 Sep with increasing depth.

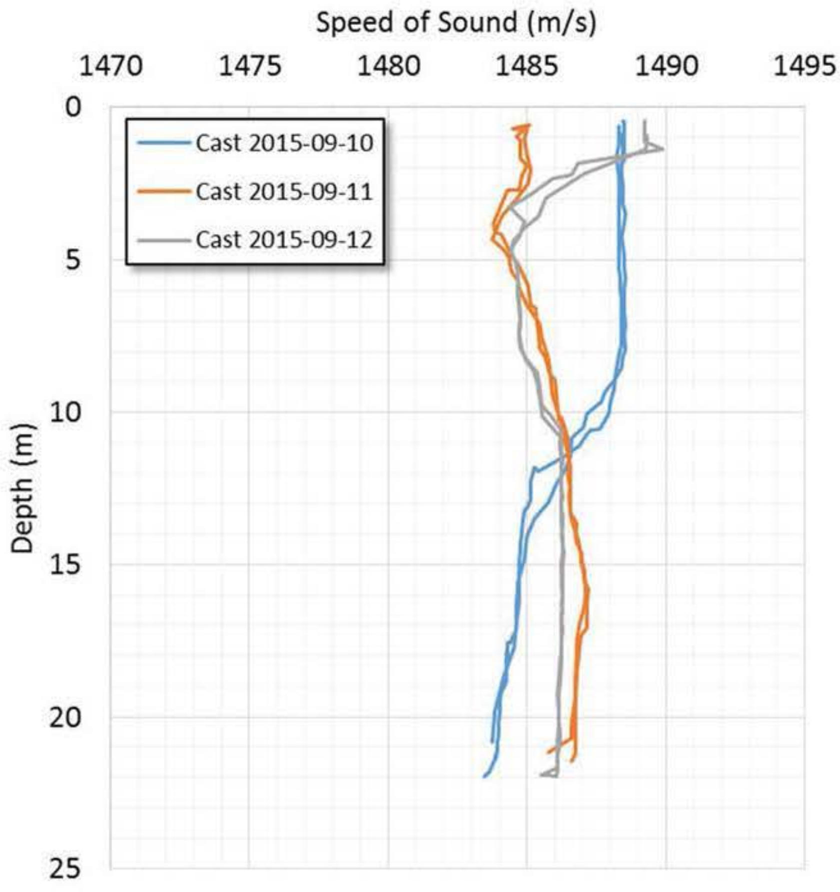

Figure A-2. Profiles of sound speed versus depth calculated from temperature and salinity data collected in Keku Strait, Kake, Alaska. Profiles were sampled between AMAR 1 and AMAR 2 on three consecutive days.

A.3. Spectrograms

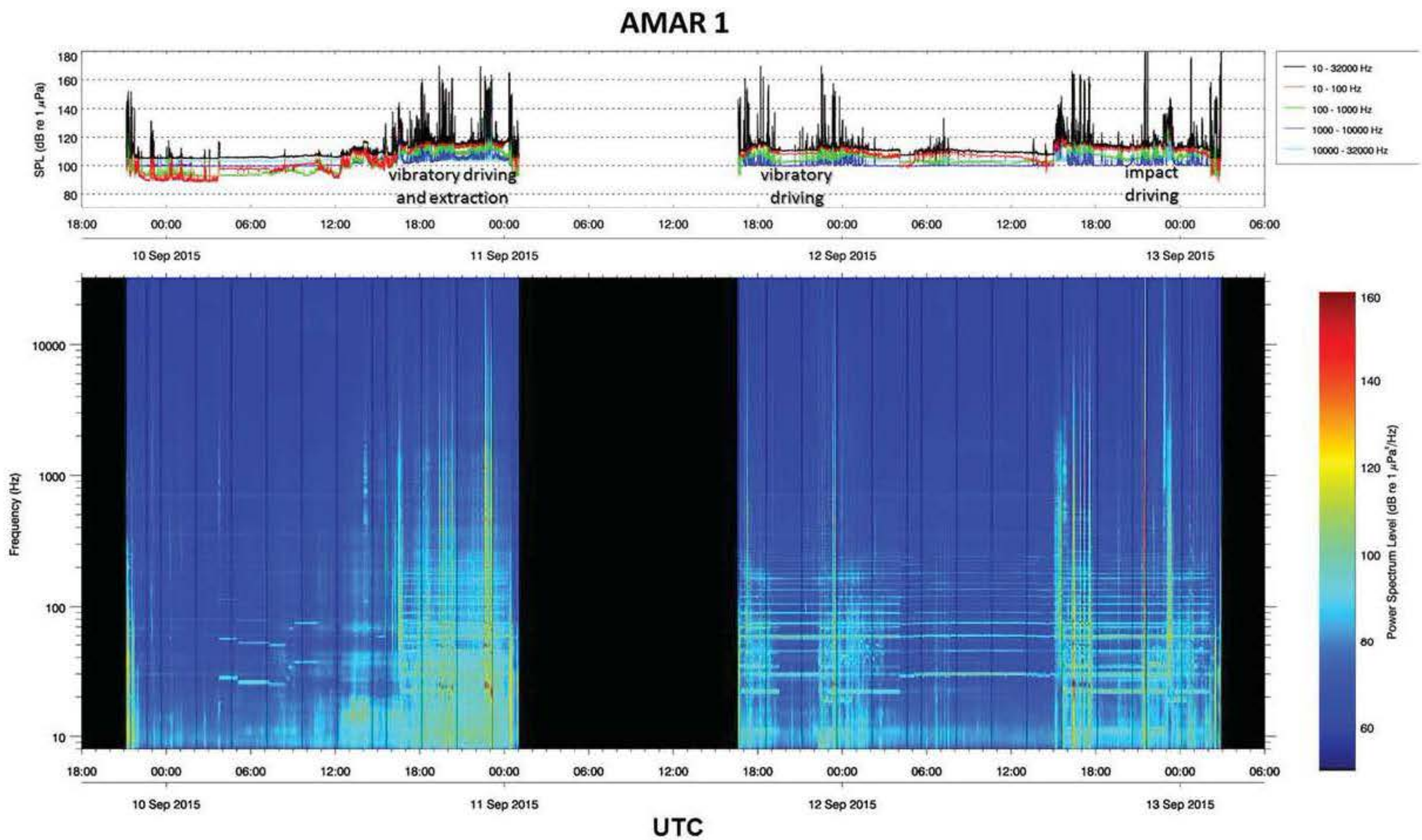

Figure A-3. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at Kake ferry terminal.

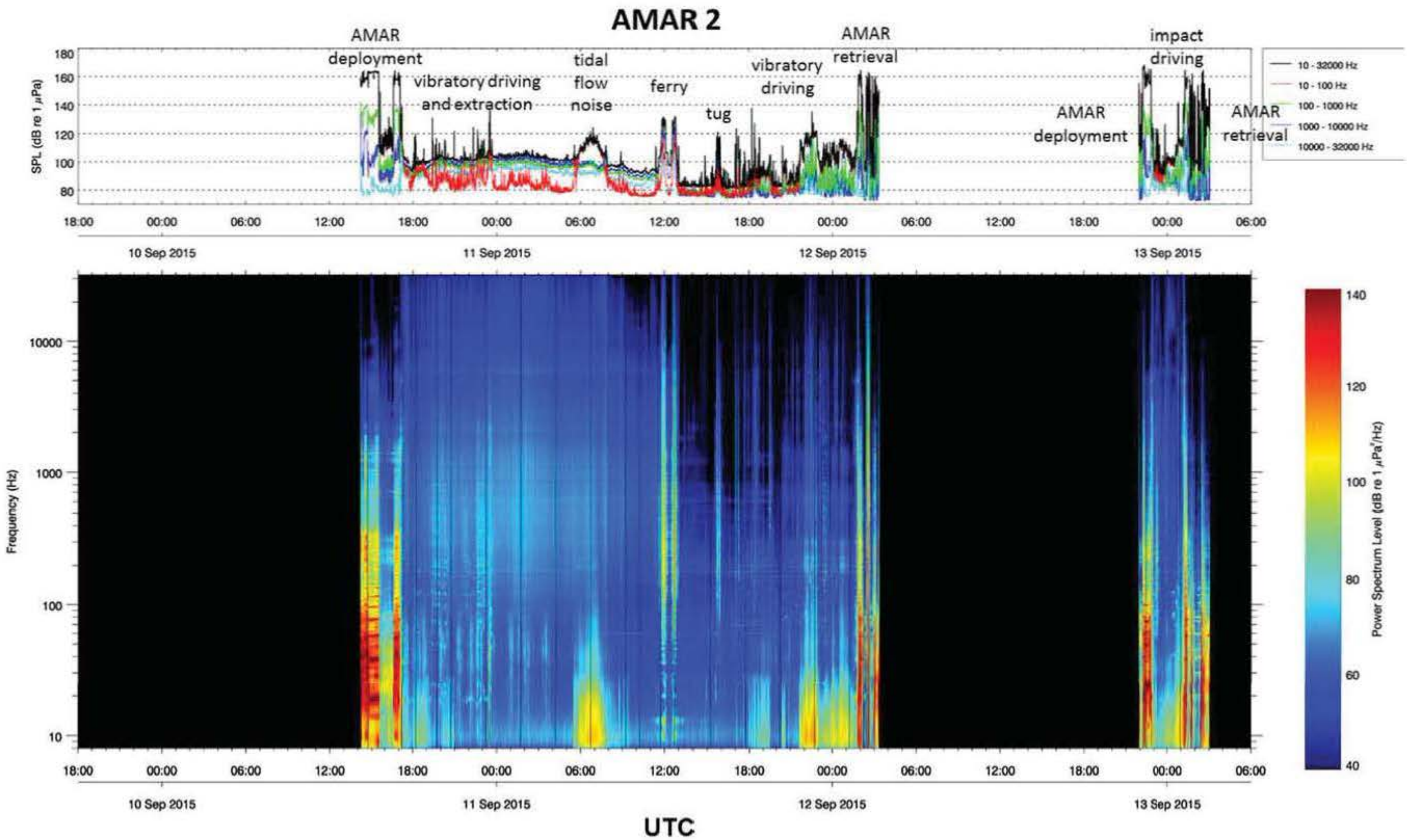

Figure A-4. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at 1 km from Kake ferry terminal.

A.4. Pile Driving Noise Levels

A.4.1. Impact Pile Driving Time Histories

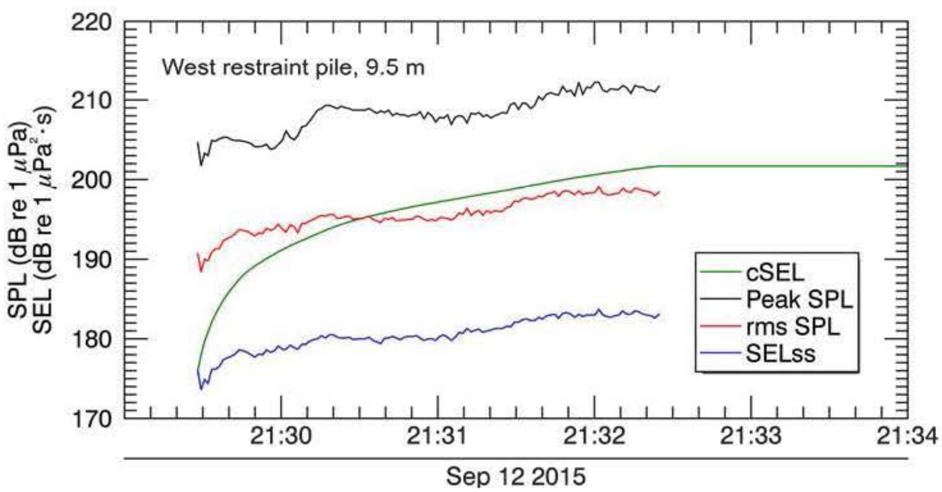

Figure A-5. Peak level, SPL, and single-strike SEL vs time (UTC) for impact driving of the 30” diameter west restraint pile. AMAR 1 data recorded at 9.5 m range.

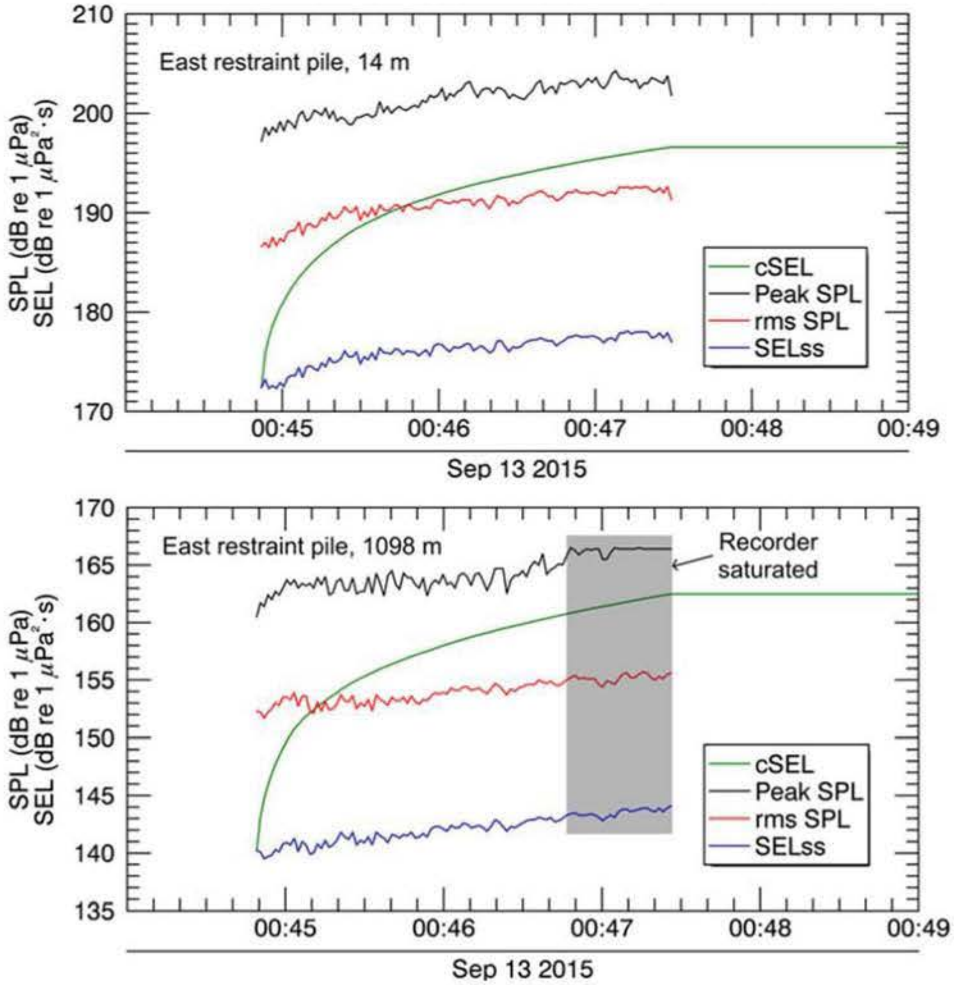

Figure A-6. Peak level, SPL, and single-strike SEL versus time (UTC) for impact driving of the 30" diameter east restraint pile. AMAR 1 data (top) recorded at 14 m range, and AMAR 2 data (bottom) recorded at 1098 m range.

A.4.2. Vibratory Driving Time Histories

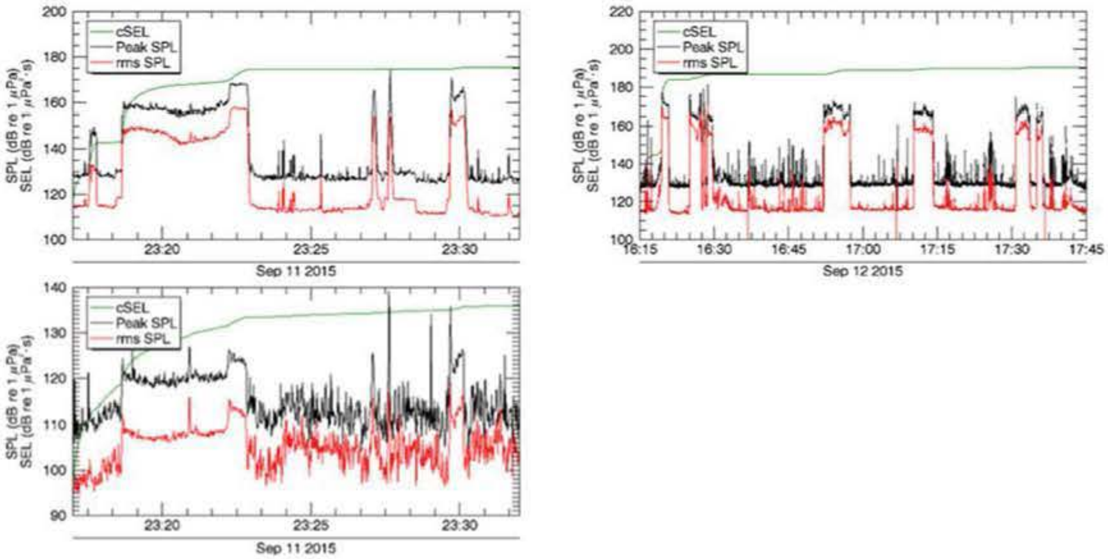

Figure A-7. SPL vs time (UTC) for vibratory driving of 30" diameter piles (1 s average). Top and bottom plots show data from AMARs 1 and 2, respectively. Left and right plots show data from driving the east and west restraint piles, respectively. Distances to AMAR 1 were 14 and 9.5 m for the east and west piles, respectively. The distance to AMAR 2 was 1161 m. AMAR 2 was not deployed during final vibratory driving of the west restraint pile.

A.4.3. Vibratory Extraction Time Histories

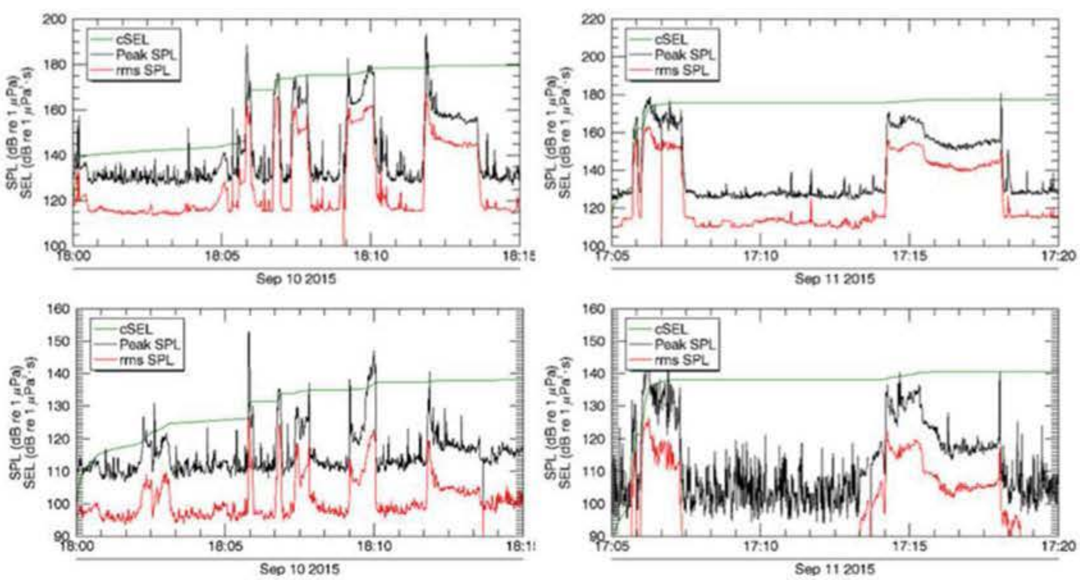

Figure A-8. SPL versus time (UTC) for vibratory extraction of 18" diameter steel piles (1 s average). Top and bottom plots show data from AMARs 1 and 2, respectively. Left and right plots show data from extraction of the west and east restraint piles, respectively. Distances to AMAR 1 were approximately 7 and 17 m for the west and east piles, respectively. Distances to AMAR 2 were approximately 1149 and 1157 m for the west and east piles, respectively.

A.5. 1/3-Octave Band Levels

One-third octave band spectra are provided in which beige bars indicate the first, second, and third quartiles (L_{25}, L_{50}, and L_{75}) in each 1/3-octave band. Upper error bars indicate the maximum levels (L_{max}). Lower error bars indicate the 95% exceedance percentiles (L_{95}). The maroon line indicates the arithmetic mean (L_{mean}).

A.5.1. Impact Hammering

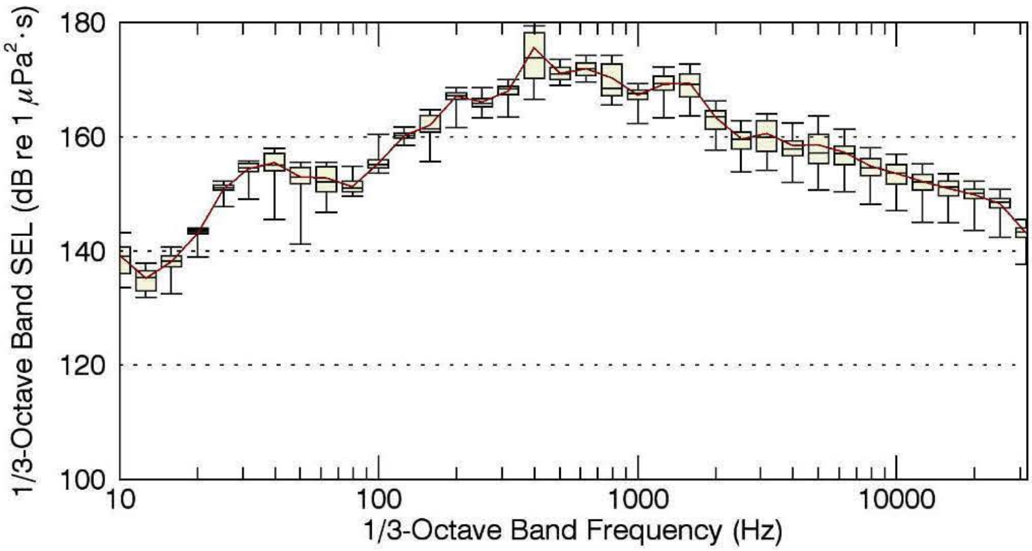

Figure A-9. 1/3-octave band SEL statistics for impact driving of the 30” diameter west restraint pile, recorded at 9.5 m range from Kake ferry terminal.

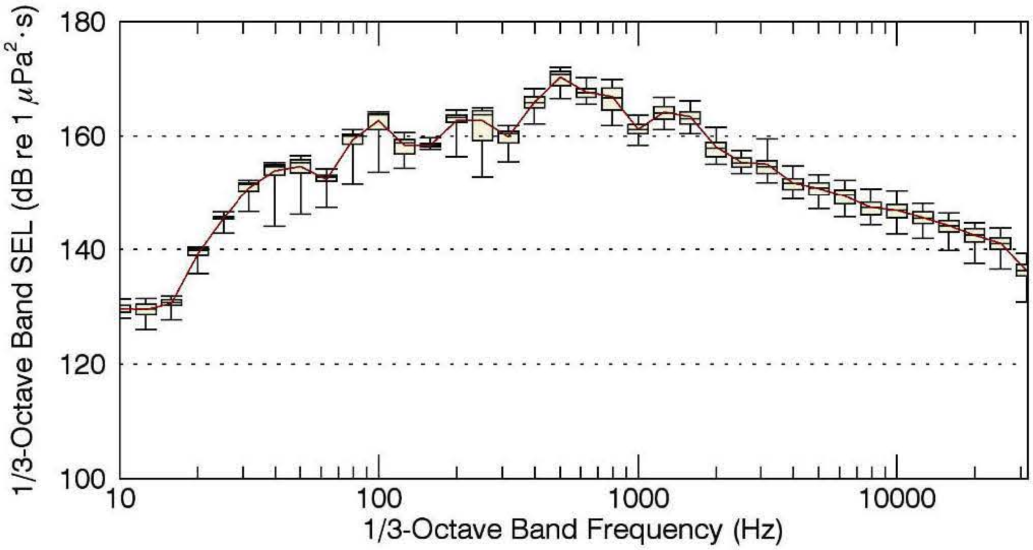

Figure A-10. 1/3-octave band SEL statistics for impact driving of the 30” diameter east restraint pile, recorded on AMAR 1 at 14 m range from Kake ferry terminal.

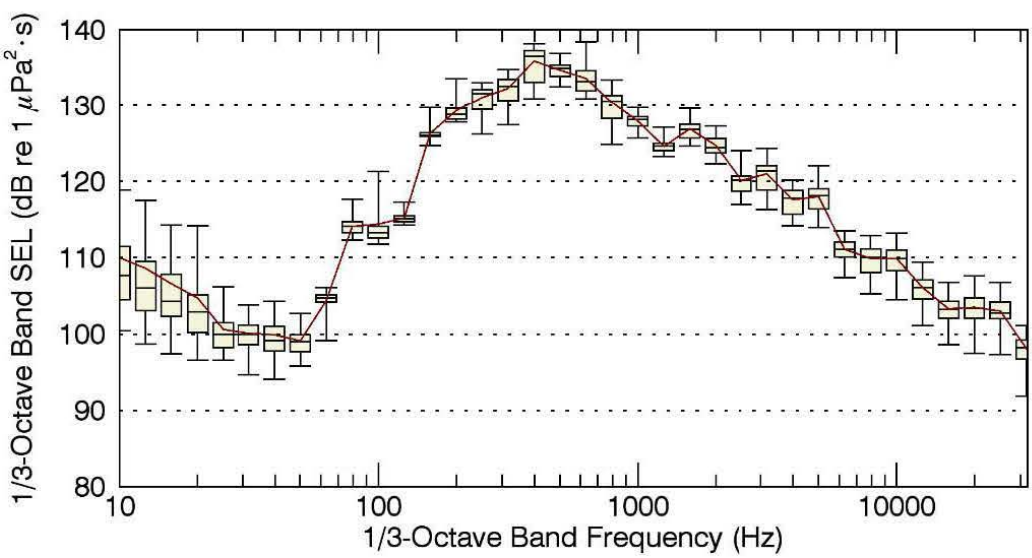

Figure A-11. 1/3-octave band SEL statistics for impact driving of the 30” diameter east restraint pile, recorded on AMAR 2 at 1098 m range from Kake ferry terminal.

A.5.2. Vibratory Driving

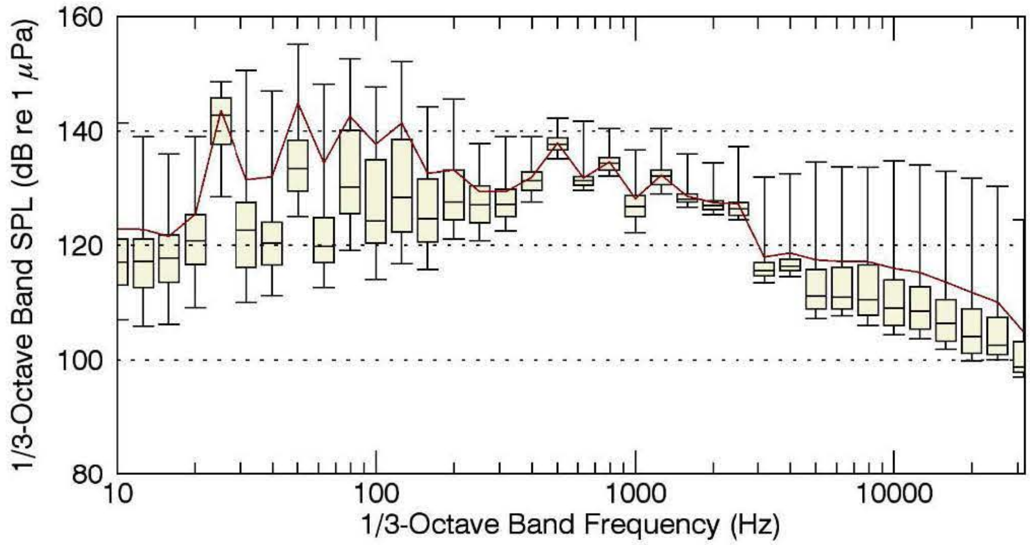

Figure A-12. 1/3-octave band SPL statistics for vibratory driving of the 30” diameter east restraint pile, recorded on AMAR 1 at 14 m range from Kake ferry terminal.

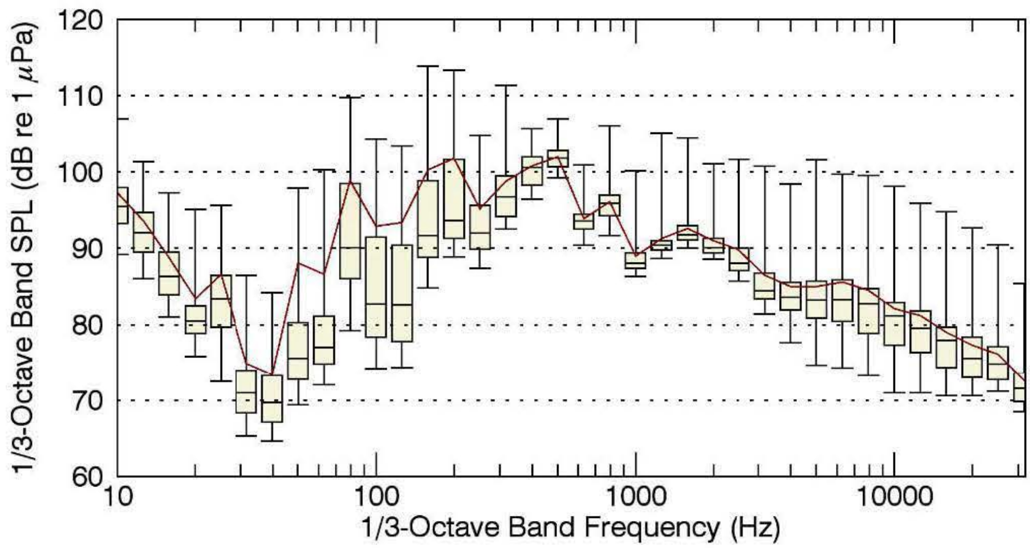

Figure A-13. 1/3-octave band SPL statistics for vibratory driving of the 30” diameter east restraint pile, recorded on AMAR 2 at 1161 m range from Kake ferry terminal.

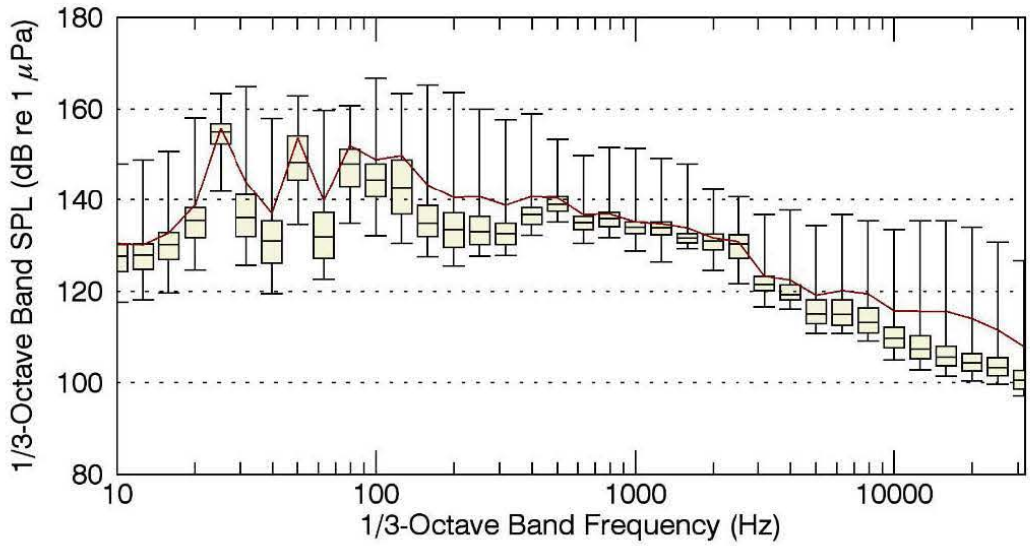

Figure A-14. 1/3-octave band SPL statistics for vibratory driving of the 30" diameter west restraint pile, recorded on AMAR 1 at 9.5 m range from Kake ferry terminal.

A.5.3. Vibratory Extraction

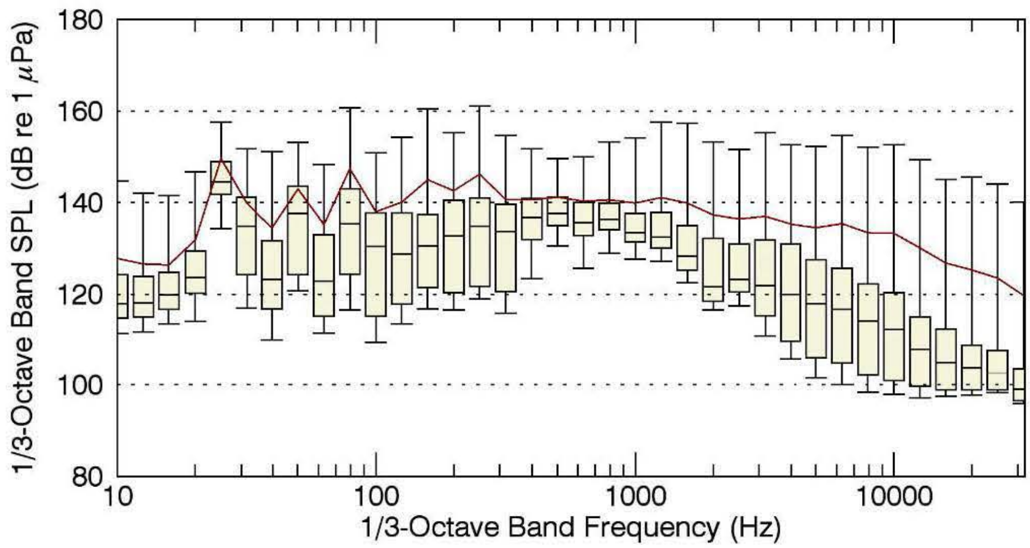

Figure A-15. 1/3-octave band SPL statistics for vibratory extraction of the 18" diameter west restraint pile, recorded on AMAR 1 at 7 m range from Kake ferry terminal.

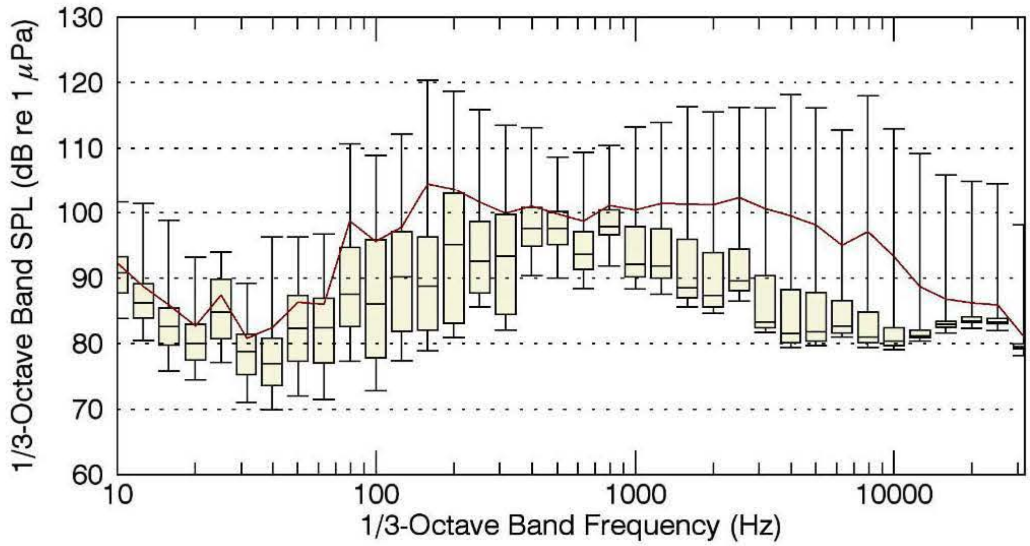

Figure A-16. 1/3-octave band SPL statistics for vibratory extraction of the 18” diameter west restraint pile, recorded on AMAR 2 at 1149 m range from Kake ferry terminal.

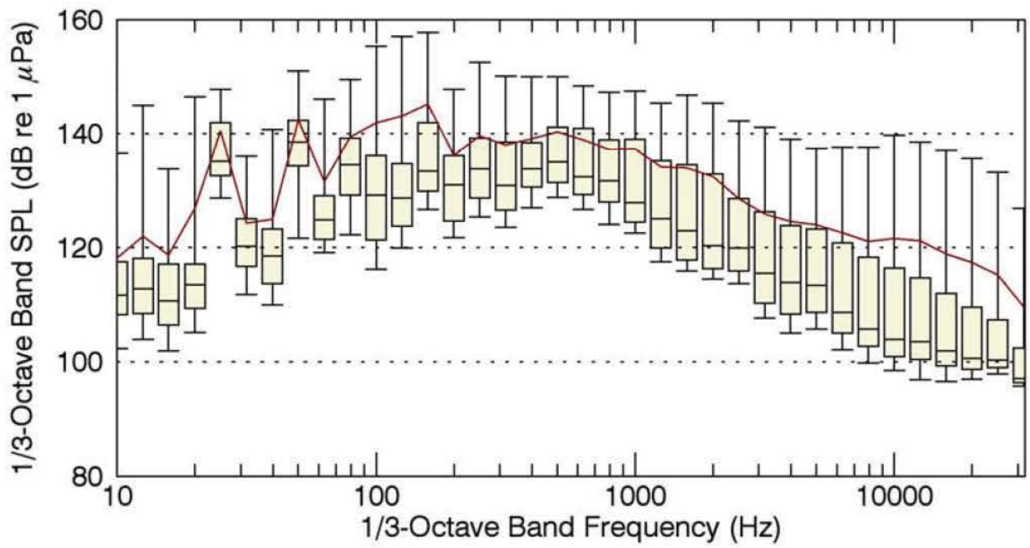

Figure A-17. 1/3-octave band SPL statistics for vibratory extraction of the 18” diameter east restraint pile, recorded on AMAR 1 at 17 m range from Kake ferry terminal.

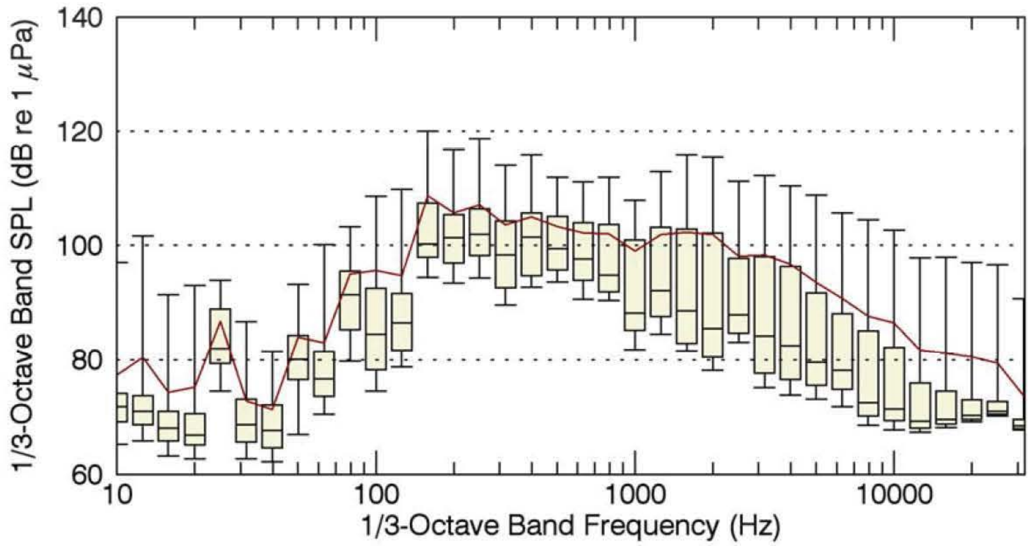

Figure A-18. 1/3-octave band SPL statistics for vibratory extraction of the 18" diameter east restraint pile, recorded on AMAR 2 at 1157 m range from Kake ferry terminal.

A.6. Background Noise Levels

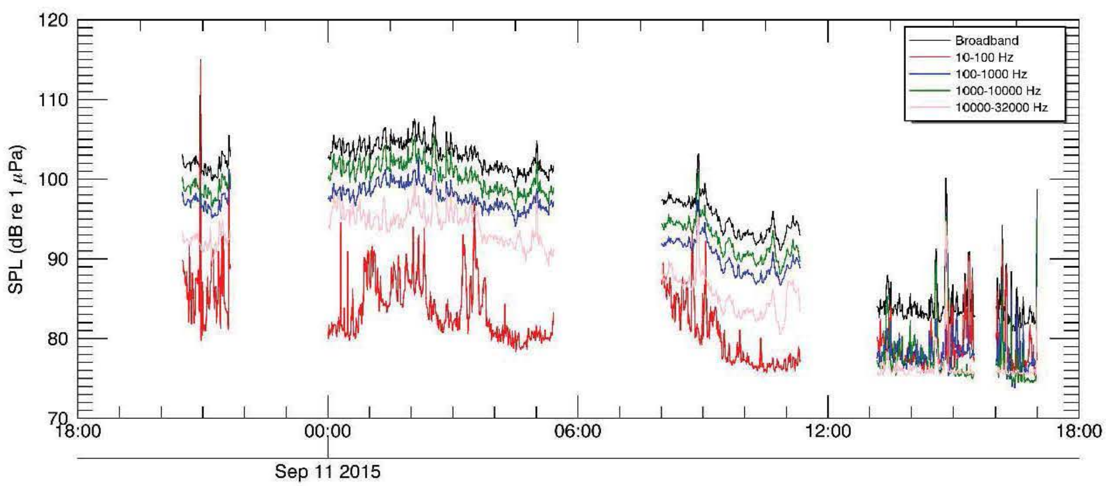

Figure A-19. Background SPL versus time (UTC) recorded on AMAR 2 (60 s average). Periods containing pile driving noise, tug noise, tidal flow noise, and ferry passes have been removed. Elevated background noise levels during the first half of the recording were caused by heavy precipitation at the study site.

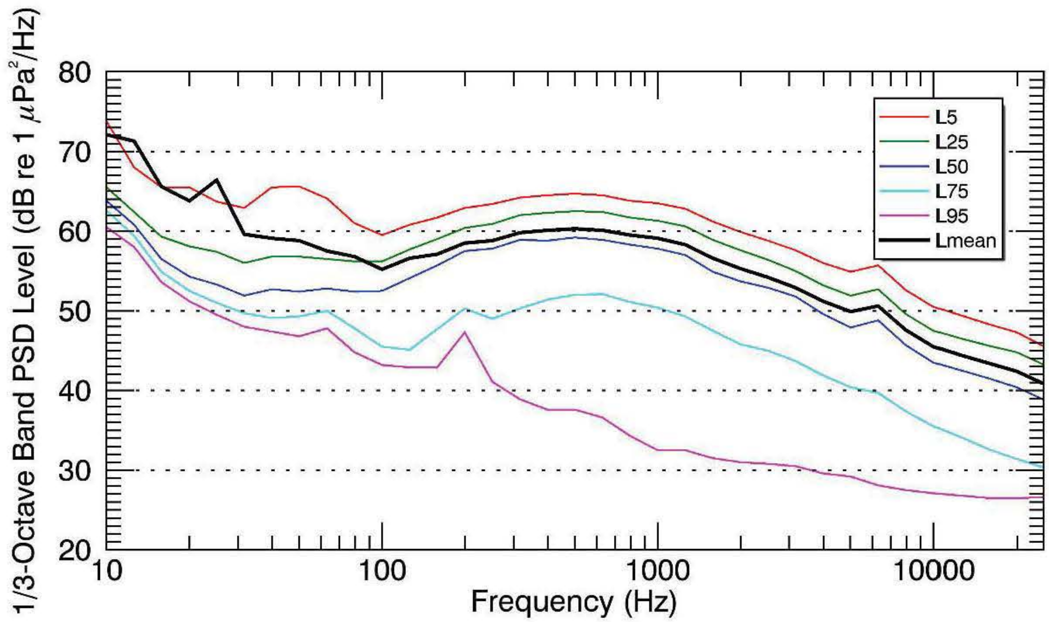

Figure A-20. Exceedance levels of 1/3-octave band background noise levels recorded on AMAR 2. The Ln value is the SPL exceeded by n% of the data. Periods containing pile driving noise, tug noise, tidal flow noise, and ferry passes have been removed.

Table A-2. Exceedance levels of background noise levels measured at Kake, Alaska (60 s average). The Ln value is the SPL exceeded by n% of the data. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = Phocid pinnipeds in water, OPW = Otariid pinnipeds in water.

Exceedance level	SPL (dB re 1 µPa)					
	Unw	LFC	MFC	HFC	PPW	OPW
L_5	105.3	104.3	97.7	95.8	102.4	102.6
L_{25}	103.0	102.0	95.2	93.4	99.9	100.1
L_{50} (median)	99.5	98.4	90.9	89.0	96.3	96.5
L_{75}	91.8	90.9	82.5	80.6	88.3	88.6
L_{95}	82.8	79.0	76.3	75.2	77.4	77.0
L_{mean}	100.9	99.7	92.9	91.1	97.7	97.9

A.7. Broadband-discounted SEL and weighted SEL differences

The NMFS Optional User Spreadsheet provides Weighting Function Adjustments (WFA) for estimating weighted SEL from unweighted SEL. The broadband SEL corrected with the WFA and the functional hearing group weighted SELs were compared. NMFS suggests that estimates generated by using the spreadsheet will conservatively estimate injury zones; however, this was not always the case. The WFA discounted SELs for the HFC functional hearing group were often lower, and therefore less conservative, than the frequency weighted SELs. Additionally, comparing the two calculations across functional hearing groups, illustrated a range of differences that exceeded 10 dB.

Table A-3. Difference between mean broadband-discounted SEL and weighted SEL for impact piling 30" diameter steel piles.

Pile	Hearing Group	AMAR 1	AMAR 2
West restraint	LFC	0.7	N/A*
	MFC	1	N/A
	HFC	-3.2	N/A
	PPW	5.6	N/A
	OPW	6.3	N/A
East restraint	LFC	0.9	0.8
	MFC	3	5.5
	HFC	-0.9	2.4
	PPW	6.1	7.1
	OPW	6.7	8.1

* N/A represents data excluded from analyses.

Table A-4. Difference between mean broadband-discounted SEL and weighted SEL for vibratory piling 30" diameter steel piles.

Pile	Hearing Group	AMAR 1	AMAR 2
West Restraint	LFC	8.5	N/A*
	MFC	19.1	N/A
	HFC	15.8	N/A
	PPW	18.8	N/A
	OPW	20	N/A
East Restraint	LFC	6.2	2.3
	MFC	11.8	5
	HFC	8	1.1
	PPW	13.8	9.5
	OPW	14.3	10.3

* N/A represents data excluded from analyses.

Table A-5. Difference between mean broadband-discounted SEL and weighted SEL for vibratory extraction of 18" diameter steel piles.

Pile	Hearing group	AMAR 1	AMAR 2
West restraint	LFC	3.8	1.3
	MFC	2	-2
	HFC	-1.7	-5.4
	PPW	8.4	3.7
	OPW	8.8	4
East restraint	LFC	3.4	1.6

Pile	Hearing group	AMAR 1	AMAR 2
	MFC	8.2	4.8
	HFC	4.3	2.1
	PPW	10.8	6.8
	OPW	11.4	7.1

Appendix B. Supporting Data for Auke Bay

B.1. Monitoring Activities

Table B-1 lists the activities of the JASCO field monitoring team during the Auke Bay pile installation.

Table B-1. Log of hydroacoustic monitoring of pile driving at Auke Bay, Alaska.

Date (UTC)	Time (UTC)	Activity
2015-11-09	22:24:50	AMAR 2: Calibrated
2015-11-09	22:35:25	AMAR 1: Calibrated
2015-11-10	00:52:47	AMAR 1: Deployed
2015-11-10	01:27:52	AMAR 2: Deployed
2015-11-10	16:48:05	CTD cast at ferry terminal
2015-11-10	17:00:05	CTD cast 0.5 km from terminal
2015-11-10	17:13:45	CTD cast 1 km from terminal
2015-11-10	17:32:02	CTD cast 0.5 km from terminal
2015-11-11	00:33:40	Pile 1: Dipping hydrophone recorded vibratory pile driving
2015-11-11	16:37:00	Pile 3: Dipping hydrophone recorded vibratory pile driving
2015-11-11	18:45:00	Dipping hydrophone: Calibrated
2015-11-11	19:20:00	Pile 2: Dipping hydrophone recorded vibratory pile driving
2015-11-11	22:46:35	Pile 3: Dipping hydrophone recorded impact pile driving
2015-11-12	00:00:55	Pile 1: Dipping hydrophone recorded impact pile driving
2015-11-12	00:05:00	Pile 2: Dipping hydrophone recorded impact pile driving
2015-11-12	0:44:45	AMAR 2: Retrieved
2015-11-12	1:00:40	AMAR 2: Calibrated
2015-11-12	1:35:50	AMAR 1: Retrieved
2015-11-12	2:58:15	AMAR 1: Calibrated

B.2. Weather Data

Light precipitation was present throughout the pile driving activities at Auke Bay (Figure B-1). The rain was accompanied by wind with gusts up to 40 mph.

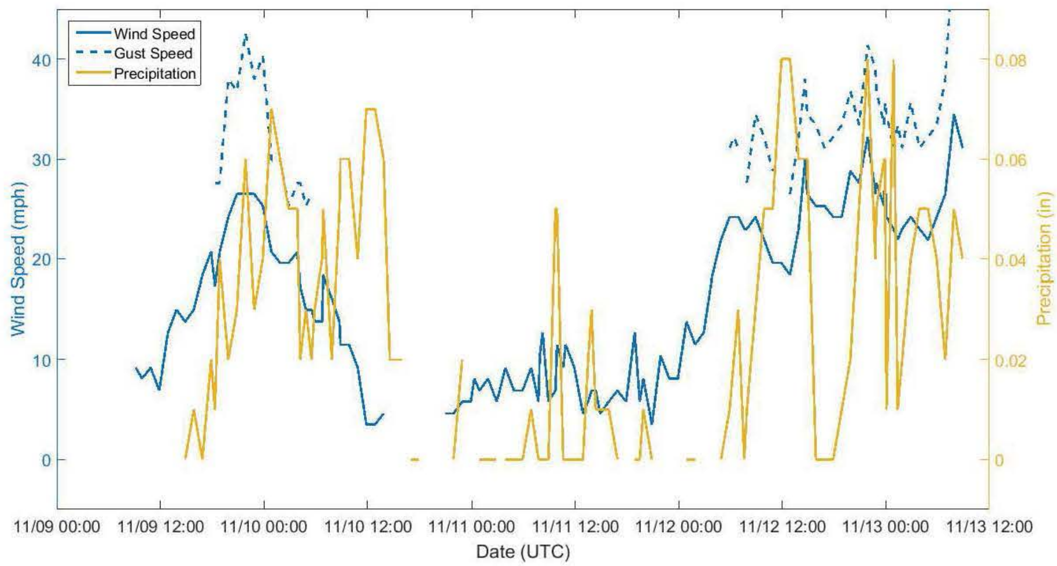

Figure B-1. Wind speed (blue) and precipitation (yellow) recorded at Juneau International Airport, approximately 7 km from Auke Bay, over the study period.

In Auke Bay, the sound speed profiles were consistent between samples taken near the terminal, 500 m from the terminal, and 1 km from the terminal (Figure B-2). The sound speed profile showed increasing sound speed with increasing depth, suggesting an upward refracting environment.

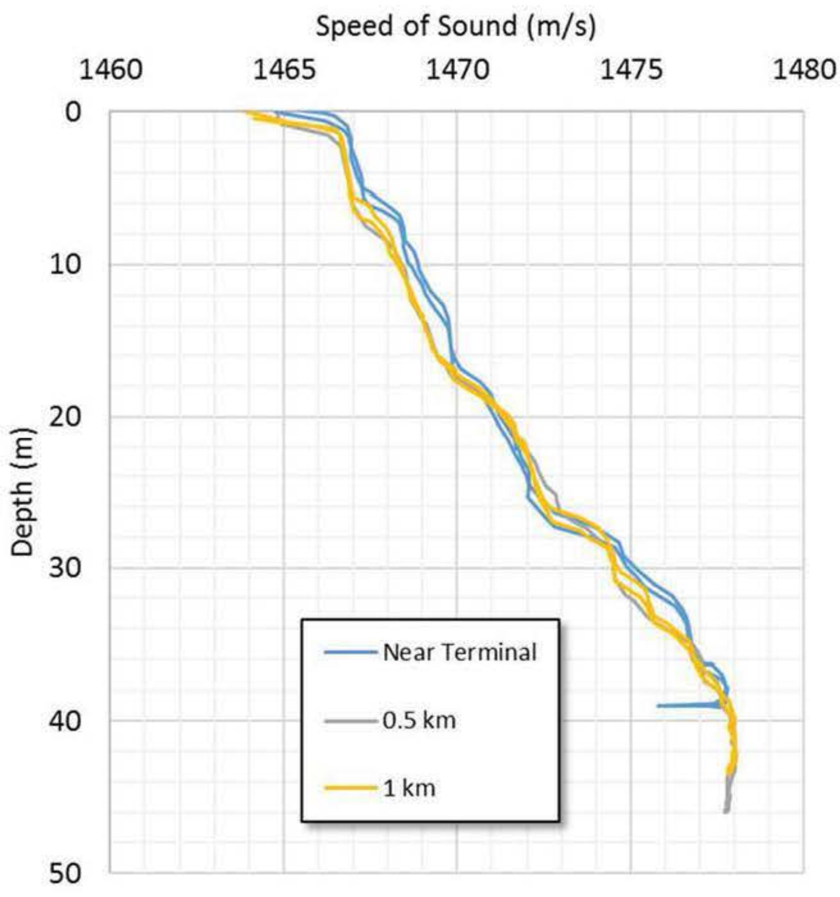

Figure B-2. Profiles of sound speed versus depth calculated from temperature and salinity data collected in Auke Bay 10 Nov 2015. Profiles were sampled near AMAR 1 (Near Terminal), between the AMARs (0.5 km), and near AMAR 2 (1 km).

B.3. Spectrograms

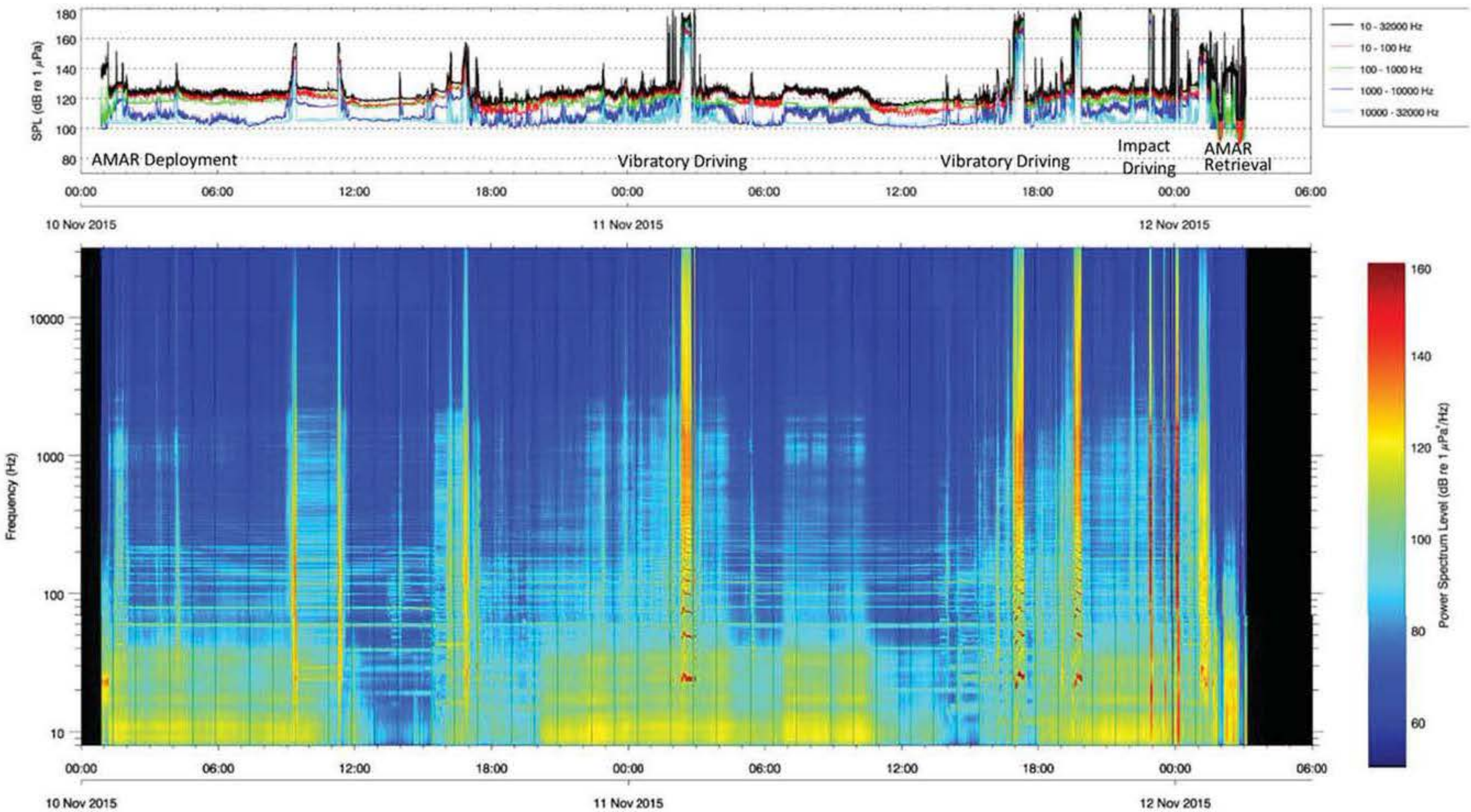

Figure B-3. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at terminal.

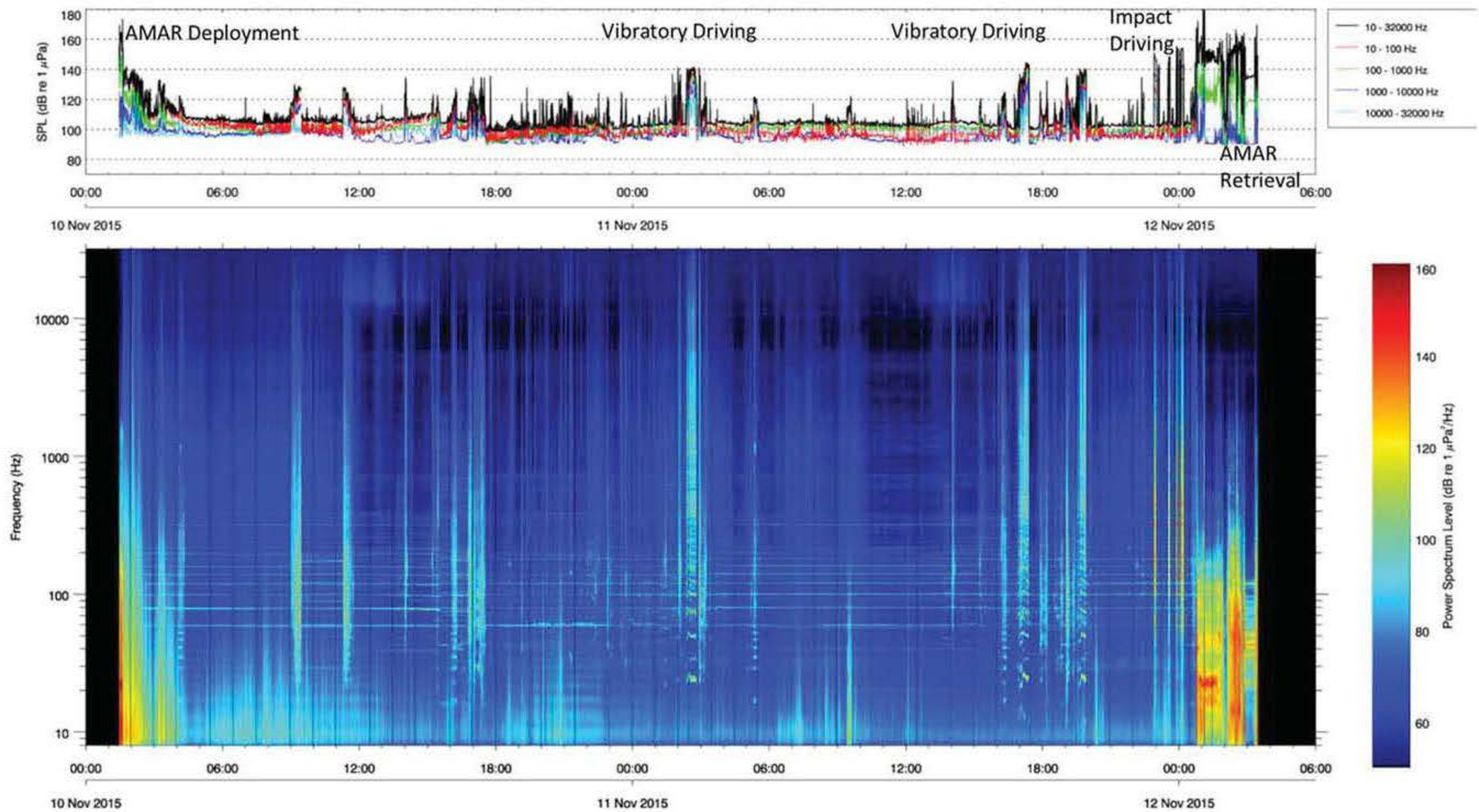

Figure B-4. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at 1 km from terminal.

B.4. Pile Driving Noise Levels

B.4.1. Impact Pile Driving Time Histories

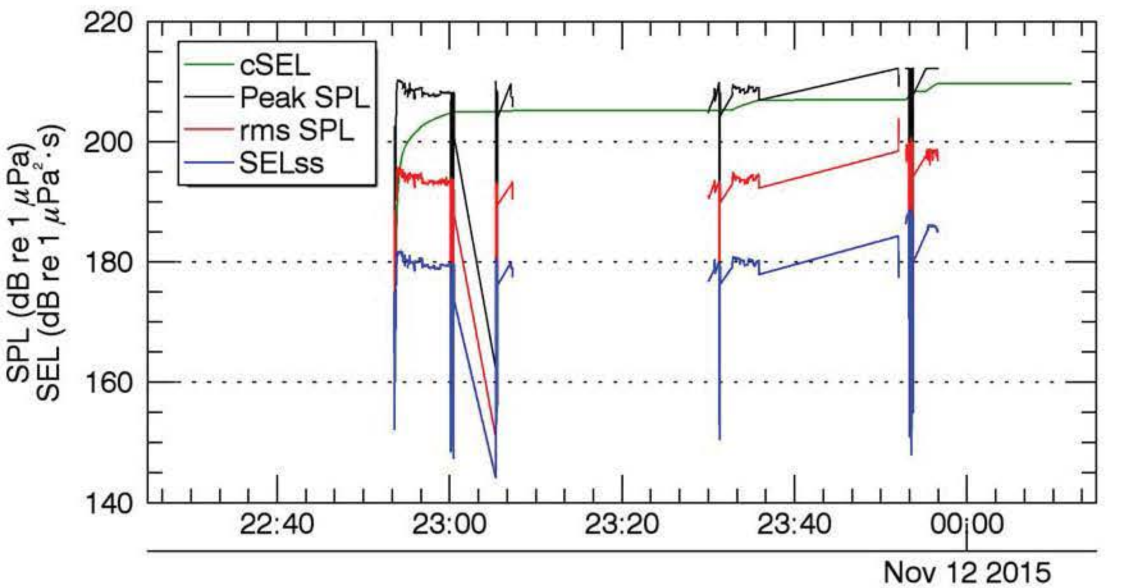

Figure B-5. Peak level, SPL and single-strike SEL vs time (UTC) for impact driving of Pile 3. AMAR 1 data recorded at 6.8±1 m range.

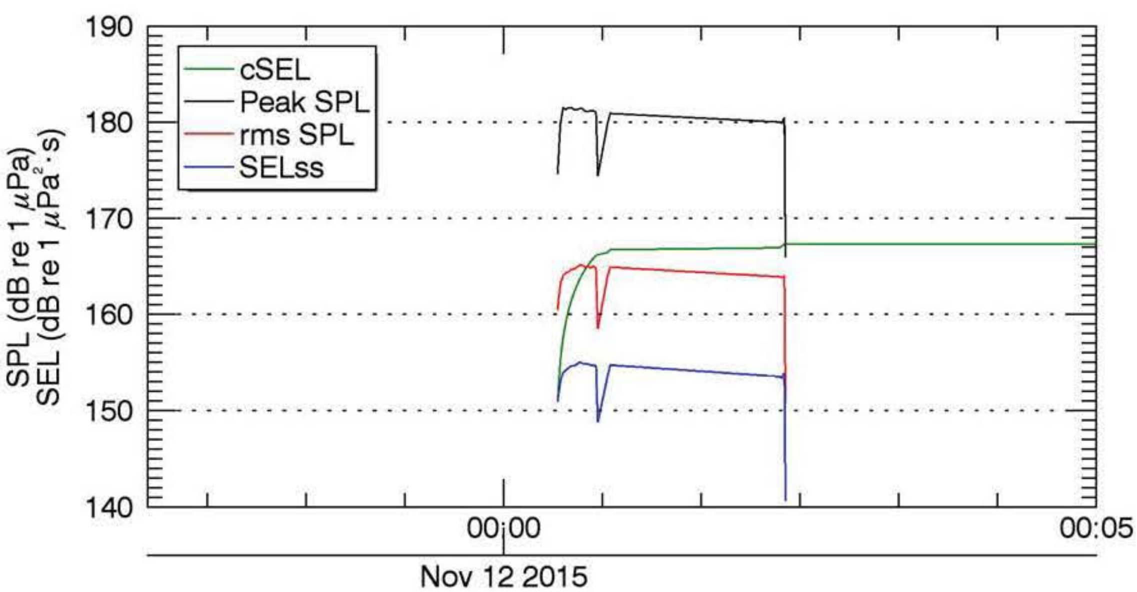

Figure B-6. Peak level, SPL and single-strike SEL vs time (UTC) for impact driving of Pile 1. AMAR 2 data recorded at 1188 m range.

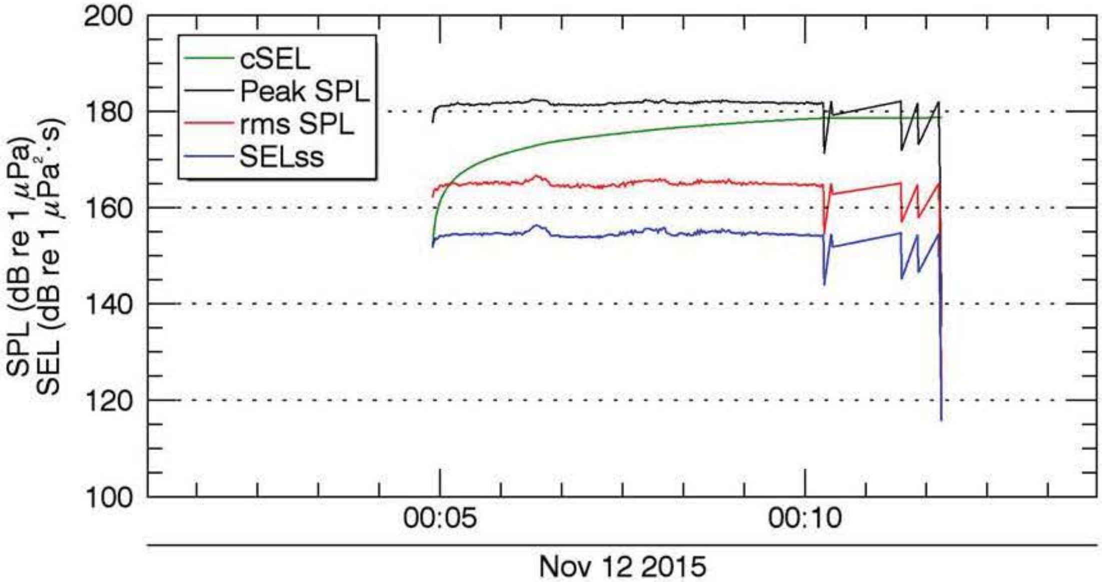

Figure B-7. Peak level, SPL and single-strike SEL versus time (UTC) for impact driving of Pile 2. AMAR 2 data recorded at 1187 m range.

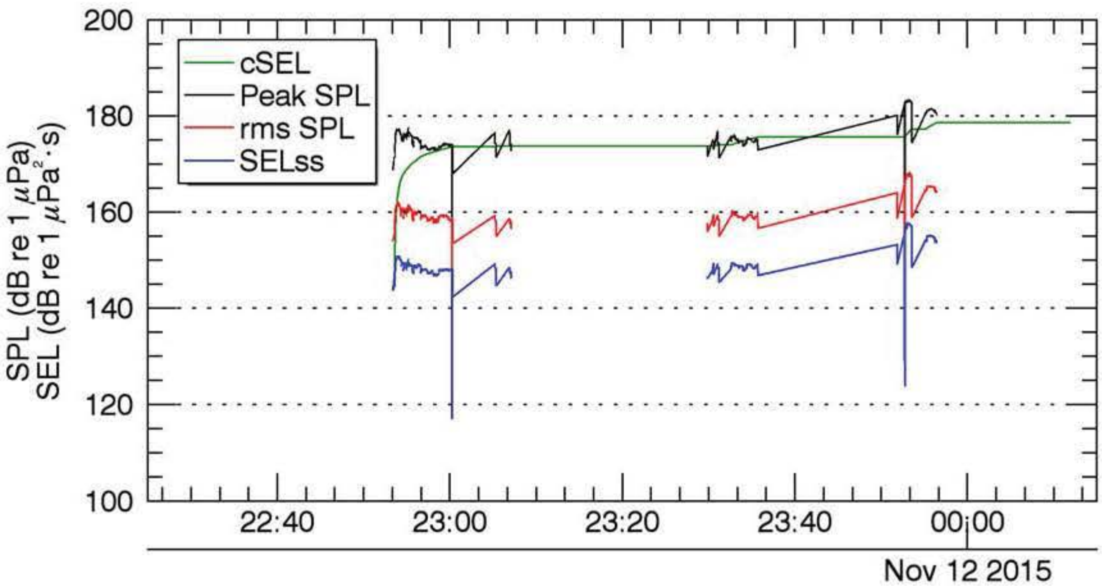

Figure B-8. Peak level, SPL and single-strike SEL versus time (UTC) for impact driving of Pile 3. AMAR 2 data recorded at 1184 m range.

B.4.2. Vibratory Driving Time Histories

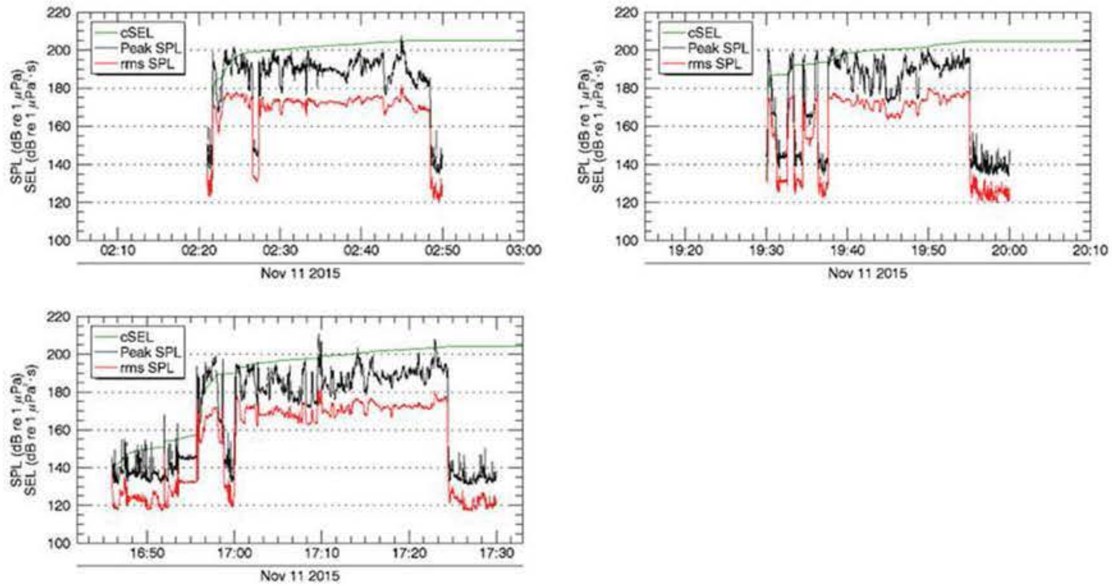

Figure B-9. Plot of SPL vs time (UTC) for vibratory driving (1 s average) measured on AMAR 1. Top left plot shows data from Pile 1 (5.3±1 m). Top right plot shows data from Pile 2 (4.0±1 m). Bottom left plot shows data from Pile 3 (6.8±1 m).

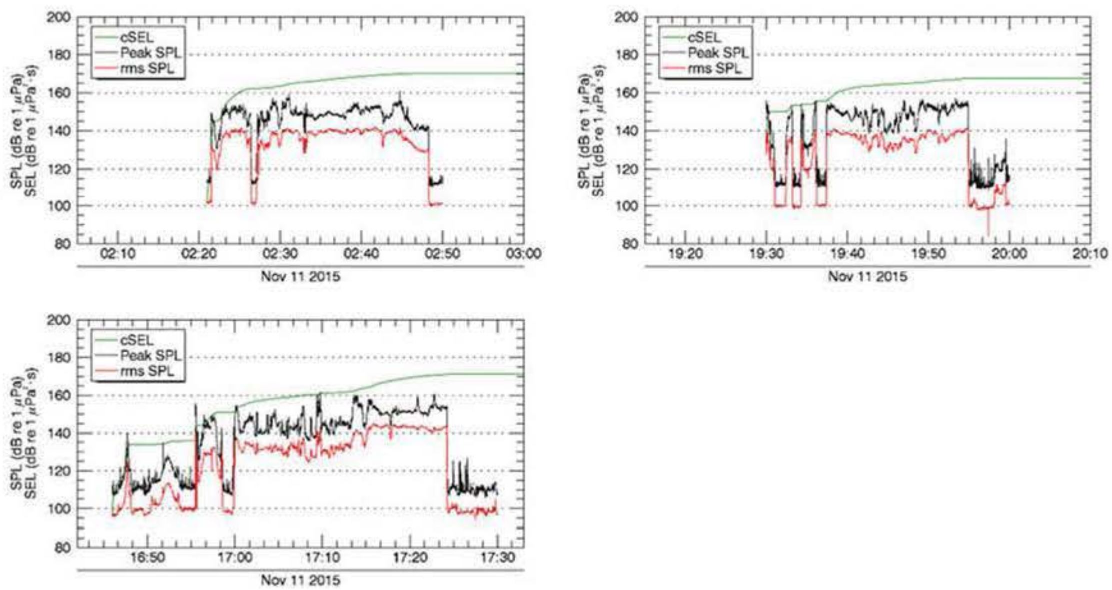

Figure B-10. Plot of SPL vs time (UTC) for vibratory driving (1 s average) measured on AMAR 2. Top left plot shows data from Pile 1 (1188 m). Top right plot shows data from Pile 2 (1187 m). Bottom left plot shows data from Pile 3 (1184 m).

B.5. 1/3-Octave Band Levels

One-third octave band spectra are provided in which beige bars indicate the first, second, and third quartiles (L_{25}, L_{50}, and L_{75}) in each 1/3-octave band. Upper error bars indicate the maximum levels (L_{max}). Lower error bars indicate the 95% exceedance percentiles (L_{95}). The maroon line indicates the arithmetic mean (L_{mean}).

B.5.1. Impact Hammering

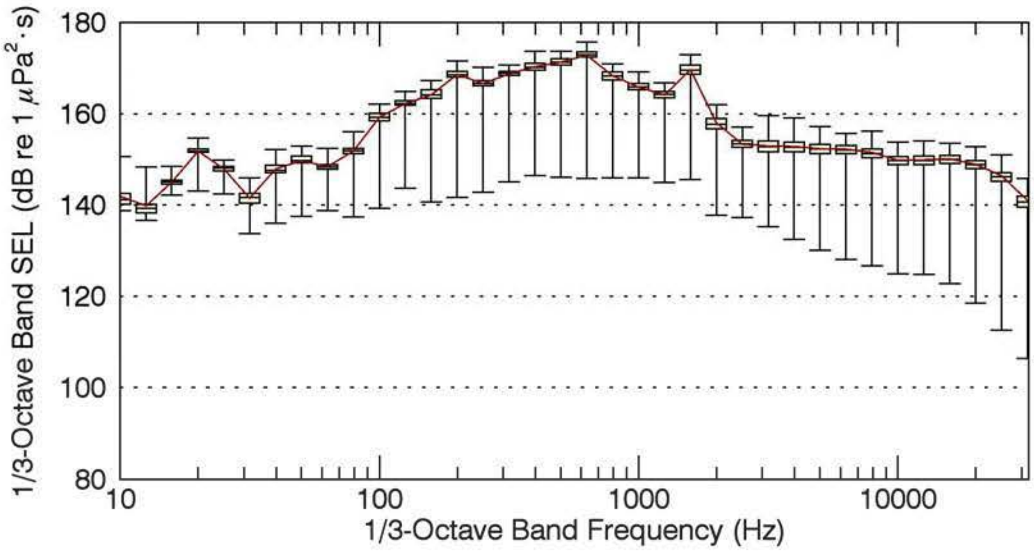

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Figure B-11. Plot of 1/3-octave band SEL statistics for impact driving of Pile 3, recorded at 6.8±1 m range.

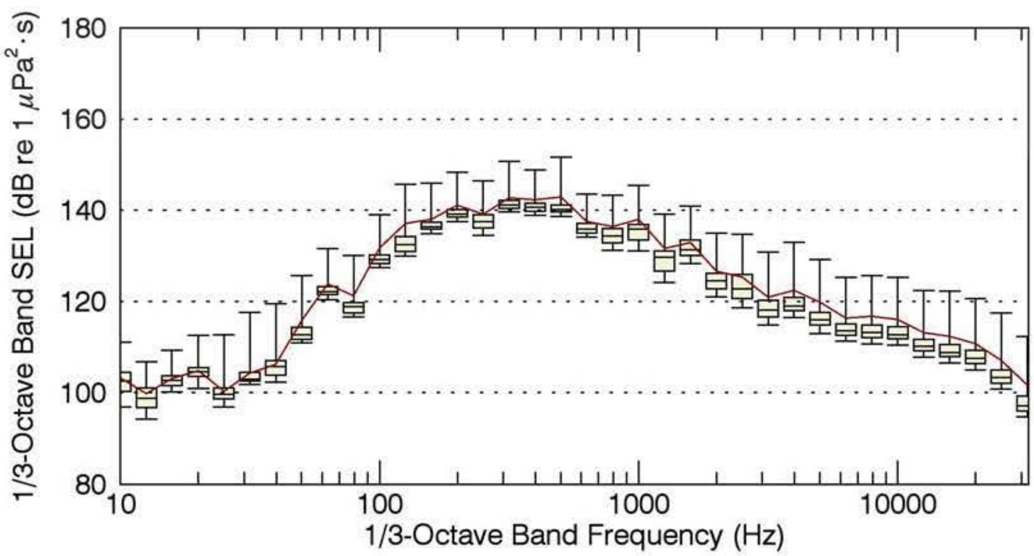


Figure B-12. Plot of 1/3-octave band SEL statistics for impact driving of Pile 3, recorded at 1184 m range.

B.5.2. Vibratory Driving

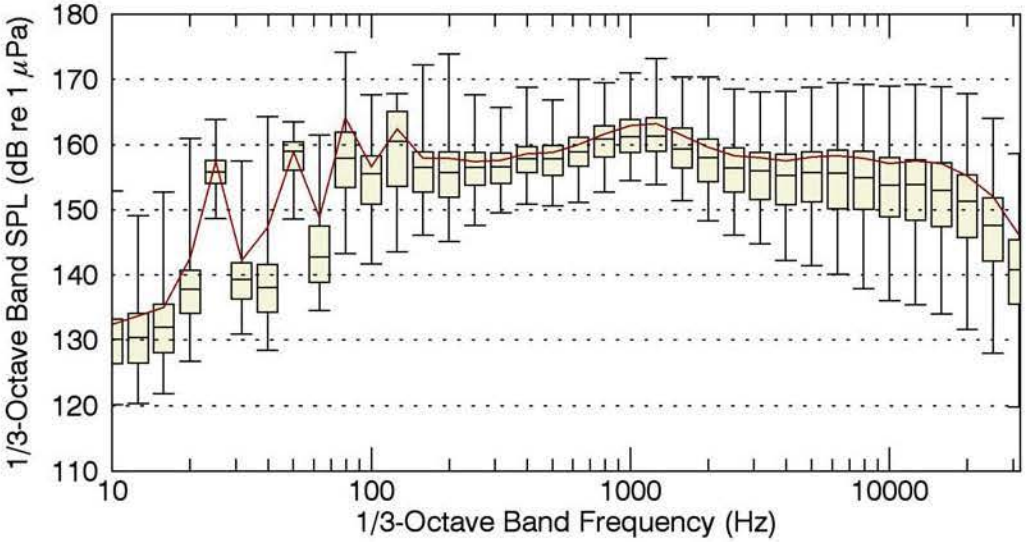


Figure B-13. Plot of 1/3-octave band SPL statistics for vibratory driving of the Pile 1, recorded at 5.3±1 m range.

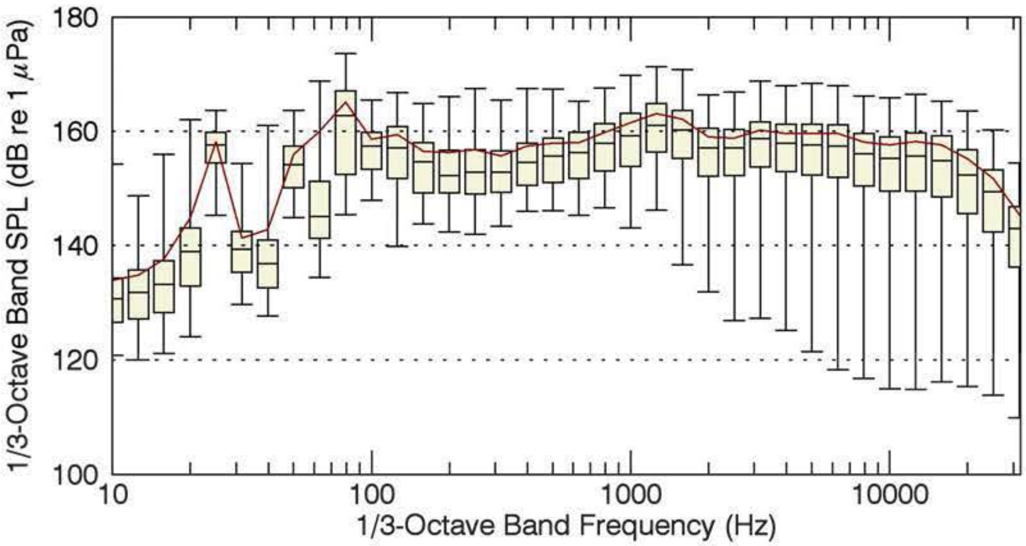


Figure B-14. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 2, recorded at 4.0±1m range.

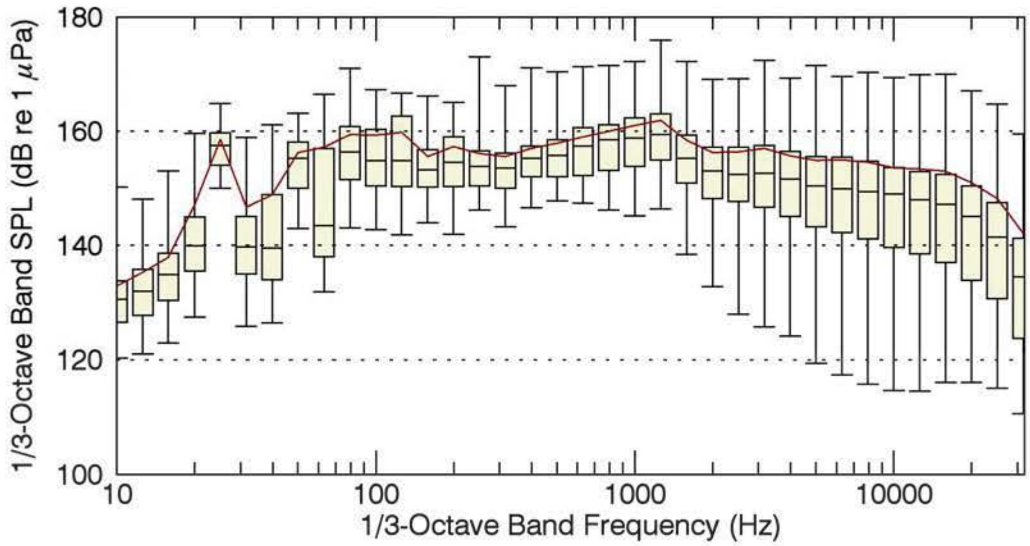


Figure B-15. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 3, recorded at 6.8±1 m range.

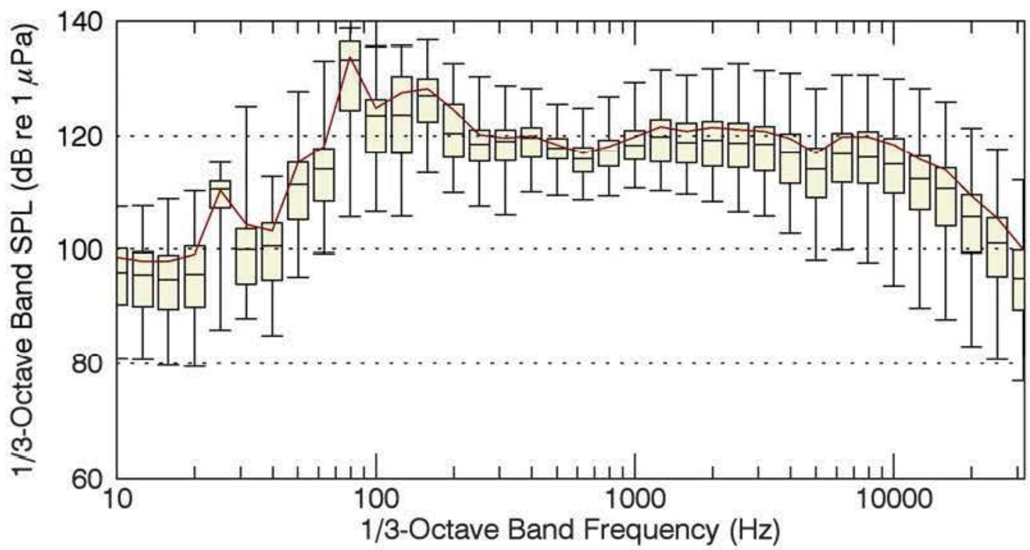


Figure B-16. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 1, recorded at 1188 m range.

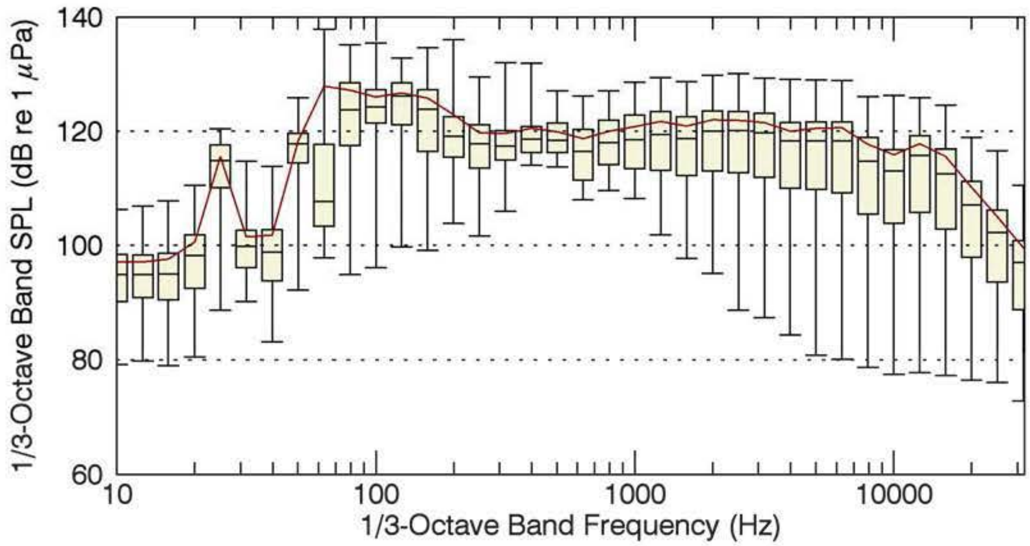


Figure B-17. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 2, recorded at 1187 m range.

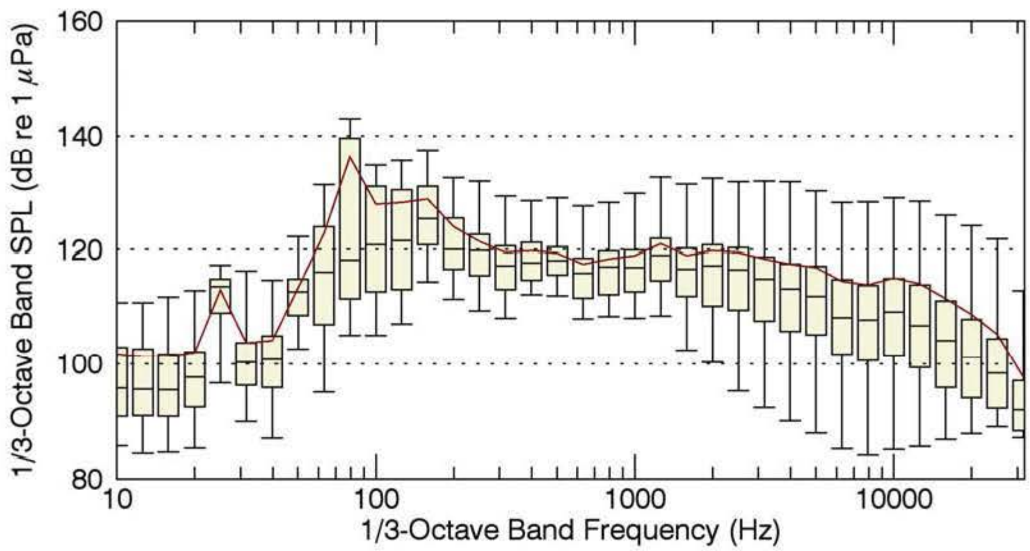


Figure B-18. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 3, recorded at 1184 m range.

B.6. Background Noise Levels

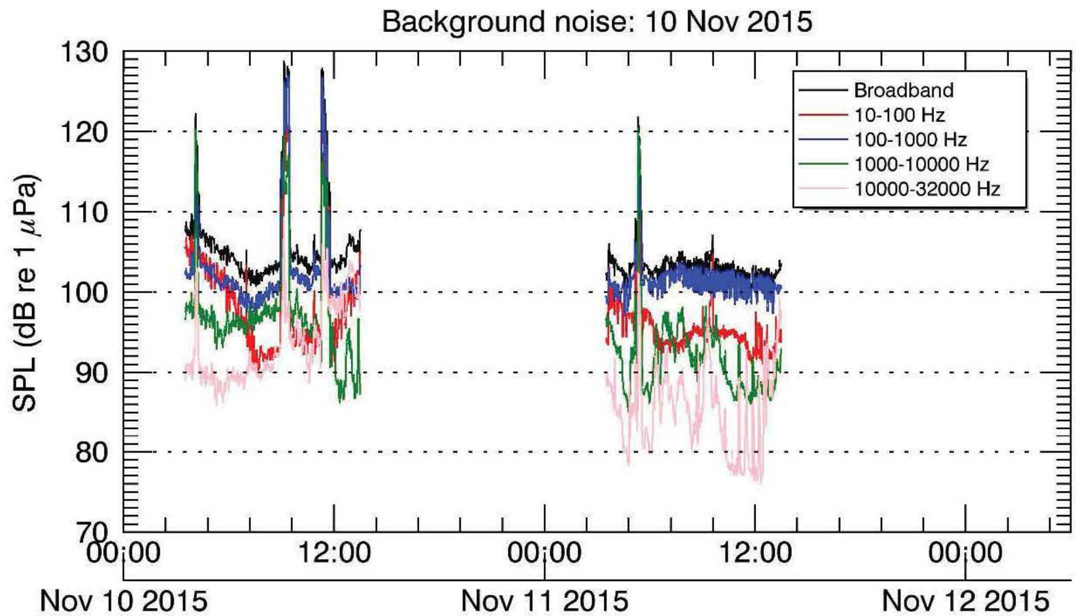


Figure B-19. Background SPL versus time (UTC) recorded on AMAR 2 (60 s average). Periods containing construction activity were removed.

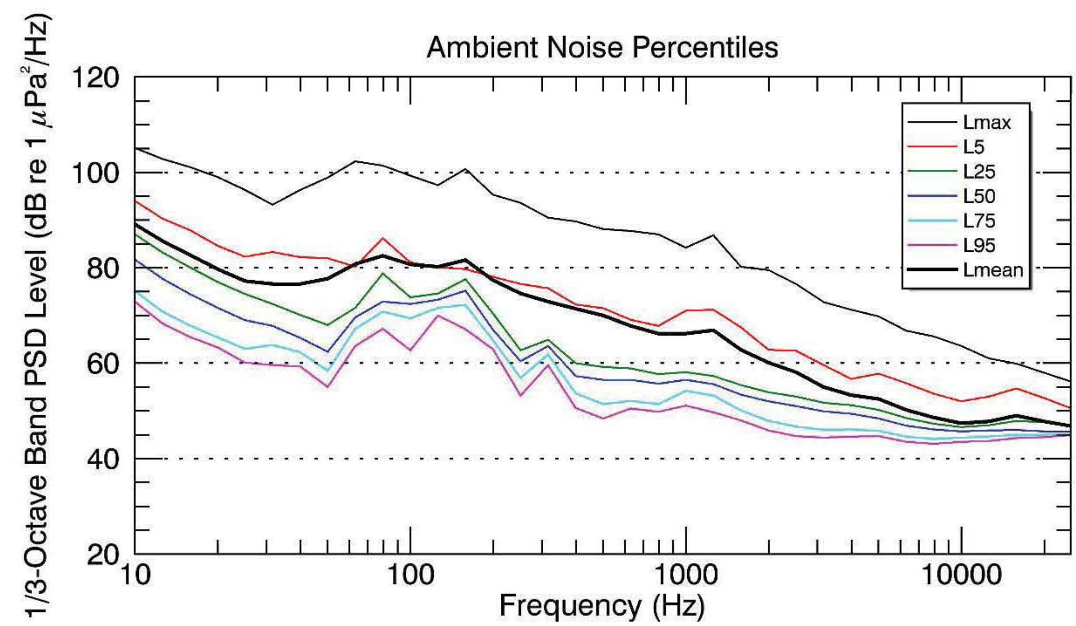


Figure B-20. Exceedance levels of 1/3-octave band background noise levels recorded on AMAR 2. The Ln value is the SPL exceeded by n% of the data. Periods containing construction activity have been removed.

Table B-2. Exceedance levels of background noise levels measured at Auke Bay, Alaska (60 s average). The Ln value is the SPL exceeded by n% of the data. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Exceedance level	SPL (dB re 1 µPa)					
	Unw	LFC	MFC	HFC	PPW	OPW
L_5	115.7	114.5	101.6	99.8	109.0	109.2
L_{25}	104.9	101.2	93.6	92.1	97.2	97.2
L_{50} (median)	103.5	100.0	90.5	88.5	95.6	95.5
L_{75}	102.5	98.8	86.4	84.5	91.7	91.5
L_{95}	101.0	97.1	78.8	77.3	87.0	86.6
L_{mean}	112.1	109.1	94.8	93.0	102.4	102.6

B.7. Broadband-discounted SEL and weighted SEL differences

The NMFS Optional User Spreadsheet provides Weighting Function Adjustments (WFA) for estimating weighted SEL from unweighted SEL. The broadband SEL corrected with the WFA and the functional hearing group weighted SELs were compared. NMFS suggests that estimates generated by using the spreadsheet will conservatively estimate injury zones; however, this was not always the case. The WFA discounted SELs for the HFC functional hearing group were often lower, and therefore less conservative, than the frequency weighted SELs. Additionally, comparing the two calculations across functional hearing groups, illustrated a range of differences that exceeded 10 dB.

Table B-3. Difference between mean broadband-discounted SEL and weighted SEL for impact piling.

Pile	Hearing Group	AMAR 1	AMAR 2
1	LFC	N/A*	1.5
	MFC	N/A	7.3
	HFC	N/A	3.2
	PPW	N/A	9.3
	OPW	N/A	10.6
2	LFC	N/A	1.2
	MFC	N/A	8.8
	HFC	N/A	5.2
	PPW	N/A	8.7
	OPW	N/A	9.9
3	LFC	0.9	1.3
	MFC	2.6	8.5
	HFC	-2	5
	PPW	6.3	8.8
	OPW	6.9	10

* N/A represents data excluded from analyses.

Table B-4. Difference between mean broadband-discounted SEL and weighted SEL for vibratory piling.

Pile	Hearing group	AMAR 1	AMAR 2
1	LFC	1.7	3.9
	MFC	-6.2	-1.4
	HFC	-10.8	-5.2
	PPW	3.5	6.9
	OPW	3.9	7.4
2	LFC	2	2.8
	MFC	-6.7	-3.1
	HFC	-11.1	-6.9
	PPW	3	5.1
	OPW	3.5	5.5

Pile	Hearing group	AMAR 1	AMAR 2
3	LFC	1.9	4.9
	MFC	-4.4	2.6
	HFC	-8.8	-1.1
	PPW	4.3	10
	OPW	4.6	10.5

Appendix C. Supporting Data for Kodiak

C.1. Monitoring Activities

The activities of the JASCO field monitoring team during the Kodiak installation is provided in Table C-1.

Table C-1. Log of hydroacoustic monitoring of pile driving at Kodiak, Alaska.

Date (UTC)	Time (UTC)	Activity
2016-03-01	19:08	AMAR 1: Calibrated
2016-03-01	19:16	AMAR 2: Calibrated
2016-03-02	01:44	AMAR 1: Deployed
2016-03-02	02:34	AMAR 2: Deployed
2016-03-04	21:13	Dipping hydrophone: Calibrated
2016-03-04	22:12	Pile D16: Dipping hydrophone recorded drilling
2016-03-04	22:45	CTD cast 130 m from terminal
2016-03-04	22:52	CTD cast 1 km from terminal
2016-03-04	23:51	Pile D16: Dipping hydrophone recorded drilling (oscillation)
2016-03-05	00:05	Piles D22, D20, D18: Dipping hydrophone recorded impact pile driving
2016-03-05	01:54	Dipping hydrophone: Calibrated
2016-03-06	02:25	AMAR 1: Retrieved
2016-03-06	02:38	AMAR 2: Retrieved
2016-03-06	03:01	AMAR 2: Calibrated
2016-03-06	03:06	AMAR 1: Calibrated

C.2. Weather Data

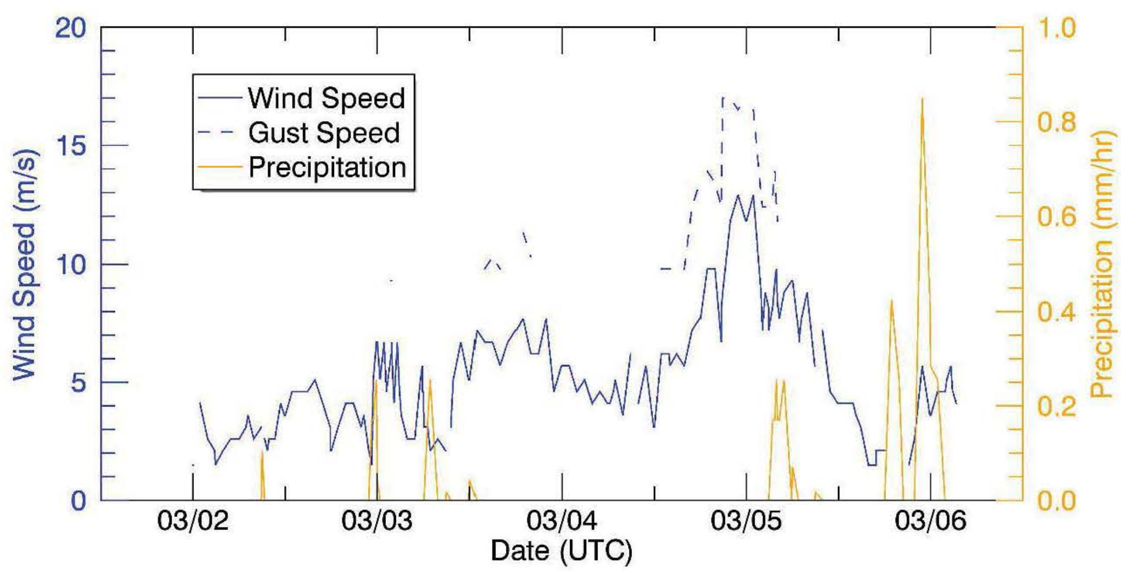


Figure C-1. Wind speed (blue) and precipitation (yellow) recorded at Kodiak Airport approximately 6 km from the Kodiak ferry terminal, over the study period.

Near the Kodiak ferry terminal, the sound speed profiles measured between the AMARs and near AMAR 2 were consistent (Figure C-2). The sound speed measured between the two AMARs 130 m from AMAR 1 and at AMAR 2 (approximately 1 km from AMAR 1) varied by less than 1 m/s over the 12–14 m of water. The shallow water contributed to this consistency and is also suggestive of a well-mixed environment.

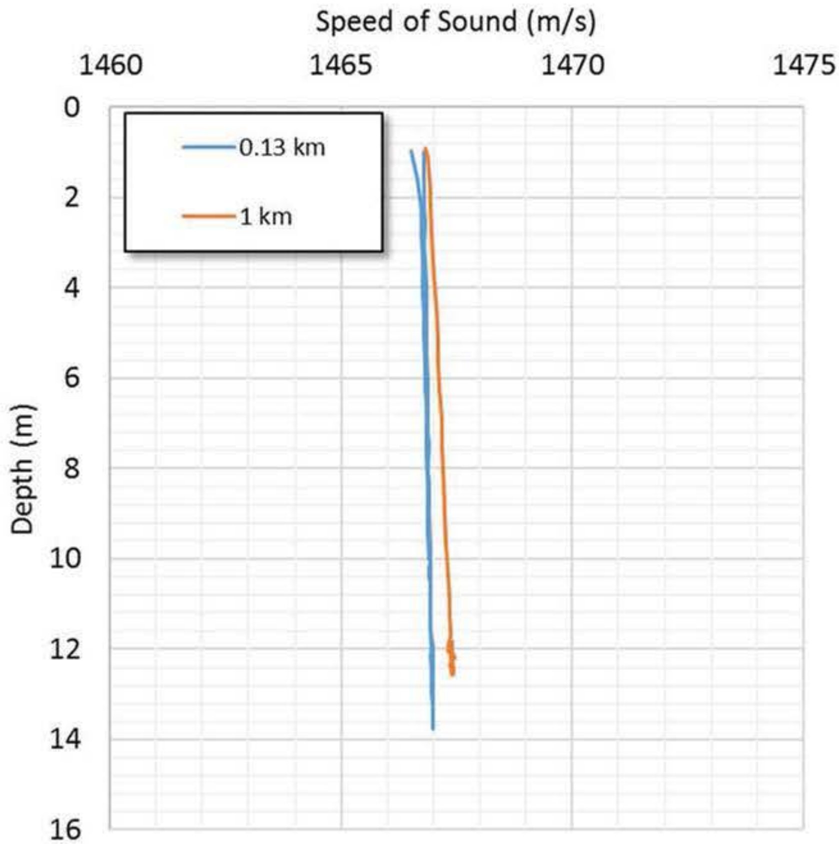


Figure C-2. Profiles of sound speed versus depth calculated from temperature and salinity data collected in Kodiak on 2016-Mar-04. Profiles were sampled near between the AMARs (0.13 km), and near AMAR 2 (1 km).

C.3. Spectrograms

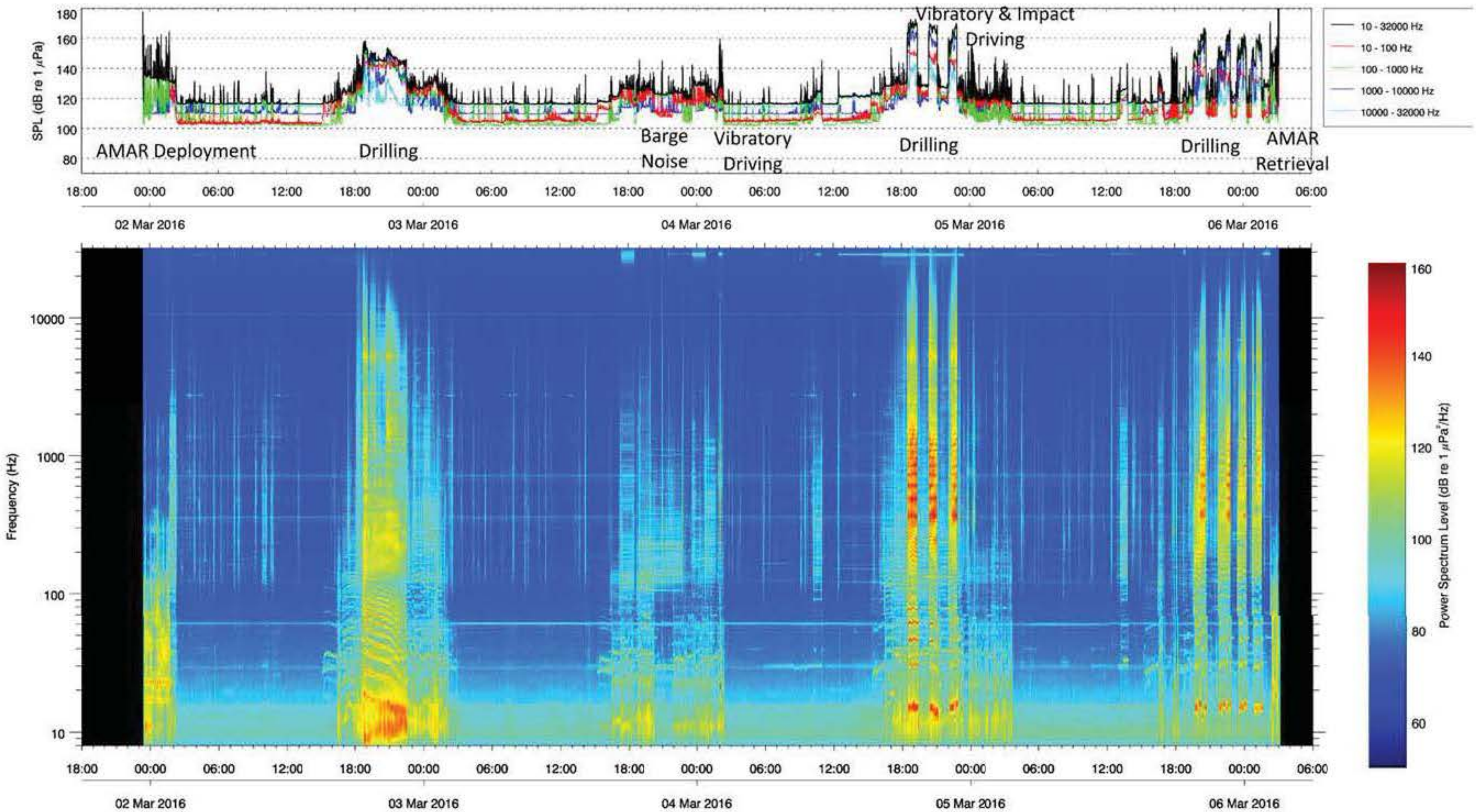


Figure C-3. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at Kodiak ferry terminal.

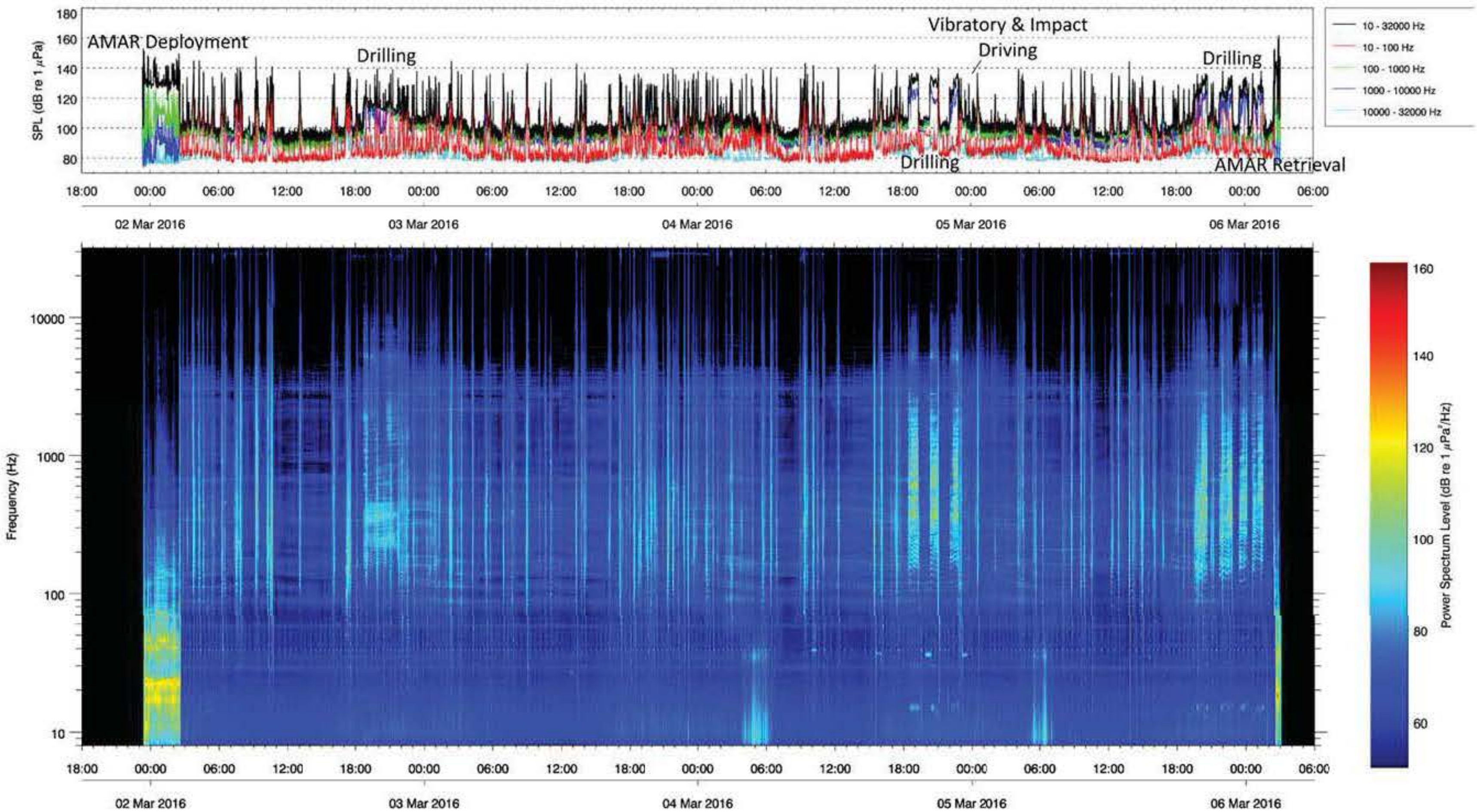


Figure C-4. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at 1 km from Kodiak ferry terminal.

C.4. Pile Driving Noise Levels

C.4.1. Impact Pile Driving Time Histories

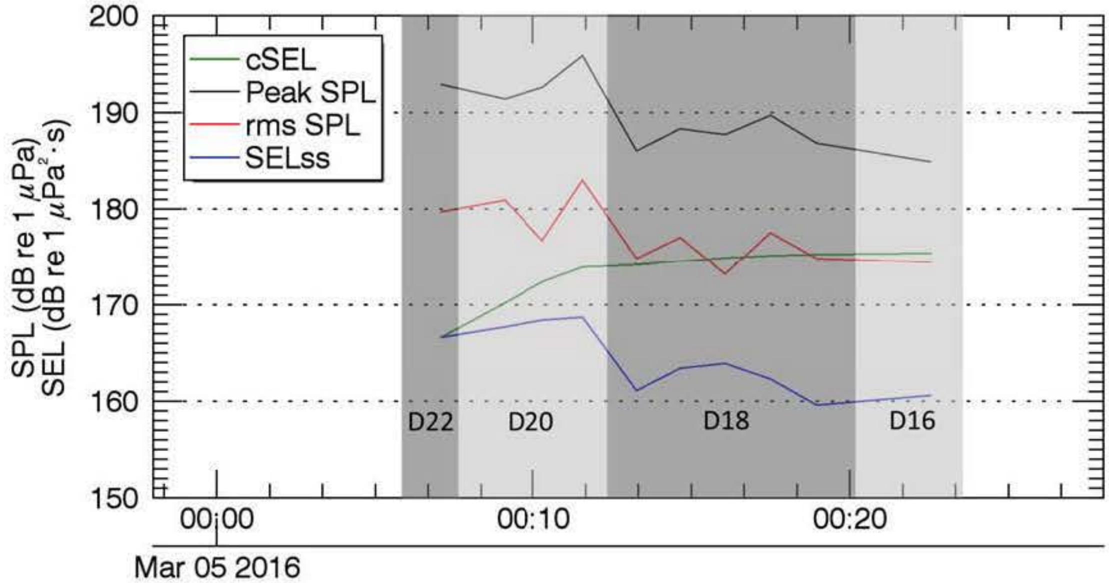


Figure C-5. Peak level, SPL and single-strike SEL vs time (UTC) for impact driving of four 24" piles from AMAR 1 data. Piles D22, D20, D18, and D16 were struck 1, 3, 5, and 1 times, respectively and were at ranges of 9.9, 12.9, 16.0, and 19.0 m from the AMAR, respectively. Shaded time windows and annotations denote data associated with each pile.

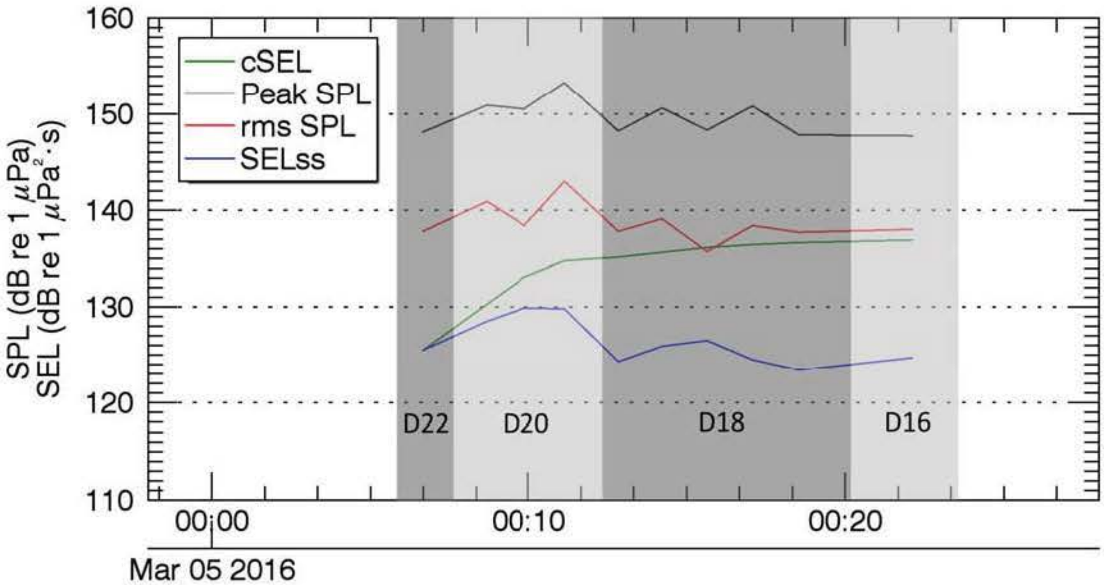


Figure C-6. Peak level, SPL and single-strike SEL vs time (UTC) for impact driving of four 24" piles from AMAR 2 data. Piles D22, D20, D18, and D16 were struck 1, 3, 5, and 1 times, respectively and were at ranges of 1117, 1119, 1122, and 1125 m from the AMAR, respectively. Shaded time windows and annotations denote data associated with each pile.

C.4.2. Vibratory Setting Driving Time Histories

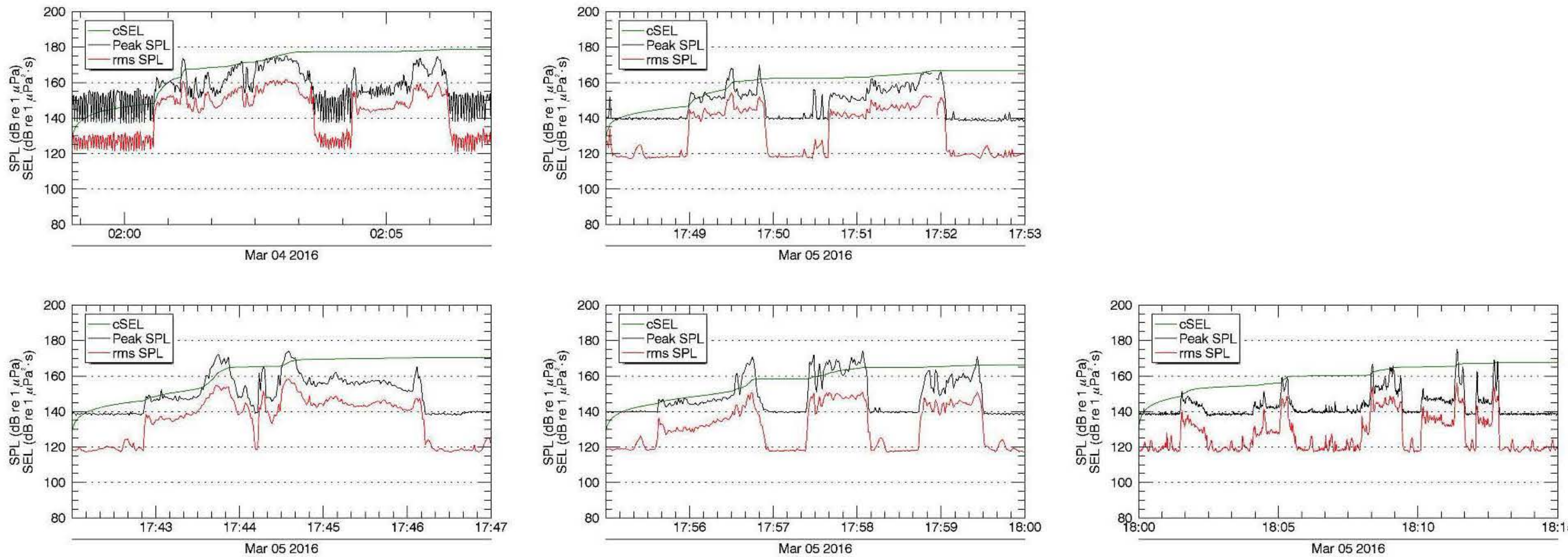


Figure C-7. Plot of SPL vs time (UTC) for setting piles into the sediment using the vibratory driver (1 s average) measured on AMAR 1. Plots show measurements of Piles D20, D15, D14, D13, and D12 at distances of 12.9, 22.0, 25.1, 28.1, and 31.1 m, respectively.

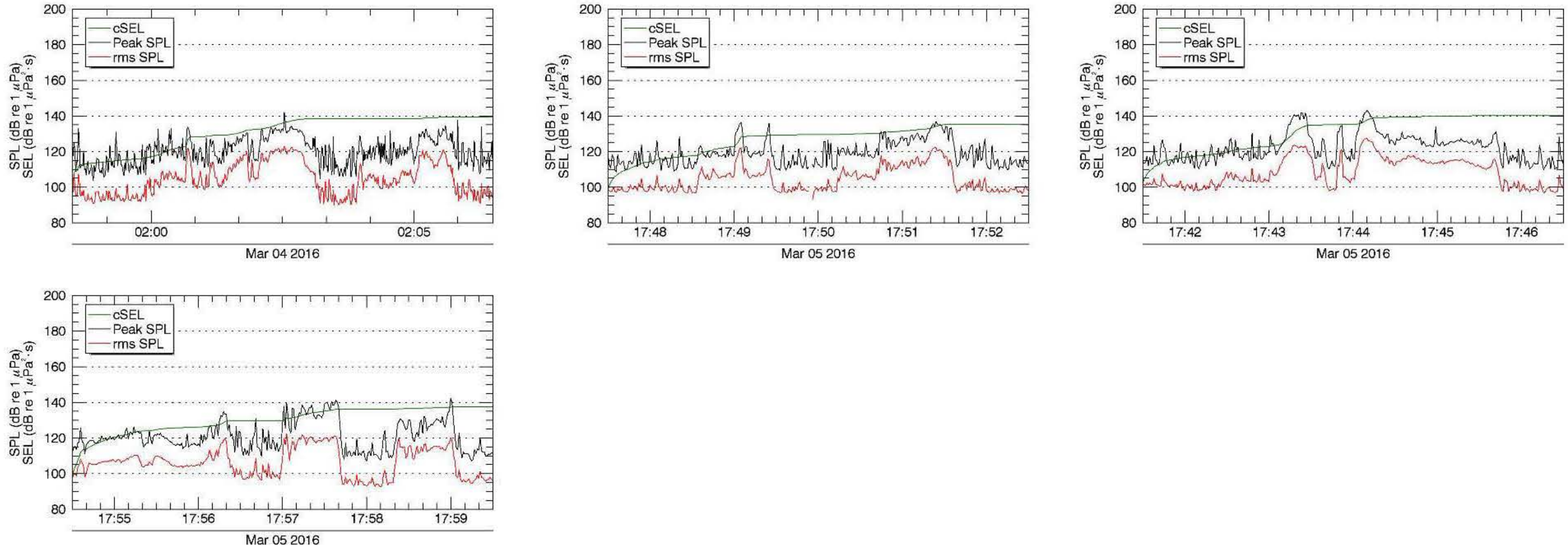


Figure C-8. Plot of SPL vs time (UTC) for setting piles into the sediment using the vibratory driver (1 s average) measured on AMAR 2. Plots show measurements of Piles D20, D15, D14, and D13 at distances of 1119, 1127, 1130, and 1133 m, respectively. Sound levels for Pile D12 recorded on AMAR 2 are not shown because noise from numerous nearby vessels contaminated vibratory driving measurements.

C.4.3. Vibratory Oscillation Driving Time Histories

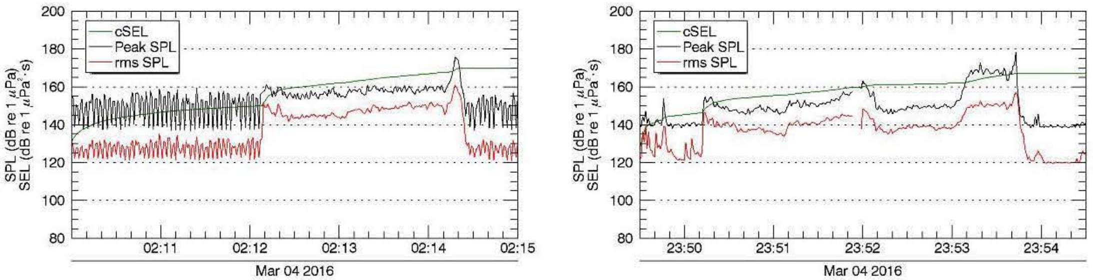


Figure C-9. Plot of SPL vs time (UTC) for oscillating piles into their sockets with the vibratory driver (1 s average) measured on AMAR 1. Left plot shows data from Pile D22 (9.9 m). Right plot shows data from Pile D16 (19.0 m).

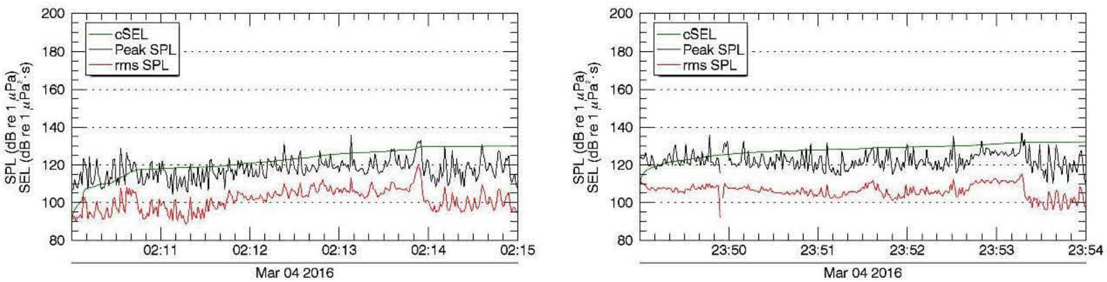


Figure C-10. Plot of SPL vs time (UTC) for oscillating piles into their sockets with the vibratory driver (1 s average) measured on AMAR 2. Left plot shows data from Pile D22 (1117 m). Right plot shows data from Pile D16 (1125 m).

C.4.4. Drilling Time Histories

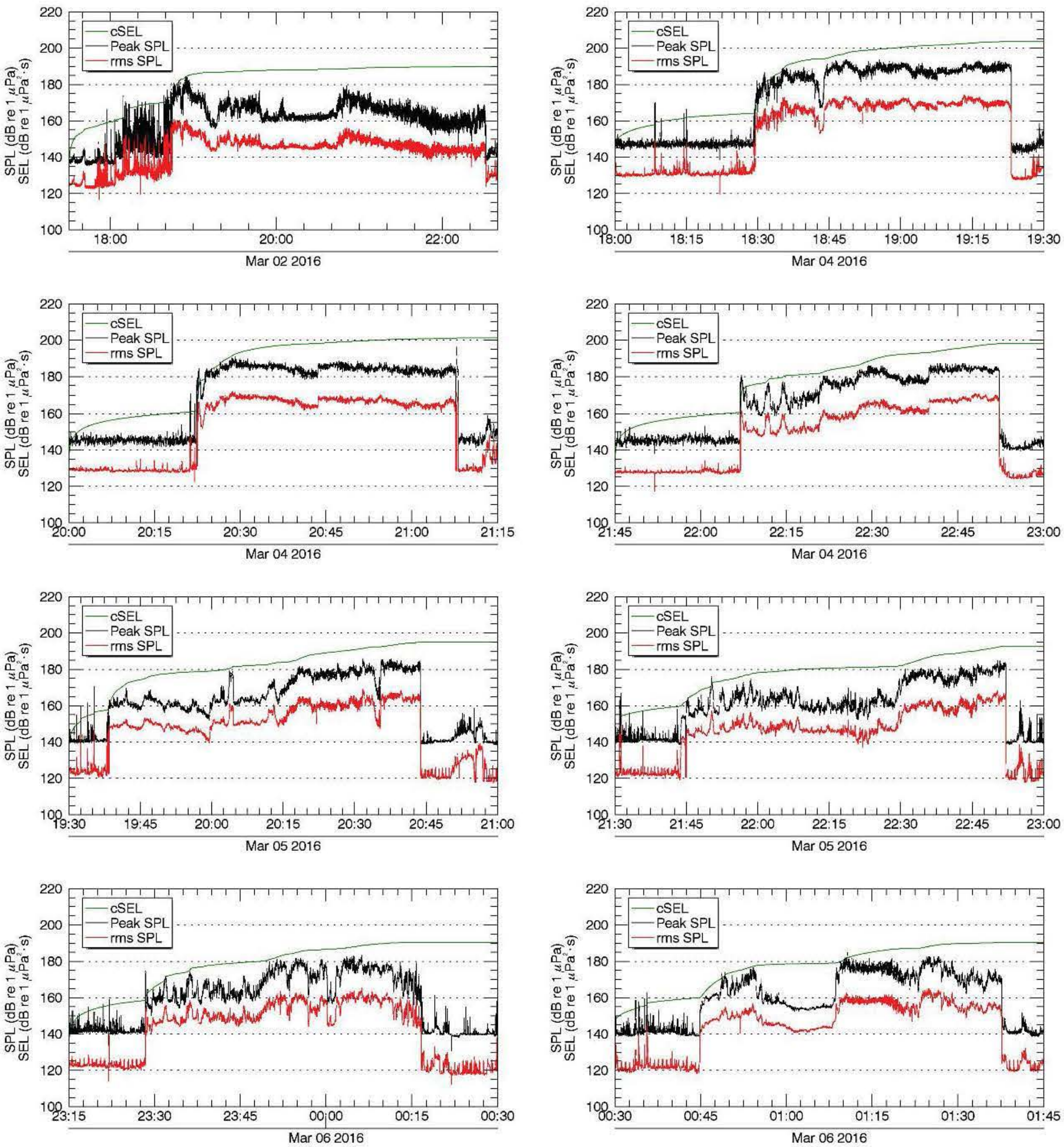


Figure C-11. Plot of SPL vs time (UTC) for drilling (1 s average) measured on AMAR 1. Plots show measurements of Piles D22, D20, D18, D16, D15, D14, D13, and D12 at distances of 9.9, 12.9, 16.0, 19.0, 22.0, 25.1, 28.1, and 31.1 m, respectively

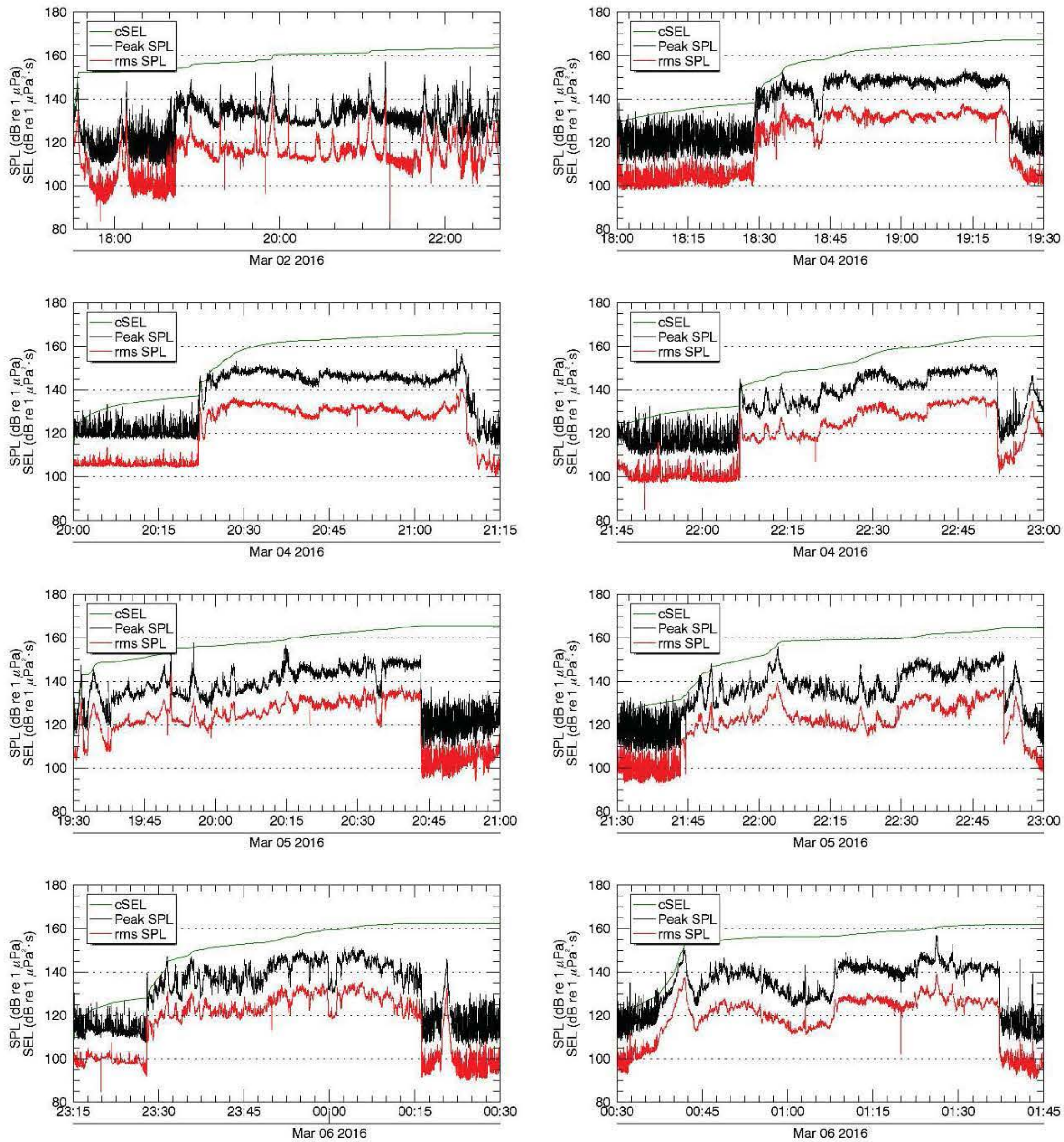


Figure C-12. Plot of SPL vs time (UTC) for drilling (1 s average) measured on AMAR 2. Plots show measurements of Piles D22, D20, D18, D16, D15, D14, D13, and D12 at distances of 1117, 1119, 1122, 1125, 1127, 1130, 1133, and 1136 m, respectively.

C.5. 1/3-Octave Band Levels

One-third octave band spectra are provided in which beige bars indicate the first, second, and third quartiles (L_{25}, L_{50}, and L_{75}) in each 1/3-octave band. Upper error bars indicate the maximum levels (L_{max}). Lower error bars indicate the 95% exceedance percentiles (L_{95}). The maroon line indicates the arithmetic mean (L_{mean}).

C.5.1. Impact Hammering

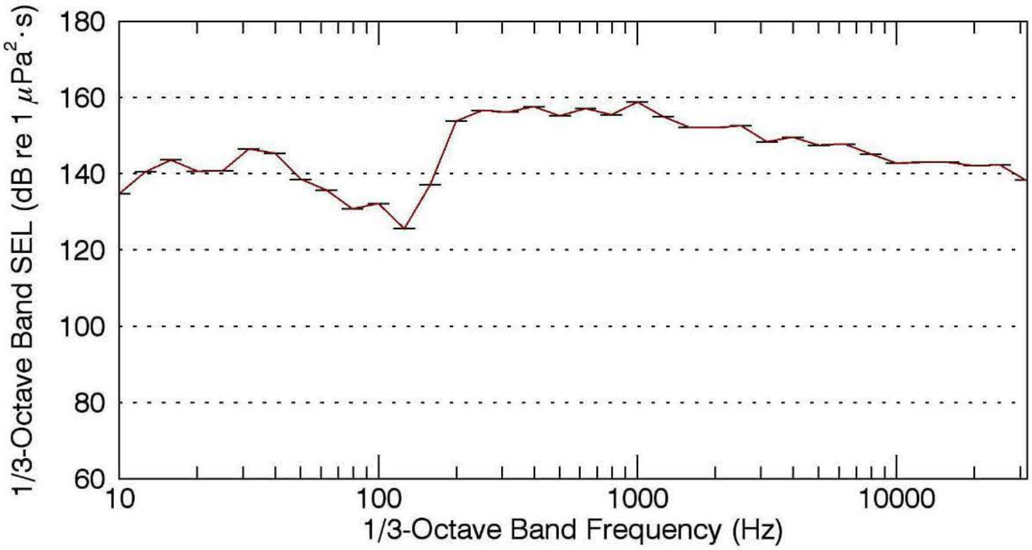


Figure C-13. Plot of 1/3-octave band SEL statistics for impact driving of Pile D22, recorded at 9.9 m range at Kodiak ferry terminal. Number of strikes: 1.

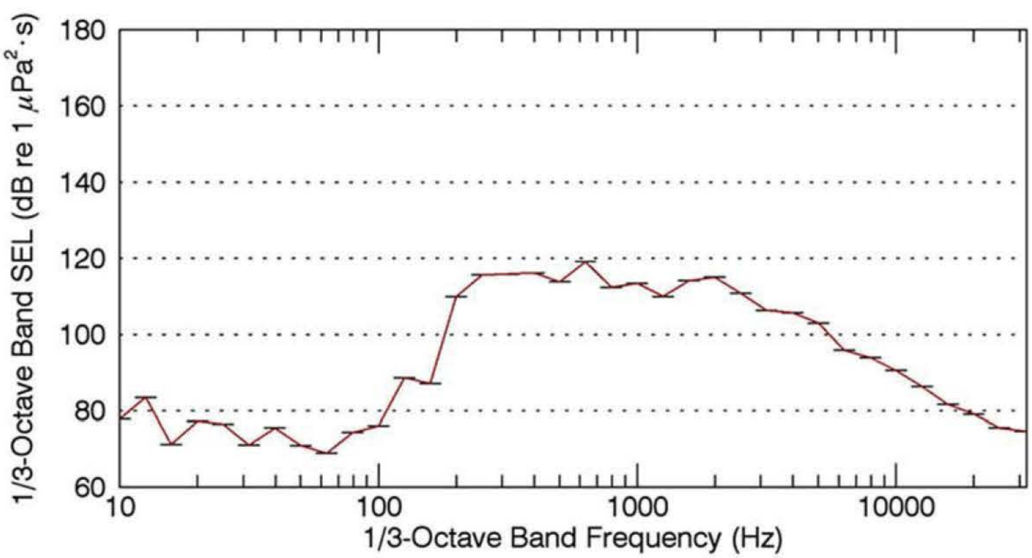


Figure C-14. Plot of 1/3-octave band SEL statistics for impact driving of Pile D22, recorded at 1117 m range at Kodiak ferry terminal. Number of strikes: 1.

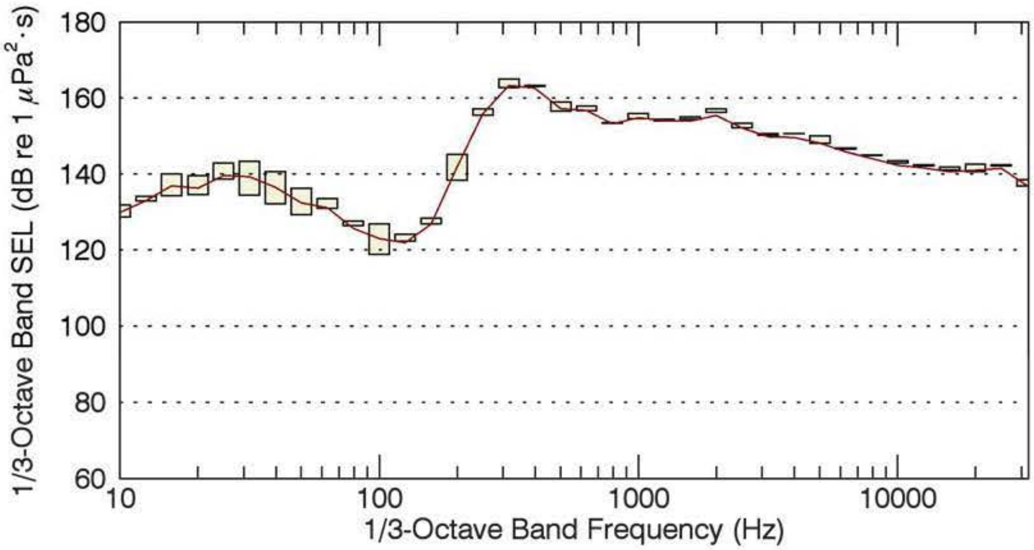


Figure C-15. Plot of 1/3-octave band SEL statistics for impact driving of Pile D20, recorded at 12.9 m range at Kodiak ferry terminal. Number of strikes: 3.

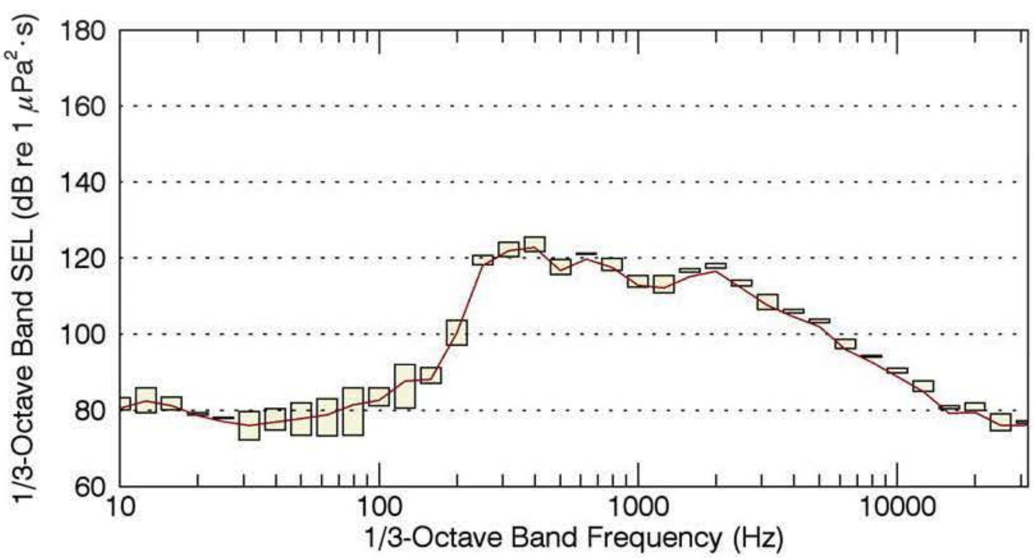


Figure C-16. Plot of 1/3-octave band SEL statistics for impact driving of Pile D20, recorded at 1119 m range at Kodiak ferry terminal. Number of strikes: 3.

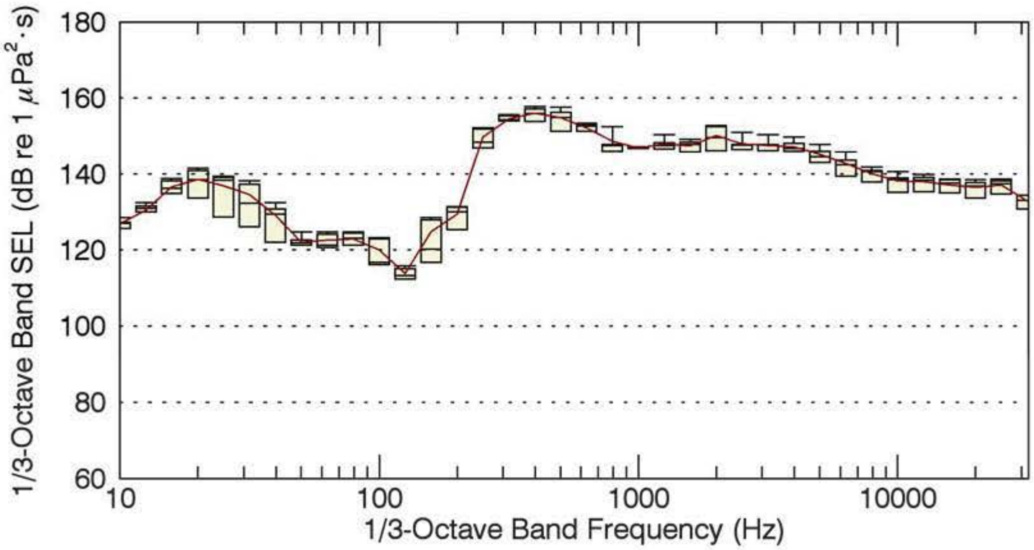


Figure C-17. Plot of 1/3-octave band SEL statistics for impact driving of Pile D18, recorded at 16.0 m range at Kodiak ferry terminal. Number of strikes: 5.

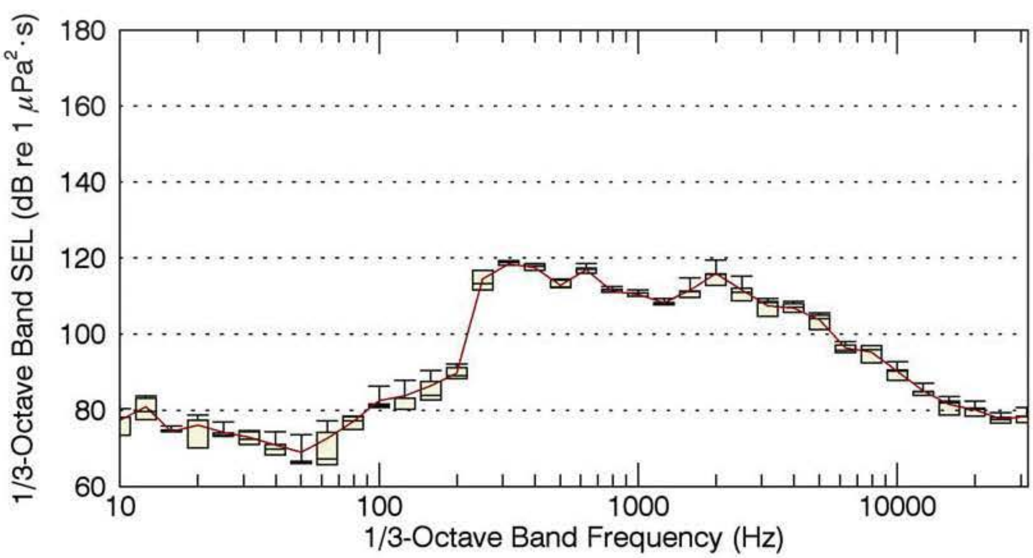


Figure C-18. Plot of 1/3-octave band SEL statistics for impact driving of Pile D18, recorded at 1122 m range at Kodiak ferry terminal. Number of strikes: 5.

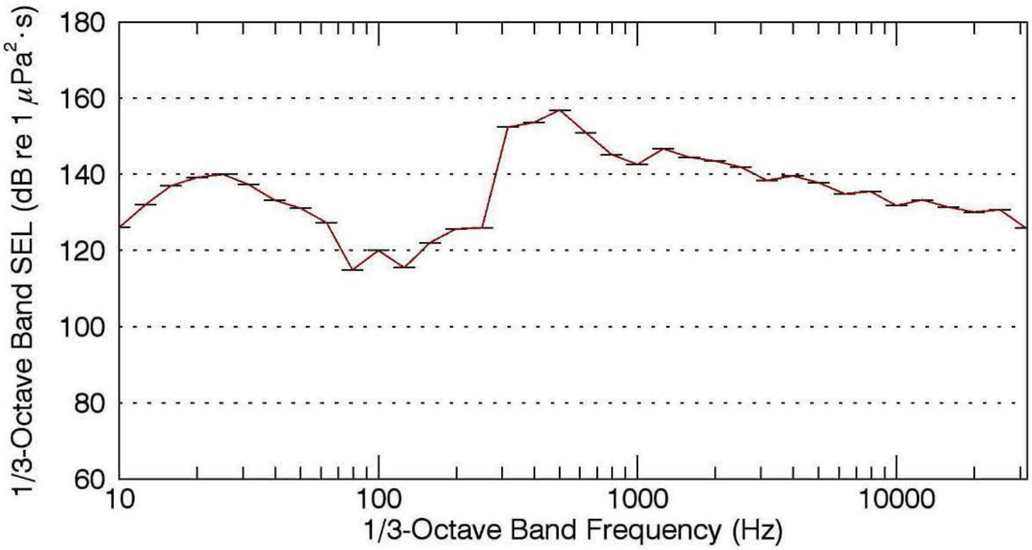


Figure C-19. Plot of 1/3-octave band SEL statistics for impact driving of Pile D16, recorded at 19.0 m range at Kodiak ferry terminal. Number of strikes: 1.

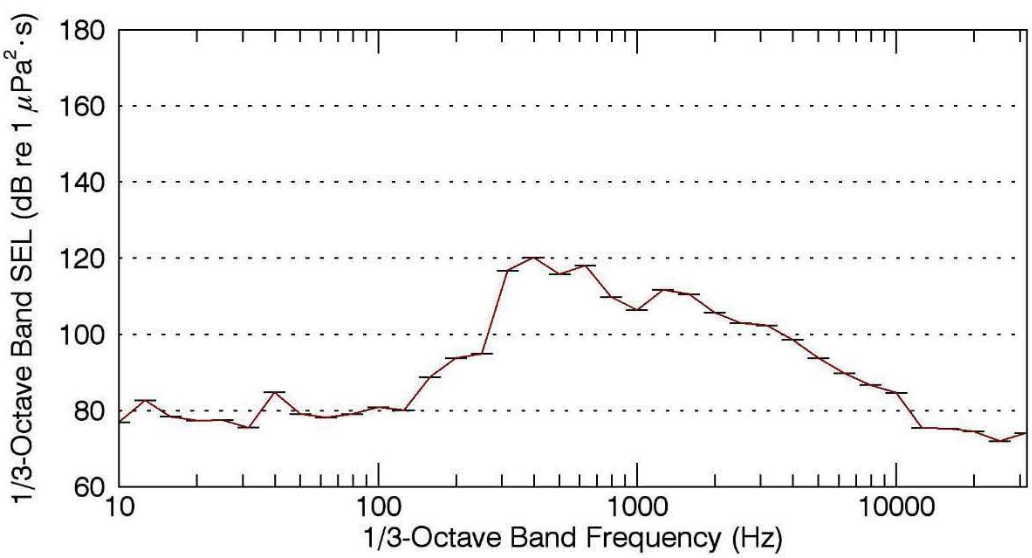


Figure C-20. Plot of 1/3-octave band SEL statistics for impact driving of Pile D16, recorded at 1125 m range at Kodiak ferry terminal. Number of strikes: 1.

C.5.2. Vibratory Driving — Setting

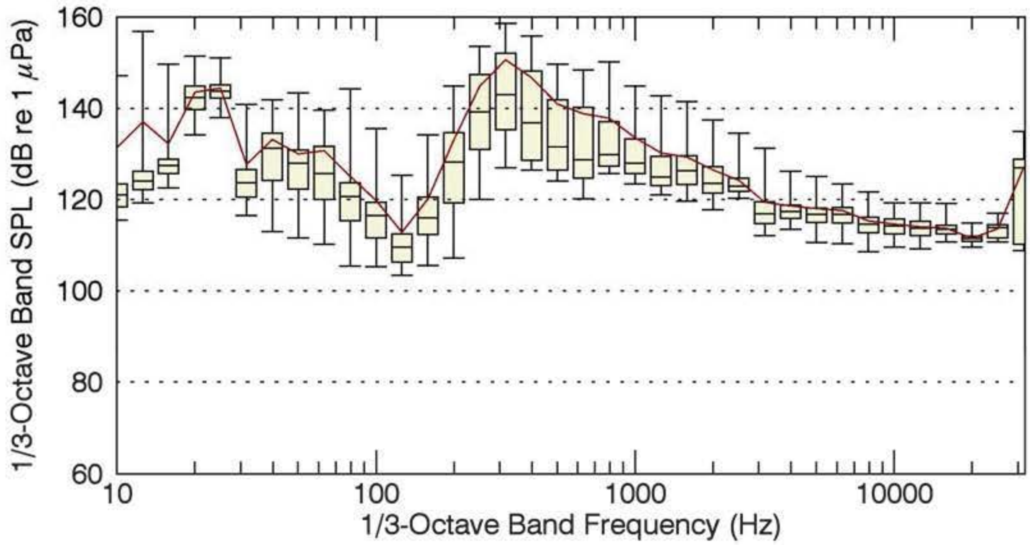


Figure C-21. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D20, recorded at 12.9 m range at Kodiak ferry terminal.

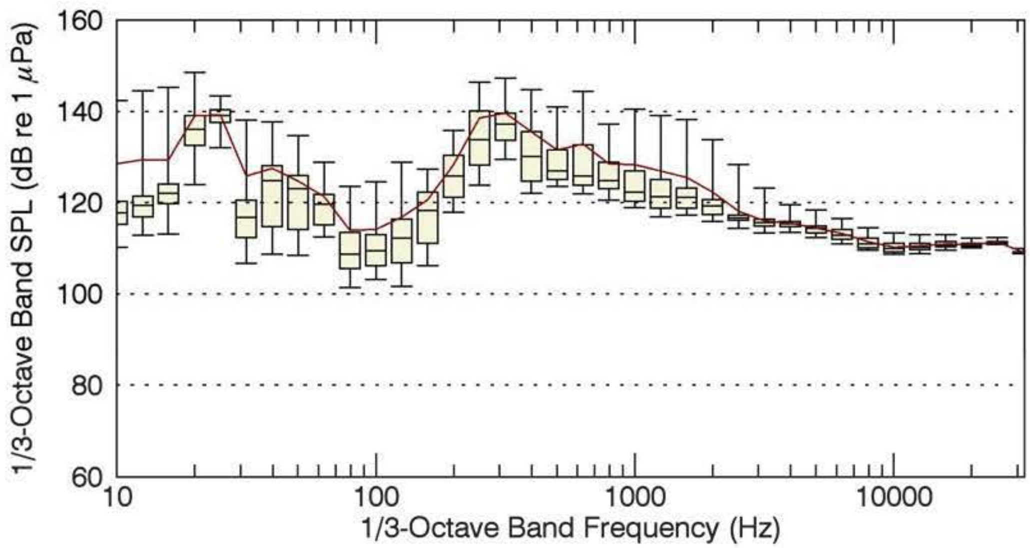


Figure C-22. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D15, recorded at 22.0 m range at Kodiak ferry terminal.

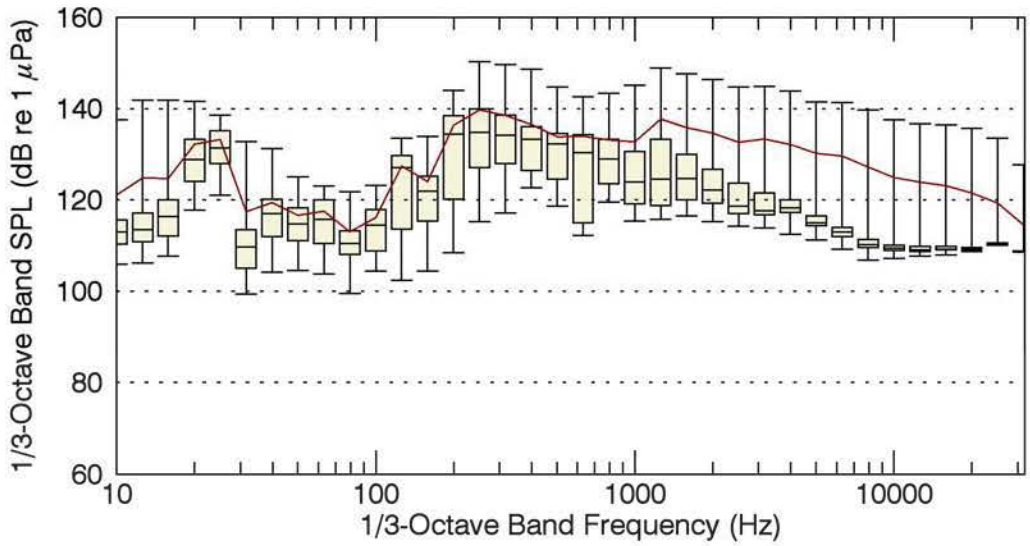


Figure C-23. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D14, recorded at 25.1 m range at Kodiak ferry terminal.

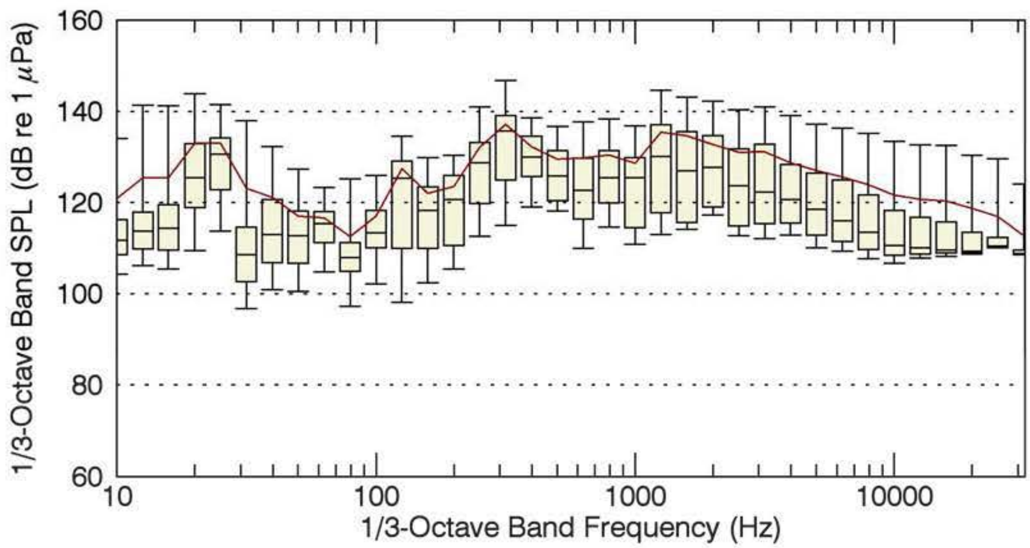


Figure C-24. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D13, recorded at 28.1 m range at Kodiak ferry terminal.

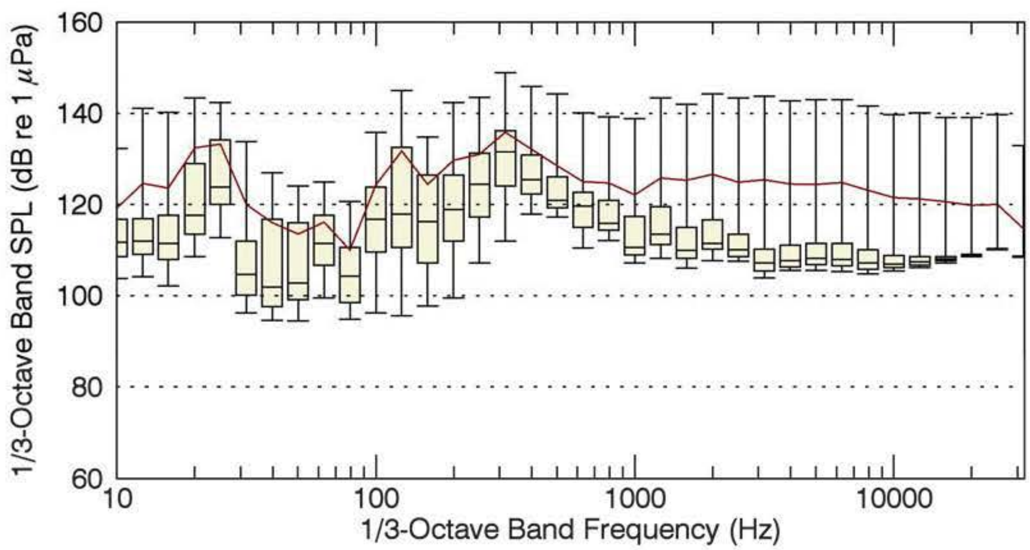


Figure C-25. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D12, recorded at 31.1 m range at Kodiak ferry terminal.

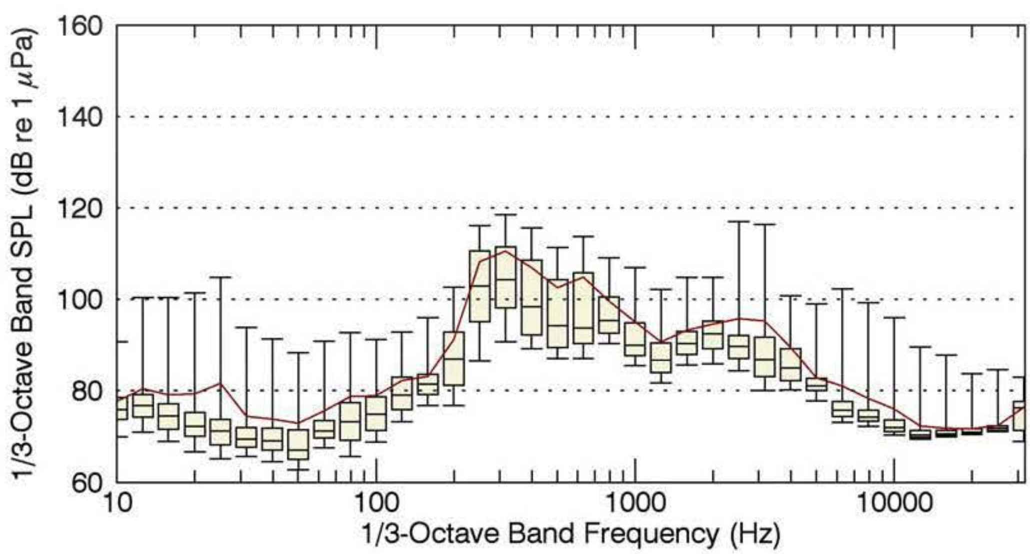


Figure C-26. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D20, recorded at 1119 m range at Kodiak ferry terminal.

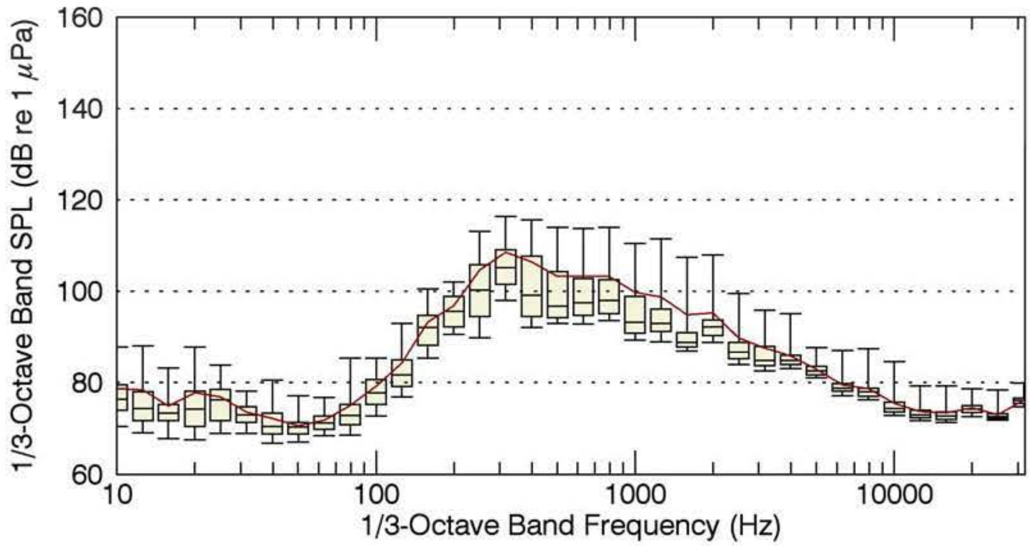


Figure C-27. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D15, recorded at 1127 m range at Kodiak ferry terminal.

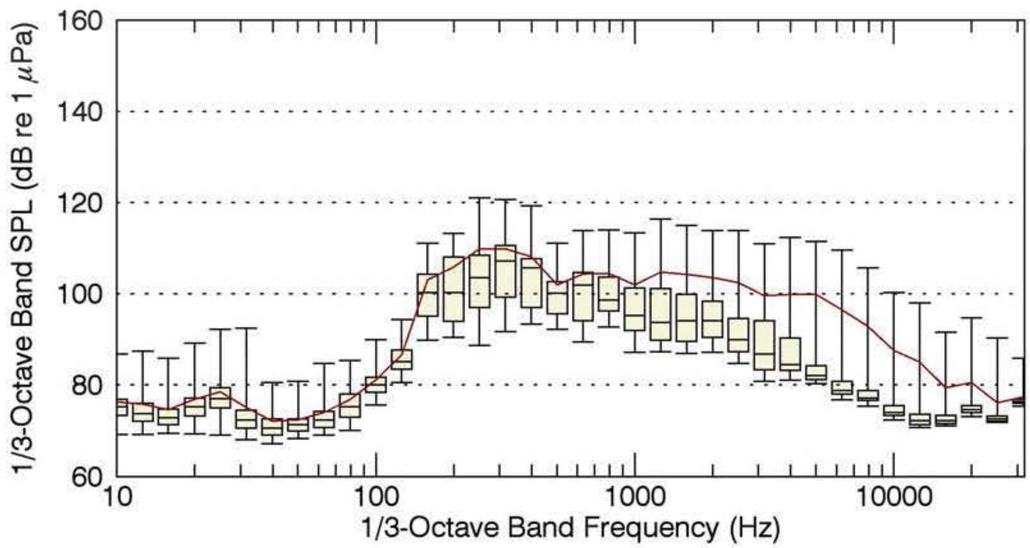


Figure C-28. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D14, recorded at 1130 m range at Kodiak ferry terminal.

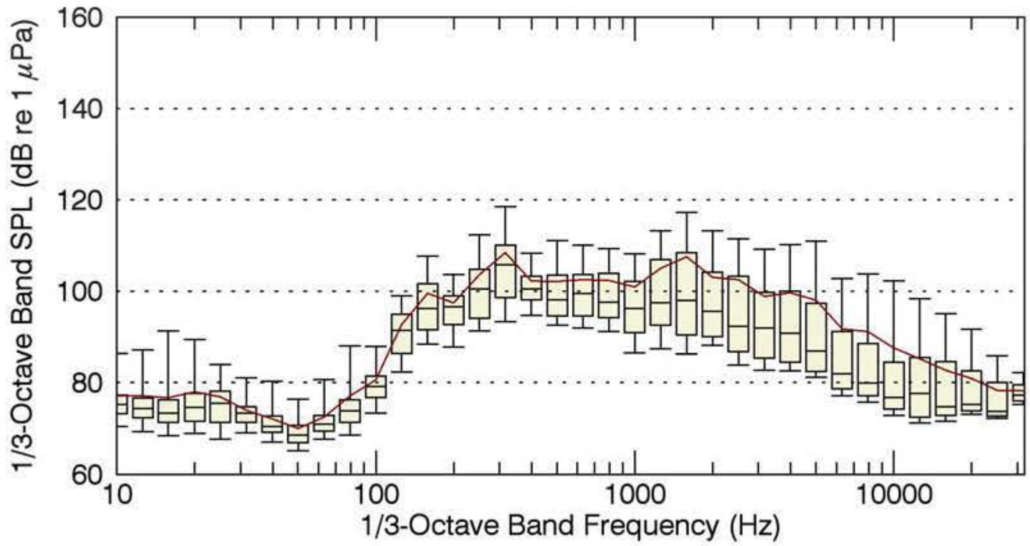


Figure C-29. Plot of 1/3-octave band SPL statistics for vibratory driving (setting) of the Pile D13, recorded at 1133 m range at Kodiak ferry terminal.

C.5.3. Vibratory Driving — Oscillating

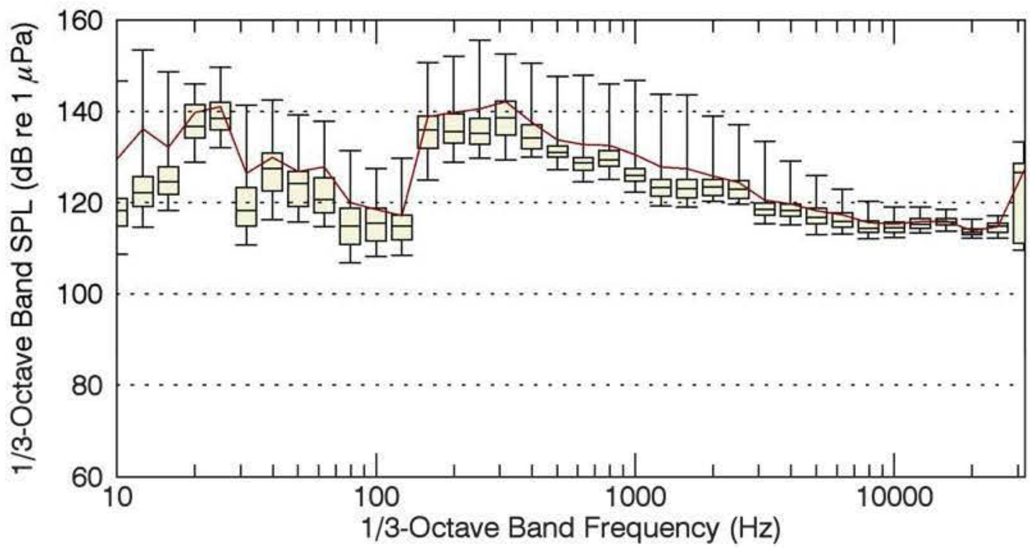


Figure C-30. Plot of 1/3-octave band SPL statistics for vibratory driving (oscillating) of the Pile D22, recorded at 9.9 m range at Kodiak ferry terminal.

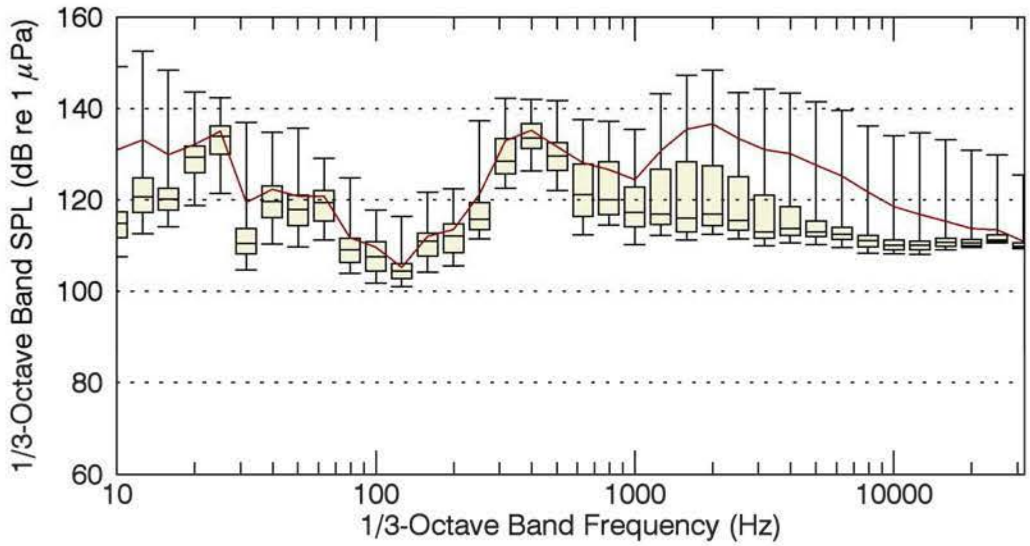


Figure C-31. Plot of 1/3-octave band SPL statistics for vibratory driving (oscillating) of the Pile D16, recorded at 19.0 m range at Kodiak ferry terminal.

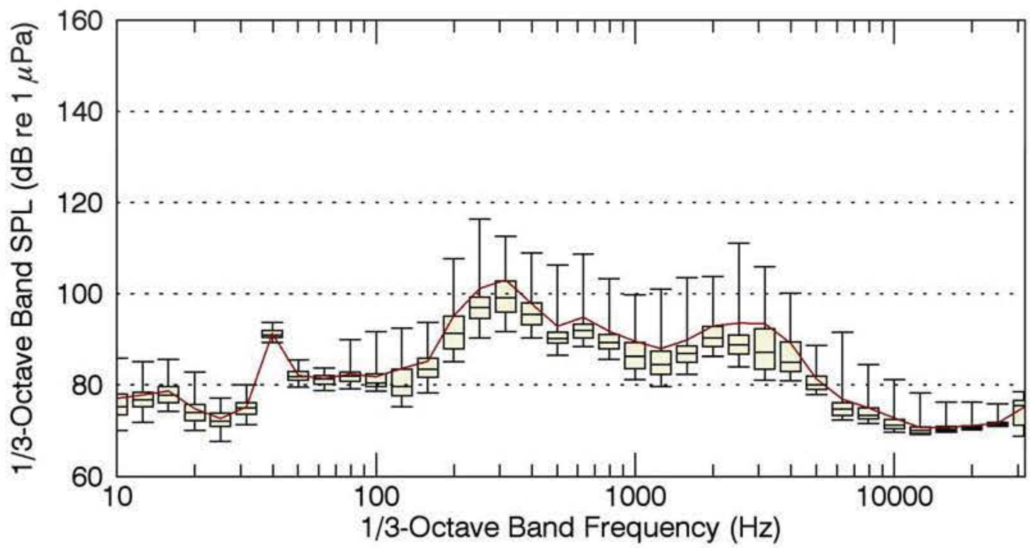


Figure C-32. Plot of 1/3-octave band SPL statistics for vibratory driving (oscillating) of the Pile D22, recorded at 1117 m range at Kodiak ferry terminal.

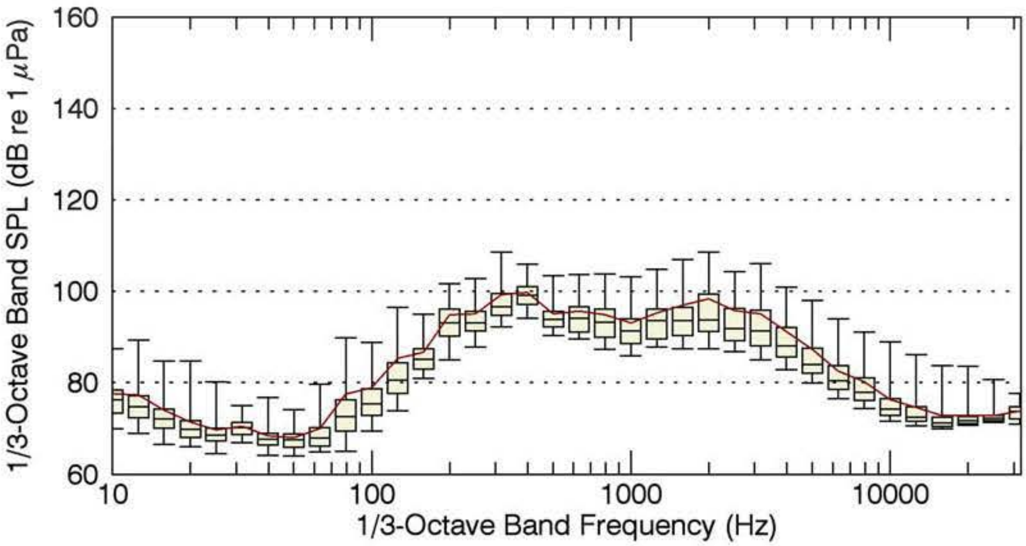


Figure C-33. Plot of 1/3-octave band SPL statistics for vibratory driving (oscillating) of the Pile D16, recorded at 1125 m range at Kodiak ferry terminal.

C.5.4. Drilling

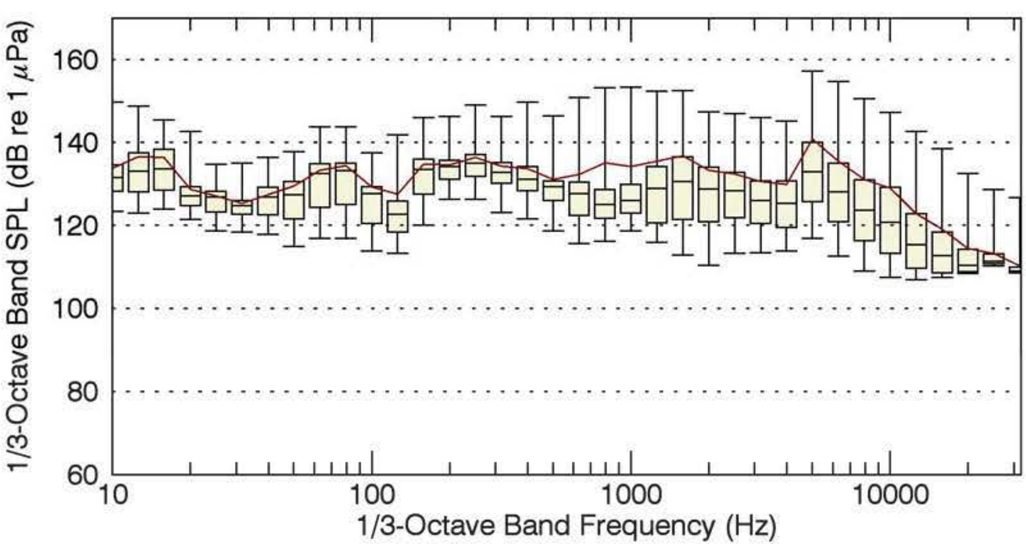


Figure C-34. Plot of 1/3-octave band SPL statistics for drilling of the Pile D22, recorded at 9.9 m range at Kodiak ferry terminal.

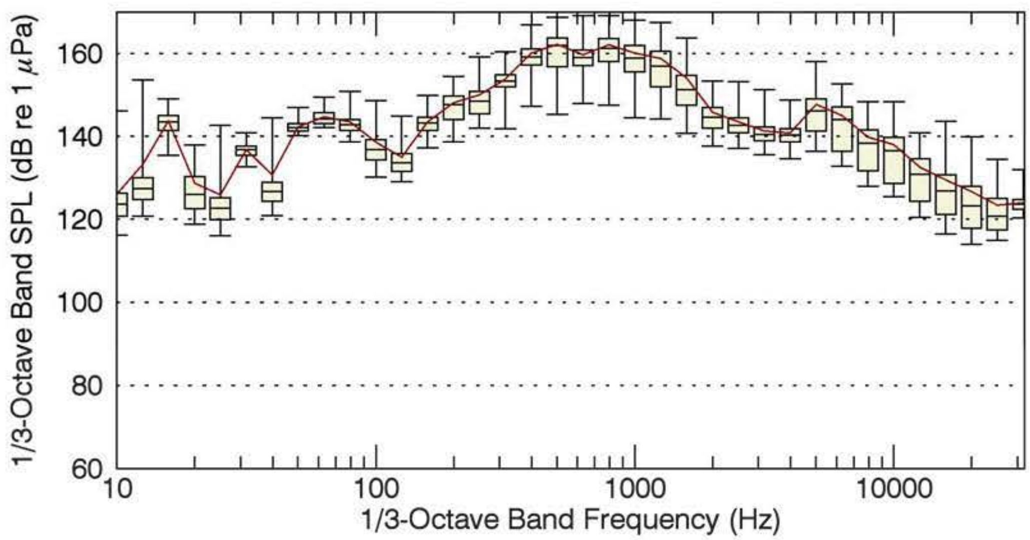


Figure C-35. Plot of 1/3-octave band SPL statistics for drilling of the Pile D20, recorded at 12.9 m range at Kodiak ferry terminal.

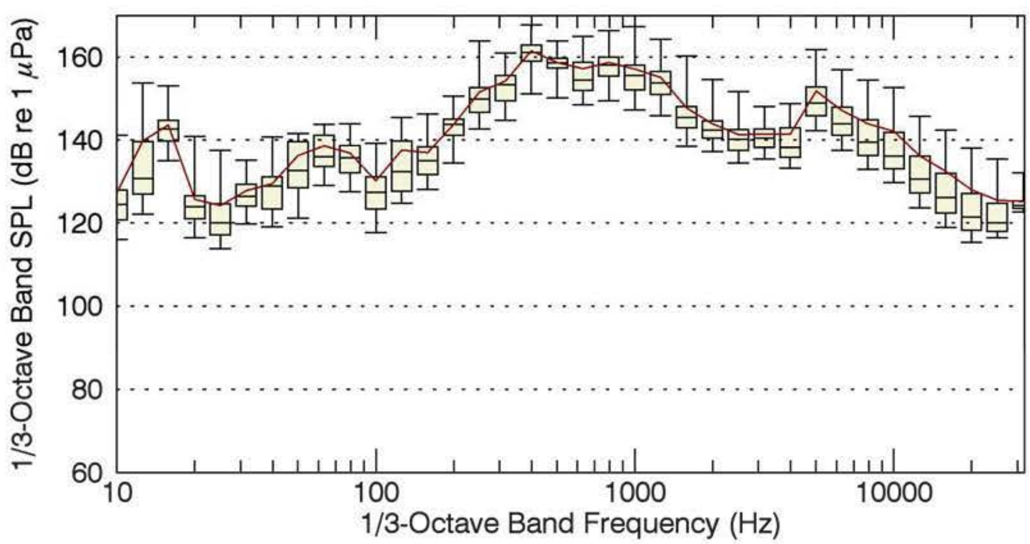


Figure C-36. Plot of 1/3-octave band SPL statistics for drilling of the Pile D18, recorded at 16.0 m range at Kodiak ferry terminal.

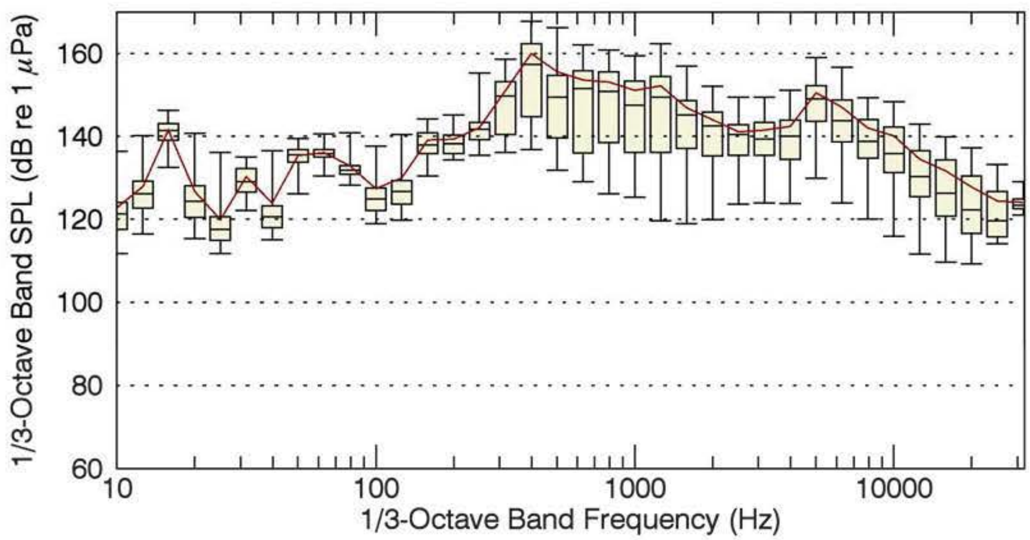


Figure C-37. Plot of 1/3-octave band SPL statistics for drilling of the Pile D16, recorded at 19.0 m range at Kodiak ferry terminal.

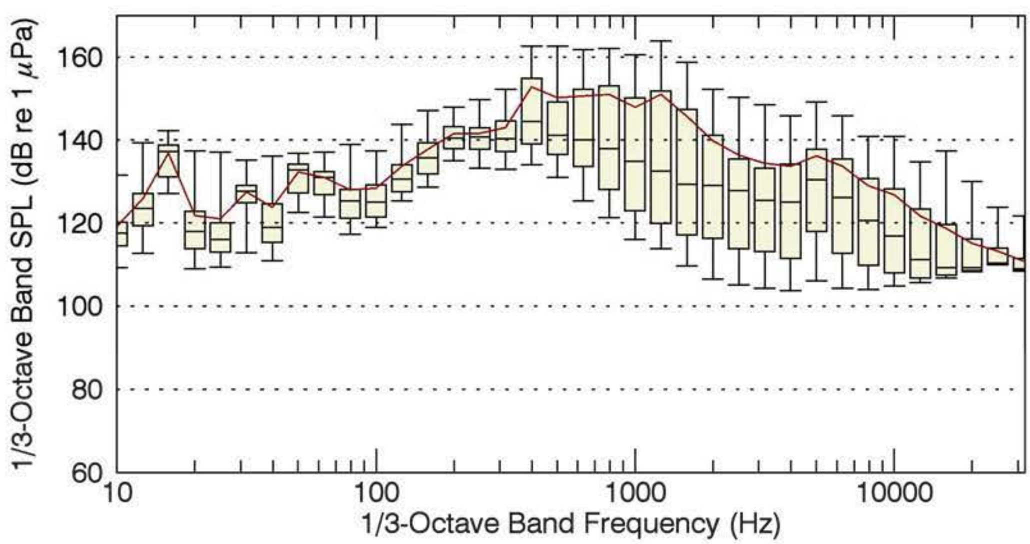


Figure C-38. Plot of 1/3-octave band SPL statistics for drilling of the Pile D15, recorded at 22.0 m range at Kodiak ferry terminal.

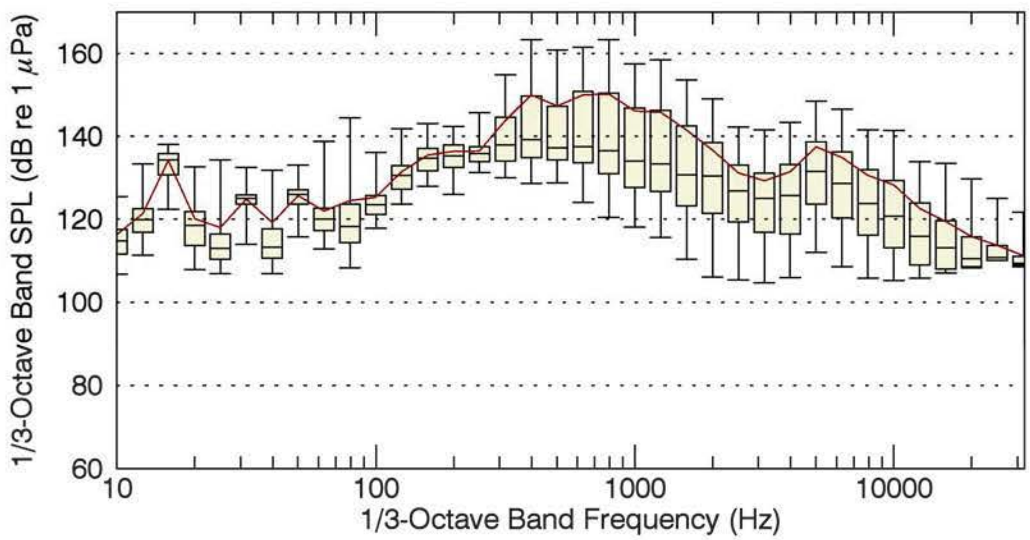


Figure C-39. Plot of 1/3-octave band SPL statistics for drilling of the Pile D14, recorded at 25.1 m range at Kodiak ferry terminal.

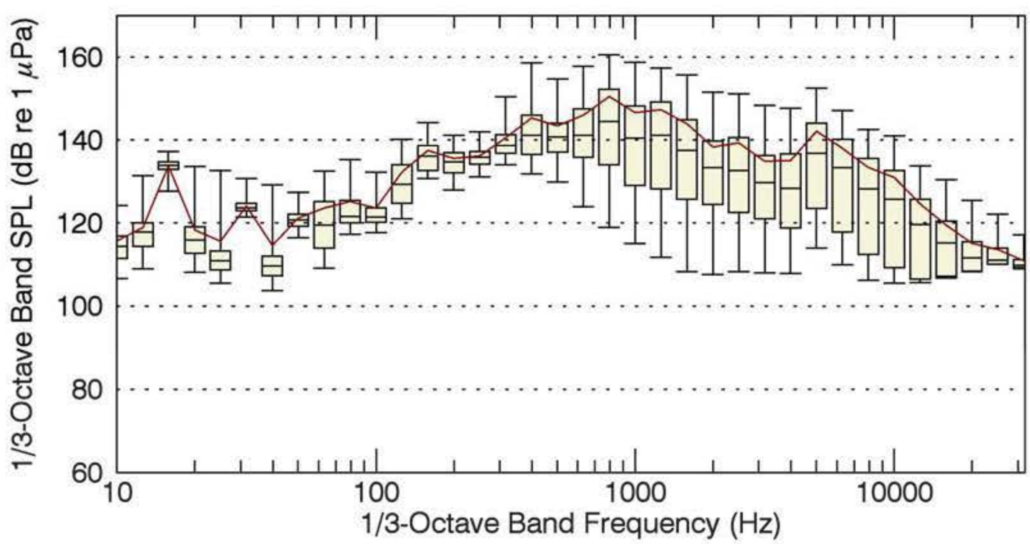


Figure C-40. Plot of 1/3-octave band SPL statistics for drilling of the Pile D13, recorded at 28.1 m range at Kodiak ferry terminal.

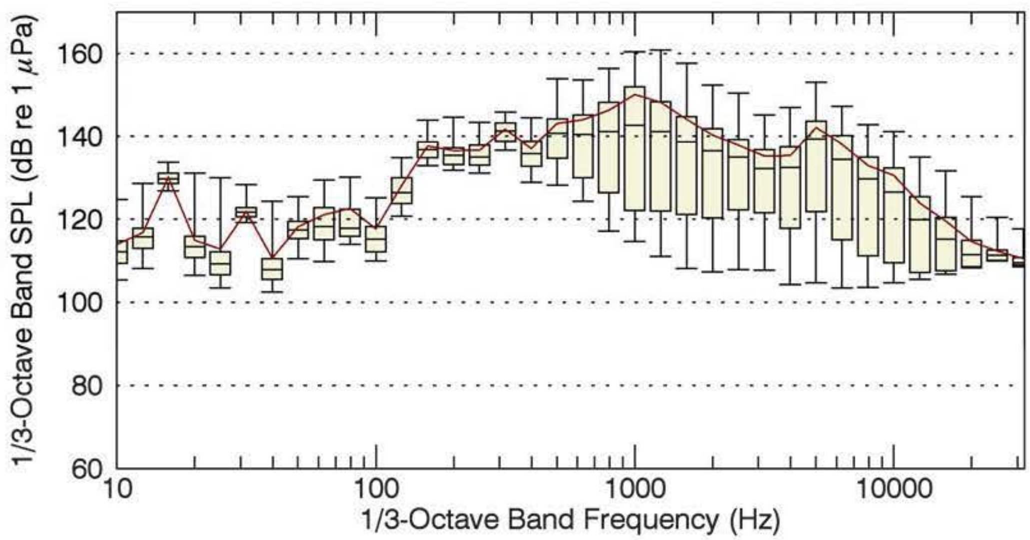


Figure C-41. Plot of 1/3-octave band SPL statistics for drilling of the Pile D12, recorded at 31.1 m range at Kodiak ferry terminal.

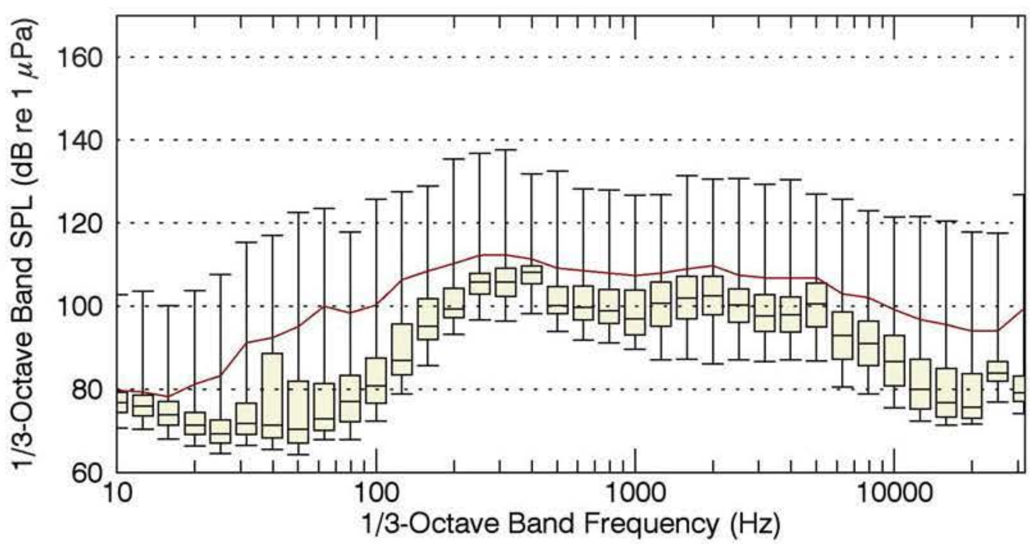


Figure C-42. Plot of 1/3-octave band SPL statistics for drilling of the Pile D22, recorded at 1117 m range at Kodiak ferry terminal.

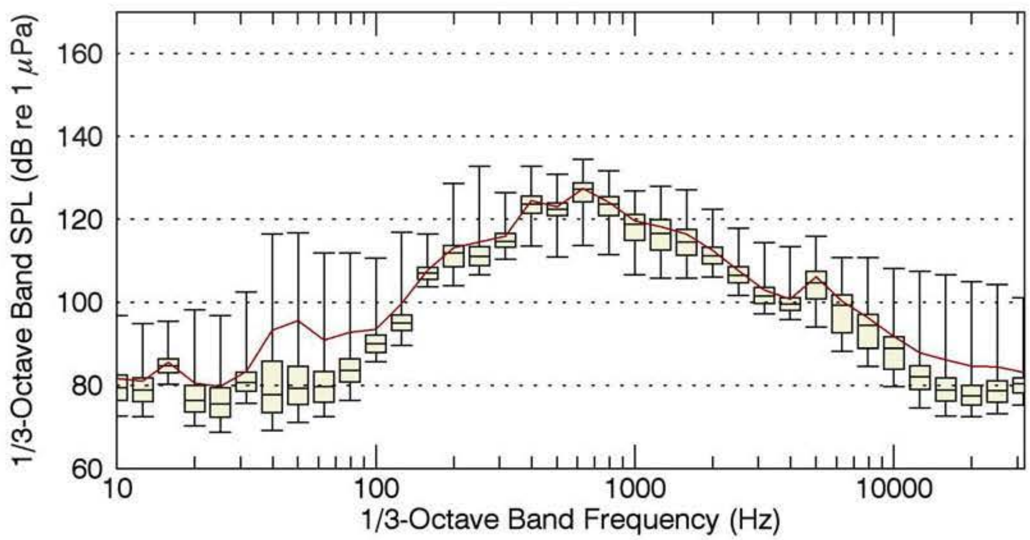


Figure C-43. Plot of 1/3-octave band SPL statistics for drilling of the Pile D20, recorded at 1119 m range at Kodiak ferry terminal.

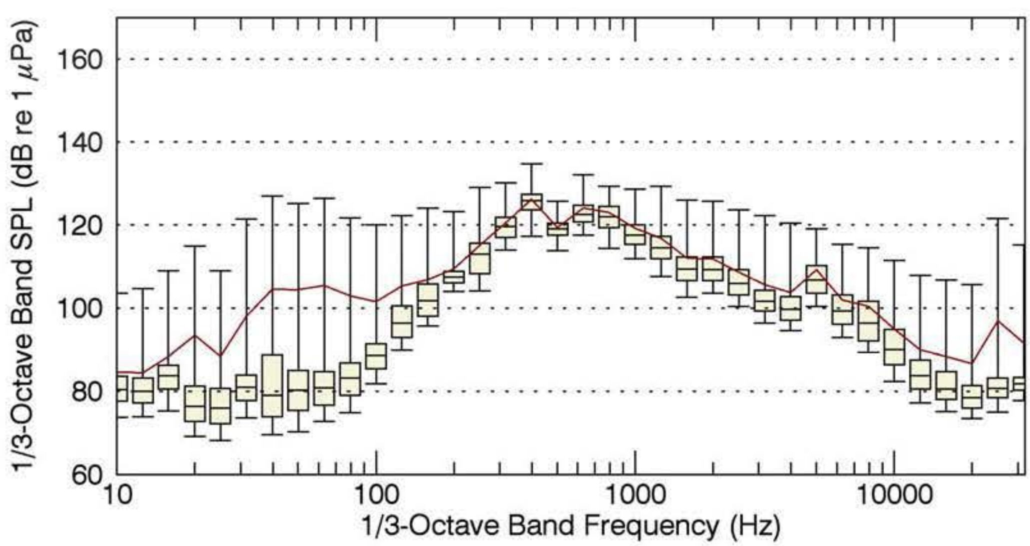


Figure C-44. Plot of 1/3-octave band SPL statistics for drilling of the Pile D18, recorded at 1122 m range at Kodiak ferry terminal.

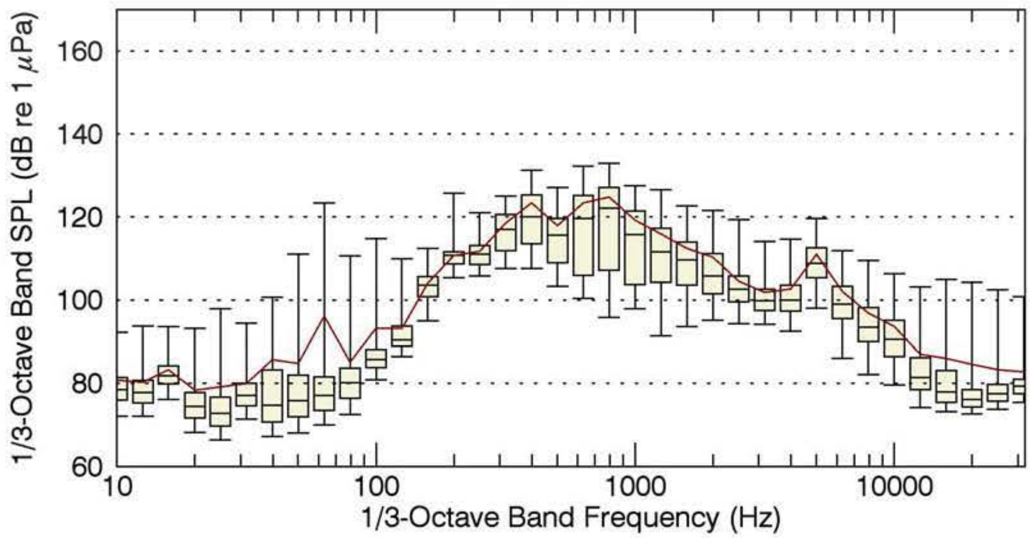


Figure C-45. Plot of 1/3-octave band SPL statistics for drilling of the Pile D16, recorded at 1125 m range at Kodiak ferry terminal.

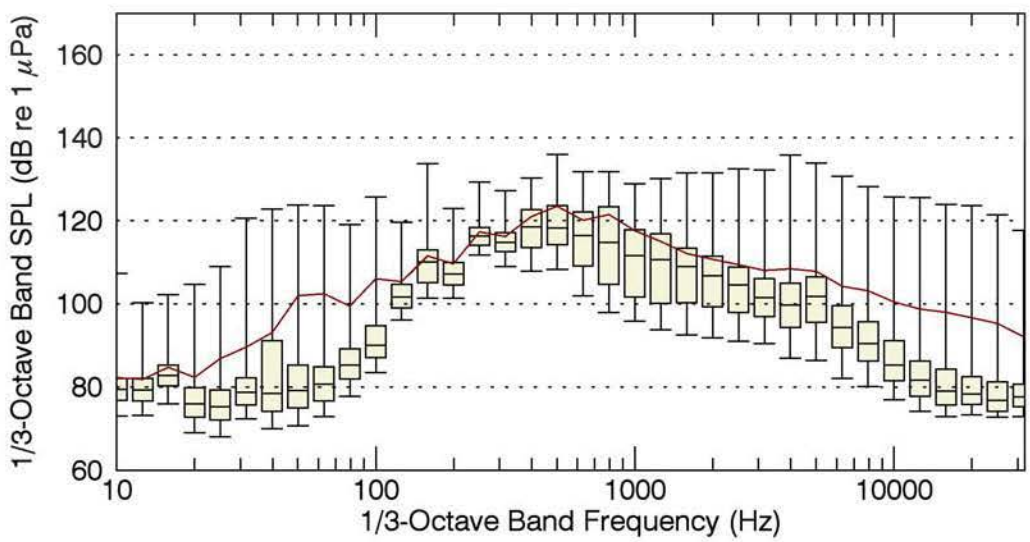


Figure C-46. Plot of 1/3-octave band SPL statistics for drilling of the Pile D15, recorded at 1127 m range at Kodiak ferry terminal.

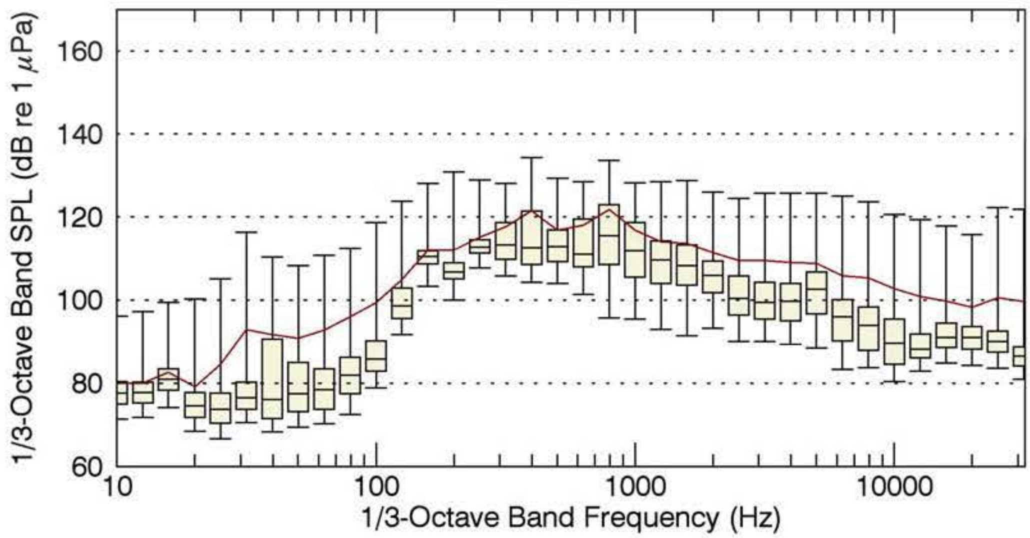


Figure C-47. Plot of 1/3-octave band SPL statistics for drilling of the Pile D14, recorded at 1130 m range at Kodiak ferry terminal.

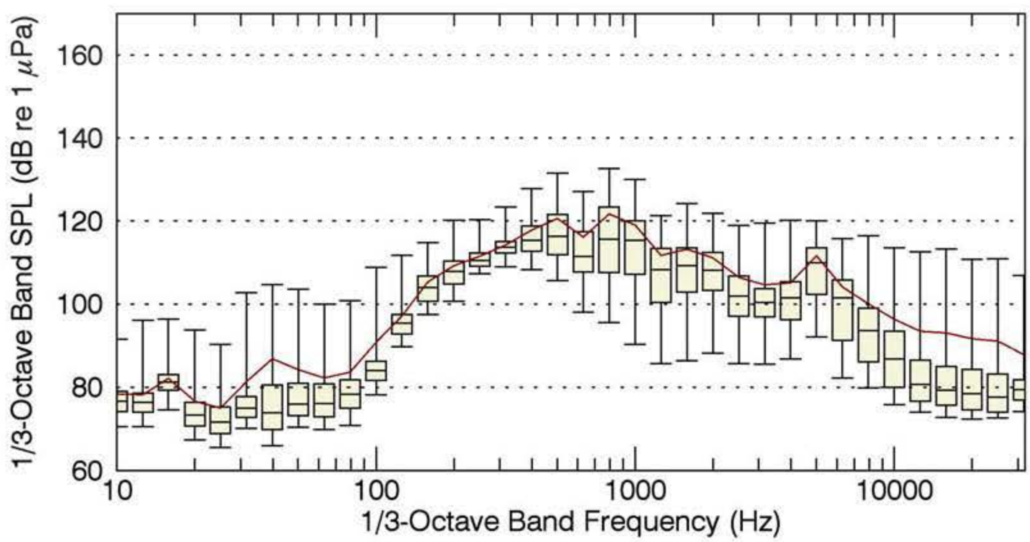


Figure C-48. Plot of 1/3-octave band SPL statistics for drilling of the Pile D13, recorded at 1133 m range at Kodiak ferry terminal.

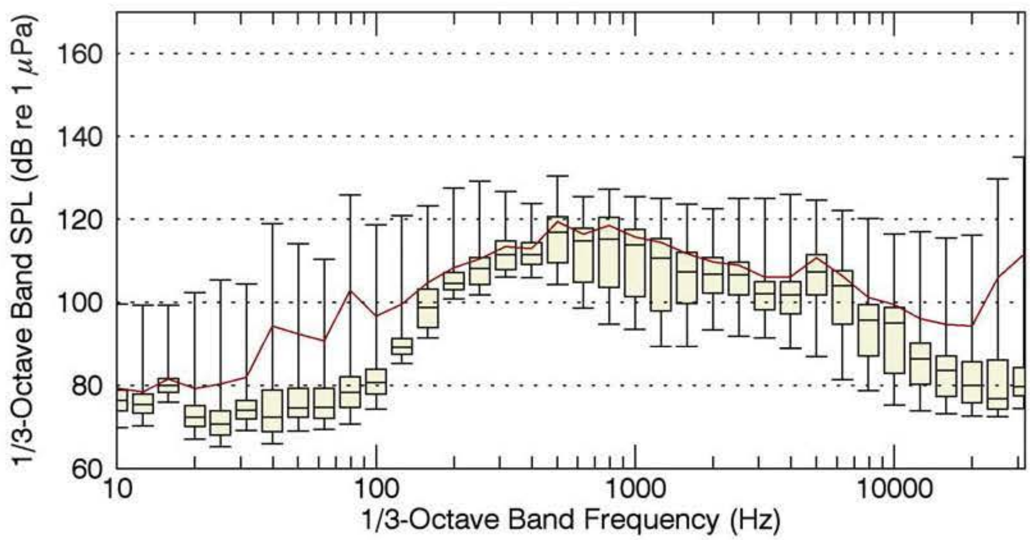


Figure C-49. Plot of 1/3-octave band SPL statistics for drilling of the Pile D12, recorded at 1136 m range at Kodiak ferry terminal.

C.6. Background Noise Levels

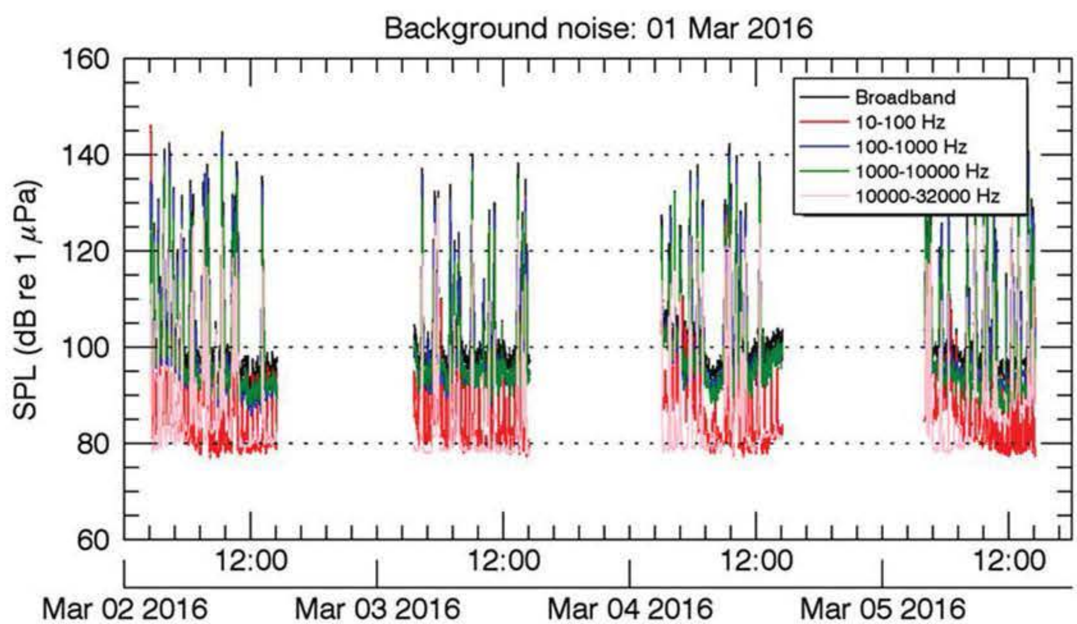


Figure C-50. Background SPL versus time (UTC) recorded on AMAR 2 (60 s average). Periods containing construction activity were removed. Peaks in the level versus time plot correspond to vessels passing close to the AMAR.

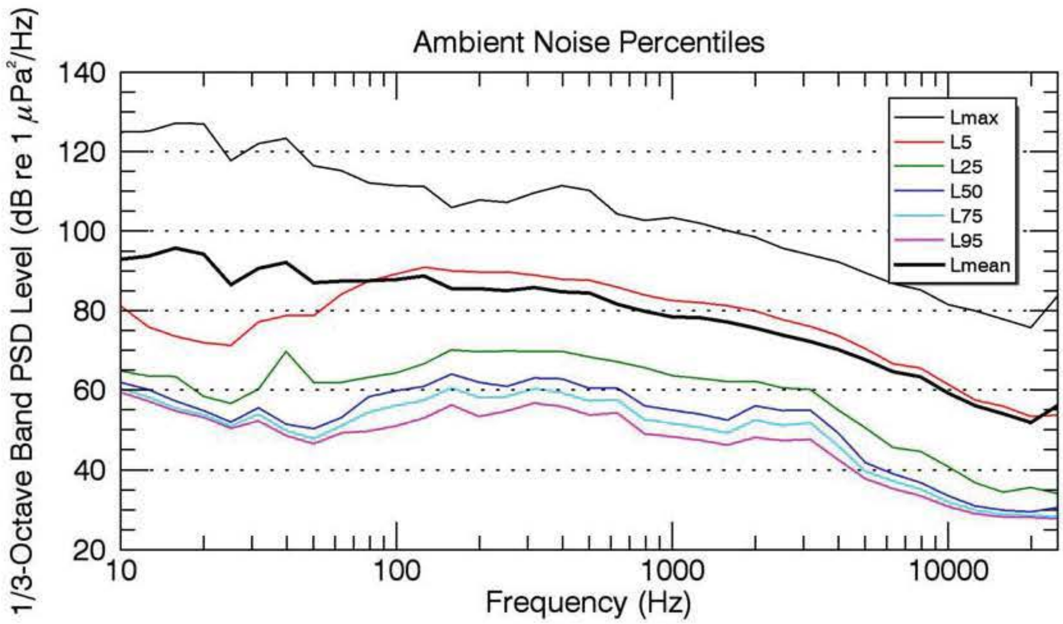


Figure C-51. Exceedance levels of 1/3-octave band background noise levels recorded on AMAR 2. The L_n value is the SPL exceeded by n% of the data. Periods containing construction activity have been removed.

Table C-2. Exceedance levels of background noise levels measured at Kodiak, Alaska (60 s average). The Ln value is the SPL exceeded by n% of the data. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Exceedance level	SPL (dB re 1 µPa)					
	Unw	LFC	MFC	HFC	PPW	OPW
L_5	126.6	125.0	110.9	108.1	120.3	120.6
L_{25}	107.6	106.2	90.5	87.8	101.8	102.2
L_{50} (median)	100.1	98.9	84.8	82.2	95.3	95.8
L_{75}	97.2	95.9	82.6	79.7	92.3	92.7
L_{95}	94.1	92.9	81.0	78.3	89.4	89.6
L_{mean}	122.7	120.6	108.7	107.2	116.0	116.4

C.7. Broadband-discounted SEL and weighted SEL differences

The NMFS Optional User Spreadsheet provides Weighting Function Adjustments (WFA) for estimating weighted SEL from unweighted SEL. The broadband SEL corrected with the WFA and the functional hearing group weighted SELs were compared. NMFS suggests that estimates generated by using the spreadsheet will conservatively estimate injury zones; however, this was not always the case. The WFA discounted SELs for the MFC and HFC functional hearing group were often lower, and therefore less conservative, than the frequency weighted SELs. Additionally, comparing the two calculations across functional hearing groups, illustrated a range of differences that exceeded 10 dB.

Table C-3. Difference between mean broadband-discounted SEL and weighted SEL for impact piling 24” diameter steel piles.

Pile	Hearing group	AMAR 1	AMAR 2
D22	LFC	0.8	0.6
	MFC	-3.9	3.3
	HFC	-8.7	1.7
	PPW	4.2	4.5
	OPW	4.7	5
D20	LFC	0.8	0.7
	MFC	-1.4	6
	HFC	-6	4.7
	PPW	5.5	6
	OPW	6.3	6.7
D18	LFC	0.7	0.6
	MFC	-3.5	2.3
	HFC	-8	0.6
	PPW	4.2	4.4
	OPW	5	4.9
D16	LFC	0.7	0.6
	MFC	1	8.6
	HFC	-3.6	7.3
	PPW	6.6	7
	OPW	7.7	7.9

Table C-4. Difference between mean broadband-discounted SEL and weighted SEL for impact piling 24” diameter steel piles.

Pile	**Hearing group**	**AMAR 1**	**AMAR 2**
D22	LFC	0.8	0.6
	MFC	-3.9	3.3
	HFC	-8.7	1.7
	PPW	4.2	4.5
	OPW	4.7	5
D20	LFC	0.8	0.7
	MFC	-1.4	6
	HFC	-6	4.7
	PPW	5.5	6
	OPW	6.3	6.7
D18	LFC	0.7	0.6

Pile	Hearing group	AMAR 1	AMAR 2
	MFC	-3.5	2.3
	HFC	-8	0.6
	PPW	4.2	4.4
	OPW	5	4.9
D16	LFC	0.7	0.6
	MFC	1	8.6
	HFC	-3.6	7.3
	PPW	6.6	7
	OPW	7.7	7.9

Table C-5. Difference between mean broadband-discounted SEL and weighted SEL for vibratory setting of 24” diameter steel piles.

Pile	Hearing group	AMAR 1	AMAR 2
D20	LFC	2.2	1.1
	MFC	9.5	10.6
	HFC	3.4	8.2
	PPW	12.5	9.6
	OPW	14.8	10.8
D15	LFC	3.6	0.9
	MFC	10.7	11
	HFC	6.1	7.9
	PPW	12.5	8.8
	OPW	13.8	9.6
D14	LFC	1.3	1.1
	MFC	-1	2.9
	HFC	-4.6	0.6
	PPW	4.6	5.8
	OPW	4.9	6.1
D13	LFC	1.5	0.6
	MFC	-0.8	1.9
	HFC	-4.6	-0.5
	PPW	4.2	3.9
	OPW	4.4	3.9
D15	LFC	2.6	N/A*
	MFC	-2.5	N/A
	HFC	-7.1	N/A
	PPW	6.7	N/A

Pile	Hearing group	AMAR 1	AMAR 2
	OPW	7.4	N/A

* N/A represents data excluded from analyses.

Table C-6. Difference between mean broadband-discounted SEL and weighted SEL for vibratory oscillation of 24" diameter steel piles.

Pile	Hearing group	AMAR 1	AMAR 2
D22	LFC	3.5	1.3
	MFC	4.5	5.5
	HFC	-1.6	2.9
	PPW	12.6	7.2
	OPW	14	7.8
D16	LFC	1.9	0.6
	MFC	0.5	2.6
	HFC	-2.2	0.5
	PPW	3.7	4
	OPW	3.8	4.1

Table C-7. Difference between mean broadband-discounted SEL and weighted SEL for drilling.

Pile	Hearing group	AMAR 1	AMAR 2
D20	LFC	2	1.1
	MFC	-3.7	-2
	HFC	-6.3	-6.1
	PPW	3.2	4.4
	OPW	3.6	4.7
D20	LFC	0.4	0.4
	MFC	7	11.3
	HFC*	4.7	10
	PPW	6.2	7.1
	OPW	6.4	7.5
D18	LFC	0.6	0.6
	MFC	2.5	8.4
	HFC*	-0.3	5.5
	PPW	6.2	7.5
	OPW	6.7	8
D16	LFC	0.7	0.5
	MFC	0.8	8.1
	HFC	-1.9	6.4

Pile	Hearing group	AMAR 1	AMAR 2
	PPW	5.9	6.8
	OPW	6.5	7.1
D15	LFC	0.5	0.6
	MFC	7.6	4.7
	HFC*	5.7	1.3
	PPW	6.1	6.8
	OPW	6.2	7.3
D14	LFC	0.5	0.7
	MFC	5.4	1.6
	HFC*	2.9	-2.5
	PPW	6.3	6
	OPW	6.7	6.4
D13	LFC	0.4	0.5
	MFC	1.2	4
	HFC*	-1.2	1.5
	PPW	4.2	5.7
	OPW	4.4	6
D12	LFC	0.3	0.7
	MFC	0.8	-4.4
	HFC*	-1.5	-10.3
	PPW	3.7	5
	OPW	3.7	5.4

* The greater than 20 dB difference for drilling recorded at AMAR 2 at these piles could be because other vessels and the navigation buoy were present.

Appendix D. Supporting Data for Ketchikan

D.1. Monitoring Activities

The activities of the JASCO field monitoring team during the Ketchikan installation is provided in Table D-1.

Table D-1. Log of hydroacoustic monitoring of pile driving at Ketchikan, Alaska.

Date (UTC)	Time (UTC)	Activity
2016-07-17	18:50	AMAR 1: Calibrated
2016-07-17	18:16	AMAR 2: Calibrated
2016-07-17	19:08	Dipping hydrophone: Calibrated
2016-07-18	02:42	AMAR 1: Deployed AMAR 2
2016-07-18	02:56	AMAR 2: Deployed
2016-07-19	22:46	CTD cast
2016-07-19	23:31	Pile 1: Dipping hydrophone recorded vibratory pile driving
2016-07-20	21:42	CTD cast
2016-07-21	00:15	Pile 1: Dipping hydrophone recorded impact hammering
2016-07-21	01:54	AMAR 1: Retrieved
2016-07-21	01:46	AMAR 2: Retrieved
2016-07-21	03:11	AMAR 2: Calibrated
2016-07-21	03:28	AMAR 1: Calibrated
2016-07-21	15:46	Dipping hydrophone: Calibrated

D.2. Weather Data

From 18-21 Jul, wind speeds at Ketchikan were ranged from 10 to 15 mph (Figure D-1). Small amounts of rain were detected, mainly at the end of the monitoring period.

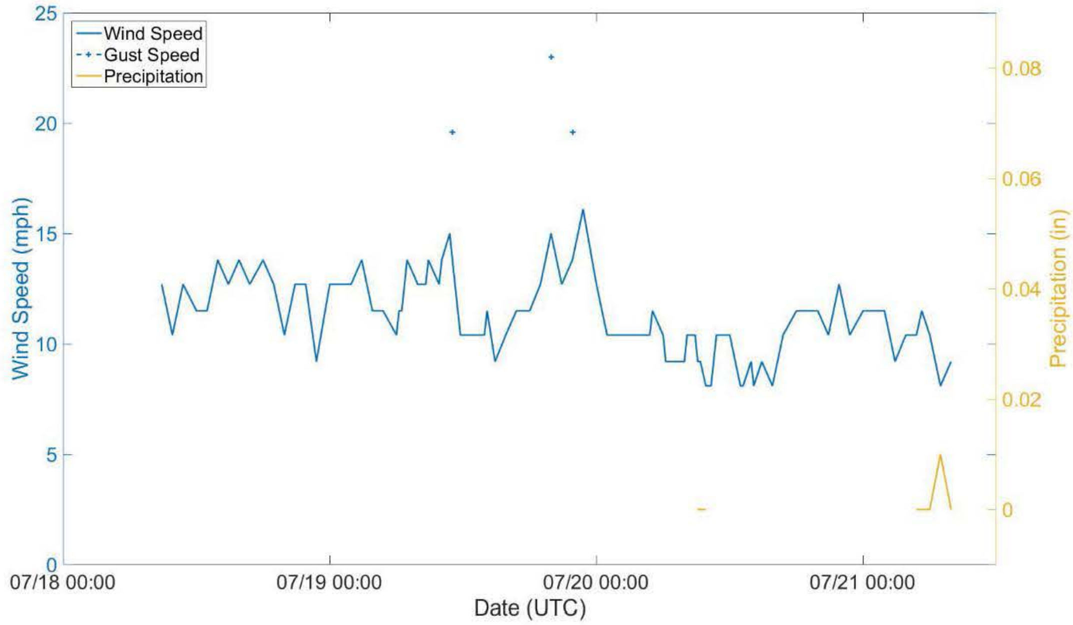


Figure D-1. Wind speed (blue) and precipitation (yellow) recorded at Ketchikan International Airport during the study period.

At Ketchikan, the sound speed profiles measured on 19 and 20 Jul 2016, were downward refracting (Figure D-2). With increasing depth, the sound speed decreased. The overall variation in sound speed was greater than 10 m/s from the surface to the maximum depth measured. The CTD casts were conducted between the two AMARs, 168 m and 208 m from AMAR 1, respectively.

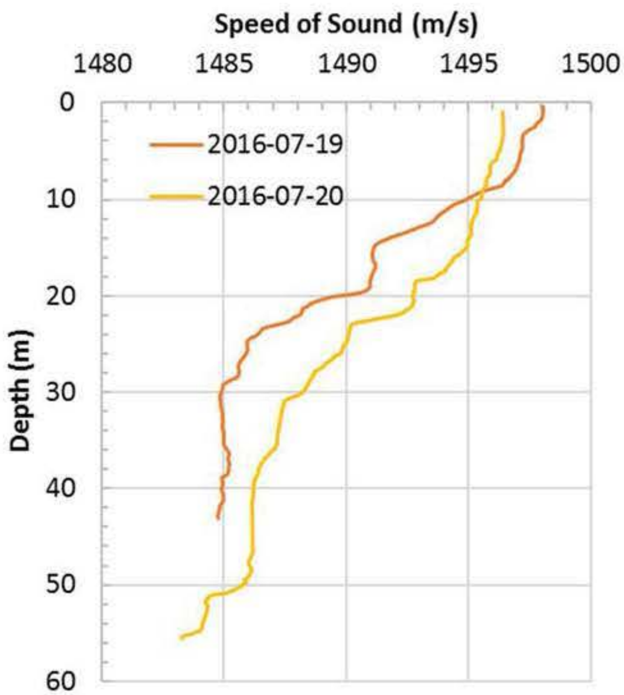


Figure D-2. Profiles of sound speed versus depth calculated from temperature and salinity data collected in Ketchikan. Profiles were sampled between the AMARs at distances of 168 and 208 m from AMAR 1, respectively.

D.3. Spectrograms

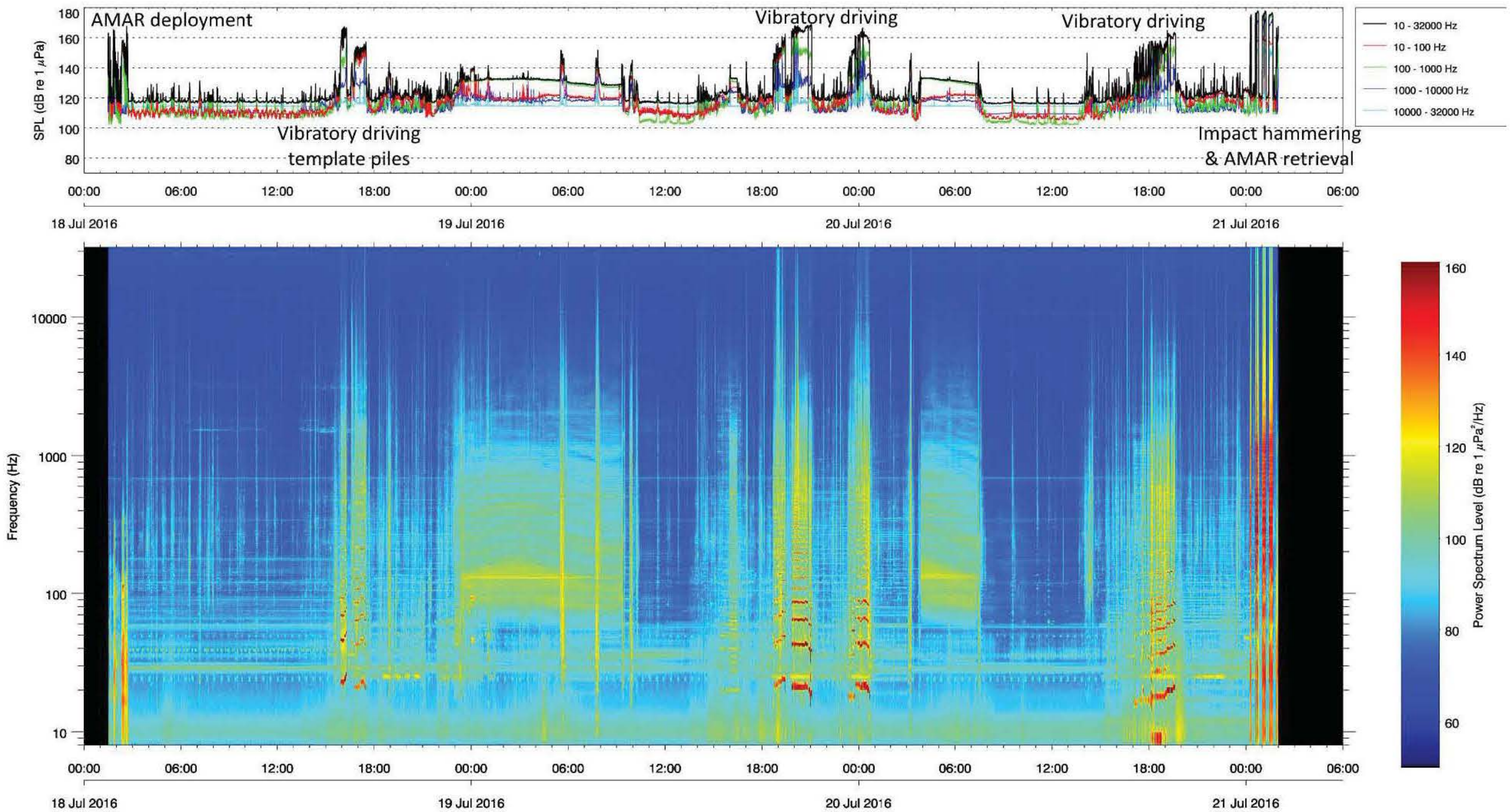


Figure D-3. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at Ketchikan ferry terminal.

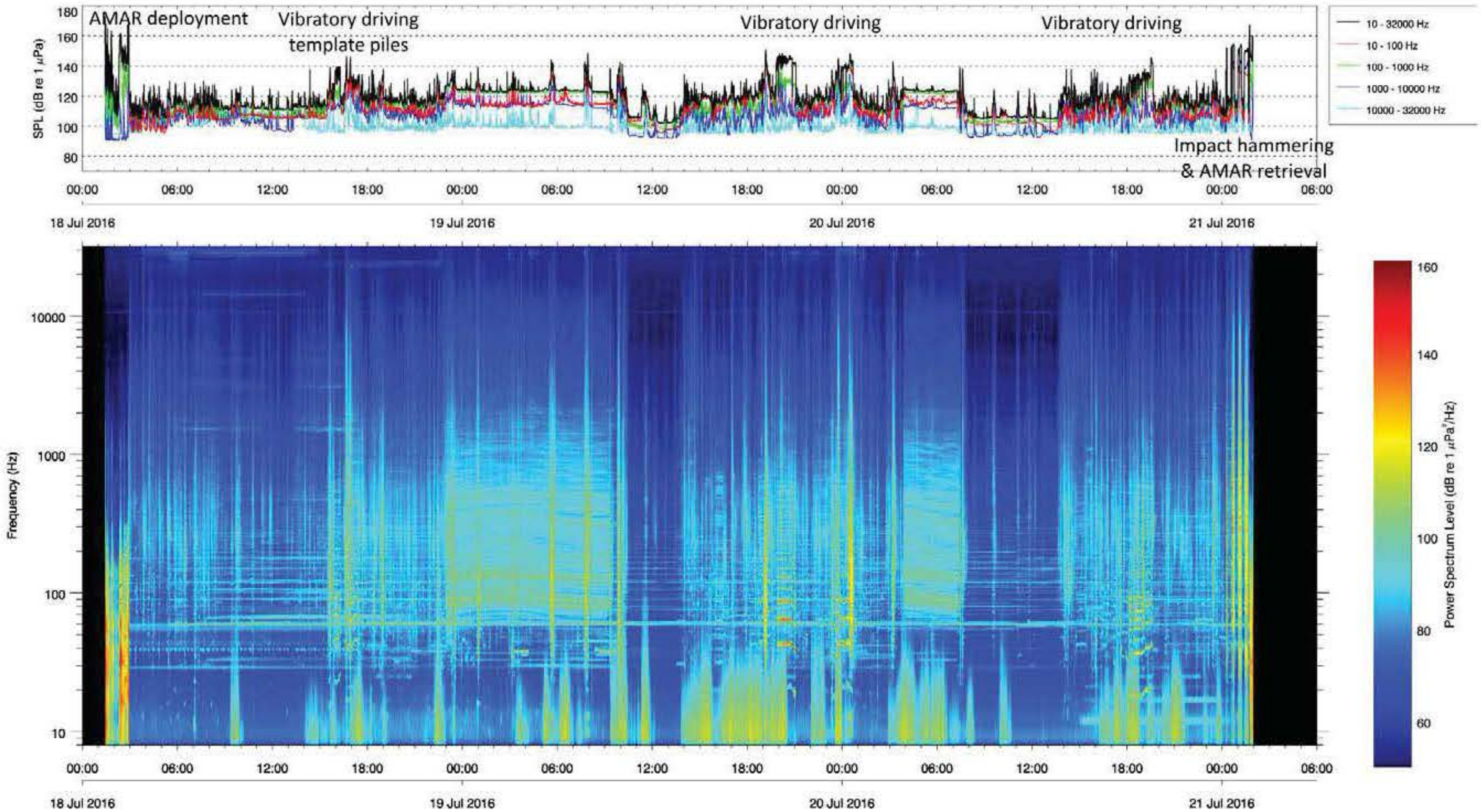


Figure D-4. Band limited energy vs time (top) and spectrogram (bottom) generated from recordings at 1 km from Ketchikan ferry terminal.

D.4. Pile Driving Noise Levels

D.4.1. Impact Pile Driving

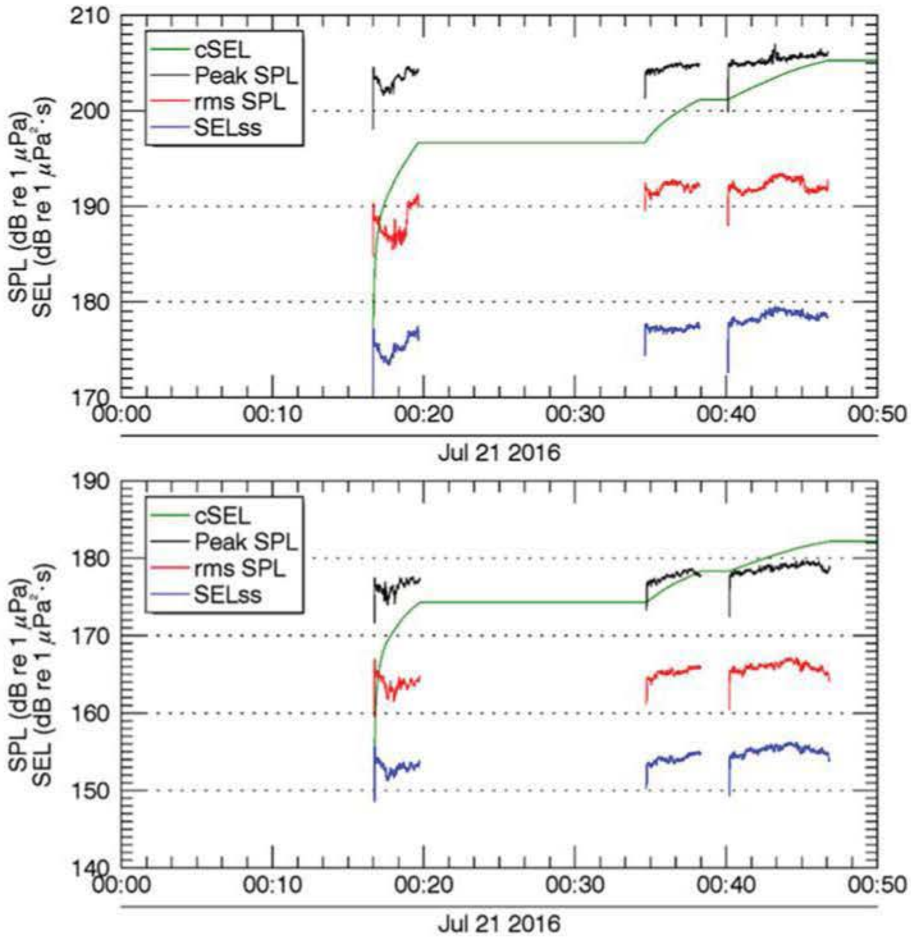


Figure D-5. Peak level, SPL and single-strike SEL vs time (UTC) for impact driving Pile 3 from AMAR 1 (top) and AMAR 2 (bottom) data at ranges of 16.3 and 947 m, respectively.

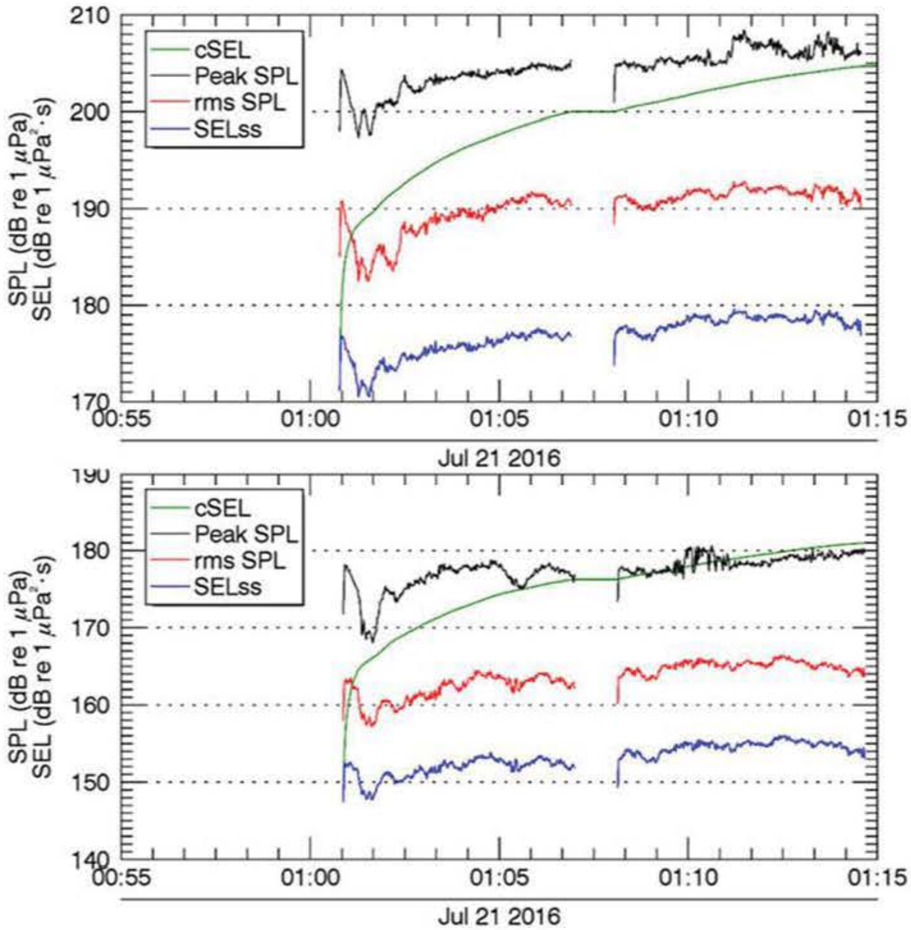


Figure D-6. Peak level, SPL and single-strike SEL vs time (UTC) for impact driving Pile 2 from AMAR 1 (top) and AMAR 2 (bottom) data at ranges of 17.3 and 948 m, respectively.

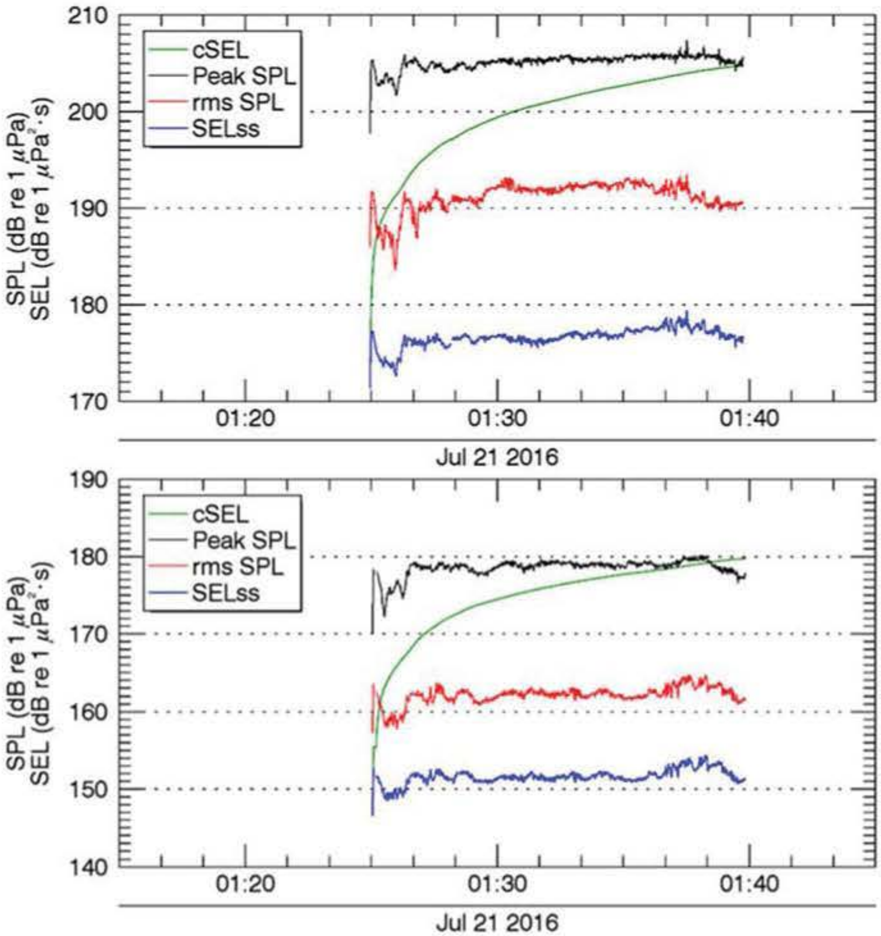


Figure D-7. Peak level, SPL and single-strike SEL vs time (UTC) for impact driving Pile 1 from AMAR 1 (top) and AMAR 2 (bottom) data at ranges of 18.4 and 949 m, respectively.

D.4.2. Vibratory Driving

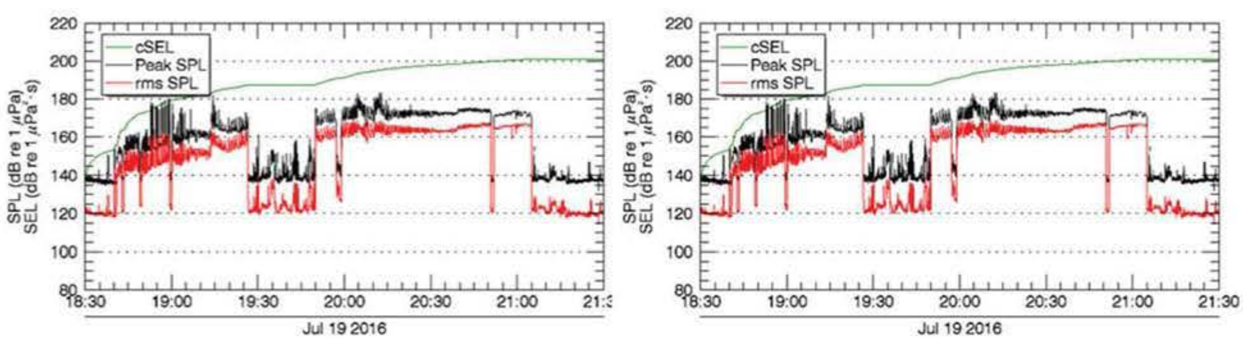


Figure D-8. Plot of SPL (1 s average) vs time (UTC) for vibratory driving Pile 2 measured on AMAR 1 at 17.3 m (left) and AMAR 2 at 948 m (right).

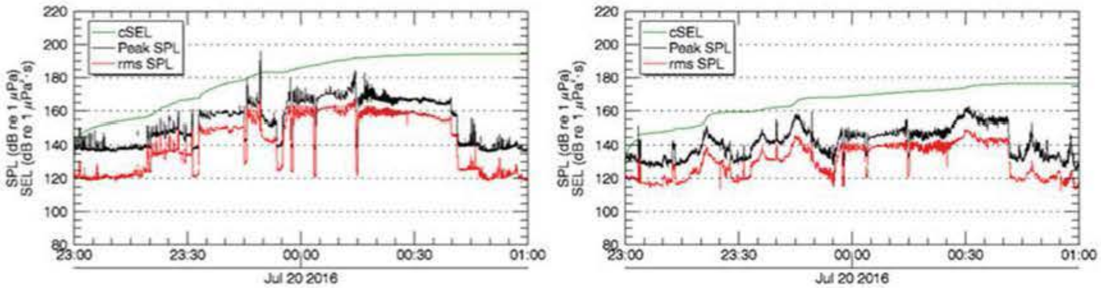


Figure D-9. Plot of SPL (1 s average) vs time (UTC) for vibratory driving Pile 1 measured on AMAR 1 at 18.4 m (left) and AMAR 2 at 949 m (right).

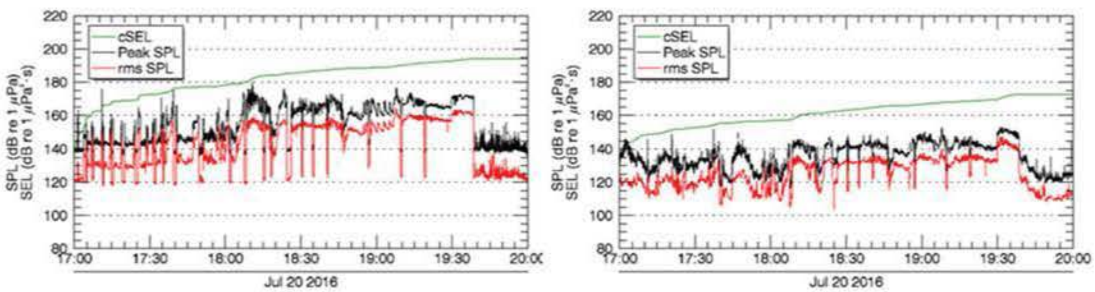


Figure D-10. Plot of SPL (1 s average) vs time (UTC) for vibratory driving Pile 3 measured on AMAR 1 at 16.3 m (left) and AMAR 2 at 947 m (right).

D.5. 1/3-Octave Band Levels

One-third octave band spectra are provided in which beige bars indicate the first, second, and third quartiles (L_{25}, L_{50}, and L_{75}) in each 1/3-octave band. Upper error bars indicate the maximum levels (L_{max}). Lower error bars indicate the 95% exceedance percentiles (L_{95}). The maroon line indicates the arithmetic mean (L_{mean}).

D.5.1. Impact Hammering

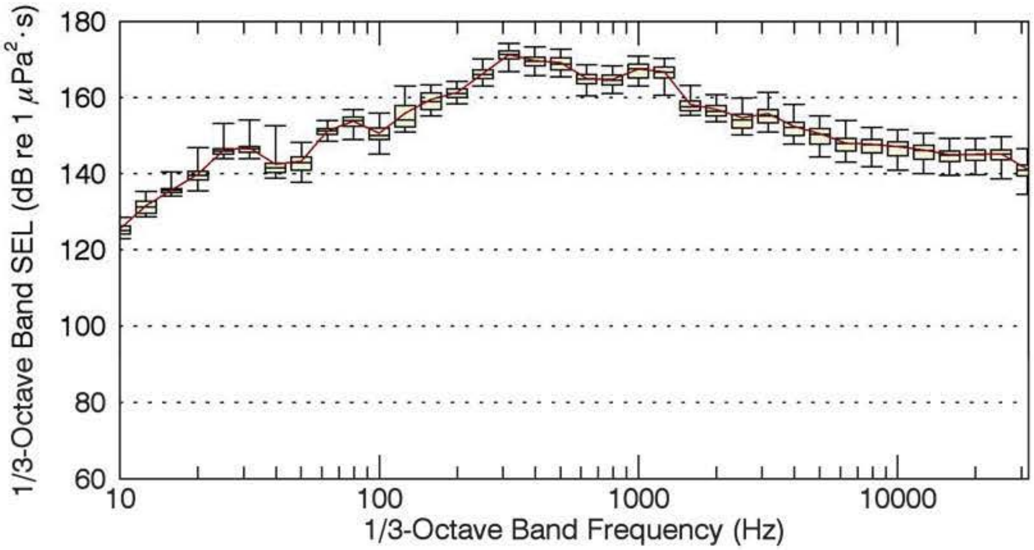


Figure D-11. Plot of 1/3-octave band SEL statistics for impact driving of Pile 3, recorded at 16.3 m range from Ketchikan ferry terminal.

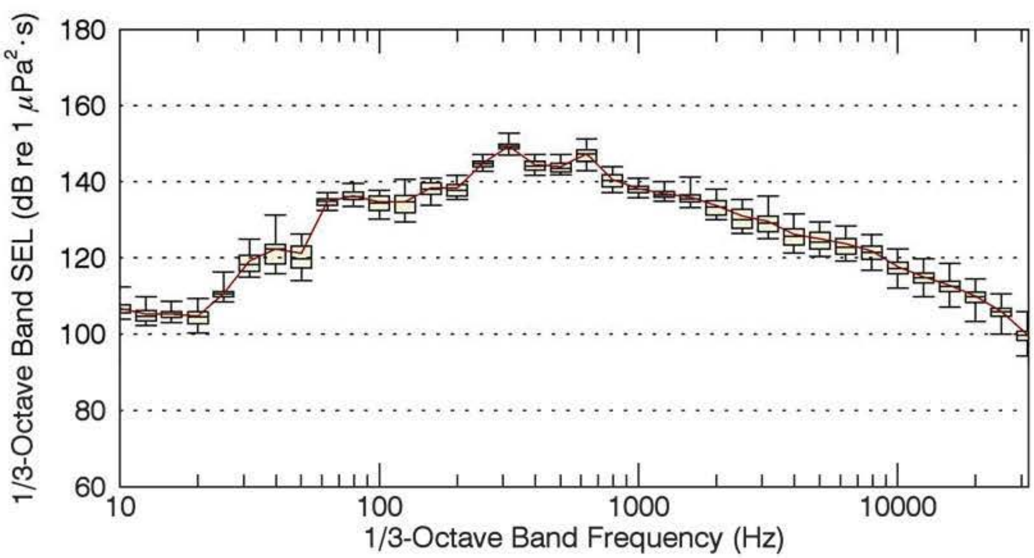


Figure D-12. Plot of 1/3-octave band SEL statistics for impact driving of Pile 3, recorded at 947 m range from Ketchikan ferry terminal.

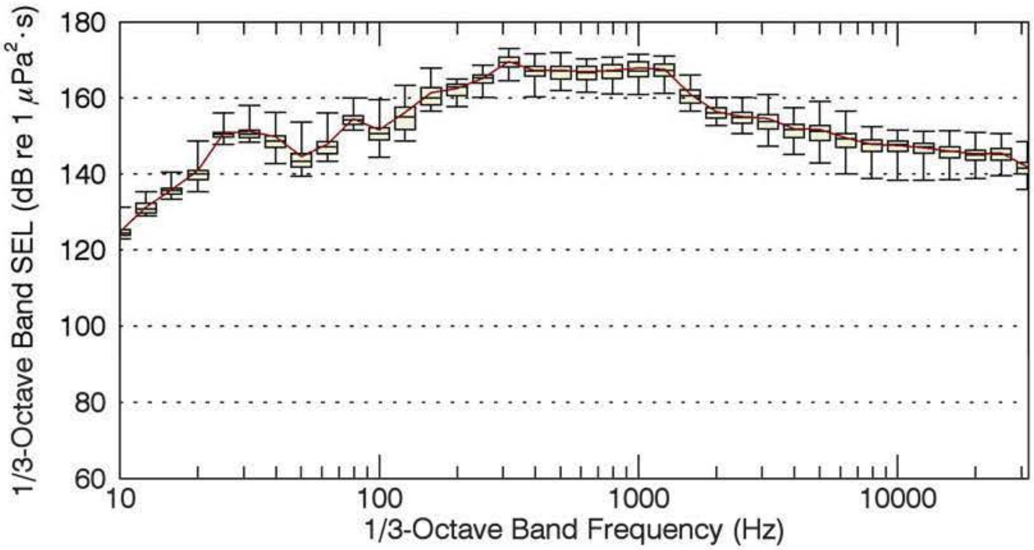


Figure D-13. Plot of 1/3-octave band SEL statistics for impact driving of Pile 2, recorded at 17.3 m range from Ketchikan ferry terminal.

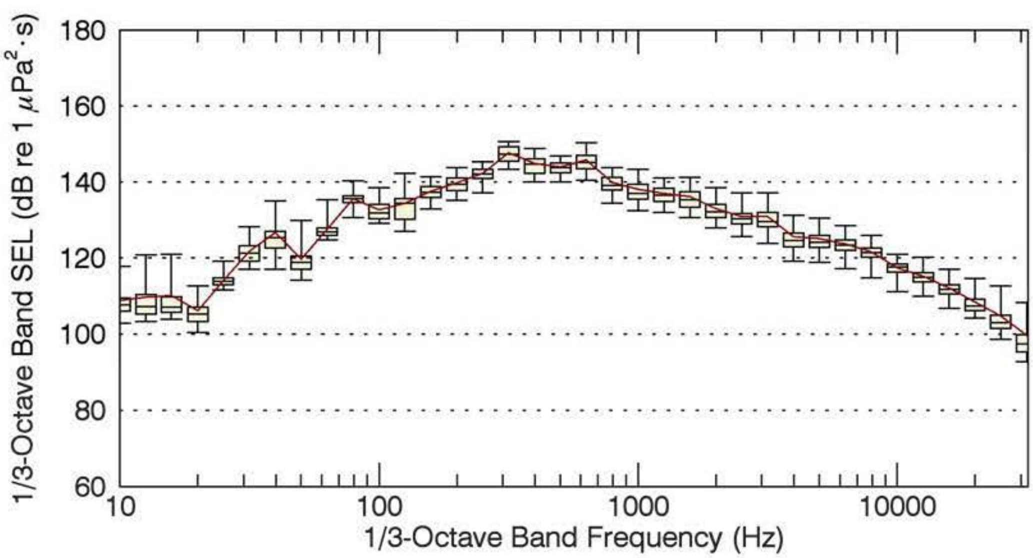


Figure D-14. Plot of 1/3-octave band SEL statistics for impact driving of Pile 2, recorded at 948 m range from Ketchikan ferry terminal.

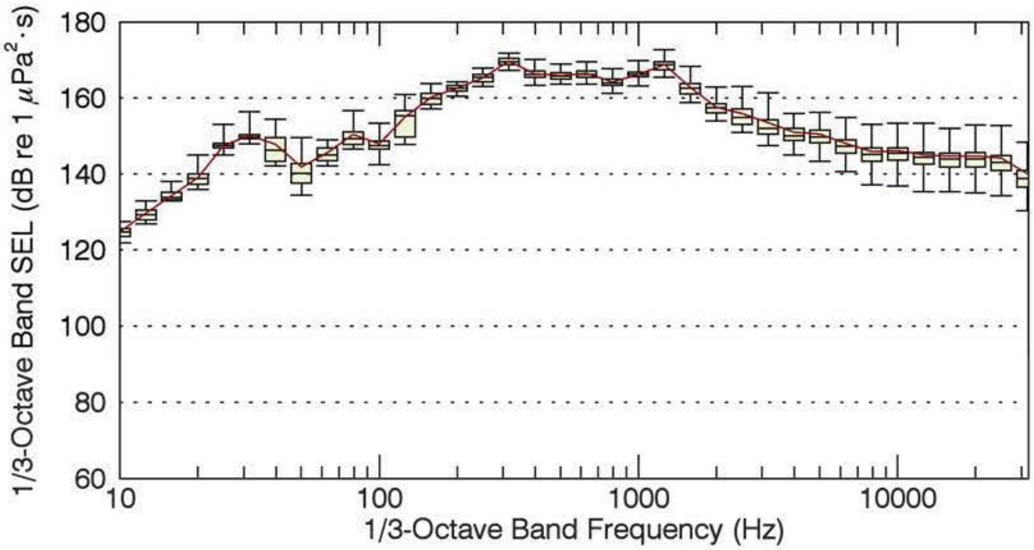


Figure D-15. Plot of 1/3-octave band SEL statistics for impact driving of Pile 1, recorded at 18.4 m range from Ketchikan ferry terminal.

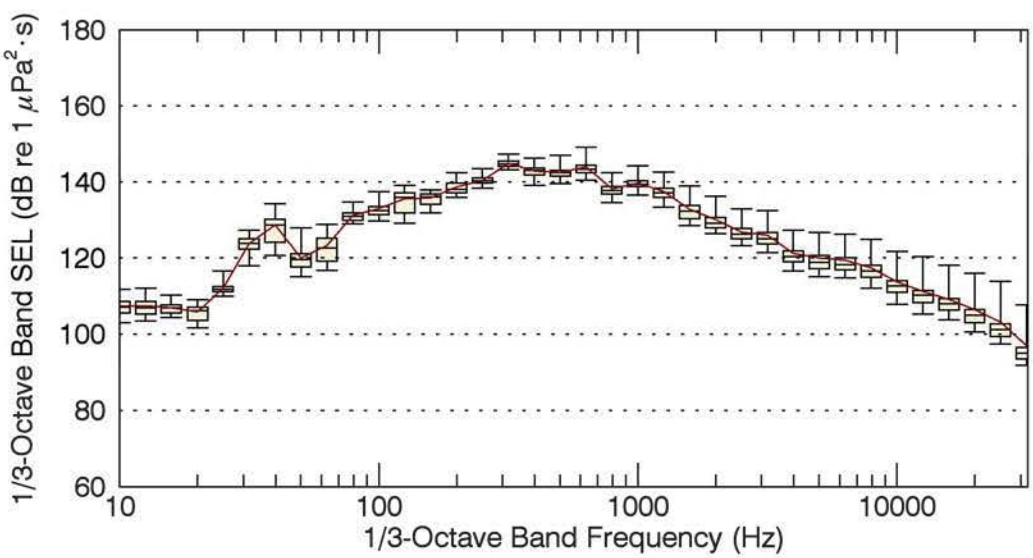


Figure D-16. Plot of 1/3-octave band SEL statistics for impact driving of Pile 1, recorded at 949 m range from Ketchikan ferry terminal.

D.5.2. Vibratory Driving

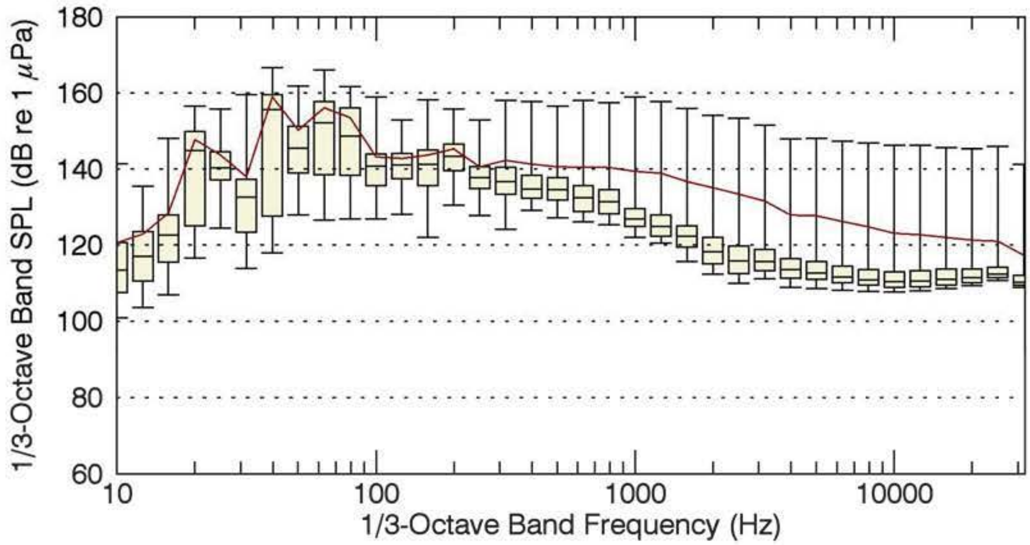


Figure D-17. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 2, recorded at 17.3 m range from Ketchikan ferry terminal.

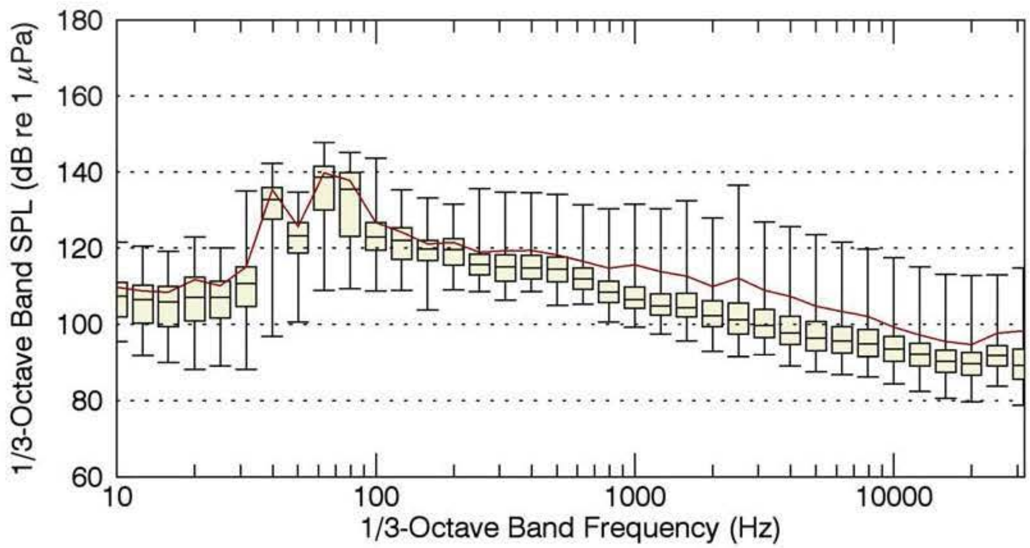


Figure D-18. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 2, recorded at 948 m range from Ketchikan ferry terminal.

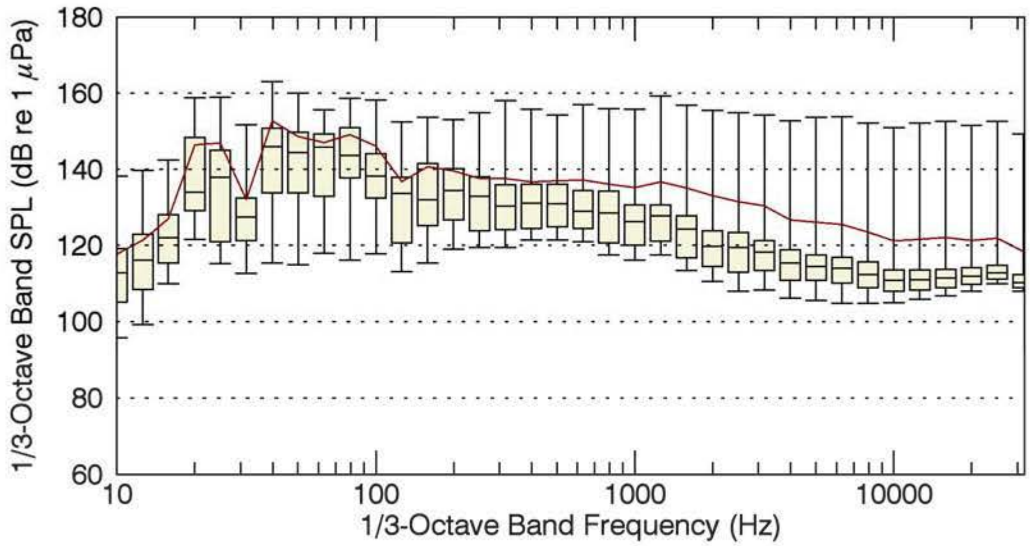


Figure D-19. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 1, recorded at 18.4 m range from Ketchikan ferry terminal.

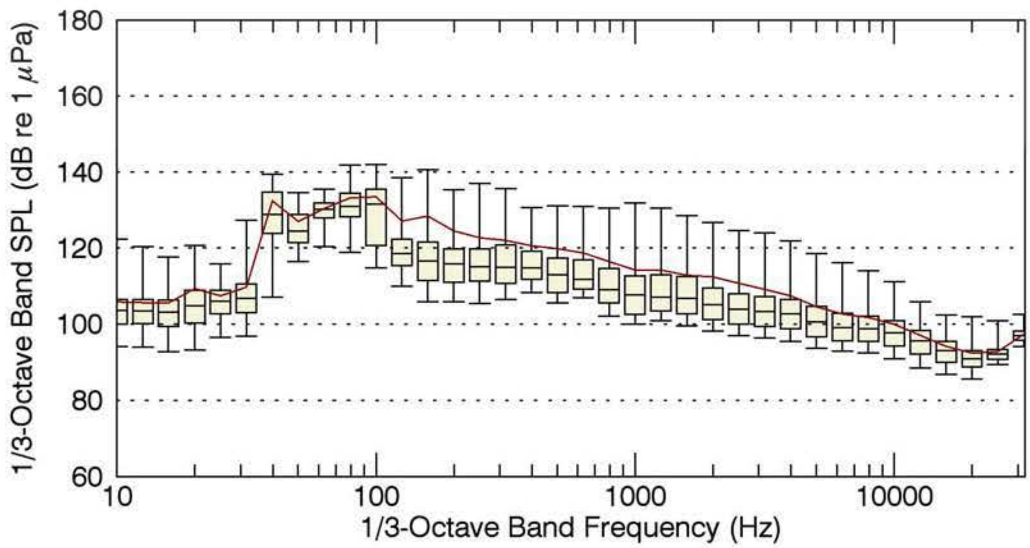


Figure D-20. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 1, recorded at 949 m range from Ketchikan ferry terminal.

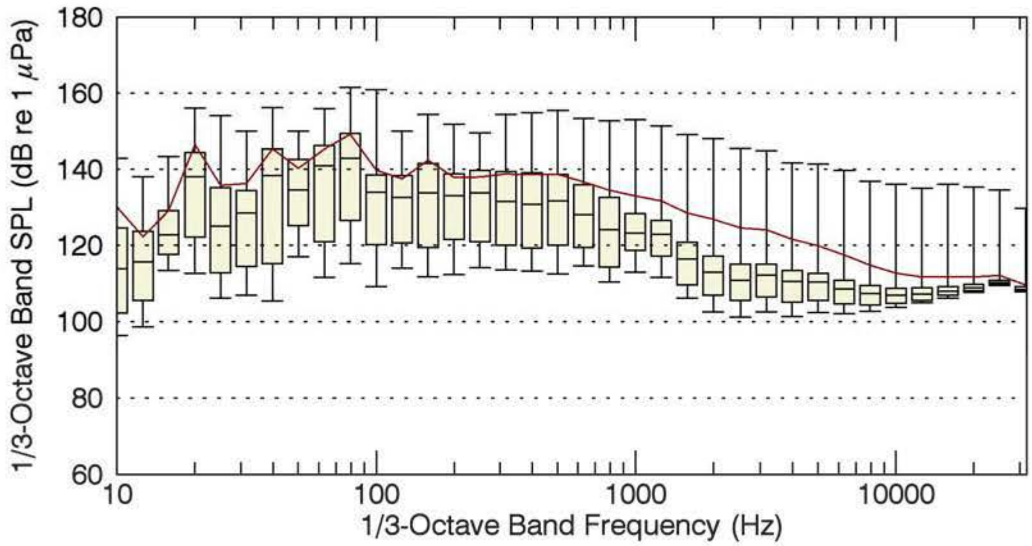


Figure D-21. Plot of 1/3-octave band SPL statistics for vibratory driving of Pile 3, recorded at 16.3 m range from Ketchikan ferry terminal.

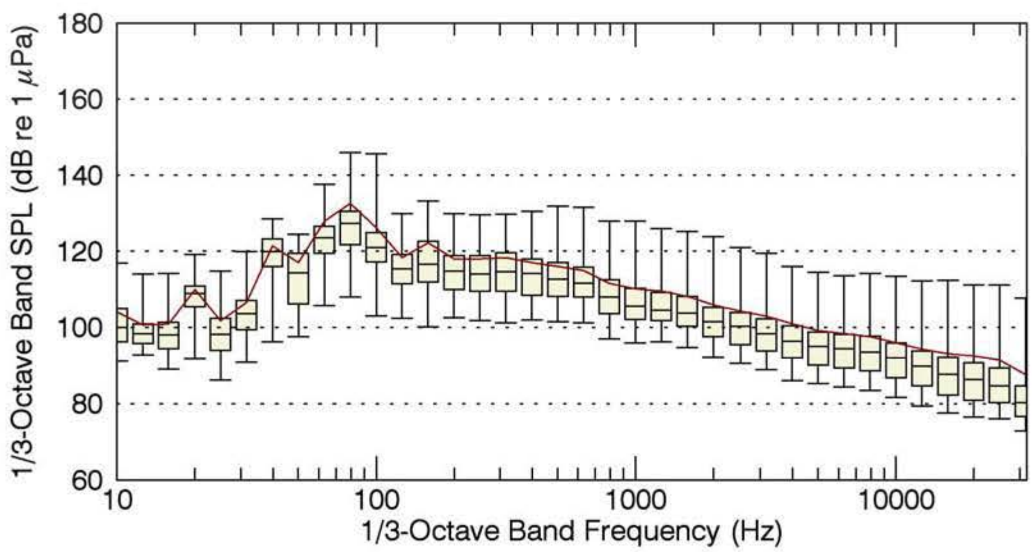


Figure D-22. Plot of 1/3-octave band SPL statistics for vibratory driving Pile 3, recorded at 947 m range from Ketchikan ferry terminal.

D.6. Background Noise Levels

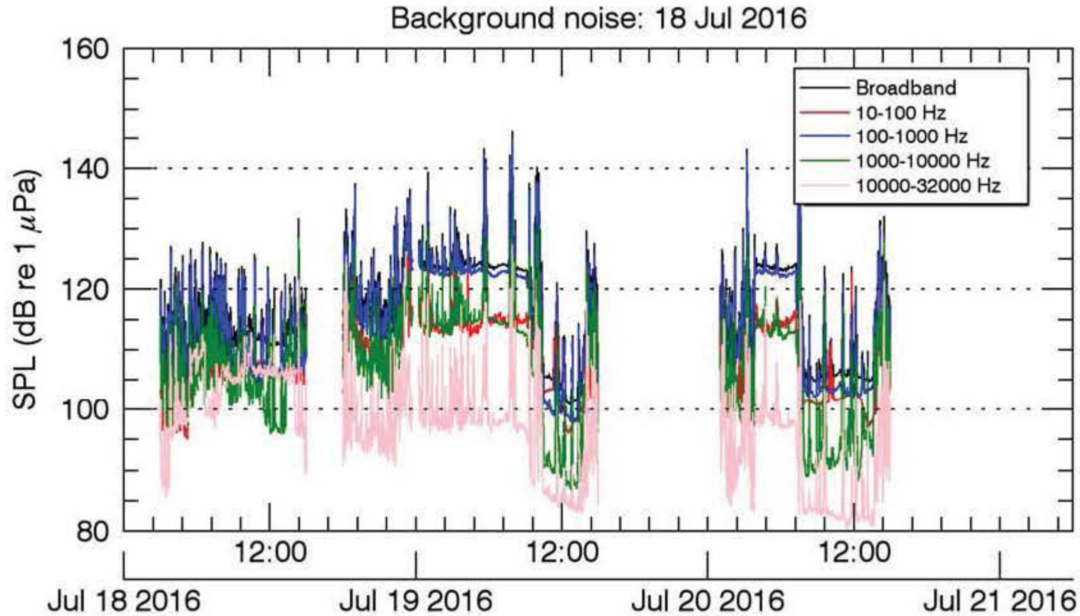


Figure D-23. Background SPL versus time (UTC) recorded on AMAR 2 (60 s average). Periods containing construction activity were removed. Peaks in the level versus time plot correspond to vessels passing close to the AMAR.

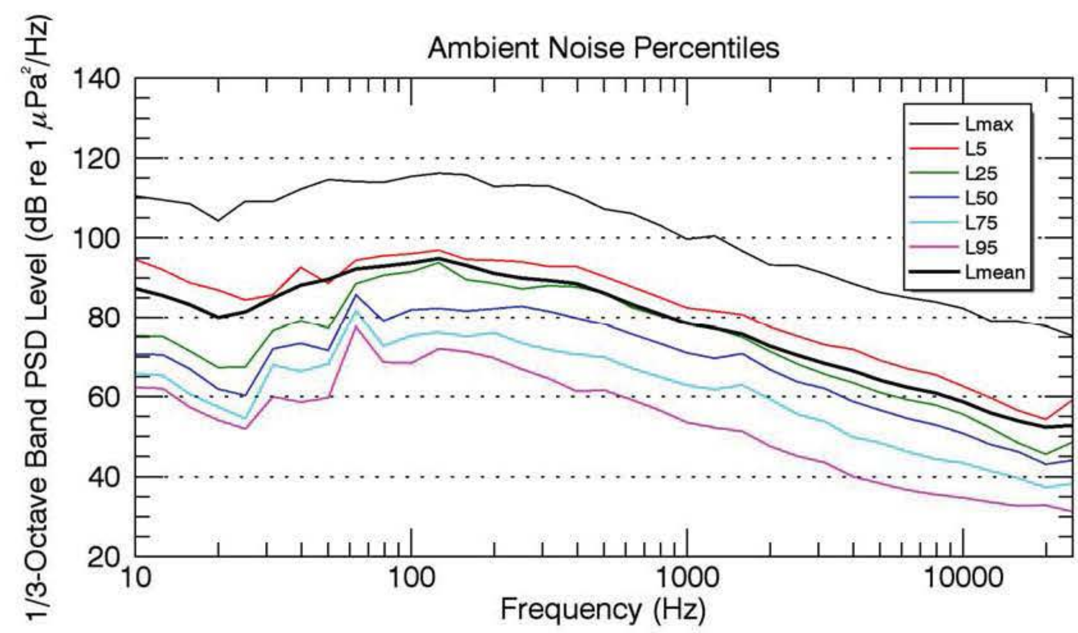


Figure D-24. Exceedance levels of 1/3-octave band background noise levels recorded on AMAR 2. The Ln value is the SPL exceeded by n% of the data. Periods containing construction activity have been removed.

Table D-2. Exceedance levels of background noise levels measured at Ketchikan, Alaska (60 s average). The Ln value is the SPL exceeded by n% of the data. Unw = unweighted, LFC = low-frequency cetaceans, MFC = mid-frequency cetaceans, HFC = high-frequency cetaceans, PPW = phocid pinnipeds in water, OPW = otariid pinnipeds in water.

Exceedance level	SPL (dB re 1 µPa)					
	Unw	LFC	MFC	HFC	PPW	OPW
L_5	128.7	126.4	110.1	108.9	119.0	119.0
L_{25}	123.6	121.5	105.1	103.2	113.5	113.6
L_{50} (median)	117.4	115.2	100.2	97.2	108.6	108.7
L_{75}	111.5	107.8	93.5	91.3	102.4	102.2
L_{95}	105.0	100.3	83.0	81.4	90.8	90.6
L_{mean}	125.0	122.5	106.0	104.2	114.6	114.6

D.7. Broadband-discounted SEL and Weighted SEL Differences

The NMFS Optional User Spreadsheet provides Weighting Function Adjustments (WFA) for estimating weighted SEL from unweighted SEL. The broadband SEL corrected with the WFA and the functional hearing group weighted SELs were compared. NMFS suggests that estimates generated by using the spreadsheet will conservatively estimate injury zones; however, this was not always the case. The WFA discounted SELs for the HFC functional hearing group were often lower, and therefore less conservative, than the frequency weighted SELs. Additionally, comparing the two calculations across functional hearing groups, illustrated a range of differences that exceeded 10 dB.

Table D-3. Difference between mean broadband-discounted SEL and weighted SEL for impact piling 30" diameter steel piles.

Pile	Hearing Group	AMAR 1	AMAR 2
1	LFC	0.7	1.1
	MFC	3.1	9.4
	HFC	-1.3	7
	PPW	5.6	7.9
	OPW	6	8.9
2	LFC	0.8	1
	MFC	2.6	7.6
	HFC	-2	5
	PPW	5.9	8
	OPW	6.5	9.1
3	LFC	0.8	1.1
	MFC	3.5	8.5
	HFC	-1.1	5.8
	PPW	6.8	8.4

Pile	Hearing Group	AMAR 1	AMAR 2
	OPW	7.5	9.6

Table D-4. Difference between mean broadband-discounted SEL and weighted SEL for vibratory piling 30" diameter steel piles.

Pile	Hearing group	AMAR 1	AMAR 2
1	LFC	8.2	6.9
	MFC	10.8	16.2
	HFC	6.4	12.4
	PPW	15.6	17.9
	OPW	16.1	19.4
2	LFC	8.8	9
	MFC	15	19
	HFC	10.9	14.8
	PPW	17.8	21.2
	OPW	18.5	23
3	LFC	6.5	6.7
	MFC	16	16.4
	HFC	12.3	12.5
	PPW	16.1	18
	OPW	17.2	19.7

Appendix E. Pile Driving Logs

E.1. Kake

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES

PILE DRIVING RECORD

Sheet 1 of

FORMULA USED TO DETERMINE BEARING

P =

INSTR: A SKETCH SHOWING THE LOCATION OF THE PILES BY NUMBER SHALL BE DRAWN ON THE BACK OF THIS FORM OR ON AN ATTACHED SHEET

STRUCTURE NAME	CONTRACTOR	PROJECT NAME	BRIDGE NUMBER
Kake Ferry Terminal	Tamico, Inc	Kake Ferry Terminal Improvements	

PROJECT NO	DISTRICT	TYPE OF BRIDGE
68238	Southcoast	

TYPE OF HAMMER	MANUFACTURER	WT OF RAM OR GRAVITY HAMMER	STROKE LENGTH MAX	NO. BLOWS PER MIN	MFG'S MAX. ENERGY RATING
IMPACT	DELMAG D19-42	8,365 lbs	3.2 / 10.5 ft		42,480 lbs

DATE	ABUTMENT OR PIER NO	PILE NO	TYPE OF PILE (specify tip & butt, diameter of timber & concrete pile in inches)	LENGTH PLACED IN LEADS INCLUDING EXTENSIONS (FT)	CUTOFF LENGTH (FT)	NET LENGTH CUTOFF TO TIP (FT)	PENETRATION IN GROUND (FT)	PILE CUTOFF ELEV	OBSERVED GROUND ELEV	PILE TIP ELEV	DROP OF HAMMER (INCHES)	AVG PENETRATION LAST 5 BLOWS	COMPUTED BEARING (TONS)	REMARKS SPECIFY BATTER IF ANY. HOW DID PILE DRIVE; SPECIFY SPLICES, CORE STOPPERS, EXTENSION LENGTHS USED
9/12	"KING"	RW	30")	93.8"	12'8"	81'	22.9"	+31°	-27.1"	-50'				
9/12	"	RE	30"	93'8"	13'8"	80'	19'8"	+31°	-29'2"	-49'				

PREPARED BY NAME	DATE	CHECKED BY NAME	DATE	TOTAL LENGTH FURNISHED
Robert Lacey	9/12/15	[illegible]	9/17/15	161.0 L.F.

25D-099

25D–186
(5/83)

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION
AND PUBLIC FACILITIES

1. Print entries in ink.
2. Original remains in book.

INSPECTOR'S DAILY REPORT

FMS No.

Project No: 68238	Project Name: KAKE FERRY TERMINAL IMPROVEMENTS

Weather: P. CLOUDY 55° SAT.	Shift: 7:00AM to 6:00PM	Contractor's Representative and Title: JIMMY MARTINSEN / TAMCO

Contractor's Equipment

No.	Description or Type	Size or Capacity	Hours Worked	Hours Stdby	Hours Down	Remarks
1	CRANE/BARGE	110'				DONNA ANN
1	TUG					JODY ANN
1	HPSI	260				VIB.
1	DELMAG	D19-42				HAMMER
1	CAT X	324D				JAMES DEAN

Contractor's Work Force

No.	Classification/Duties
	ROBERT – FOREMAN
	" – CRANE
	BRIAN > LA
	"
	RYAN – WELDER
MAMM.	CHARLIE
SURV.	GEORGE

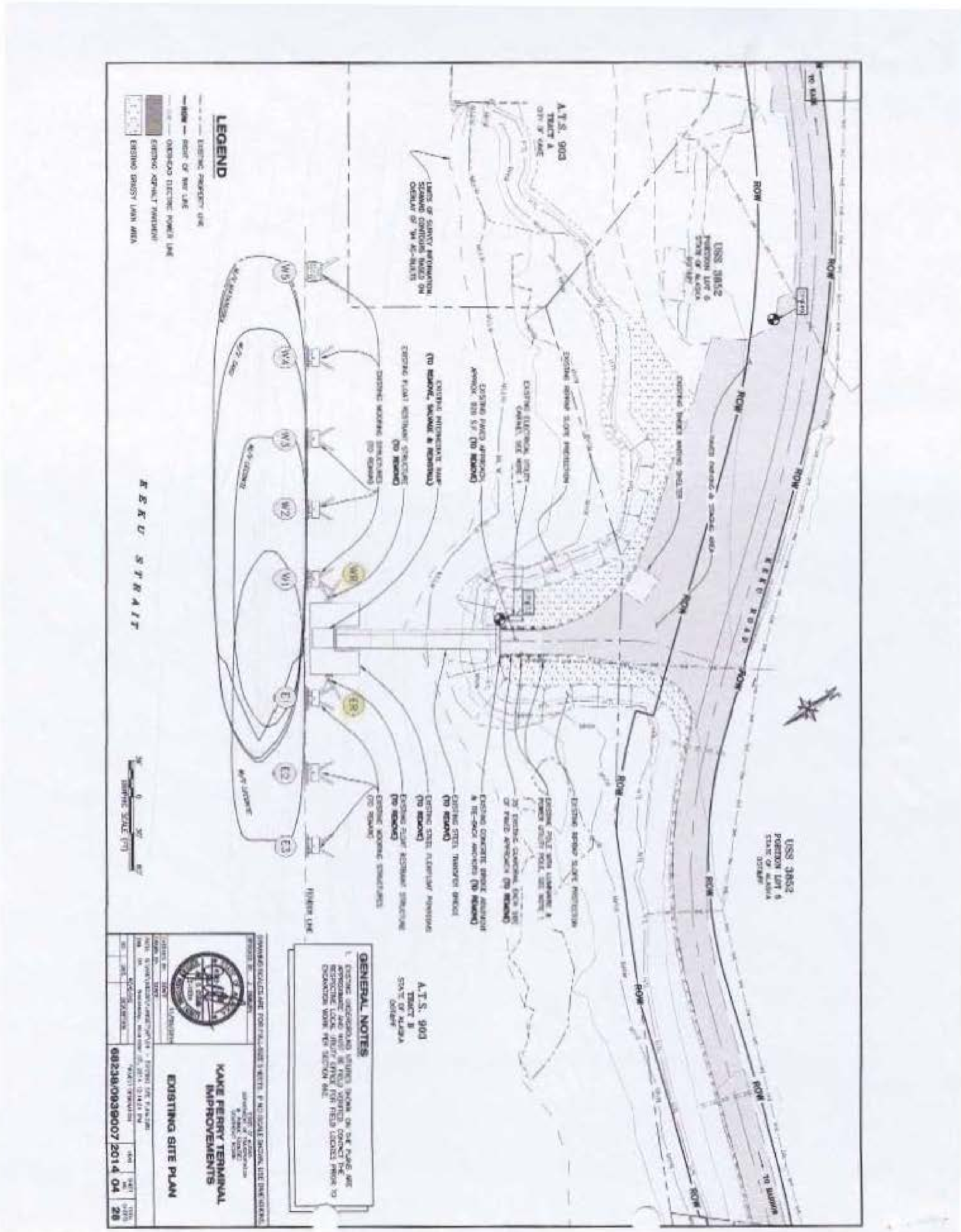
Limits of Work/Material Placement

Item No.	Description	Source (Limits) From	Source (Limits) To	Placement (Limits) From	Placement (Limits) To	Approx. Quantity	Sections/Work Completed & Accepted
505(2)	30" x 93' "KING" PILES DRIVEN =	(RW) = CUTOFF ELEV. = 31.0 FT, PILE CUTOFF @ 81.0 FT = TIP ELEV. = -50.0 FT, NET PILE LENGTH = 81'0"					
		(RE) = TIP ELEV. = -49.0 FT, NET PILE LENGTH = 80.0 FT, CUTOFF @ 80 FT					
	AS OF 9:45 AM THIS DAY —	RW = 20', RE = 19' > VIBED TO REFUSAL.					

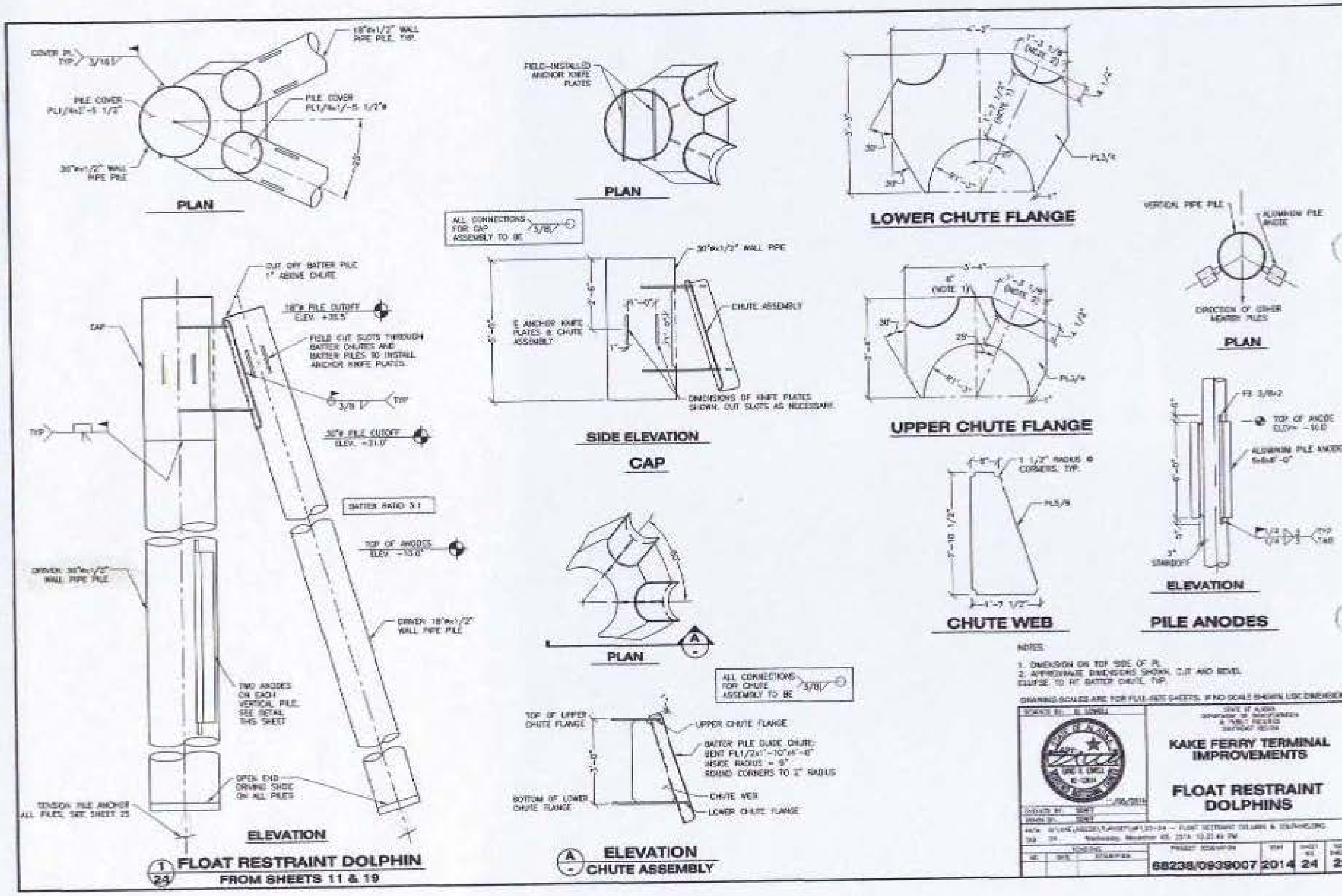
DIARY: (Include report of day's operations, contractor's production rates and efficiency, unusual conditions or problems encountered, orders given and received, discussions with contractor, etc.) ARRIVE ON SITE @ 7:00AM, CREW ON BOARD BARGE.- HAMMER LOOKS "NOT" TO BE FIXED @ THIS TIME – 7:15AM, CREW PREPS TO MOVE BARGE → "RW" POSITION, WILL PULL 30" THERE, MOVE IT TO NEW POSITION & VIB.– THIS, WHILE HAMMER IS WORKED ON – 7:45AM, BARGE @ "RW" POSITION – CHARLIE ON SITE – 8:10AM, VIB IS UP TO MOVE "RW" TO THE NEW POSITION – 9:20AM, CREW IS IN A STRUGGLE TO GET "RW" POSITIONED – 9:45AM, RW IS VIBED IN → 20' – WORK NOW IS FOCUSED ON HAMMER REPAIR, ALSO, JIMMY IS CHANGING THE BRAKES OUT ON CRANE. 10:15AM, JIMMY MOVES TO HELP GEORGE STAKE TOE OF RIP RAP, WHILE OTHERS WORK ON BRAKES – 12:00PM, LUNCH – 1:20PM, ALL HANDS ON DECK, BEGIN DRIVING @ RW – DRIVING ENDS @ 1:35PM – PREP TO CUT PILE OFF @ +31.0 FT / @ 81.0 FT – 3:05PM RW IS CUT OFF, BARGE IS ON THE MOVE → RE @ 3:15PM – BEGIN DRIVING @ RE @ 4:40PM — RE DRIVEN 8" TO BEDROCK @ 4:49PM — BEGIN PILE CUT-OFF – PILE CUT OFF & PREPED – 6:00PM, CREW RETREATS TO BARGE FOR CLEAN-UP — END DAY @ 6:00PM ⟶

Date: 9/12/15	Inspector's Signature: Robert L. Laay	Page No.: 1 OF 1

118805



LEGEND
GENERAL NOTES
KEKU STRAIT
A.T.S. 903
USS 3852
W5
W4
W3
W2
W1
E1
E2
E3
KAKE FERRY TERMINAL IMPROVEMENTS
EXISTING SITE PLAN
2014 04 28


PLAN
PLAN
LOWER CHUTE FLANGE
SIDE ELEVATION
CAP
UPPER CHUTE FLANGE
PLAN
ELEVATION
CHUTE WEB
PILE ANODES
PLAN
ELEVATION
FLOAT RESTRAINT DOLPHIN
FROM SHEETS 11 & 19
ELEVATION
CHUTE ASSEMBLY
KAKE FERRY TERMINAL IMPROVEMENTS
FLOAT RESTRAINT DOLPHINS
68238/0939007
2014
24
28

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES

PILE DRIVING RECORD

Sheet ___ of ___

FORMULA USED TO DETERMINE BEARING

P = ______

INSTR: A SKETCH SHOWING THE LOCATION OF THE PILES BY NUMBER SHALL BE DRAWN ON THE BACK OF THIS FORM OR ON AN ATTACHED SHEET

STRUCTURE NAME	CONTRACTOR	PROJECT NAME	BRIDGE NUMBER
W-1	Manson	Auke Bay Ferry Terminal	

PROJECT NO	DISTRICT	TYPE OF BRIDGE
67463	SCR	Fender Mooring Dolphin

TYPE OF HAMMER	MANUFACTURER	WT OF RAM OR GRAVITY HAMMER	STROKE LENGTH MAX	NO. BLOWS PER MIN	MFG'S MAX. ENERGY RATING
Vibratory	APE Vibratory 200-6	N/A	N/A	N/A	N/A

DATE	ABUTMENT OR PIER NO	PILE NO	TYPE OF PILE (specify tip & butt, diameter of timber & concrete pile in inches)	LENGTH PLACED IN LEADS INCLUDING EXTENSIONS (FT)	CUTOFF LENGTH (FT)	NET LENGTH CUTOFF TO TIP (FT)	PENETRATION IN GROUND (FT)	PILE CUTOFF ELEV	OBSERVED GROUND ELEV	PILE TIP ELEV	DROP OF HAMMER (INCHES)	AVG PENETRATION LAST 5 BLOWS	COMPUTED BEARING (TONS)	REMARKS SPECIFY BATTER IF ANY. HOW DID F DRIVE; SPECIFY SPLICES, CORE STOPPERS, EXTENSION LENGTHS USED
11-20	W-1	Batter #1	20"x½" pipe pile	141	8.0	133	39.6	32.6	-58	-96.4	N/A			BATTER 1:4
11-21	W-1	Batter #2	20"x½" pipe pile	142	12.0	130	43.8	32.6	-51	-93.5	N/A			

PREPARED BY NAME	DATE	CHECKED BY NAME	DATE	TOTAL LENGTH FURNISHED
CA Brennan	12-1-15	R. JOHNSTON	12/03/15	203.0 LF

25D-099

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

PILE DRIVING DATA SHEET

SHEET 1 OF 1

PROJECT NAME: Auke Bay Ferry Terminal Improvements — Proj. 67463

CONTRACTOR: Manson Const. Co. — INSPECTOR: C.A. Bowman

STRUCTURE TYPE: Floating Fender Dolphin — PILE LOCATION: W-1 Batter #1 (outer)

PILE
- TYPE: wall pipe pile
- DIA: 20" WALL: 1/2" TIP DIAMETER: 20 BUTT DIAMETER:
- LENGTH IN LEADS: 141 ft. 0 in. WEIGHT (or approx): lbs.
- FOLLOWER (type, weight, length):

HAMMER
- MAKE / MODEL / TYPE: APE 200-6 Vibe
- RATED STROKE: ft. RATED ENERGY: ft.lbs.
- RAM WEIGHT: lbs. RAM LENGTH:
- MODIFICATIONS / CONDITION:

PENETRATION
- TOTAL LENGTH IN PLACE: 133 ft. in. TOTAL PENETRATION: 39.6 ft.
- CUTOFF ELEV: +32.6 TIP ELEV: -96.4' GROUND ELEV: -58

HAMMER CUSHION
- MATERIAL:
- THICKNESS: AREA:
- MODULUS ELASTICITY: COEFFICIENT of RESTITUTION:

PILE CAP
- TYPE (helmet bonnet anvil block drivehead): WEIGHT:

REMARKS: cutoff at 133' mark

START DATE: 11-20-15 START TIME: 8:30 a.m. FINISH DATE: 11-20-15 FINISH TIME: 8:35 a.m. TOTAL DRIVING TIME: 5 min

FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
0-45 Vibe													

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

All Piles Had Shoes

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

PILE DRIVING DATA SHEET

SHEET 1 OF 1

PROJECT NAME: Auke Bay Ferry Terminal Improvements
PROJECT NUMBER: 67463

CONTRACTOR: Manson
INSPECTOR: CA Bowman

STRUCTURE TYPE: Floating Fender Dolphin
PILE LOCATION: W-1 Batter #2

PILE
TYPE: wall pipe pile
DIA: 20" WALL: 1/2" TIP DIAMETER: 20" BUTT DIAMETER:
LENGTH IN LEADS: 142 ft. 4" in. WEIGHT (or approx): lbs.
FOLLOWER (type, weight, length):

HAMMER
MAKE / MODEL / TYPE: APE Vibehammer 200-6
RATED STROKE: ft. RATED ENERGY: ft.lbs.
RAM WEIGHT: lbs. RAM LENGTH:
MODIFICATIONS / CONDITION:

PENETRATION
TOTAL LENGTH IN PLACE: 130 ft. 0 in. TOTAL PENETRATION: 43.8 ft. in.
CUTOFF ELEV: +32.6 TIP ELEV: -93.5 GROUND ELEV: -51

HAMMER CUSHION
MATERIAL:
THICKNESS: AREA:
MODULUS ELASTICITY: COEFFICIENT of RESTITUTION:

PILE CAP
TYPE (helmet bonnet anvil block drivehead): WEIGHT:

REMARKS: Pile viced in 11/19/15, then pulled on 11/20/15, re booted + re driven

START DATE: 11/19/15
START TIME: 3:34 PM / 9:14 a.m. p.m.
FINISH DATE: 11/20/15
FINISH TIME: 3:41 PM / 9:21 a.m. p.m.
TOTAL DRIVING TIME: 14 min

	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
11/19	0-42'		Vibed 3:34 to 3:41 PM											
11/20	0-48		Vibed 9:14 to 9:21 AM											

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

ALL PILES HAD SHOES

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES

PILE DRIVING RECORD

Sheet of

FORMULA USED TO DETERMINE BEARING

P =

INSTR: A SKETCH SHOWING THE LOCATION OF THE PILES BY NUMBER SHALL BE DRAWN ON THE BACK OF THIS FORM OR ON AN ATTACHED SHEET

STRUCTURE NAME	CONTRACTOR	PROJECT NAME	BRIDGE NUMBER
E-4 Mooring Dolphin	**Manson**	**Auke Bay Ferry Terminal Improvements**	

PROJECT NO	DISTRICT	TYPE OF BRIDGE
67463	Southcoast	Mooring Dolphin

TYPE OF HAMMER	MANUFACTURER	WT OF RAM OR GRAVITY HAMMER	STROKE LENGTH MAX	NO. BLOWS PER MIN	MFG'S MAX. ENERGY RATING
IMPACT	IHC SC-200	30.1 KIPS	5.0 ft	MAX = 38	153. KIP-ft

DATE 2015	ABUTMENT OR PIER NO	PILE NO	TYPE OF PILE (specify tip & butt, diameter of timber & concrete pile in inches)	LENGTH PLACED IN LEADS INCLUDING EXTENSIONS (FT)	CUTOFF LENGTH (FT)	NET LENGTH CUTOFF TO TIP (FT)	PENETRATION IN GROUND (FT)	PILE CUTOFF ELEV	OBSERVED GROUND ELEV	PILE TIP ELEV	DROP OF HAMMER (INCHES)	AVG PENETRATION LAST 5 BLOWS	COMPUTED BEARING (TONS)	REMARKS SPECIFY BATTER IF ANY. HOW DID DRIVE; SPECIFY SPLICES, CORE STOPPERS, EXTENSION LENGTHS USED
11/10	E4	V1	30"x34 Pipe Pile	187.8"	1.33	186.5	101.5	+27	-58'	-158.5'	60"			
11/11	E4	V3	30"x34"	"	187.8	1.17	185.5	101.5	+27	-58'	-158.5	60'		
11/11	E4	V2	"	"	187.8	1.17	186.5	101.5	+27	-58'	-158.5	60'		

PREPARED BY NAME	DATE	CHECKED BY NAME	DATE	TOTAL LENGTH FURNISHED
CA Bowman	11-13-15	R. Johnston	12/03/15	558.5 LF

25D-099

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

LE DRIVING DATA SHEET

SHEET 1 OF 1

PROJECT NAME: Auke Bay Ferry Terminal Improvements — PROJECT NUMBER: 67463

CONTRACTOR: Manson — INSPECTOR: CA Bowman

STRUCTURE TYPE: — PILE LOCATION: E4 V1

PILE
- TYPE: wall pipe pile
- DIA: 30" — WALL: 3/4" — TIP DIAMETER: 30" — BUTT DIAMETER:
- LENGTH IN LEADS: 187 ft. 10 in. — WEIGHT (or approx): lbs.
- FOLLOWER (type, weight, length):

HAMMER
- MAKE / MODEL / TYPE: IHC, SC 200
- RATED STROKE: 5.0 ft. — RATED ENERGY: 153 kip ft.
- RAM WEIGHT: 30.1 kips — RAM LENGTH:
- MODIFICATIONS / CONDITION: STROKE LENGTH AVG. 2.2'

PENETRATION
- TOTAL LENGTH IN PLACE: 186 ft. 6 in. — TOTAL PENETRATION: 101 ft. 6 in.
- CUTOFF ELEV: +27 — TIP ELEV: -159.5 — GROUND ELEV: -58

REMARKS: 16" cutoff

HAMMER CUSHION
- MATERIAL:
- THICKNESS: — AREA:
- MODULUS ELASTICITY: — COEFFICIENT of RESTITUTION:

PILE CAP
- TYPE (helmet bonnet anvil block drivehead): — WEIGHT:

START DATE: 11-10-15 — START TIME: 3:02 p.m. — FINISH DATE: 11-12-15 — FINISH TIME: 3:04 p.m. — TOTAL DRIVING TIME: 29 min

FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
0-	91'	Vibed in w/ APE200						92	1		Restrike		
		From 5:21 PM to 5:50						93	0		11-12-15		
		accual drive time 23 min						94	0		3:16 PM to 3:20		
								95	0				
								96	0			99	
								97	0			100	
								98	10			101	37
								98.7	10			101.5	

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

When the IHC SC 200 was put on pile on 11-11-15 a single blow dropped the pile aprox 6 ft.
24 hrs later they re struck the pile with PDA attached from 3:16 to 3:20 PM.

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

[PI]LE DRIVING DATA SHEET

SHEET 1 OF 1

PROJECT NAME: Auke Bay Ferry Terminal Improvements	PROJECT NUMBER: 67463
CONTRACTOR: Manson	INSPECTOR: CA Bowman
STRUCTURE TYPE: Fender Mooring Dolphin	PILE LOCATION: E4 - V2

PILE
- TYPE: wall pipe pile
- DIA: 30" | WALL: 3/4" | TIP DIAMETER: 30 | BUTT DIAMETER:
- LENGTH IN LEADS: 187 ft 10 in. | WEIGHT (or approx): lbs.
- FOLLOWER (type, weight, length):

HAMMER
- MAKE / MODEL / TYPE: IHC SC 200 Impact
- RATED STROKE: 5.0 ft. | RATED ENERGY: 153 Kip ft.lbs.
- RAM WEIGHT: 30.1 Kip lbs. | RAM LENGTH:
- MODIFICATIONS / CONDITION: Stroke Length Avg. 2.2'

PENETRATION
- TOTAL LENGTH IN PLACE: ✓ 186 ft 6 in. | TOTAL PENETRATION: ✓ 101 ft 6 in.
- CUTOFF ELEV: +27 ✓ | TIP ELEV: -159.5 ✓ | GROUND ELEV: -58 ✓

HAMMER CUSHION
- MATERIAL:
- THICKNESS: | AREA:
- MODULUS ELASTICITY: | COEFFICIENT of RESTITUTION:

REMARKS: Total of 16" cutoff

PILE CAP TYPE (helmet bonnet anvil block drivehead): | WEIGHT:

START DATE:	START TIME:	FINISH DATE:	FINISH TIME:	TOTAL DRIVING TIME:
11-11-15	10:31 a.m. p.m.	11-12-15	10:57 a.m. p.m.	

FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
0 -	86	Vibed in	w/ APE 200					87	22	98	12		
		10:31	to	10:57				88	16	99	15		
								89	18	100	19		
								90	13	101	19		
								91	14	101.5	9		
								92	20				
								93	21				
								94	16				
								95	13				
								96	15				
								97	15				

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

The IHC SC200 impact hammer started at 3:06 PM and ended at 3:19 PM

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

LE DRIVING DATA SHEET

SHEET 1 OF 1

PROJECT NAME: Auke Bay Ferry Terminal Improvements	PROJECT NUMBER: 67463
CONTRACTOR: Manson	INSPECTOR: CA Bowman
STRUCTURE TYPE: Fender Mooring Dolphin	PILE LOCATION: E4 V3

PILE

- TYPE: wall pipe pile
- DIA: 30"
- WALL: 3/4"
- TIP DIAMETER: 30
- BUTT DIAMETER:
- LENGTH IN LEADS: 187 ft. 10 in.
- WEIGHT (or approx): lbs.
- FOLLOWER (type, weight, length):

HAMMER

- MAKE / MODEL / TYPE: IHC SC 200 Impact
- RATED STROKE: 5.0 ft.
- RATED ENERGY: MAX 153 Kip·ft ~~ft-lbs~~
- RAM WEIGHT: 30.1 kips lbs.
- RAM LENGTH:
- MODIFICATIONS / CONDITION: stroke length avg. 2.2'

PENETRATION

- TOTAL LENGTH IN PLACE: 185 ft. 6 in.
- TOTAL PENETRATION: 100 ft. 6 in.
- CUTOFF ELEV: +27
- TIP ELEV: -158.5
- GROUND ELEV: -58'

HAMMER CUSHION

- MATERIAL:
- THICKNESS:
- AREA:
- MODULUS ELASTICITY:
- COEFFICIENT of RESTITUTION:

PILE CAP

- TYPE (helmet bonnet anvil block drivehead):
- WEIGHT:

REMARKS: 1.0' cut off = 186.9'
7" cut off = 186.5

START DATE:	START TIME:	FINISH DATE:	FINISH TIME:	TOTAL DRIVING TIME:
11-11-15	1154 a.m. p.m.	11-12-15	2:59 a.m. p.m.	52 min

	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
11/11	0-85'		Vibe in						86	49	97	15		
			8:01 AM to 8:26						87	76	98	16		
			24 min actual drive time						88	67	99	15		
									89	78	99.7	12		
								Paused →	90	82		Restrike		
									91	59	100.5	20		
									92	65				
									93	30				
									94	10				
									95	8				
									96	14				

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

1154 Impact hammer starts; stops at 2:10; starts again after adjustment at 2:55 to 2:59 finishes drive on 11-11-15
11-12-15 3:00 PM Restrike with PDA attached

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES

PILE DRIVING RECORD

Sheet 1 of 1

FORMULA USED TO DETERMINE BEARING

P =

INSTR: A SKETCH SHOWING THE LOCATION OF THE PILES BY NUMBER SHALL BE DRAWN ON THE BACK OF THIS FORM OR ON AN ATTACHED SHEET

STRUCTURE NAME	CONTRACTOR	PROJECT NAME	BRIDGE NUMBER
E-4 Mooring Dolphin	**Manson**	**Auke Bay Ferry Terminal Improvements**	

PROJECT NO	DISTRICT	TYPE OF BRIDGE
67463	SOUTH COAST REG	FLOATING FENDER DOLPHIN

TYPE OF HAMMER	MANUFACTURER	WT OF RAM OR GRAVITY HAMMER	STROKE LENGTH MAX	NO. BLOWS PER MIN	MFG'S MAX. ENERGY RATING
VIBRATORY / IMPACT	APE 200-6 VIBE / IHC SC-200-6	30.1 KIPS	5.9 Ft	MAX = 38	153 KIP-Ft

DATE	ABUTMENT OR PIER NO	PILE NO	TYPE OF PILE (specify tip & butt, diameter of timber & concrete pile in inches)	LENGTH PLACED IN LEADS INCLUDING EXTENSIONS (FT)	CUTOFF LENGTH (FT)	NET LENGTH CUTOFF TO TIP (FT)	PENETRATION IN GROUND (FT)	PILE CUTOFF ELEV	OBSERVED GROUND ELEV	PILE TIP ELEV	DROP OF HAMMER (INCHES)	AVG PENETRATION LAST 5 BLOWS	COMPUTED BEARING (TONS)	REMARKS SPECIFY BATTER IF ANY. HOW DID IT DRIVE; SPECIFY SPLICES, CORE STOPPERS, EXTENSION LENGTHS USED
11-17	E4	Batter #1	30"x3/4" pipe pile	219.5	16.5	203	116.6	+34	-48	-155.6	NA			BATTER 1:3
11-22	E4	Batter #2	30"x3/4" pipe pile	206	2.0	204	117.6	+34	-48	-159.6	NA			"
11-21	E4	Batter #3	30"x3/4" pipe pile	206	5.0	201	114.6	+34	-48	-156.55	N/A			"

PREPARED BY NAME	DATE	CHECKED BY NAME	DATE	TOTAL LENGTH FURNISHED
CA Bowman	12-1-15	R Johnson	12/02/15	608.00 LF

25D-099

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

…LE DRIVING DATA SHEET

SHEET 1 OF 2

PROJECT NAME: Auke Bay Ferry Terminal Improvements	PROJECT NUMBER:67463
CONTRACTOR: Manson	INSPECTOR: CA Bowman
STRUCTURE TYPE: Mooring Dolphin	PILE LOCATION: E4 Batter #1

PILE

- TYPE: wall pipe pile
- DIA: 30" WALL: 3/4" TIP DIAMETER: 30" BUTT DIAMETER:
- LENGTH IN LEADS: 206 ft. WEIGHT (or approx): lbs.
- FOLLOWER (type, weight, length):

HAMMER

- MAKE / MODEL / TYPE: APE 200-6 Vibe/Delmag 19
- RATED STROKE: 10.2 ft. RATED ENERGY: 42.8 ft.lbs.
- RAM WEIGHT: 4.0 lbs. RAM LENGTH:
- MODIFICATIONS / CONDITION:

PENETRATION

- TOTAL LENGTH IN PLACE: ft. in. TOTAL PENETRATION: ft. in.
- CUTOFF ELEV: +34' ✓ TIP ELEV: GROUND ELEV:

HAMMER CUSHION

- MATERIAL:
- THICKNESS: AREA:
- MODULUS ELASTICITY: COEFFICIENT of RESTITUTION:

PILE CAP

- TYPE (helmet bonnet anvil block drivehead): WEIGHT:

REMARKS: Pipe cut off at 203.5' mark 16' pipe spliced on = 219.5'

START DATE: 11/16/15 / 11/17/15 START TIME: 5:01 PM / 8:17 a.m. FINISH DATE: cont. FINISH TIME: 5:45 PM / 8:18 a.m. TOTAL DRIVING TIME: 75 min

	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
/16	0-56' penetration													
/17	56-93' penetration													
11/18	93-93.7			330 blows										

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

11/18/15 Manson crew uses Delmag 19 Impact hammer from 12:25 to 12:34 330 Blows only gain 0.4' penetration so they decide to use IHC SC-200 hammer to finish (see sheet 2)

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

PILE DRIVING DATA SHEET

SHEET 2 OF 2

PROJECT NAME: Auke Bay Ferry Terminal Improvements
PROJECT NUMBER: 67463

CONTRACTOR: Manson
INSPECTOR: CA Bowman

STRUCTURE TYPE: Mooring Dolphin
PILE LOCATION: E4 Batter #1

PILE
TYPE: wall pipe pile
DIA: 30" WALL: 3/4" TIP DIAMETER: 30" BUTT DIAMETER:
LENGTH IN LEADS: 219.5 ft. WEIGHT (or approx): lbs.
FOLLOWER (type, weight, length):

HAMMER
MAKE / MODEL / TYPE: IHC SC-200 Impact
RATED STROKE: 5.0 max ft. RATED ENERGY: 153 Kips ft.lbs.
RAM WEIGHT: 30.1 Kips lbs. RAM LENGTH:
MODIFICATIONS / CONDITION:

PENETRATION
TOTAL LENGTH IN PLACE: ✓ 203 ft. in.
TOTAL PENETRATION: ✓ 116.6 ft.
CUTOFF ELEV: +34' ✓ TIP ELEV: ✓ 158.65 GROUND ELEV: ✓ -48'

HAMMER CUSHION
MATERIAL:
THICKNESS: AREA:
MODULUS ELASTICITY: COEFFICIENT of RESTITUTION:

PILE CAP
TYPE (helmet bonnet anvil block drivehead): WEIGHT:

REMARKS: 16.5' cut off leaving 203.0 in place

START DATE: 11/13/15 / 11/20/15
START TIME: 2:44 PM / 10:45 a.m.
FINISH DATE: 11-20-15
FINISH TIME: 3:02 / 11:01 a.m.
TOTAL DRIVING TIME: 34 min

FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
93.7	/			101	33								
94	3			102	51								
95	19			103	62								
96	21			104	108								
97	24			105	158								
98	40			106	104								
99	66			107	107								
100	52			108	132								
				109	137								

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:
All piles read sheet

ALASKA DEPT. OF TRANSPORTATION PUBLIC FACILITIES

LE DRIVING DATA SHEET

SHEET 1 OF 1

PROJECT NAME: Auke Bay Ferry Terminal Improvements		PROJECT NUMBER: 67483	
CONTRACTOR: Manson		INSPECTOR: CA Bowman	
STRUCTURE TYPE: Fender Mooring Dolphin		PILE LOCATION: E4 Batter # 2	
PILE	TYPE: wall pipe pile; DIA: 30"; WALL: 3/4"; TIP DIAMETER: 30"; BUTT DIAMETER:; LENGTH IN LEADS: 206 ft. in.; WEIGHT (or approx): lbs.; FOLLOWER (type, weight, length):	HAMMER	MAKE / MODEL / TYPE: APE Vibe Hammer 200-6; RATED STROKE: ft.; RATED ENERGY: ft.lbs.; RAM WEIGHT: lbs.; RAM LENGTH:; MODIFICATIONS / CONDITION:
PENETRATION	TOTAL LENGTH IN PLACE: 204 ft. in.; TOTAL PENETRATION: 117.6 ft. in.; CUTOFF ELEV: +34'; TIP ELEV: -159.6; GROUND ELEV: -48'	HAMMER CUSHION	MATERIAL:; THICKNESS:; AREA:; MODULUS ELASTICITY:; COEFFICIENT of RESTITUTION:
REMARKS:		PILE CAP	TYPE (helmet bonnet anvil block drivehead):; WEIGHT:

START DATE:	START TIME:	FINISH DATE:	FINISH TIME:	TOTAL DRIVING TIME:
11-22-15	7:38 AM	11-22-15	9:37 a.m. p.m.	74 min.

FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
0-		Vibe											

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

All Piles HAD SHOES

ALASKA DEPT. OF
TRANSPORTATION
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.E DRIVING DATA SHEET

SHEET 1 OF 1

PROJECT NAME: Auke Bay Ferry Terminal Improvements | PROJECT NUMBER: 67463

CONTRACTOR: Manson | INSPECTOR: CA Bowman

STRUCTURE TYPE: Fender Mooring Dolphin | PILE LOCATION: EH Batter #3

PILE
TYPE: wall pipe pile
DIA: 30" | WALL: 3/4" | TIP DIAMETER: 30" | BUTT DIAMETER:
LENGTH IN-LEADS: 206 ft. in. | WEIGHT (or approx): lbs.
FOLLOWER (type, weight, length):

HAMMER
MAKE / MODEL / TYPE: APE 200-6 Vibe Hammer
RATED STROKE: ft. | RATED ENERGY: ft.lbs.
RAM WEIGHT: lbs. | RAM LENGTH:
MODIFICATIONS / CONDITION:

PENETRATION
TOTAL LENGTH IN PLACE: ✓ 201 ft. in. | TOTAL PENETRATION: ✓ 114.6 ft.
CUTOFF ELEV: +31 | TIP ELEV: -156.75 | GROUND ELEV: -48

HAMMER CUSHION
MATERIAL:
THICKNESS: | AREA:
MODULUS ELASTICITY: | COEFFICIENT of RESTITUTION:

PILE CAP
TYPE (helmet bonnet anvil block drivehead): | WEIGHT:

REMARKS:

START DATE: 11-21-15 | START TIME: 9:46 a.m. p.m. | FINISH DATE: 11-21-15 | FINISH TIME: 11:45 a.m. p.m. | TOTAL DRIVING TIME: 87 min

FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT	FEET	BLOW COUNT
0 -	113		Vibe										

SPECIAL NOTES: describe jetting equipment if used, driving delays, boulders, drive shoes, banding, plumbness, alignment, equipment condition, etc.:

All PILES HAD SHOES

E.3. Kodiak

Pacific Pile&Marine

PILE DRIVINC .ECORD

Project: KODIAK FERRY TERMINAL	Prepared By: Eric Toussaint
Project No: 14017	Date: 3-2-16

Pile Type: Galvy Spiral Steel	Initial Length: 69' 3"	Pile #: D-22 3-2-16
Diameter: 24"	Cutoff Length: 14.3	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 55'	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15'	Cushion Block Type: Micarta
Template Elev: 12'	Tip Elev: -52'	Start Time Drill: 9:03
Mudline Elev: -25'	Embedded Length: ~~[illegible]~~ +27'	End Time Drill: 1:58
Bedrock Elev: -38'	Post-Drill Sounding Elev:	Post-Impact Sounding Elev: 68

Pile Type: Galvy Spiral Steel	Initial Length: 69' 3"	Pile #: D-20 3-4-16
Diameter: 24"	Cutoff Length: 10.55	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 59' 6"	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15'	Cushion Block Type: Micarta
Template Elev: 12'	Tip Elev: -56	Start Time Drill: 8:27
Mudline Elev: -25'	Embedded Length: 31'	End Time Drill: 10:24
Bedrock Elev: -38'	Post-Drill Sounding Elev:	Post-Impact Sounding Elev: 69.4

Pile Type: Galvy Spiral Steel	Initial Length: 69' 3"	Pile #: D-18
Diameter: 24"	Cutoff Length: 9.5	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 60' 3"	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15'	Cushion Block Type: Micarta
Template Elev: 12'	Tip Elev: -57'	Start Time Drill: 10:43
Mudline Elev: ~~[illegible]~~ -23	Embedded Length: 34'	End Time Drill: 12:09
Bedrock Elev: ~~[illegible]~~ 40	Post-Drill Sounding Elev:	Post-Impact Sounding Elev: 69.3

Pile Type: Galvy Spiral Steel	Initial Length: 69' 3"	Pile #: D-16
Diameter: 24"	Cutoff Length: 11.35	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 58'	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15'	Cushion Block Type: Micarta
Template Elev: +12	Tip Elev: -55'	Start Time Drill: 12:27
Mudline Elev: -22'	Embedded Length: 33'	End Time Drill: 1:55
Bedrock -39'		Post impact 68.2

Pacific Pile & Marine

PILE DRIVING RECORD

Project: KODIAK FERRY TERMINAL
Project No: 14017

Prepared By: Eric [illegible]
Date: 3-5-16

Pile Type: Spiral Galv Steel	Initial Length: 69' 3"	Pile #: D-15
Diameter: 24"	Cutoff Length: 14' 1"	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 55'	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15'	Cushion Block Type: Micarta
Template Elev: 12'	Tip Elev: 52'	Start Time Drill: 10:20
Mudline Elev: 23'	Embedded Length: 29'	End Time Drill: 11:51
Bedrock Elev: 38'	Post-Drill Sounding Elev:	Post-Impact Sounding Elev: 68

Pile Type: Galv Spiral Steel	Initial Length: 69' 3"	Pile #: D-14
Diameter: 24"	Cutoff Length: 13' 8"	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 56'	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15'	Cushion Block Type: Micarta
Template Elev: 12'	Tip Elev: -53	Start Time Drill: 12:10
Mudline Elev: 22'	Embedded Length: -31	End Time Drill: 1:53
Bedrock Elev: 38'	Post-Drill Sounding Elev:	Post-Impact Sounding Elev: 65.65

Pile Type: Galv Spiral Steel	Initial Length: 69' 3"	Pile #: D-13
Diameter: 24"	Cutoff Length: 14' 1"	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 55'	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15'	Cushion Block Type: Micarta
Template Elev: 12'	Tip Elev: 52'	Start Time Drill: 2:05
Mudline Elev: 23'	Embedded Length: 29'	End Time Drill: 3:17
Bedrock Elev: 40'	Post-Drill Sounding Elev:	Post-Impact Sounding Elev: 68

Pile Type: Galv Spiral Steel	Initial Length: 69' 3"	Pile #: D-12
Diameter: 24"	Cutoff Length: 16'	Hammer Type: ICE 44B Vibro / ICE I-36 Impact
Tip Type: internal Shoe	Final Length: 53'	Rated Energy: / 93,740 ft. lbs.
Coated Length: 69'	Cut Off Elev: 15	Cushion Block Type: Micarta
Template Elev: 12'	Tip Elev: -50'	Start Time Drill: 3:28
Mudline Elev: 24'	Embedded Length: -26'	End Time Drill: 4:38
Bedrock 39'		Post Sounding 68.18

E.4. Ketchikan

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES

PILE DRIVING RECORD

Sheet of

FORMULA USED TO DETERMINE BEARING

Ru = [1.75√Er log(10Nb)]-100

INSTR: A SKETCH SHOWING THE LOCATION OF THE PILES BY NUMBER SHALL BE DRAWN ON THE BACK OF THIS FORM OR ON AN ATTACHED SHEET

STRUCTURE NAME	CONTRACTOR	PROJECT NAME	BRIDGE NUMBER
W5, W6, & E6 Dolphins	Turnagain Marine Construction	Ketchikan Ferry Terminal	

PROJECT NO	DISTRICT	TYPE OF BRIDGE
SAMHS00015/0911007		

TYPE OF HAMMER	MANUFACTURER	WT OF RAM OR GRAVITY HAMMER	STROKE LENGTH MAX	NO. BLOWS PER MIN	MFG'S MAX. ENERGY RATING
Diesel Impact Hammer	Pileco	19,580 lbs.	10.5 FT	52	107,280 ft.lbs

DATE	ABUTMENT OR PIER NO	PILE NO	TYPE OF PILE (specify tip & butt, diameter of timber & concrete pile in inches)	LENGTH PLACED IN LEADS INCLUDING EXTENSIONS (FT)	CUTOFF LENGTH (FT)	NET LENGTH CUTOFF TO TIP (FT)	PENETRATION IN GROUND (FT)	PILE CUTOFF ELEV	OBSERVED GROUND ELEV	PILE TIP ELEV	DROP OF HAMMER (INCHES)	AVG PENETRATION LAST 5 BLOWS	COMPUTED BEARING (TONS)	REMARKS SPECIFY BATTER IF ANY. HOW DID PILE DRIVE; SPECIFY SPLICES, CORE STOPPERS, EXTENSION LENGTHS USED
	W5	V1	Pipe - 30" 1/2"WT	145	2	141	99.51	23		-119.51		.857 in	332.497	
	W5	V2	Pipe - 30" 1/2"WT	145	2	141	99.34	23		-119.34		1.09 in	323.047	
	W5	V3	Pipe - 30" 1/2"WT	145	2	141	99.495	23		-119.495		.80 in	335.158	
	W5	B1	Pipe - 30" 1/2"WT	155	4	151	101.68	30.03		-116.68		.60 in	346.06	
	W5	B2	Pipe - 30" 1/2"WT	155	4	151	99.12	30.03		-111.12		.375 in	363.254	
	W5	B3	Pipe - 30" 1/2"WT	155	4	151	99.80	30.03		-112.8		.2667 in	416.824	
	W6	V1	Pipe - 30" 1/2"WT	100	2	98	62.01	23		-77.01		1.5 in	310.188	
	W6	V2	Pipe - 30" 1/2"WT	100	2	98	61.04	23		-76.04		1.2 in	319.245	
	W6	B1	Pipe - 30" 1/2"WT	115	4	111	61.174	30.60		-76.1744		1.09 in	323.047	
	W6	B2	Pipe - 30" 1/2"WT	115	4	111	61.21	30.60		-76.21		.667 in	392.102	
	E5	V1	Pipe - 30" 1/2"WT	135										
	E5	V2	Pipe - 30" 1/2"WT	135										
	E5	B1	Pipe - 30" 1/2"WT	155										
	E5	B2	Pipe - 30" 1/2"WT	150										

PREPARED BY NAME	DATE	CHECKED BY NAME	DATE	TOTAL LENGTH FURNISHED

25D-099

Appendix F. Recording Parameters

Table F-1. Acoustic equipment recording parameters and sensitivities for each location and each recorder.

Recorder	Auke Bay	Kake	Ketchikan	Kodiak
1	AMAR (s/n 218)	AMAR (s/n 218)	AMAR (s/n 217)	AMAR (s/n 218)
	Sample rate: 64 ksps			
	Resolution: 24-bit			
	Geospectrum M8-K hydrophone (s/n 474)	Geospectrum M8-K hydrophone (s/n 474)	Geospectrum M36-V0-101 hydrophone (s/n A004595)	Geospectrum M36-V0-101 hydrophone (s/n A004595)
	Sensitivity: −210 dB//V/µPa (nominal)	Sensitivity: −210 dB//V/µPa (nominal)	Sensitivity: −220 dB//V/µPa (nominal)	Sensitivity: −220 dB//V/µPa (nominal)
	Deployment depth: 18 m	Deployment depth: 8 m	Deployment depth: 9.9 m	Deployment depth: 5 m
2	AMAR (s/n 217)	AMAR (s/n 217)	AMAR (s/n 218)	AMAR (s/n 217)
	Sample rate: 64 ksps			
	Resolution: 24-bit			
	Deployment depth: 47 m	Deployment depth: 30 m	Deployment depth: 28.3 m	Deployment depth: 15.2 m
	Channel 1			
	Geospectrum M36-V0 hydrophone (s/n A002571)	Geospectrum M8-E hydrophone (s/n 247)	Geospectrum M36-V0-100 hydrophone (s/n A004593)	Geospectrum M36-V0-100 hydrophone (s/n A002571)
	Sensitivity: −202 dB//V/µPa (nominal)	Sensitivity: −165 dB//V/µPa (nominal)	Sensitivity: −202 dB//V/µPa (nominal)	Sensitivity: −202 dB//V/µPa (nominal)
	Channel 2			
	Geospectrum M8-E hydrophone (s/n 247)	-	Geospectrum M8-E hydrophone (s/n 201)	Geospectrum M8-E hydrophone (s/n 222)

Recorder	Auke Bay	Kake	Ketchikan	Kodiak
	Sensitivity: −165 dB//V/µPa (nominal)	-	Sensitivity: −165 dB//V/µPa (nominal)	Sensitivity: −165 dB//V/µPa (nominal)
Dipping hydrophone	Sound Devices 722 hard drive recorder			
	Sample rate: 64 ksps			
	Resolution: 24-bit			
	Reson TC4043 hydrophone			
	Sensitivity: −201 dB//V/µPa (nominal)			
	Deployment depth: 6.1 m	Deployment depth: 6.5 m	Deployment depth: 6.1 m	Deployment depth: 6.1 m

Appendix G. Acoustic Metrics

Underwater sound amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 µPa. Because the perceived loudness of sound, especially impulsive noise such as from impact-hammer pile driving, 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.

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

$$\text{Peak level} = 10\log_{10}\left[\frac{\max\left(\left|p^2(t)\right|\right)}{p_0^2}\right] \quad \text{(G-1)}$$

At high intensities, the peak level can be a valid criterion for assessing whether a sound is potentially injurious; however, because the peak level does not account for the duration of a noise event, it is a poor indicator of perceived loudness.

The root-mean-square (rms) SPL (dB re 1 µPa) is the rms pressure level in a stated frequency band over a time window (T, s) containing the acoustic event:

$$\text{SPL} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \quad \text{(G-2)}$$

The SPL is a measure of the average pressure or of the effective pressure over the duration of an acoustic event, such as the emission of one acoustic pulse. Because the window length, T, is the divisor, events more spread out in time have a lower SPL for the same total acoustic energy density.

In studies of impulsive noise, T is often defined as the "90% energy pulse duration" (T_{90}): the interval over which the pulse energy curve rises from 5% to 95% of the total energy. The SPL computed over this T_{90} interval is commonly called the 90% SPL (dB re 1 µPa):

$$90\%\ \text{SPL} = 10\log_{10}\left(\frac{1}{T_{90}}\int_{T_{90}} p^2(t)dt \Big/ p_0^2\right) \quad \text{(G-3)}$$

The sound exposure level (SEL, dB re 1 µPa²·s) is a measure of the total acoustic energy contained in one or more (N) acoustic events. The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T_{100}):

$$\text{SEL} = 10\log_{10}\left(\int_{T_{100}} p^2(t)dt \Big/ T_0 p_0^2\right) \quad \text{(G-4)}$$

where T_0 is a reference time interval of 1 s. The SEL represents the total acoustic energy received at some location during an acoustic event; it measures the total sound energy to which an organism at that location would be exposed.

SEL can be calculated over periods with multiple acoustic events (e.g., multiple pile driving impulses) or over a fixed period. For multiple events, the SEL (dB re 1 μPa²·s) can be computed by summing (in linear units) the SELs of the *N* individual events:

$$\text{Cumulative SEL} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{\text{SEL}_i}{10}}\right) \quad \text{(G-5)}$$

Because the SPL and SEL are both computed from the integral of square pressure, these metrics are related by the following expression, which depends only on the duration of the energy time window *T*:

$$\text{SPL} = \text{SEL} - 10\log_{10}(T) \quad \text{(G-6)}$$

$$\text{SPL} = \text{SEL} - 10\log_{10}(T_{90}) - 0.458 \quad \text{(G-7)}$$

where the term −0.458 dB, which is $10\log_{10}(0.9)$, accounts for the SPL containing 90% of the total energy from the per-pulse SEL.

G.1. 1/3-Octave 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 is more meaningful to marine-mammal hearing. In underwater acoustics, a spectrum is commonly split into 1/3-octave bands, which are one-third of an octave wide; each octave represents a doubling in sound frequency. The center frequency of the *i*th 1/3-octave band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{i/10}, \quad \text{(G-8)}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the *i*th 1/3-octave band are defined as:

$$f_{lo} = 10^{-1/20} f_c(i) \text{ and } f_{hi} = 10^{1/20} f_c(i) \quad \text{(G-9)}$$

The 1/3-octave bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure G-1).

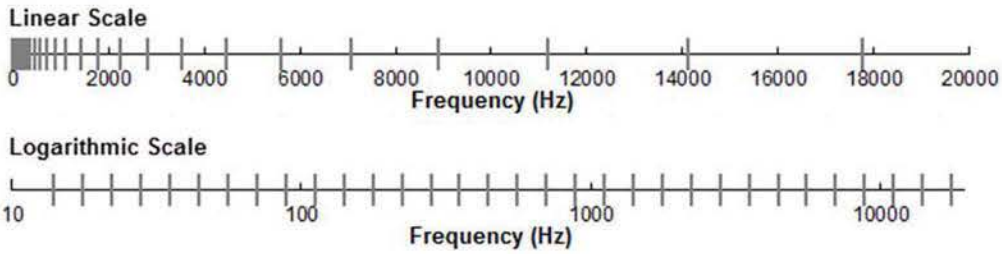

Figure G-1. One-third-octave bands shown on a linear frequency scale and on a logarithmic scale.

The sound pressure level in the ith 1/3-octave band $(L_b^{(i)})$ is computed from the power spectrum $S(f)$ between f_{lo} and f_{hi}:

$$L_b^{(i)} = 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right) \qquad \text{(G-10)}$$

Summing the sound pressure level of all the 1/3-octave bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10\log_{10}\sum_i 10^{L_b^{(i)}/10} \qquad \text{(G-11)}$$

Figure G-2 shows an example of how the 1/3-octave band sound pressure levels compare to the power spectrum of an ambient noise signal. Because the 1/3-octave bands are wider with increasing frequency, the 1/3-octave band SPL is higher than the power spectrum, especially at higher frequencies.

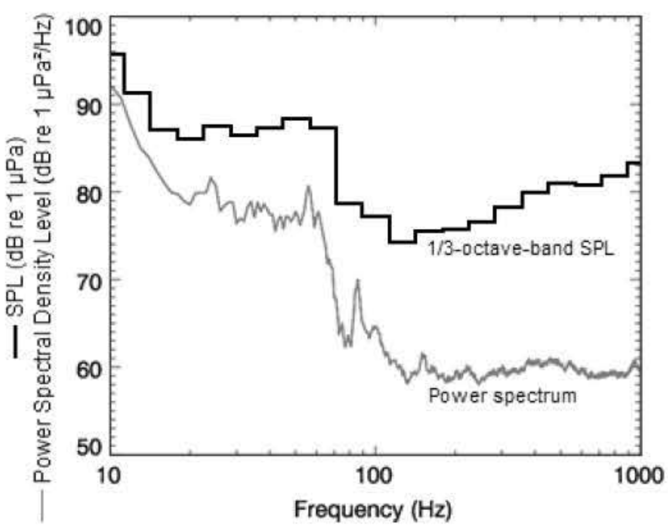

Figure G-2. A power spectrum and the corresponding 1/3-octave band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

G.2. Marine Mammal Auditory Weighting Functions

The potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

Prior to August 2016, the NMFS SPL criteria for acoustic exposure injury to marine mammals were set according to recommendations for cautionary estimates of sound levels leading to onset of permanent hearing threshold shift (PTS). These criteria prescribed injury thresholds of 190 dB re 1 µPa SPL for pinnipeds and 180 dB re 1 µPa SPL for cetaceans. A corresponding injury threshold was not defined for non-impulsive sounds at that time. NMFS indicated that the SPL criteria should be used for all sources including sonars and explosives. These injury thresholds were applied to individual noise pulses and did not consider the overall duration of the noise or its acoustic frequency distribution.

Criteria that do not take into account exposure duration or noise spectra are generally insufficient for assessing hearing injury. Human workplace noise assessments consider the SPL as well as the duration of exposure and sound spectral characteristics. For example, the International Institute of Noise Control Engineering (I-INCE) and the Occupational Safety and Health Administration (OSHA) suggests thresholds in C-weighted peak pressure level and A-weighted time-average sound level (dB(A) L_{eq}). They also suggest exchange rates that increase the allowable thresholds for each halving or doubling of exposure time. This approach assumes that hearing damage depends on the relative loudness perceived by the human ear. It also assumes that the ear might partially recover from past exposures, particularly if there are periods of quiet nested within the overall exposure.

In recognition of shortcomings of the SPL-only based injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas the SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: Low-, Mid- and High-Frequency Cetaceans (LFC, MFC, and HFC respectively) and Pinnipeds in Water (PINN). These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for human). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it infers a 3 dB exchange rate).

Wood et al. (2012) refined Southall et al.'s (2007) thresholds, suggesting lower injury values for LFC and HFC while retaining the filter shapes. Their revised thresholds were based on TTS-onset levels in harbor porpoises from Lucke et al. (2009), which led to a revised impulsive sound PTS threshold for HFC of 179 dB re 1 $\mu Pa^2 \cdot s$. Because there were no data available for baleen whales, Wood et al. (2012) based their recommendations for LFC on results obtained from MFC studies. In particular they referenced Finneran and Schlundt (2010) research, which found mid-frequency cetaceans are more sensitive to non-impulsive sound exposure than Southall et al. (2007) assumed. Wood et al. (2012) thus recommended a more conservative TTS-onset level for LFC of 192 dB re 1 $\mu Pa^2 \cdot s$.

Also in 2012, the US Navy recommended a different set of criteria for assessing Navy operations (Finneran and Jenkins 2012). Their analysis incorporated new dolphin equal-loudness contours[1] to update weighting functions and injury thresholds for LFC, MFC, and HFC. They recommended separating the pinniped group into otariids (eared seals) and phocids (earless seals) and assigning adjusted frequency thresholds to the former based on several sensitivity studies (Schusterman et al. 1972, Moore and Schusterman 1987, Babushina et al. 1991, Kastak and Schusterman 1998, Kastelein et al. 2005, Mulsow and Reichmuth 2007, Mulsow et al. 2011a, Mulsow et al. 2011b).

In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature, NMFS finalized technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing. The guidance describes injury criteria with new thresholds and

[1] An equal-loudness contour is the measured sound pressure level (dB re 1 µPa for underwater sounds) over frequency, for which a listener perceives a constant loudness when exposed to pure tones.

frequency weighting functions for five functional hearing groups described by Finneran and Jenkins (2012).

In the NMFS proposed guidelines the SEL are computed as frequency-weighted sums of per-pulse SEL at the receiver (animal) position. These levels are directly compared with set thresholds to determine if a take has occurred. The frequency weighting filters and thresholds have been designed for up to five marine mammal classes: Low-Frequency Cetaceans (LFC), Mid-Frequency Cetaceans (MFC), High-Frequency Cetaceans (HFC), and two classes of Pinnipeds in water: phocids (PPW) and otariids (OPW). These weighting functions are graphed in the figure below.

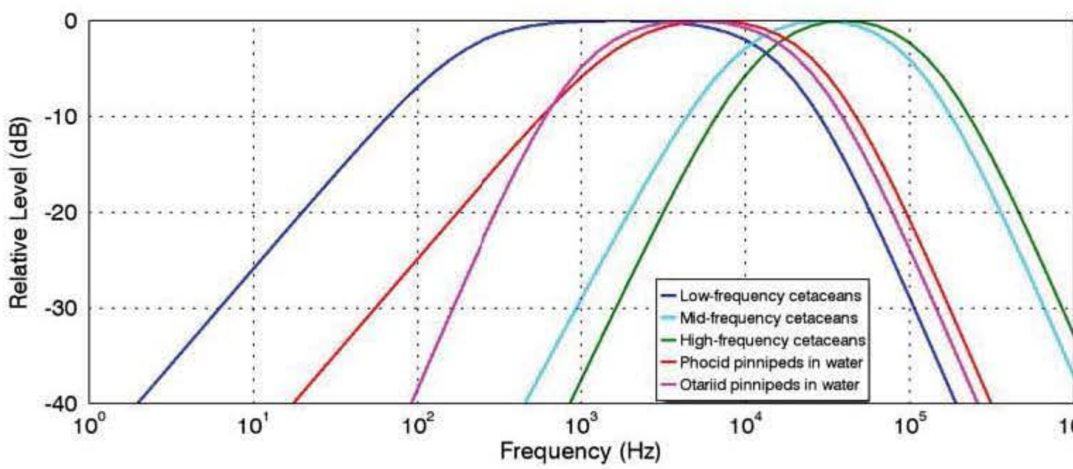

Figure G-3. Frequency weighting filters defined the NMFS Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (NMFS 2016a).

Appendix H. Literature Review

A Literature Review of Pile Driving Noise

Alaska Department of Transportation and Public Facilities Pile Driving Noise Study

Submitted to:

Janelle White
Alaska Department of Transportation and
Public Facilities

Authors:

Harald Yurk
Angela Schlesinger
Alex MacGillivray

24 July 2015

P001272-001
Document 1010
Version 2.0

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Suggested citation:

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Contents

Figures

Tables

1. Introduction

1.1. Background and Objectives

This report reviews literature about noise and its effects on marine life for pile driving construction projects near the shore. Most pile driving sound assessments focus predominantly on how large-scale construction projects—such as oil and gas exploration platforms or large offshore wind farms, which use hammers with high energy ratings and large-diameter piles—affect the soundscape and marine life. However, this document focuses on projects that used smaller piles (15-42 inches diameter) because the Alaska Department of Transportation and Public Facilities (ADOT&PF) has proposed smaller piles for its pile driving projects.

Although most studies described and analyzed sound emissions emanating from pile driving, some studies also discussed their effects on marine wildlife, primarily marine mammals and fish, and impact zones. Only one study addressed drilling noise that occurred during construction. Most studies reported broadband sound levels and their potential to affect marine wildlife and/or zones of impact based on threshold levels as set out by regulatory agencies such as NOAA/NMFS[1]. Few studies referred to the spectral composition of underwater sound or how animals perceive sound, despite this issue having spurred numerous discussions of the best ways to determine how noise affects animals' hearing sensitivities and their behavioral responses (Nedwell et al. 2005, Nedwell et al. 2007, Southall et al. 2007). Because existing noise impact assessments have not considered these influences, we have not considered them in this literature review but have noted a few studies that analyzed the sound spectrum.

1.2. Sound Propagation

Sound is the result of mechanical vibration waves traveling through a fluid medium such as air or water. These vibration waves generate a time-varying pressure disturbance that oscillates above and below the hydrostatic pressure. Sound waves may be perceived by the auditory system of an animal, or they may be measured using an acoustic sensor (typically a hydrophone, in water). Water conducts sound with a velocity four times faster than air due to its lower compressibility and higher density. The speed of sound traveling in water is approximately 1500 m/s (4900 ft/s). Sound is used extensively by marine organisms for communication and for learning about their environment. Humans may use sound purposely to probe the marine environment through technologies like sonar. More often, human activities such as marine construction generate underwater noise as an unintended side-effect.

Sound pressure is most commonly measured on the decibel (dB) scale, and expressed in terms of the sound pressure level (SPL). The dB scale is a logarithmic scale that expresses a quantity relative to a predefined reference level (see Glossary). Sources of underwater noise, such as pile driving and drilling, generate radiating sound waves whose pressure generally decays with distance from the source. The dB reduction in sound level that results from propagation of sound away from an acoustic source is called transmission loss (TL). The loudness of a noise source is quantified in terms of the source level (SL), which is the sound level adjusted to some reference distance from a noise source. The standard reference distance for underwater sound is 1 m. By convention, transmission loss is quoted in units of dB re 1 m and underwater acoustic source levels are specified in units of dB re 1 μPa at 1 m. In the source-path-receiver model of sound propagation, the received sound level RL is equal to the source level minus the transmission loss along the propagation path between the source and the receiver (RL = SL − TL).

[1] http://www.westcoast.fisheries.noaa.gov/protected_species/marine_mammals/threshold_guidance.html

1.3. Noise Generated by Pile Driving

1.3.1. Impact Pile Driving

Impact pile driving is carried out using an impact hammer, which in essence consists of a falling ram that strikes the top of a pile and drives it into the ground (Figure 1). The ram is lifted or driven by one of several methods, including diesel combustion, pneumatic air pressure, or hydraulic pressure.

Figure 1. Photo of a temporary pile being driven by a hydraulic impact hammer during construction of a highway bridge in Queensland, Australia (from Erbe 2009).

When the ram strikes the pile the impact creates stress waves traveling down the length of the pile, which couples with the surrounding medium, radiating acoustic energy into the water. Sound travels very fast and with low attenuation through water. Pile driving also generates vibration waves in the sediment, which can radiate acoustic energy back into the water from the seabed. The sound from impact pile driving is transient, repetitive, and discontinuous, i.e., pulsed (Figure 2). Hydrophone array measurements (Reinhall and Dahl 2011) and computational acoustic models (Zampolli et al. 2013) have been used to investigate the different propagation paths of underwater sound waves generated by impact pile driving.

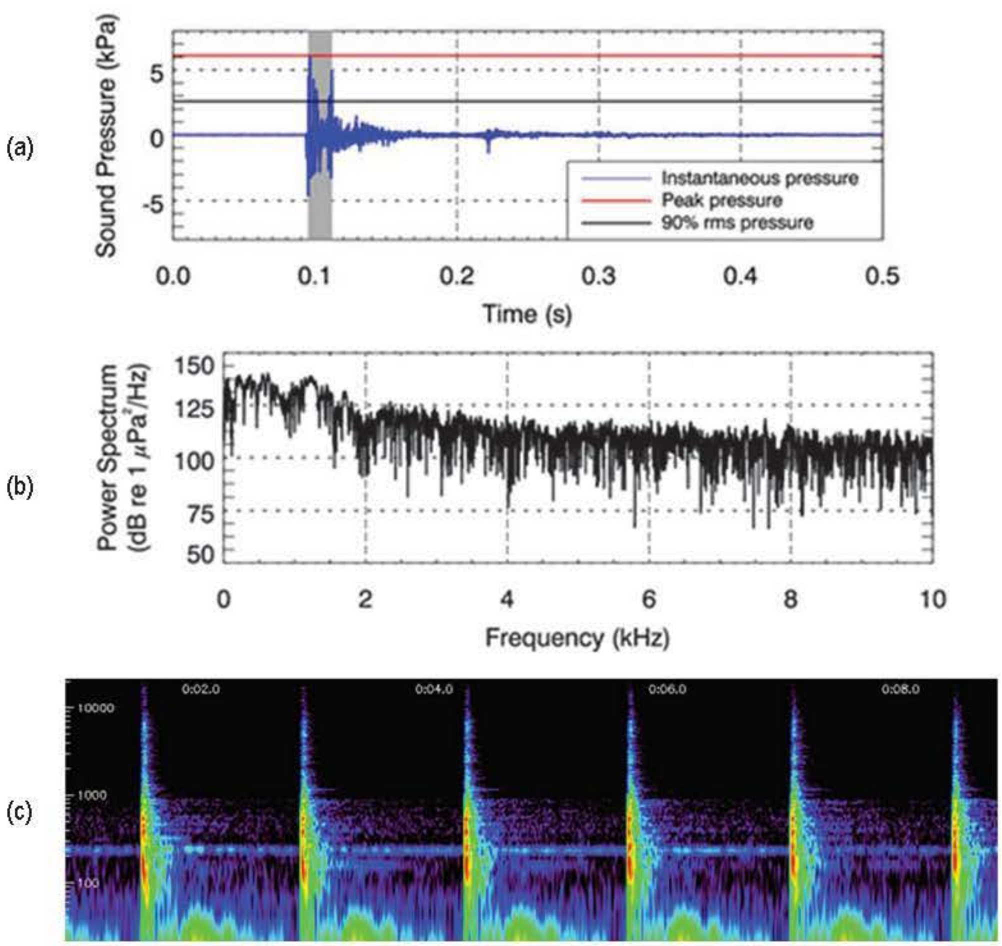

Figure 2. Example of waveform, power spectrum and spectrogram of pulsed sounds produced by impact pile driving. Panel (a) shows a pile driving pressure pulse (blue), with horizontal lines indicating the peak pressure (red) and 90% rms pressure (black). Panel (b) shows the acoustic frequency spectrum. Panel (c) shows the spectrogram of a series of pile driving pulses.

Figure 2(a) depicts two typical broadband (across a range of frequencies) measurement metrics (peak pressure and rms pressure) that are generally reported as sound pressure levels in dB re·1μPa over the duration of a single pulse. Other standard metrics of impact pile driving sound levels (expanded on in the Glossary) include the following:

- Peak-to-peak sound pressure level: the pressure difference between lowest and highest pressures
- Sound exposure level (SEL): reflects the cumulative acoustic energy emitted by the source over a specified time period; either from a single strike, or from an entire pile driving event.

The above levels are measured as received levels and, as such, are affected by the transmission loss between the source and receiver locations.

1.3.2. Vibratory Pile Driving

Vibratory pile driving is conducted using a vibrating hammer which is clamped at the top of the pile. Oscillating elliptical weights in the hammer generate strong vibrations in the pile, which liquefy the surrounding sediments and allow the weight of the hammer to push the pile into the ground. Vibratory hammers are also used to extract piles. As with impact driving, the vibration of the pile radiates acoustic energy into the surrounding water. Unlike impact driving, sound from vibratory driving is steady and continuous. Vibratory driving peak and rms sound levels are typically lower than impact driving sound levels (Figure 3).

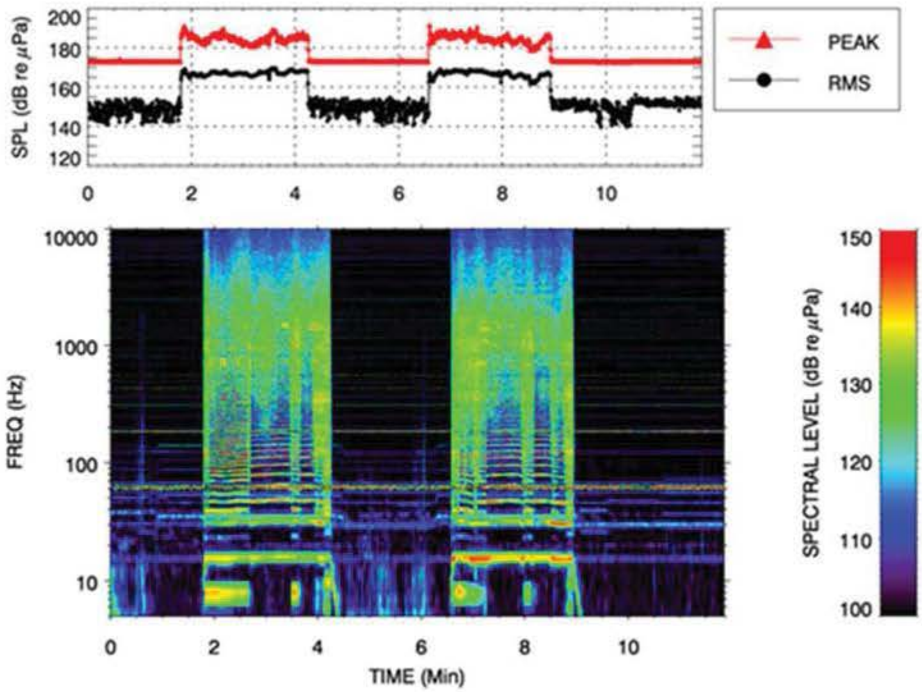

Figure 3. Example of broadband levels (peak and rms) and spectrogram of two intervals of non-pulsed (continuous) sounds produced during vibro-hammering.

1.3.3. Pile Drilling

Pile drilling generally refers to auger drilling or down-the-hole (DTH) drilling, which are used to create pile sockets and to install pile anchors. Limited information exists on noise generated by pile drilling, but the available data suggest that sound levels generated by drilling are lower than either impact or vibratory pile driving. DTH drilling employs a pneumatic percussion hammer (i.e., jack hammer) to chip away rock and other material at the base of a pile. Auger drilling employs a rotating auger bit to drill away material at the base of a pile. Sound from drilling is generally continuous (non-pulsed), though DTH drilling may produce pulses in addition to continuous sound. Auger drilling is primarily used to install casings for DTH pile drilling and it is likely the casing installation, rather than the drilling itself, that is the main source of sound.

1.4. U.S. Regulatory Guidelines

The Marine Mammal Protection Act (MMPA) aims to protect marine mammals from harmful effects resulting from human activities and the Endangered Species Act (ESA) does the same for threatened and endangered species, including species groups not covered under the MMPA. Commercial operations that generate underwater noise that can negatively affect marine mammals, including species not listed under the ESA, may require incidental take authorizations under the MMPA. Operations that could affect species listed under the ESA (for example, Cook Inlet beluga whale or Steller sea lion) may need to meet additional permitting requirements. The MMPA defines a take as harassing, hunting, capturing, killing, or collecting, or attempting to harass, hunt, capture, kill, or collect an animal. The ESA defines a take as harassing, harming, pursuing, hunting, shooting, wounding, killing, trapping, capturing, or collecting, or attempting to engage in any such conduct. Under the 1994 Amendments to the MMPA, harassment is statutorily defined as "any act of pursuit, torment, or annoyance which could potentially injure a marine mammal or marine mammal stock in the wild (Level A Harassment), or which could disturb a marine mammal or marine mammal stock in the wild by disrupting its behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering, but which does not have the potential to injure a marine mammal or marine mammal stock in the wild (Level B Harassment)."

The NOAA/NMFS policy about injury thresholds and the process of assessing marine mammal injuries is currently under review. The current guidelines state that to avoid injuring (i.e., Level A harassment) cetaceans and pinnipeds, they should not be exposed to pulsed sounds that exceed rms SPLs of 180 and 190 dB re 1 µPa, respectively (NMFS 2000). NOAA also assumes animals will be behaviorally disturbed (Level B harassment) by impulsive sounds with rms SPL above 160 dB re 1 µPa. NMFS generally requires pile driving stops when a marine mammal enters the Level A zone. NMFS regulations require bubble curtains to mitigate sound in areas where they are likely to be effective. Pile driving and seismic operations are generally required to have a soft-start. Regulations are often more stringent when mother-calf pairs are present.

NMFS is currently reviewing its policy and guidelines of how to assess the impact of underwater noise on marine mammals. Until new regulations become available NMFS assumes that Level A Harassment from pile driving could occur if a cetacean or pinniped was exposed to sound levels at or above 180 or 190 dB re 1 µPa rms SPL, respectively. In the case of exposure to pulsed sounds, such as produced by impact pile driving, sound levels of at least 160 dB re 1 µPa rms SPL, but below Level A Harassment thresholds, could result in Level B Harassment.

For exposure to non-pulsed sounds, the current NMFS Level B Harassment threshold for marine mammals is 120 dB re 1 µPa rms SPL. This includes noise generated by vibratory pile driving. The sound level from vibratory pile driving at any point in time is lower than that generated by impact pile driving, but the exposure is continuous. Therefore, the threshold (RMS SPL 120 dB instead of 160 dB) for Level B Harassment is set lower than that for impulses. Due to difference of 40 dB between the two thresholds, behavioral disturbances from vibratory pile driving may occur at much greater distances than from impact driving. Nonetheless, received sound level alone may not be a reliable predictor of behavioral disturbance. Other mediating factors, particularly exposure context, relative background level, and chronic exposure, may be equally important (Ellison et al. 2012). These factors are not yet accounted for in the NMFS Level B Harassment criteria.

2. Review of Small Diameter Pile Driving Sound and Impact Assessments

The studies are organized into three sections according to the type of pile driving or drilling that was applied: impact pile driving, vibratory pile driving, and pile drilling. Within each section, studies listed are published journal papers or publicly available reports. The beginning of each section summarizes studies while important information from each study is listed in table format at the end of each section, except for pile drilling for which only one example study was found.

Underwater sound levels depend on many operational and environmental factors, some of which are listed below:

- Pile size: diameter, thickness
- Pile shape: cylindrical, H-pile, sheet pile
- Pile material: steel, concrete
- Hammer type and energy
- Sediment type and thickness
- Bedrock type and depth
- Water depth and bathymetry
- Water sound speed profile

Not every study we reviewed contained information about all possible influential factors. Particularly, information on sound speed profiles and sediment structure was often absent.

2.1. Impact Pile Driving Measurements

Erbe (2009) investigated the sound levels emitted by impact driving 30 and 60 inch diameter steel pipe piles at various distances (Table 1). This study did not report distances to the NMFS Level A and B take thresholds, but based on the reported rms SPLs data, levels of 180 dB re 1 µPa were not exceeded beyond 1050 ft. (320 m) and levels of 160 dB re 1 µPa were not exceeded beyond 4230 ft (1290 m). The water was, however, very shallow at the study location which likely increased the observed transmission loss.

Data compiled by the Department of Transportation of California (ICF Jones & Stokes and Illingworth and Rodkin 2009) indicate that steel piles most often exceeded Level A and Level B thresholds at 33 ft. (10 m) from the source. Other types of piles (plastic and concrete) generally only exceeded the Level B threshold at this range.

Laughlin (2005) showed that in addition to pile size, the actual hammer type used to drive the piles to affects the emitted sound levels. He compared sound levels from diesel, pneumatic, and hydraulic hammers driving the same pile sizes at the same location and tested the effectiveness of bubble curtains at different heights along the pile. He reported that bubble curtain rings at the bottom of the piles reduced sound levels by an average of 3 dB rms SPL.

Vagle (2003) studied the effects of sound levels emitted by impact pile driving using different pile materials, such as wood and steel, on caged fish. He determined that pile size was a better indicator of behavioral responses than pile material. Vagle (2003) also found that bubble curtains had little effect on emitted sound levels from piles with small diameters (< 12 inches).

MacGillivray and Racca (2005) also measured sound levels and particle velocities when sound was mitigated with a bubble curtain (released into PVC sleeve surrounding the steel pipe). Their results showed that contained bubble curtains can reduce the rms and peak pressure levels by 10 dB, and reduce the SEL by around 8 dB.

The collected data and resulting measurements vary greatly depending on the purpose of each project, e.g., assessing sound for a NMFS take application or observing how sounds affect marine life.

URS (2007) provides a good example of the kind of data collected and measurements taken to comply with a take authorization permit process and to assess the risk of impact that necessitates mitigation measures. To meet the requirements for a permit application the authors:

- Developed a sound index to represent noise levels associated with the marine construction project
- Identified sound isopleths (ranges) that correspond to impact thresholds set by NOAA or NMFS for each type of pile driving.

Their sound index characterized the spectral composition of the noise signals and measured the received sound pressure levels, which together with an estimated transmission loss were used to determine safety zones. The authors coordinated their measurements with data collected by a beluga whale observational monitoring program to determine presence, absence, and behavioral alteration of whales when pile driving occurred. Unusually high ambient noise levels (> 150 dB rms SPL) reported in this study suggest that the measurements may have been adversely affected by the strong tidal currents in Cook Inlet, and possibly by engine noise from the boat used to collect the data. The authors concluded that the pile driving sounds were much louder than ambient noise at any given time and could always be distinguished by investigating the spectral composition of the noise, but masking has not been considered as a separate factor. This example illustrates that the procedure by which sound data is collected is an important component of sound level assessment and all factors that could introduce errors need to be carefully considered.

MacGillivray et al. (2007) measured the effectiveness of various sound attenuation methods, including bubble curtains and isolation casings with foam layers (Figure 4). Received sound levels were measured at 10 m, 50 m, 100 m, 200 m, and 1100 m. The authors noted that both the foam-walled attenuation systems (TNAP) and the bubble curtain effectively reduced sound pressure levels at short distances (approximately 20 dB reduction at 10 m distance), but the effectiveness of the sound mitigation dropped as the distance from pile driving increased (approximately 6 dB reduction at 1100 m distance). The authors suggested that the roll-off in sound attenuation over distance might be attributed to sound energy traveling through the sub-bottom and not in the water column. The 14º slope of the seabed at the pile driving site likely contributed to the importance of the bottom-conducted sound energy.

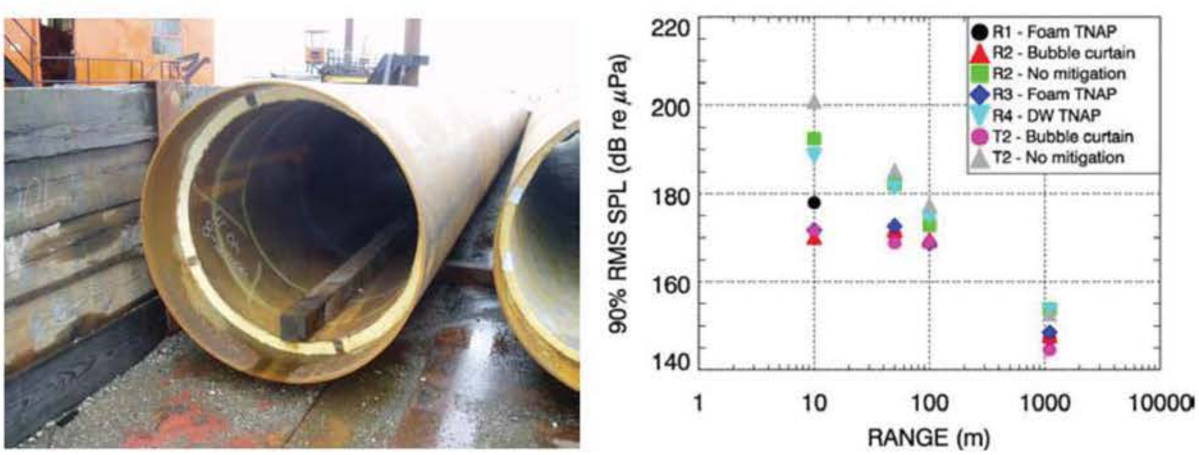

Figure 4. (Left) Sound attenuation methods. The pipe on the left in the picture is a double walled steel pipe with foam layer between walls. The pipe beside it on the right shows a single steel sleeve pipe with a foam layer. (Right) The diagram on the rights shows the effects of sound mitigation methods on the received 90% RMS SPL at four distances from the pile driver: 10 m, 50 m, 100 m, and 1100 m. All piles were 36-inch diameter steel pipes.

Table 1. Summary of sound level measurements of impact pile driving studies using piles with diameters of 12 to 60 inches. All reported metrics (SEL, rms SPL, and peak SPL) are averaged. A dash (-) indicates data or value was not available. SEL values reported are single-strike measurements.

Location	Pile Type	Water depth (m)	Pile diameter (in)	Hammer type	Rated hammer energy (kN·m)	Measured distance (ft)	Single-strike SEL (dB re 1 µPa²s)	rms SPL (dB re 1 µPa)	peak SPL (dB re 1 µPa)	Measured frequency range (Hz)
California[1]	Steel H (thin)	< 5	12	Diesel	-	33	160	175	-	-
	Steel H (thick)	~ 5	12	Diesel	-	33	170	183	-	-
		~ 6	14	Diesel	-	33	177	-	208	-
	AZ steel sheet	~ 15	24	Diesel	-	33	180	190	205	-
	Steel pipe	< 5	12	Drop/Diesel	-	33	-	177	192	-
		~ 15	14	Diesel	-	33	174	184	200	-
		3	16	Drop/Diesel	-	33	158	-	182	-
		~ 3	20	Diesel	-	33	-	161	204	-
		~ 5	24	Diesel	-	33	177	190	203	-
		~ 15	24	Diesel	-	33	178	194	207	-
		~ 3	30	Diesel	-	33	177	190	210	-
		< 5	36	Diesel	-	33	180	190	208	-
		~ 10	36	Diesel	-	33	183	193	210	-
	Steel pipe CISS	< 5	60	Diesel	-	33	185	195	210	-
	Plastic	10	13	Diesel—ICE-60	-	33	-	153	177	-
	Concrete	< 3	18	Diesel—ICE-60 & D-30	-	33	155	166	185	-
		~ 5	24	Diesel—D-30, D62-22	-	33	160	170	185	-
		~ 15	24	Diesel—D-30, D62-22		33	160	170	185	--
Anchorage, AK[2]	H steel & sheets	15-20	14	Diesel—APE Delmag D30-42	102	62	163	177	194	10-5,000
Bainbridge	Steel pipe	10	36	Diesel—Delmag D 62	187	33	Unmitigated sound pressure			

[1] ICF Jones & Stokes and Illingworth and Rodkin (2009): Compendium report of pile driving measurements collected for CALTRANS.

[2] URS (2007): Marine terminal construction which also included vibratory pile driving; all measurements from vessel suspended hydrophones (2 m of bottom and 7 m from surface). Reported ambient sound levels appear very high, likely due to flow and drift noises leading to high background levels.

Location	Pile Type	Water depth (m)	Pile diameter (in)	Hammer type	Rated hammer energy (kN·m)	Measured distance (ft)	Single-strike SEL (dB re 1 µPa²s)	rms SPL (dB re 1 µPa)	peak SPL (dB re 1 µPa)	Measured frequency range (Hz)
Isl., WA[3]							190.8	192.4	203	10–16,000
		10	36	Diesel—Delmag D 62	187	33	Sound pressure with bubble curtain			
							182	182.35	193.6	10–16,000
Friday Harbor, WA[4]	Steel pipe	12-14	24	Diesel	81.4	30	180	189	199	10–16,000
			24	Pneumatic	67.8	30	173	179	195	10–16,000
			24	Hydraulic	119.3	30	178	183	198	10–16,000
Moreton Bay, Australia[5]	Steel pipe	1-1.5	30	Hydraulic	180 & 280	46	183	194	207	0–15,000
						4,232	107	115	126	0–15,000
			60	Hydraulic	180 & 280	46	179	189	205	0–15,000
						4,364	114	124	133	0–15,000
Columbia River Crossing, Oregon[6]	Steel pipe	10-11	24	Diesel	64	33	Unmitigated			
							175	190	205	10-40,000
							Open bubble curtain			
							163	176	190	
							Closed bubble curtain			
							169	183	197	
		10.5-11	48	Diesel	256.9	33	Unmitigated			
							184	201	214	10-40,000
							Open bubble curtain			
							173	187	199	

[3] MacGillivray and Racca (2005): Unmitigated sound levels were compared to those with bubble curtain mitigation; particle velocity measurements, which are important to assess fish impacts, were also reported.

[4] Laughlin (2005): Restoration of Ferry terminal; compares sound levels from different hammer types.

[5] Erbe (2009).

[6] David Evans and Associates (2011).

Location	Pile Type	Water depth (m)	Pile diameter (in)	Hammer type	Rated hammer energy (kN·m)	Measured distance (ft)	Single-strike SEL (dB re 1 µPa²s)	rms SPL (dB re 1 µPa)	peak SPL (dB re 1 µPa)	Measured frequency range (Hz)
							Closed bubble curtain			
							173	186	199	
Mukilteo Ferry Terminal, WA[7]	Steel (unmitigated)	7-12	36	Diesel-Delmag D62	187	33	180.1	196.3	206.2	10-16,000 Hz
		20				165	170.3	184.3	197	
		30				330	161.4	173.9	187.7	
		280				3630	144.7	156	166.3	
	Concrete	30	36	Diesel-Delmag D62	187	330	164.4	179	190.7	
		60				660	154.4	166.9	179.2	

[7] MacGillivray et al. (2007): Estimated take zones for steel piles: Level A pinnipeds (190 dB): ≤ 66 ft; Level A cetaceans (180 dB): ≤ 331 ft; Level B both (160 dB): ≤ 1650 ft. Estimated take zones for concrete piles: Level A pinnipeds (190 dB): ≤ 193 ft; Level A cetaceans (180 dB): ≤ 301 ft; Level B (160 dB): ≤ 777 ft.

2.2. Vibratory Pile Driving Measurements

Vibratory pile driving produces continuous sound, which usually generates lower instantaneous sound levels than impulsive impact pile driving of the same pile at the same distance. The rms and peak sound levels generally would only reach Level A (acoustic injury) thresholds at very close distances to pile driving (less than 10 m). Because the sound exposure is continuous and the threshold level for these sounds currently used by NOAA to identify Level B harassment (behavioral harassment or behavioral disturbance) is 120 dB rms SPL, the threshold may be exceeded at considerable distance from the source.

The rms SPL for vibratory pile driving is typically calculated as the mean over a certain time (Laughlin 2006), or over several pile driving events (David Evans and Associates 2011), whereas peak SPL is the highest reported value during pile driving. Measurements of near field rms SPLs are sometimes used as inputs in practical spreading (TL=15 × log range) and spherical spreading (TL=20 × log range) transmission loss models, for estimating the distance to Level A and Level B thresholds. Estimates based on practical spreading loss models generally result in larger threshold distances. Warner (2014) compared practical spreading loss estimates to actual received level based on recordings made with bottom-mounted recorders (AMARs) (Table 2) and concluded that the spherical transmission loss model provided more realistic distances for vibratory pile driving noise assessments.

Figure 5 shows the spectral composition of sound during vibratory pile driving. Another important piece of information the noise spectrum provides is that the frequencies with the highest levels of noise vary with distance from the source.

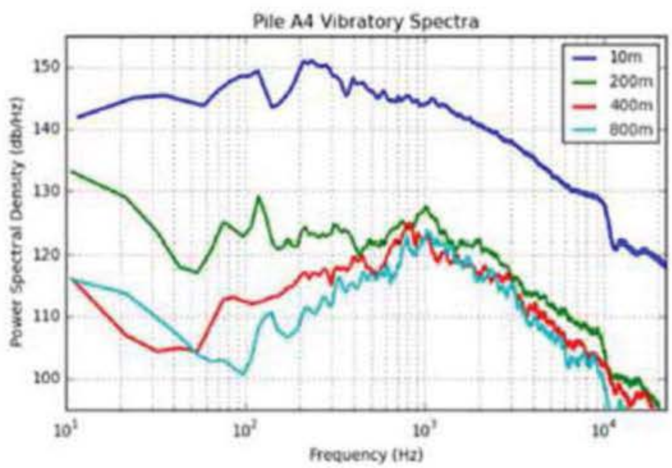

Figure 5. Example of a Power Spectral Density (PSD) plot for vibratory pile driving at various distances based on a calculation of sound levels per 1 Hz steps (taken from David Evans and Associates 2011, pages 4-8).

Table 2. Summary of sound level measurements of vibratory pile driving. All reported metrics (rms SPL, and peak SPL) are averaged. A dash (-) indicates data or value was not available.

Location	Water depth (m)	Pile type	Pile diameter (in)	Hammer Model	Rated hammer force (kNm)	Measurement range (ft)	rms SPL (dB re 1 µPa)	peak SPL (dB re 1 µPa)	Measured frequency range
Anchorage, AK[1]	9-20	Steel H	14	APE 200	-	33	168	-	10-10,000
						46	-	179	
Port of McKenzie, AK[2]	18	Steel pipe	36	APE King Kong 400	1011	184	164	-	(400-2,500)
Vashon Island, WA[3]	10-12	Steel pipe	30	APE King Kong 400	-	36	160-169	175-180	-
	10-12					52	160	187-190	
	9					2592	126-130	159-168	
	30					2644	127-131	155-162	
Columbia River, WA-OR[4]	~ 20	Steel pipe	24	APE King Kong 400	-	33	157-162	-	10-22,000 (70-3,000)
							167-176*		
			48				161-181	-	
							170-174*		

[1] URS (2007) Port of Anchorage construction. Levels measured from a drifting boat. Reported ambient sound levels are high. According to this report, the distance to the 190 dB (pinniped Level A) and 180 dB (cetacean Level A) thresholds would be less than 33 ft. Approximately 2625 ft is a conservative estimate of the distance to the 120 dB threshold

[2] Blackwell (2005): Dock modifications; rms SPL exceeding 120 dB at a distance > 1,000 m

[3] Warner (2014): Vashon ferry terminal repair and construction test pile driving and threshold distance modeling.

[4] David Evans and Associates (2011): Pile driving and pile extraction was measured. rms pressure levels were averaged from actual pile driving periods recorded over 30 s.

*Measurements are from vibratory pile extraction.

2.3. Pile Drilling and Extraction Measurements

Dazey et al. (2012) reported sound level measurements from pile drilling and pile extraction during pier construction related activities in Bechers Bay, California. Acoustic data were collected during vibratory hydraulic extraction, DTH drilling, and auger drilling. Received level rms SPL statistics were reported by the investigators, but they did not report the specific ranges at which the different levels were measured (Table 3). The investigators calculated source levels and threshold distances based on the unusual assumption of cylindrical spreading transmission loss (TL= 10 × log range), but they did not justify why they felt this assumption was appropriate. Their estimated distances to the 160 dB re 1 µPa rms SPL safety threshold from drilling and extraction activities were 68-660 ft (21-200 m). The investigators reported no statistically significant difference between source levels from the different activities they monitored; however this conclusion may be misleading, given the large spread in received sound levels that they measured.

Table 3. Descriptive statistics for rms SPLs from pile drilling and extraction measured during construction monitoring in Bechers Bay.

Measurement Range (ft)	Statistics	rms SPL (dB re·1µPa)
155-636	Min	101
	Max	165
	Mean	133
	S.D.	12

2.4. Studies Reporting Sound Measurements with Impact Assessments

While reporting the received sound levels and threshold distances is the first step in an acoustic impact assessment, it is equally important to report any available information about the animals, such as their acoustic exposure history (how many other noise producing projects take place in the same area and in close temporal proximity) and duration of exposure, as this will affect the extent to which animals might respond to the exposure (Southall et al. 2007). Furthermore, the occurrence or magnitude of a response depends on the physiological, reproductive, and behavioral state of the animal at the time of exposure (Nowacek et al. 2007).

Blackwell et al. (2004) reported no noticeable change in behavior of ringed seals (*Phoca hispida*) when they were exposed to sounds from impact pipe and impact sheet pile driving (see Table 4 for sound levels and measured distances). The authors also noted that previous studies assessing pile driving sounds and impact on pinnipeds in the same area also failed to report long term disturbance responses and that other types of noises, such as those produced by grading concrete slabs, were present during pile driving. Because received levels of sound data were measured in very shallow water (6 m) and under fast ice, measured received levels in this study are comparatively low to other studies.

Table 4. Summary of sound level measurements from studies of piles with diameters of 12 to 94 inches reporting NOAA threshold exceedances and reporting animal disturbance.

Location	Pile Type	Water depth (m)	Pile diameter (in)	Hammer Type	Rated hammer energy (kN·m)	Measured distance (ft)	SEL (dB re 1 µ²·s)	rms SPL (dB re 1 µPa)	Peak SPL (dB re 1 µPa)	Measure Frequency Range	Threshold exceedance distances/ Impacts on Marine Mammals
Prudhoe Bay, AK[1]	Steel	6	20	Impact/Diesel	224	207	146	152	158	10-10,000	No exceedance and no behavioral impact observed
Port Philip Bay, Australia[2]	Steel pipes	8.5−13	28	2 Impact/Diesel	56-90	125	~165-171	-	198-204	20-12,000	Level A pinnipeds at ≤ 82 ft, cetaceans at ≤ 197ft^^; Level B ≤ 3,000 ft
Port MacKenzie, AK[3]	Steel pipes	19-23	36	Impact/Diesel	223	203	178-180	187-190	205	10-12,00	Level A cetaceans at ≤ 738 ft; pinnipeds at ≤ 238 ft; Level B at ≤ 7382 ft,
		18	36	Vibratory APE 400B		184	-	164	-	10-12000	Level B at <12,300 ft
San Francisco, CA[4]	Steel pipe	~7-9	94.5	Impact/Hydraulic	750 & 1750	338	-	185-196	197-207		Level A pinnipeds: 607 ft (sm hammer) & 935 ft (lg hammer), < 328 ft (both hammers) when mitigated with fabric barrier; Alert behavior at start but no avoidance behavior of safety zones was observed during small hammer operation, no seals or sea lions entered safety zone during large hammer operations.
						1175		167-179	181-191		

[1] Blackwell et al. (2004): Construction of oil production island; all 20 inch pile driving under ice.

[2] Duncan et al. (2010): Wharf repair and construction at two sites; has detailed information on sediment structure and sound speed profiles; ^^threshold distance depends on location.

[3] Blackwell (2005): Port MacKenzie; good representation of transmission loss of different pile driving sounds.

[4] Caltrans (2001): Threshold exceedance and marine mammal monitoring, only pinnipeds detected; project study provides information on marine mammal distribution in relation to study site and potential activities that could interfere with pinniped daily activities (harassment as defined in MMPA and ESA).

2.5. Example for the Application of NOAA Regulations: Port of Anchorage Expansion Project, Alaska

As an example of specific U.S. regulatory guidelines and take authorizations, on 20 Feb 2008, NMFS received an application from the Port of Anchorage requesting a one-year IHA, which was based on the sound assessment by URS (2007) to take, by Level B Harassment, up to 34 Cook Inlet beluga whales (*Delphinapterus leucas*), 20 harbor seals (*Phoca vitulina*), 20 harbor porpoises (*Phocoena phocoena*), and 20 killer whales (*Orcinus orca*) incidental to the exposure to noise from pile driving. The applicant expected Level B Harassment would consist of short term, mild to moderate behavioral (altered headings, fast swimming changes in dive, surfacing, respiration, and feeding patterns, and changes in vocalizations) and physiological (stress) responses.

Based on an acoustic study conducted at the Port of Anchorage in October 2007 (Table 2 B and 3 in URS 2007), average sound levels of impact pile driving were expected to be approximately 177 dB re 1 µPa rms SPL at 19 m range in the frequency band of 100–15,000 Hz; vibratory pile driving sounds were expected to be approximately 162 dB re 1 µPa rms SPL at 20 m range in the frequency band of 400–2500 Hz. Further empirical data were collected to identify Level A and Level B Harassment thresholds. For impact pile driving, the 190, 180, and 160 dB re 1 µPa thresholds were approximately 10, 20, and 350 m from the pile hammer, respectively. The pile driver used was a Delmag D30-42 diesel equipped with a 13,571 lb (6154 kg) hammer and a maximum rated energy of 74,750 ft-lbs. (about 101 kJ). Vibratory driving thresholds for 190 and 180 dB re 1 µPa rms SPL were both less than 10 m, and the 120 dB re 1 µPa rms SPL thresholds was reached at 800 m from the pile hammer.

NMFS authorized taking the animals in their stated amounts. As per its permit, the Port of Anchorage was required to obtain three years of sighting data around the Port before beginning construction. Data, including information on animal abundance, group size and composition, behavior, and presence relative to tidal cycles were collected in all months that pile driving occurred and supplemented with commercial vessel usage in the area. These data were used to calculate monthly densities and expected monthly harassment based on hours of pile driving.

Bubble curtains were considered to mitigate sound, but were not used due to the strong prevailing currents, which would disperse bubbles very quickly and render their acoustic dampening effect inefficient.

NMFS had the following requirements:

- Construction activities scheduled when few beluga whales were present.
- Pile driving was not to occur within 2 h of low tide because that was when the most animals were in the area.
- If one animal is seen within 200 m, operations would shut down.
- If more than five beluga whales in a group or calves are seen, operations shut down when animals entered a 350 m radius.
- Pile driving could recommence only when no more animals were seen within 15 min.
- Once the maximum authorized take was reached, if any beluga entered a zone that exceeded the Level B Harassment threshold, there must be a mandatory shut-down.
- Piles had to be driven with a vibratory hammer (less impact) to the maximum depth possible before switching to impact pile driving.

NMFS required the Port to use a soft-start procedure at the beginning of each pile to allow marine mammals the opportunity to leave the area before pile driving reached full energy. For vibratory piling, this meant driving the vibrator for 15 s at reduced energy, followed by waiting for 1 min, three times in a row. For impact pile driving, this meant three strikes at 40% energy followed by a 1 min waiting period, then two subsequent sets of three strikes. If an animal moved into the 200 m safety zone during the soft-start procedure, pile driving had to be delayed until the animal had left the zone or until it was not seen again for 15 min.

NMFS required pile driving to stop if weather conditions prevented adequate monitoring of the 200 m safety zone. Only trained marine mammal observers were permitted to monitor the harassment zones, which they did 30 min before and during pile driving. If animals appeared in the area, they called for the area to be shut down for as long as animals were present and until no animals were seen for 15 min.

In addition to the marine mammal observers, an independent beluga whale monitoring team that consisted of one or two observers stationed on land was required to report on the following:

- The frequency at which beluga whales appeared in the project area.
- Whale habitat use, behavior, and group composition near the Port. The observers correlated this data with construction activities.
- Beluga whales' behavioral reactions and physiological responses to sounds.

NFMS asked the Port to install hydrophones or other effective methodologies to the maximum extent possible necessary to detect and localize passing whales and to determine the proportion of beluga whales not included in visual surveys. The reported study (URS 2007) was coordinated with the concurrent beluga whale monitoring program; construction and noise exposures to operations were correlated with beluga whale presence, absence, and any altered behavior observed during construction and operations. Weekly monitoring reports were submitted to NMFS.

The major concern to increasing development in upper Cook Inlet was increasing noise and degrading or losing habitat around prime feeding areas. The Port is not located within beluga whale prime feeding territory, but whales used the area around it to migrate to such habitats. Although other marine mammal species were seen in the area, their presence was irregular and the habitat not critical to their survival (i.e., no rookeries, mating, feeding, or calving grounds). With proper mitigation and management, NMFS expected that the project, alone or in conjunction with other actions, would not result in significant impacts to Cook Inlet beluga whales (NMFS 2008). There were 245 detections of animals in harassment zones and 13 takes (12 belugas and 1 harbor seal) during pile driving operations that occurred between 15 Jul 2008 and 14 Jul 2009 (Integrated Concepts & Research Corporation 2009).

3. Conclusions

As expected, the reported variation in sound pressure levels from pile driving operations showed influences of hammer type and energy, pile material and diameter, water depth and bathymetry. Most studies reported broadband sound levels without considering the spectral composition of the emitted sounds or the hearing abilities of the affected animals. This is likely due to regulatory requirements, which are currently solely based on broadband noise level assessments. As NOAA/NMFS change their guidelines for anthropogenic noise assessments on marine mammals, IHA application will likely need to consider factors more relevant to animal biology (NOAA 2013). Studies often do not address sediment composition except where it is has been shown to affect sound levels.

Most of the information on sound levels emitted by pile driving operations is in reports for regulatory bodies. Currently, researchers collect data on pile driving sounds and use a range of methods and reporting styles and it is not always obvious from reviewing the literature if potential confounding influences on sound level measurements were adequately addressed. One common confounding factor we noticed was that many drifting-vessel based recordings were made with hydrophones suspended into the water column, resulting in a variable distance to the sound source. Acoustic data collection should be standardized preferably using fixed acoustic recorders that maintain the same depth and distance to the sound source while they record.

4. Glossary

peak sound pressure
Peak pressure is the maximum absolute value of the amplitude of a pressure time series P(t). It is also called the zero-to-peak amplitude.

peak sound pressure level (peak SPL)
The zero-to-peak SPL, or peak SPL (dB re 1 µPa), is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, p(t): The peak sound pressure level (dB re 1 µPa) is the logarithmic ratio of the peak pressure to the reference pressure (P_{ref}):

$$\text{Peak SPL} = 10\log_{10}\left[\frac{\max\left(\left|p^2(t)\right|\right)}{p_0^2}\right]$$

peak-to-peak sound pressure level (peak-to-peak SPL)
The *peak-to-peak sound pressure level* (dB re 1 µPa) is the difference (expressed in decibels) between the maximum and the minimum of the recorded pressure time series:

$$\text{Peak-to-peak SPL} = 10\log_{10}\left\{\frac{\left[\max(p(t)) - \min(p(t))\right]^2}{p_0^2}\right\}$$

power spectrum density
Power spectrum density describes how the power of a signal is distributed with frequency.

power spectrum density level
The power spectrum density level is computed as $10\log_{10}$ of the squared sound pressure in 1 Hz bands (dB re 1 µPa^2/Hz).

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: *p*.

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

rms sound pressure
The root-mean-square (rms) sound pressure is the root-mean-square value of the pressure time series P(t) over some specified time period.

rms sound pressure level (rms SPL)
The rms sound pressure level (dB re 1 µPa) is the logarithmic ratio of the rms pressure to the reference pressure:

$$\text{rms SPL} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right)$$

For pulsed sound such as that from airguns or pile driving, the rms SPL depends on the duration over which the pressure is averaged. This duration would ideally be the pulse duration. However, it is difficult to determine the pulse start and end times. By convention, the pulse duration is taken as the time between the 5% and the 95% points on the cumulative energy curve, containing the central 90% of the cumulative energy of the pulse. The 90% rms SPL is computed by averaging the squared pressure over that time window:

$$\text{90\% rms SPL} = 10\log_{10}\left(\frac{1}{T_{95}-T_5}\int_{T_5}^{T_{95}} P^2(t)\,dt\right)$$

sound exposure level (SEL)

The sound exposure level (SEL, dB re 1 µPa^2·s) is the time integral of the square pressure over the fixed time window containing the entire pulse, T_{100}:

$$\text{SEL} = 10\log_{10}\left(\int_{T_{100}} p^2(t)dt \Big/ T_0 p_0^2\right)$$

source level (SL)

The acoustic source level is the sound pressure level referenced to a distance of 1 m from a point source. For practical purposes, the received level is measured at some range, and a sound propagation model is used to adjust the sound level to 1 m range from an equivalent point source. The source level can be expressed in terms of pressure (dB re 1 µPa @ 1 m) or sound exposure (dB re 1 µPa^2·s @ 1 m).

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Appendix A. Southall Noise Exposure Criteria

After reviewing the literature on marine mammal hearing and physiological and behavioral responses to anthropogenic sound, Southall et al. (2007) proposed injury criteria for marine mammals, based on the peak SPL and SEL metrics. These criteria account for the type of sound (non-pulse, single-pulse, or multi-pulse), as well as the approximate hearing ranges of the mammals involved. Marine mammal species were assigned to one of five functional hearing groups: low-, mid-, and high-frequency cetaceans, and pinnipeds listening in water and in air. The Southall injury criteria are for the onset of PTS in marine mammals. They are dual criteria, in that if either criterion is exceeded, injury is assumed. The peak SPL criteria are un-weighted, whereas the SEL criteria are frequency weighted for the relevant functional hearing group (known as M-weighting).

The proposed exposure criteria for injury were derived from measured or assumed TTS-onset thresholds for each hearing group plus TTS growth rate estimates, although data were limited to few species. Available TTS data for two mid-frequency cetacean species (bottlenose dolphin (*Tursiops truncatus*) and beluga (*Delphinapterus leucas*)) and three pinniped species (harbor seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*), and northern elephant seal (*Mirounga angustirostris*)) were used as the basis for estimating PTS-onset thresholds (Table A-1). Southall et al. (2007) also outlined research recommendations to enhance future marine mammal noise exposure criteria (Table A-2).

Table A-1. Proposed injury and behavioral disturbance threshold criteria for individual marine mammals exposed to discrete noise events, as either single or multiple exposures within 24 hours (Southall et al. 2007). Non-pulses are defined as sounds that do not possess impulsive characteristics, such as fast rise times.

Functional hearing group	Injury*			Behavioral disturbance†
	Single pulses	Multiple pulses	Non-pulses	Single pulses
Low-frequency cetaceans				
unweighted peak SPL (dB re 1 µPa)	230	230	230	224
M-weighted SEL (dB re 1 µ²·s)	198	198	215	183
Mid-frequency cetaceans				
unweighted peak SPL (dB re 1 µPa)	230	230	230	224
M-weighted SEL (dB re 1 µ²·s)	198	198	215	183
High-frequency cetaceans				
unweighted peak SPL (dB re 1 µPa)	230	230	230	224
M-weighted SEL (dB re 1 µ²·s)	198	198	215	183
Pinnipeds (in water)				
unweighted peak SPL (dB re 1 µPa)	218	218	218	212
M-weighted SEL (dB re 1 µ²·s)	186	186	203	171

* All SPL injury criteria are based on the peak pressure known or assumed to elicit TTS-onset, plus 6 dB. SEL injury criteria are based on the SEL eliciting TTS-onset plus (1) 15 dB for any type of marine mammal exposed to single or multiple pulses, (2) 20 dB for cetaceans or pinnipeds in water exposed to non-pulses, or (3) 13.5 dB for pinnipeds in air exposed to non-pulses.
† Behavioral response criteria are based on (1) results for beluga TTS-onset thresholds for cetaceans, and (2) estimates of TTS-onset for pinnipeds.

Table A-2. Research recommendations to enhance future marine mammal noise exposure criteria (Southall et al. 2007 Table 24).

Research topic	General description	Critical information needs
Acoustic measurements of relevant sound sources	Detailed measurements needed of source levels, frequency content, and radiated sound fields around intense and/or chronic noise sources.	Comprehensive, calibrated measurements of the properties of human-generated sound sources, including frequency dependent propagation and received characteristics in different environments.
Ambient noise measurements	Systematic measurements of underwater ambient noise are needed to quantify how human activities are affecting the acoustic environment.	Comprehensive, calibrated measurements of ambient noise, including spectral, temporal, and directional aspects, in different oceanic environments; ambient noise budgets indicating relative contribution of natural and anthropogenic sources and trends over time.
Absolute hearing measurements	Audiometric data are needed to determine functional bandwidth, species and individual differences, dynamic hearing ranges, and detection thresholds for realistic biological stimuli.	Carefully controlled behavioral and electrophysiological measurements of hearing sensitivity vs. frequency for more individuals and species, particularly for high-priority species, such as beaked whales and mysticetes. Also, detection thresholds for complex biological signals.
Auditory scene analysis	Measurements to determine the sophisticated perceptual and processing capabilities of marine mammals that enable them to detect and localize sources in complex, 3-D environments.	Measurements of stream segregation, spatial perception, multidimensional source localization, frequency discrimination, temporal resolution, and feedback mechanisms between sound production and hearing systems.
Marine mammal behavioral responses to sound exposure	Measurements of behavioral reactions to various sound types are needed, including all relevant acoustic, contextual, and response variables.	Carefully constructed observational and exposure experiments that consider not only RL but also source range, motion, signal-to-noise ratio, and detailed information on receivers, including baseline behavior, prior experience with the sound, and responses during exposure.
Effects of sound exposure on marine mammal hearing: masking, TTS, and PTS	Continued effort is needed on the simultaneous and residual physiological effects of noise exposure on marine mammal hearing.	Masked hearing thresholds for simple stimuli in more species and individuals, as well as complex biological signals and realistic maskers; allowance for directional effects; comparative data on TTS-onset and growth in a greater number of species and individuals for non-pulse and pulsed anthropogenic sources; recovery functions after exposures and between repeated exposures.
Effects of sound exposure on marine mammal non-auditory systems	Physiological measurements are needed for both acute and chronic sound exposure conditions to investigate effects on non-auditory systems.	Various baseline and exposure-condition measurements, including nitrogen saturation levels; bubble nuclei; the formation of hemorrhages, emboli, and/or lesions; stress hormones; and cardiovascular responses to acute and chronic noise exposure.

The equal energy hypothesis states that two sounds with equal energy are equally harmful (with the exception of extreme pulsed noise, which can induce rupture of the tympanic membranes and fracture of the ossicular chain). This implies that TTS data obtained from studies of impulsive signals could be used to predict effects from exposure to longer lasting sounds. Several well-controlled TTS studies on marine mammals provide data supporting this hypothesis, and most regulations regarding underwater noise exposure have successively applied the so-called dual criteria of peak SPL and SEL as suggested by Southall et al. (2007). However, new studies have found that hearing loss after noise exposure is not necessarily correlated with the total energy of exposure. Exposure experiments with bottlenose dolphins

Finneran et al. (2009) revealed that the correlation between SEL and TTS is limited to pulses and that the equal energy hypothesis does not apply to long-duration exposures. Furthermore, rapid amplitude change (kurtosis) was identified as another factor influencing the amount of TTS elicited (Le Prell 2010).

The sound received by an animal depends not only on the acoustic characteristics of the sound source, but also on the receiver's position relative to the sound source and on the oceanographic characteristics (bathymetry, sound speed profile, etc.) of the area. While some noise exposure criteria (e.g., in the US) consequently focus on the received sound levels, other regulations include a stand-off distance from the sound source where the noise exposure criterion must be met at its perimeters (e.g., Germany).

The aim of implementing noise exposure criteria into offshore marine regulations is to prevent negative effects to marine fauna from exposure to intense anthropogenic sounds. This implies that all species at risk should be equally protected from auditory damage if these criteria are to be enforced. The biggest deficit, however, is the current lack of data on auditory sensitivity and tolerance to intense sound in many marine species. Most data on TTS have been measured in only a small number of marine mammal species, and the data indicate substantial differences with regard to hearing sensitivity and vulnerability to TTS between functional groups (species using high-frequency echolocation signals vs. species emitting mid-frequency signals, for example). Consequently, any noise exposure criterion may be effective only if it is based on data from the most sensitive species occurring in the area of concern.