Turbine Foundation and Cable Installation at South Fork Wind Farm

Underwater Acoustic Modeling of Construction Noise

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8 February 2021

P001383
Document 01584
Version 4.0

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Suggested citation:

Denes., S.L., D.G. Zeddies, and M.M. Weirathmueller. 2018. *Turbine Foundation and Cable Installation at South Fork Wind Farm: Underwater Acoustic Modeling of Construction Noise*. Document 01584, Version 4.0. Technical report by JASCO Applied Sciences for Stantec Consulting Services Inc.

Executive Summary

Deepwater Wind South Fork LLC (DWSF) is proposing to install an offshore wind energy facility consisting of the South Fork Wind Farm (SFWF), located in its lease area on the Atlantic Outer Continental Shelf, as well as the offshore and onshore components of the South Fork Export Cable (SFEC). The SFWF will consist of up to 15 wind turbine generators (WTG) and an offshore substation, each of which will be supported by a foundation, as well as an inter-array cable connecting the WTG to the offshore substation. The SFEC is an electrical energy export cable that will connect the SFWF to an existing onshore substation in East Hampton, NY. Installation of the SFWF and SFEC is expected to begin in 2021.

Underwater construction noise from the project is expected from impact pile driving, vibratory pile driving and the operation of the thrusters on dynamically-positioned vessels. Impact pile driving will occur during the installation of monopile foundations. Vibratory pile driving will occur during the installation of a nearshore sheet-pile cofferdam to facilitate the sea-to-shore transition of the SFEC. Dynamically-positioned vessels will be used to install the SFWF interarray cable system and the SFEC. Noise from monopile installation and a dynamically-positioned cable-lay vessel was modeled to determine sound propagation in the wind farm area, and along the SFEC corridor and SFWF interarray cable routes. Noise from cofferdam construction was modeled at a nearshore location.

The objective of this modeling study was to generate predictions of the ranges to acoustic thresholds that may result in injury (Level A Take) to or behavioral disruption (Level B Take) of cetaceans, sea turtles, and fish near the construction areas. The basic modeling approach was to characterize the sound sources and then determine how the sounds propagated within specific construction sites. It was assumed that any of the proposed activities could be performed at any time during the year.

Acoustic thresholds used in this study represented the best available science. For potential injury to marine mammal species the Technical Guidance issued by NOAA (NMFS 2016) was used. For potential behavioral disruption of marine mammals, the threshold values currently considered by NMFS were used along with an approach suggested by Wood et al. (2012) that account for the hearing range of the animals. For potential effects of sound on fish and sea turtles, the guidelines established by Popper et al. (2014), representing the consensus efforts of a scientific working group, were used as well as those developed by Stadler and Woodbury (2009) for fish and Blackstock et al. (2018) for turtles.

Acoustic fields were modeled for the sound sources expected to contribute to the noise produced during construction of the wind farm. Impulsive noise from impact pile driving of the monopile foundations was modeled at two sites, for 8 and 11 m monopiles, using hammers from two manufacturers (see following summary tables). Non-impulsive noise generated by a dynamically-positioned vessel was modeled at two locations along the SFEC corridor. Non-impulsive noise resulting from vibratory pile driving for cofferdam installation was modeled at one location. The ranges to specific thresholds are reported for each scenario.

8 m Monopile – IHC S4000

Faunal Group	Distance to Level A (m)						Faunal Group	Distance to Level B (m)					
	Summer			Winter				Summer			Winter		
	0 dB	6 dB	12 dB	0 dB	6 dB	12 dB		0 dB	6 dB	12 dB	0 dB	6 dB	12 dB
LF $L_{E,24hr}$	10,240	5,927	3,174	15,642	7,272	3,423	LF $L_{P, flat}$	9,126	5,101	3,358	12,103	6,151	3,532
MF $L_{E,24hr}$	129	25	25	158	0	0	MF $L_{P, flat}$	9,126	5,101	3,358	12,103	6,151	3,532
HF $L_{E,24hr}$	7,626	3,493	1,355	10,151	4,186	1,454	HF $L_{P, flat}$	9,126	5,101	3,358	12,103	6,151	3,532
PW $L_{E,24hr}$	2,754	1,172	343	2,957	1,082	320	PW $L_{P, flat}$	9,126	5,101	3,358	12,103	6,151	3,532
Sturgeon $L_{E,24hr}$	10,709	6,525	3,822	15,730	7,917	4,182	Sturgeon $L_{P, flat}$	20,021	12,388	7,712	43,878	19,802	9,997
Sea Turtle TU $L_{E,24hr}$							Sea Turtle $L_{P, flat}$	2,845	1,792	963	2,926	1,931	972

8 m Monopile – Menck 3500S

Faunal Group	Distance to Level A (m)						Faunal Group	Distance to Level B (m)					
	Summer			Winter				Summer			Winter		
	0 dB	6 dB	12 dB	0 dB	6 dB	12 dB		0 dB	6 dB	12 dB	0 dB	6 dB	12 dB
LF $L_{E,24hr}$	13,216	7,641	4,306	23,674	10,190	4,917	LF $L_{P, flat}$	10,783	6,112	3,774	14,265	7,888	4,117
MF $L_{E,24hr}$	215	61	25	255	71	0	MF $L_{P, flat}$	10,783	6,112	3,774	14,265	7,888	4,117
HF $L_{E,24hr}$	10,418	5,262	2,170	15,554	6,913	2,476	HF $L_{P, flat}$	10,783	6,112	3,774	14,265	7,888	4,117
PW $L_{E,24hr}$	3,976	1,851	677	4,690	1,916	570	PW $L_{P, flat}$	10,783	6,112	3,774	14,265	7,888	4,117
Sturgeon $L_{E,24hr}$	13,267	7,921	4,671	21,890	10,467	5,385	Sturgeon $L_{P, flat}$	22,901	13,637	9,055	67,720	24,746	12,244
Sea Turtle TU $L_{E,24hr}$	336	1,263	519	403	1,264	501	Sea Turtle $L_{P, flat}$	3,061	2,091	1,116	3,172	2,154	1,105

11 m Monopile – IHC S4000 (12MW WTG)

Faunal Group	Distance to Level A (m)						Faunal Group	Distance to Level B (m)					
	Summer			Winter				Summer			Winter		
	0 dB	6 dB	12 dB	0 dB	6 dB	12 dB		0 dB	6 dB	12 dB	0 dB	6 dB	12 dB
LF $L_{E,24hr}$	12,831	7,773	4,660	20,001	10,003	5,370	LF $L_{P, flat}$	10,150	6,275	4,045	12,614	7,493	4,282
MF $L_{E,24hr}$	103	46	33	111	40	20	MF $L_{P, flat}$	10,150	6,275	4,045	12,614	7,493	4,282
HF $L_{E,24hr}$	7,800	3,587	1,508	10,779	4,437	1,637	HF $L_{P, flat}$	10,150	6,275	4,045	12,614	7,493	4,282
PW $L_{E,24hr}$	3,085	1,350	445	3,363	1,400	428	PW $L_{P, flat}$	10,150	6,275	4,045	12,614	7,493	4,282
Sturgeon $L_{E,24hr}$	14,315	9,103	5,726	21,391	11,484	6,492	Sturgeon $L_{P, flat}$	20,594	12,933	8,771	38,180	19,709	10,969
Sea Turtle TU $L_{E,24hr}$	3163	1,478	683	3465	1,500	696	Sea Turtle $L_{P, flat}$	3,190	2,250	1,300	3,354	2,316	1,344

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1. Introduction

Deepwater Wind South Fork LLC (DWSF) is submitting for approval to the Bureau of Ocean Energy Management (BOEM) a Construction and Operations Plan pursuant to 30 CFR 585 *et seq.* to install and operate a commercial wind farm within its federal lease area on the Atlantic Outer Continental Shelf (Figure 1). The South Fork Wind Farm (SFWF) includes up to 15 wind turbine generators (WTG), an offshore substation, and inter-array cables connecting the WTG and offshore substation. The WTG and offshore substation will be supported by foundations. The South Fork Export Cable (SFEC) will connect the SFWF to an existing onshore substation in East Hampton, NY. The SFEC includes a submarine cable that will land along the southern shore of Long Island and transition to an underground cable. Installation of the SFWF and SFEC is expected to begin in 2021.

As part of the application, JASCO Applied Sciences (JASCO) has modeled underwater noise likely to be created during the installation. The objective of this modeling study was to predict the ranges to acoustic thresholds that could result in injury (Level A Take) or behavioral disruption (Level B Take) of marine mammals, sea turtles, and fish during installation of the wind farm.

1.1. Modeling Scope & Assumptions

Noise associated with the construction of the wind farm will come from three sources: 1) impact pile driving associated with installing wind-turbine foundations, 2) vibratory pile driving for the installation of a cofferdam, and 3) thrusters of a dynamically-positioned vessel used for cable installation. For regulatory purposes, impact pile driving produces impulsive sounds while vibratory pile driving and thrusters produce non-impulsive sound. Appendix A contains a glossary of technical acoustic terms, and Appendix C provides an overview of underwater acoustics. Appendix B summarizes project and study assumptions. Project data were provided by DWSF in response to data requests from JASCO. When project data were supplied in Imperial units the values were converted to SI (metric) units for modeling. Imperial values are parenthetically included at first mention of a parameter. Results reported using SI units.

1.1.1. Impact pile driving

Monopile foundations consisting of a single pile of 8.128 m (320 in) diameter or 10.97 m (432 in) were modeled at two representative locations in the lease area (P1 and P2 in Figure 1). The amount of sound produced during pile driving varies with the energy required to drive piles to a desired depth. Two hammers for the foundations were modeled because the hammer or hammers that will be used during construction are not known at this time. Modeling for multiple hammers provides a more general analysis based on possible operational alternatives.The tentative make and model of impact hammers, and a preliminary hammering energy schedule were provided by DWSF. Piles are assumed to be vertical, and driven to a penetration depth of 40 m (130 ft). The estimated number of strikes required to drive piles to completion were provided by DWSF.

Assumptions for the 8 m monopile are as follows:

- 8.128 m (320 in) steel cylindrical pilings with wall thickness of 7.62 cm (3 in).
- Impact pile driving hammer
  - IHC S-4000 (4,000 kJ rated energy; 1,977 kN ram weight, 3,234 kN helmet weight)
  - Menck 3500 (3,500 kJ rated energy; 1,717 kN ram weight, 1,107 kN helmet weight)
- One pile installed per day (2,400 strikes per 24 hr)
- Piling barge noise was not included in the model.

Assumptions for the 11 m monopile are as follows:

- 10.970 m (432 in) steel cylindrical pilings with wall thickness of 10.0 cm (4 in).
- Impact pile driving hammer
  - IHC S-4000 (4,000 kJ rated energy; 1,977 kN ram weight, 3,234 kN helmet weight)
- One pile installed per day (most installations require 4,500 strikes per 24 hr; a difficult pile may require up to 8,000 strikes per 24 hr)
- Piling barge noise was not included in the model.

1.1.2. Vibratory Pile Driving for Cofferdam installation

Vibratory pile driving of the sheet piling at the SFEC landfall (CD in Figure 1) was modeled for cofferdam installation. The model assumed the use of an APE 200T vibratory hammer to drive Z-type sheet pile 9 m (30 ft) into the sediment under 9 m (30 ft) of water.

1.1.3. Thrusters of dynamically-positioned cable-lay vessel

Noise associated with cable installation will primarily come from the dynamically-positioned cable-lay vessel. Noise from the vessel was modeled at two locations for representative sound propagation along the potential export (to shore) cable corridor and interarray (between wind turbines) cable routes (C1 and C2 in Figure 1). Modeling of the noise produced by thrusters was based on measured data and previous work conducted by JASCO. It was assumed that the thrusters were operating at 4000 BHP.

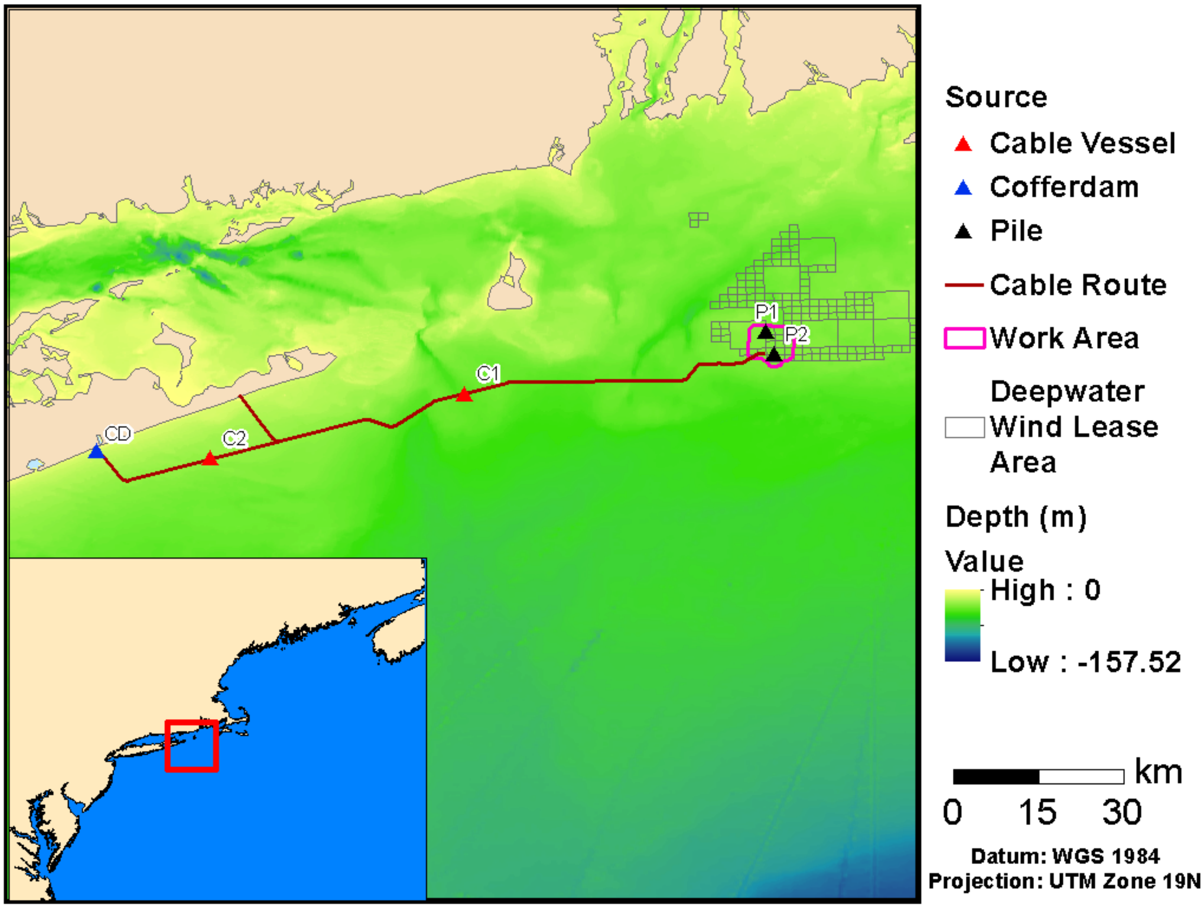

Figure 1. Site of South Fork Wind Farm. Black triangles show impact pile driving modeling locations, red triangles show modeling locations for dynamic positioning thrusters, blue triangle shows modeling location for the cofferdam. The proposed SFEC route is shown in red and the wind farm development area is outlined in pink.

2. Methods

The aim of this acoustic modeling effort is to determine the ranges to thresholds for Level A Take and potential Level B Take of species near the proposed construction site. The basic modeling approach is to characterize the sound sources and then determine how those sounds propagate within the specific construction areas.

For evaluating underwater noise, sounds are divided into two types: impulsive sounds and non-impulsive sounds. Impact pile driving for installing monopile foundtations produces impulsive sounds, while dynamic positioning thrusters and vibratory hammers produce non-impulsive sounds.

For impulsive sounds, time-domain representations of the pressure waves generated in the water are required to calculate the sound pressure level (L_p, also denoted as SPL), sound exposure level (L_E, also denoted as SEL), and peak sound pressure (L_{pk}). The source signatures of each pile are predicted using a finite-difference model that determines the physical vibration of the pile caused by hammer impact. The sound field radiating from the pile is simulated using a vertical array of point sources. Because sound itself is an oscillation (vibration) of water particles, acoustic modeling of sound in the water column is inherently an evaluation of vibration. For this study, synthetic pressure waveforms were computed using a Full Waveform Range-dependent Acoustic Model (FWRAM), which is JASCO's acoustic propagation model capable of producing time-domain waveforms.

The modeling process is similar for non-impulsive sounds, but it is simplified relative to modeling impulsive sounds because phase information is not included. The sound source signature is estimated from previously recorded sources and the propagation modeling performed by JASCO's Marine Operations Noise Model (MONM), which computes received sound energy for directional sources.

The sound propagation modeling incorporates site-specific environmental data that describes the bathymetry, sound speed in the water column, and seabed geoacoustics in the proposed construction area. Ranges to pre-determined threshold levels are obtained from the calculated sound fields for use in evaluating potential impacts to marine fauna.

2.1. Acoustic Environment

2.1.1. Bathymetry

A bathymetry grid for the acoustic propagation model was compiled based on the data provided by DWSF and Shuttle Radar Topography Mission (SRTM) referred to as SRTM-TOPO15+ (Becker et al. 2009).

2.1.2. Geoacoustics

In shallow water environments where there is increased interaction with the seafloor, the properties of the substrate have a large influence over the sound propagation. Compositional data of the surficial sediments were provided by DWSF. The dominant soil type is expected to be sand. Table 1 shows the sediment layer geoacoustic property profile based on the sediment type and generic porosity-depth profile using a sediment grain-shearing model (Buckingham 2005).

Table 1. Estimated geoacoustic properties used for modeling, as a function of depth, in meters below the seabed. Within an indicated depth range, the parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm³)	P-wave speed (m/s)	P-wave attenuation (dB/λ)	S-wave speed (m/s)	S-wave attenuation (dB/λ)
0–5	Sand	1.99–2.04	1,488–1,662	0–1.0	275	3.65
5–10		2.2	1,662–1,950	1.0–1.2		
10–100			1,950–2,040	1.2–12.1		
> 100			2,604	2.1		

2.1.3. Sound Velocity Profile

The speed of sound in in sea-water is a function of temperature, salinity and pressure (depth) (Coppens 1981). Sound velocity profiles were obtained from the U.S. Navy's Generalized Digital Environmental Model (GDEM; NAVO 2003). The sound speed profiles change little with depth near the proposed construction area (Figure 2). The months of April through October are weakly downwardly refracting (Figure 2) leading to more interaction with the sea bed and (somewhat) greater attenuation with propagation distance. The months of November through March are nearly isovelocity (same velocity with depth), though with slower sound speed, and will interact (somewhat) less with the sea bed. The absolute velocity of November and December is greater than January, February, and March, so the sound velocity profile for averaged over November and December is used in this study to represent winter because it is expected to produce the greatest propagation distances—though little difference in propagation is expected from these seasonal sound velocity profiles.

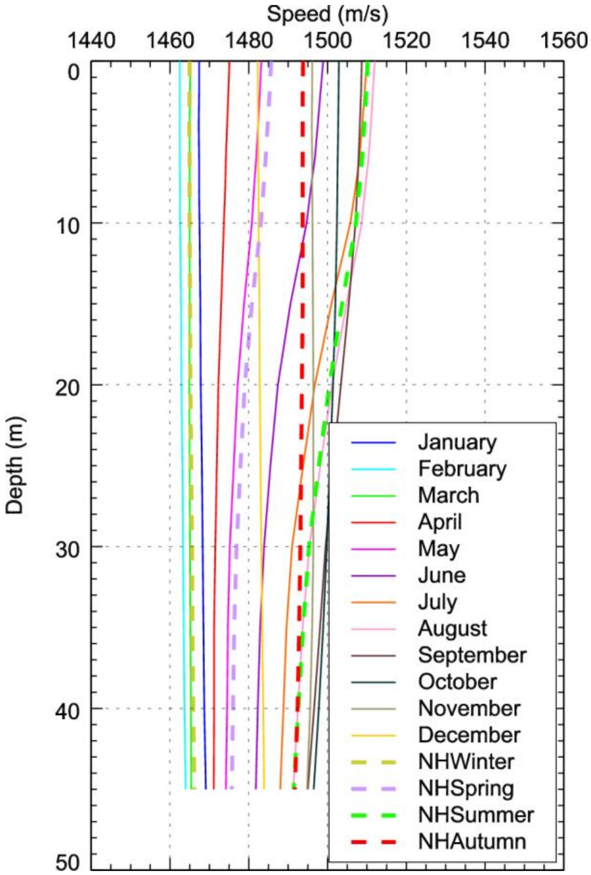

Figure 2. Month and seasonal average sound velocity profiles in proposed construction area.

2.2. Modeling Locations

Two sites were modeled to represent the potential locations for foundations (P1 and P2) within the SFWF project rea, two sites for SFEC installation (C1 and C2), and one site for the SFEC cofferdam (CD) (Table 2 & Figure 1). Sites were selected to produce representative sound fields for the construction area. The water depths at the site locations were extracted from a bathymetry file provided by DWSF.

Table 2. Locations for modeling.

Scenario	Location (UTM Zone 19N)		Water depth (m)	Sources	Source type
	Easting	*Northing*			
P1	317,803	4,553,388	34	Monopile	Impulsive
P2	318,822	4,549,318	36		
C1	277,317	4,543,503	40	Dynamic Position Thrusters	Non-impulsive
C2	243,041	4,533,254	28		
CD	227,901	4,535,221	9	Sheet Pile	Non-impulsive

2.3. Pile Driving Schedule

Typical pile driving schedules and hammer data were supplied by DWSF and used to calculate the sound fields (and accumulate the overall sound energy) at different points during pile driving (Tables 3-5). Assuming an average strike rate of 36 strikes/minute for the IHC S-4000 and Menck 3500S hammers, the minimum time to drive an 8 m monopile foundation is 67 minutes. For the 11 m monopile foundation with an IHC S-4000 operating at 32 strikes per minute, the minimum driving time is 140 minutes and up to 250 minutes for a difficult to drive pile. The maximum number of foundations driven per day is one.

Table 3. Typical pile driving schedule for 8 m monopiles. Hammer energy level, number of blows at that energy, and penetration depth are shown for the IHC S-4000 or Menck 3500S hammers.

IHC S-4000		**Menck 3500S**		**Pile penetration** (m)
Energy level (kJ)	*Blow count*	*Energy level (kJ)*	*Blow count*	
1,000	200	1,000	200	5
1,500	800	1,500	800	5
2,500	1,000	2,500	1,000	17
4,000	400	3,500	400	3

Table 4. Typical pile driving schedule for 11 m monopiles. Hammer energy level, number of blows at that energy, and penetration depth are shown for the IHC S-4000 hammer.

IHC S-4000		**Pile penetration** (m)
Energy level (kJ)	*Blow count*	
1,000	500	6
1,500	1,000	17.5
2,500	1,500	17.5
4,000	1,500	4

Table 5. Pile driving schedule for difficult 11 m monopiles . Hammer energy level, number of blows at that energy, and penetration depth are shown for the IHC S-4000 hammer.

IHC S-4000		**Pile penetration** (m)
Energy level (kJ)	*Blow count*	
1,000	800	6
1,500	1.200	17.5
2,500	3,000	17.5
4,000	3,000	4

2.3.1. Impulsive Sources: Impact Pile Driving

A pile is a distributed sound source but can be treated as a linear array of point sources. The underwater sound radiating from the pile can be calculated from equations of motion for a cylindrical shell. To solve these equations, information is needed about the state of the pile system (the boundary conditions) such as the forcing function of the hammer at the top of the pile, the soil resistance at the base of the pile, and vibrational damping due to water loading. The output of the equations of motion are the computed acoustic (Mach) waves emanating from the pile wall. The equations of motion are used with the finite difference (FD) method and are solved on a discrete time and depth mesh. The modeling approach is illustrated in Figure 3, where the pile is shown as a linear array of point sources, the hammer as the forcing function at the top of the pile, soil resistence at the bottom, and the acoustic waves emanating from the pile starting nearest the impact hammer at the top of the pile.

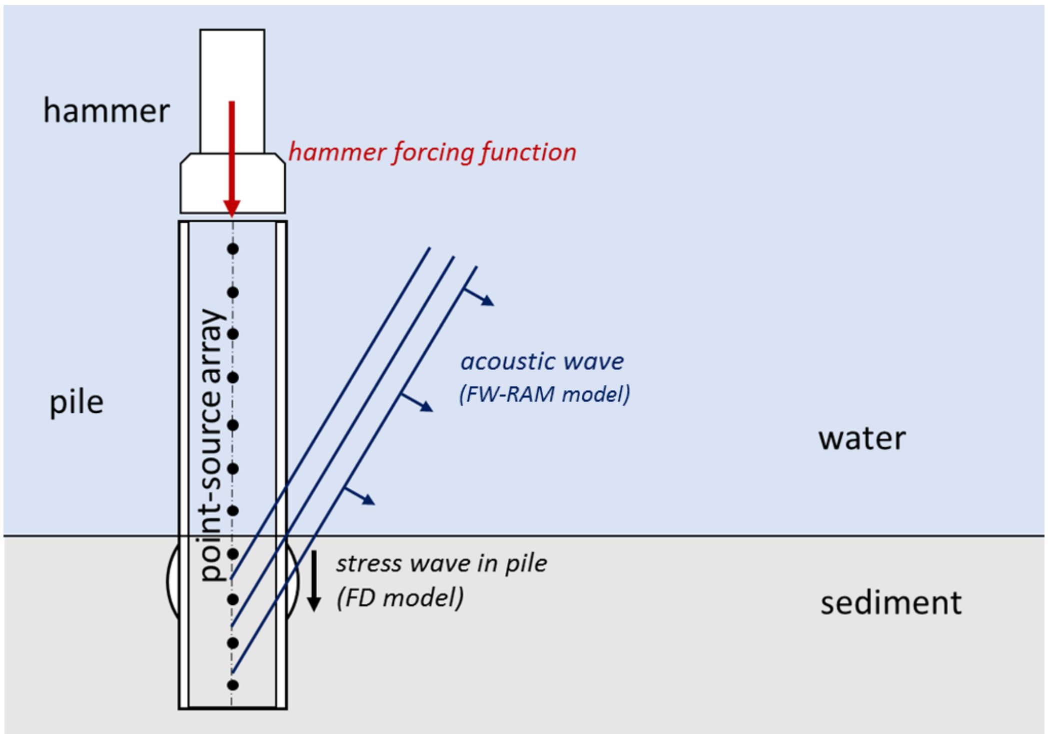

Figure 3. Modeling components for impact driving of a cylindrical pile. The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the FWRAM model to compute the acoustic waves radiated by the pile wall.

The sound radiation from the pile is simulated using a vertical array of discrete point sources. The point sources are centered on the pile. Their amplitudes are derived using an inverse technique, such that their collective particle velocity—calculated using a near-field wave-number integration model—matches the particle velocity in water to that of the pile wall. A detailed description of the theory behind the physical model is provided in MacGillivray (2014). The accuracy of JASCO's pile driving model has been verified by comparing its output against benchmark scenarios (Lippert et al. 2016). The sound field from the vertical source array is then calculated using a full-wave propagation model (Section 2.3.1.1).

To model sound emissions from the piles, the impact force of the pile driving hammers must first be determined. For the purposes of this investigation, two representative impact hammers were modeled for monopile foundation installation, an IHC S-4000 and Menck S3500. The force at the top of each pile, associated with the typical hammers, was computed using the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010). The database associated with GRLWEAP contains parameters of pile driving hammers needed for modeling the forcing function.

The forcing functions are computed assuming direct contact between the hammers, helmets, and the piles (i.e., no cushion material) (Figures 4 and 5). The FD model is then used to compute the resulting pile vibrations. The stress wave generated at the top of the pile by the hammer travels downward to the pile toe, where it is partially reflected. The reflected stress waves travel up and down the pile and are gradually dissipated by soil resistance and radiative damping.

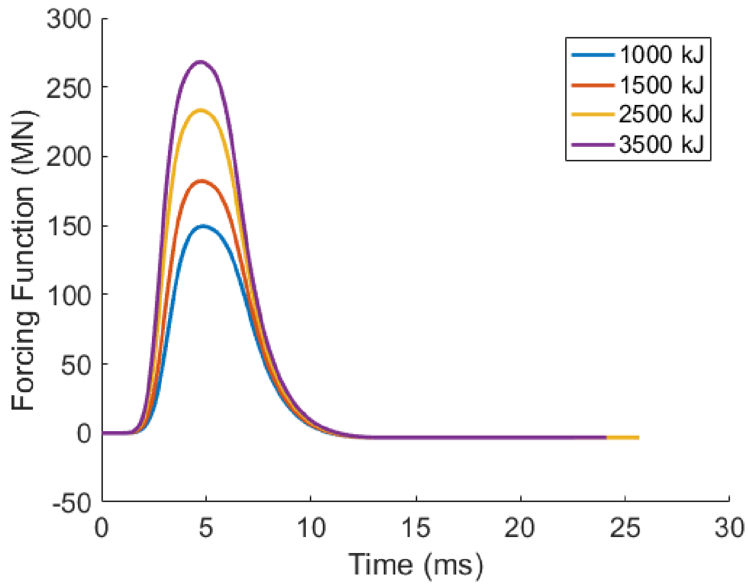

Figure 4. Modeled forcing functions versus time for the Menck 3500S (3,500 kJ) diesel impact hammers for an 8 m monopile as a function of hammer energy.

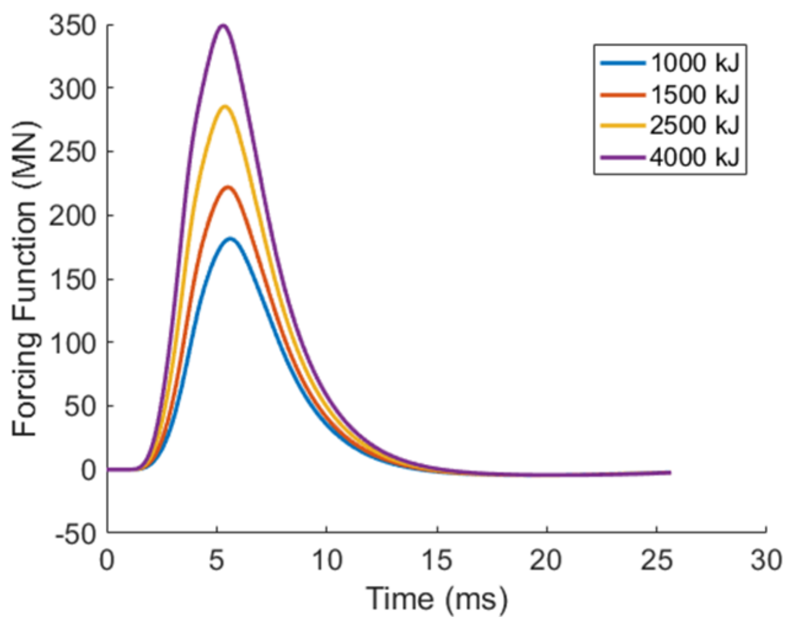

Figure 5. Modeled forcing functions versus time for the IHC S-4000 (4,000 kJ) diesel impact hammers for an 11 m monopile as a function of hammer energy.

To model the sound waves associated with the pile vibration in an acoustic propagation model, the piles are represented as vertical arrays of discrete point sources. The discrete sources are distributed throughout the length of the pile below the sea surface and into the sediment with vertical separation of 3 m. The length of the acoustic source is adjusted for the site-specific water depth and penetration at each energy level. The section length of the pile within the sediment is based on the pile schedule (Tables 3-5). Pressure signatures for the point-sources are computed from the particle velocity at the pile wall up to a maximum frequency of 2,048 Hz. This frequency range is suitable because most of the sound energy generated by the piles is below 1,000 Hz. Figures 6 and 7 show the decidecade-band (Appendix C.2) spectral source levels for an 8-meter and 11-meter pile, respectively.

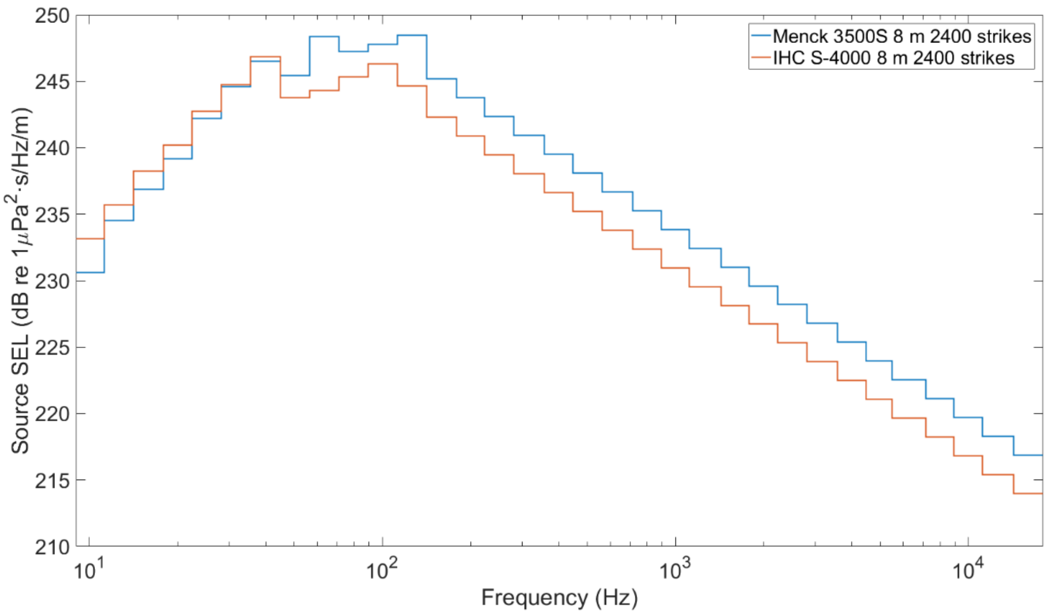

Figure 6. Decidecade band spectral source levels for monopile (8-meter) installation using IHC S-4000 (4,000 kJ) and Menck 3500S (3,500 kJ) hammers.

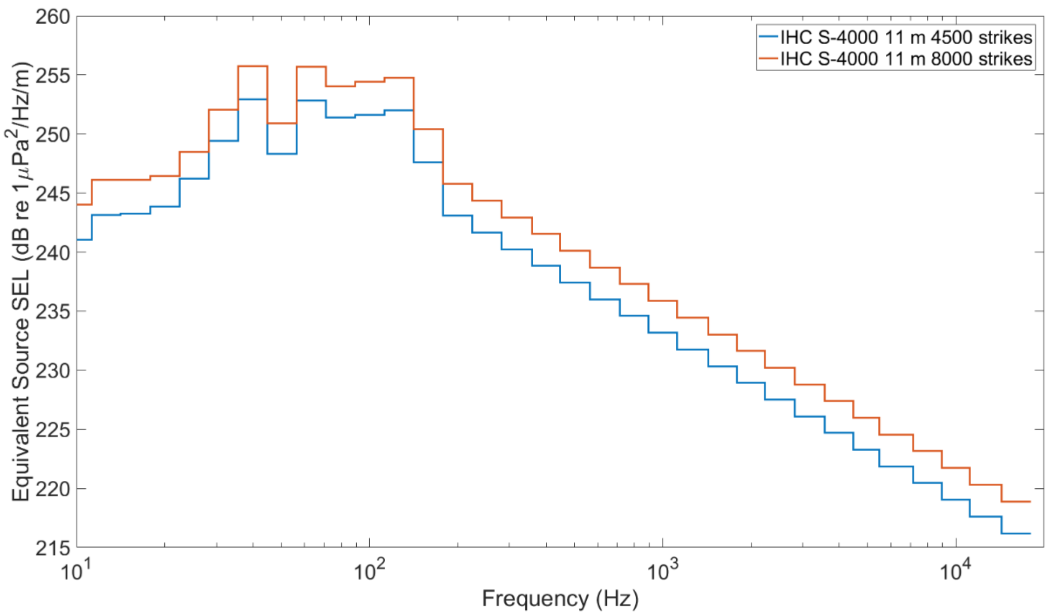

Figure 7. Decidecade band spectral source levels for monopile (11-meter) installation using an IHC S-4000 (4,000 kJ) hammer.

2.3.1.1. Sound propagation: Time domain signals

Pulse characteristics of impulsive sounds change as sound propagates away from a source. Sound waves generally refract (bend) due to different sound speeds at different depths, and the waves interact with boundaries such as the ocean bottom and surface. As a result, impulses typically spread out in time farther from the source. To accurately calculate metrics of an impulsive sound, a time-domain representation of the pressure wave in the water is required. JASCO's Full-Wave Range-dependent Acoustic Model (FWRAM) is an acoustic model based on the wide-angle parabolic equation (PE) algorithm (Collins 1993). FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments. It takes environmental inputs (bathymetry, water sound velocity profile, and seabed geoacoustic profile) and computes pressure waveforms at grid points of range and depth. Figure 8 shows an example of a synthetic pressure waveform as a function of range from a source pile for an 8-meter pile. It can be seen in Figure 8 that the pulse length increases away from the source as a result of multipath arrivals.

Because calculating route mean square (rms) is an averaging process, calculating the rms for transient signals requires special consideration. If, for example, the time window is long compared to the signal, many zeros could be included in the averaging and the rms value decreased. Because the pulse length changes with range (and depth) there is no fixed time window over which to compute the rms of the sound pressure. Instead, the pulse duration is conventionally taken to be the interval during which 90% of the pulse energy is received. When the time-domain pressure waveforms are available, the 90% rms sound pressure (L_p) is easily calculated by starting the window when 5% of the total energy is received and ending when 95% of the total energy has been received. Full-wave models are computationally expensive, but they are necessary for accurately predicting L_p. In addition, because the pile is represented as a linear array and FWRAM employs the array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012), using FWRAM ensures accurate characterization of vertical directivity effects in the near-field zone.

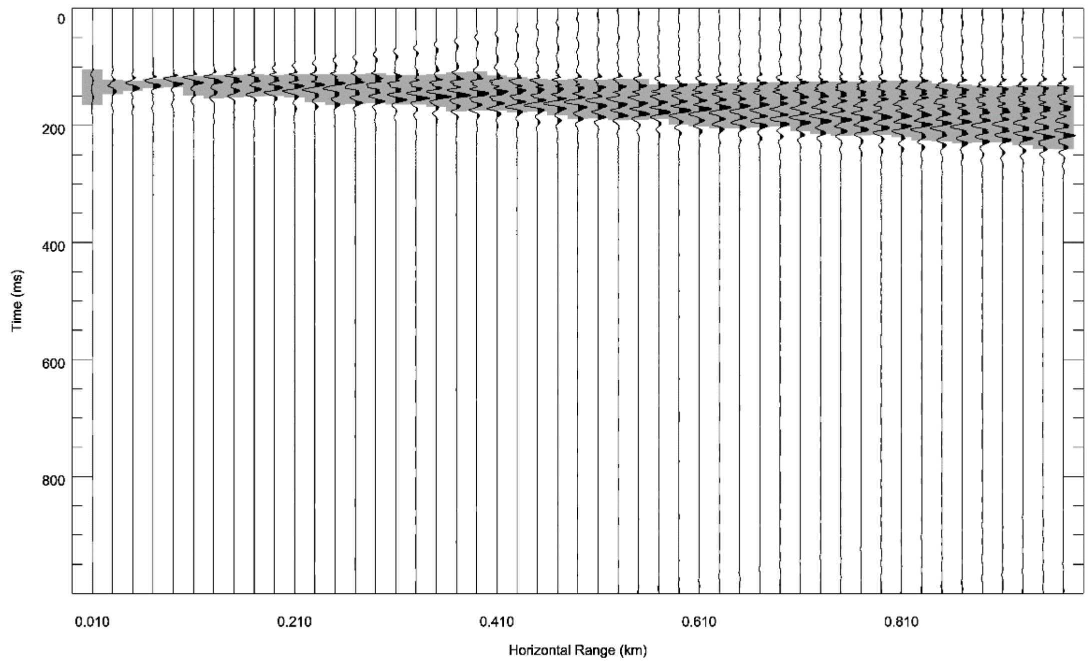

Figure 8. Synthetic pressure waveforms computed by FWRAM for an 8-meter pile driven with an IHC S-4000 hammer at multiple range offsets. Receiver depth is 10 m. For display purposes, the amplitudes of the pressure traces have been normalized and the starting time of the pulse has corrected for sound travel time.

2.3.1.2. Underwater Construction Noise Mitigation

Noise attenuation systems, such as bubble curtains, are sometimes used to decrease the sound levels in the water near a source. Bubbles create a local impedance change that acts as a barrier to sound transmission. The size of the bubbles determines their effective frequency band, with larger bubbles needed for lower frequencies. There are a variety of bubble curtain systems, confined or unconfined bubbles, and some with encapsulated bubbles or panels. These systems may be deployed in series, such as a double bubble curtain with two rings of bubbles encircling a pile. Attenuation levels also vary by type of system, frequency band, and location. Small bubble curtains have been measured to reduce sound levels from ~10 dB to more than 20 dB but are highly dependent on depth of water and current, and configuration and operation of the curtain (Koschinski and Lüdemann 2013, Bellmann 2014, Austin et al. 2016). Larger bubble curtains tend to perform a bit better and more reliably, particularly when deployed with two rings (Koschinski and Lüdemann 2013, Bellmann 2014, Nehls et al. 2016). Encapsulated bubble systems, Hydro Sound Dampers (HSDs), are effective within their targeted frequency ranges, e.g. 100–800 Hz, and when used in conjunction with a bubble curtain appear to create the greatest attenuation, up to 30 dB (Elmer and Savery 2014).

A California Department of Transportation (CalTrans) study, however, tested several systems and found that the best systems resulted in 10–15 dB of attenuation, summarizing that attenuation greater than 10 dB is not reliably predicted (Buehler et al. 2015). The reason for the less than expected performance is that sound transmitted through the seabed and re-radiated into the water column becomes the dominant source of sound in the water (Buehler et al. 2015). The measured results, and manufactures claims, make sense in the context of attenuation levels measured in the water column near the bubble curtain where they may indeed reduce the sound levels by >20 dB if there is little re-radiated sound from the seabed. It is useful to keep in mind that a reduction of 10 dB means reducing the sound energy level by 90%, and to achieve 20 dB attenuation means removing 99% of the sound energy. If 10% of the total sound energy is reintroduced via the seabed then it will limit the overall performance of the attenuation system to 10 dB (i.e. there is a theoretical ceiling or limit to attenuation due to the propagation of sound through the seabed). For these reasons we included in the modeling study hypothetical broadband attenuation levels of 6 and 12 dB to gauge the effects on the ranges to thresholds. Attenuation of 6 dB is conservatively expected to be achieved with the use of a properly functioning noise attenuation system, and 12 dB represents the likely performance level.

2.3.2. Non-impulsive Sources: Vibratory Pile driving (Cofferdam)

Similar to cylindrical piles, sheet piles are a distributed acoustic source that can be treated as a linear array of point sources. The acoustic source modeling of vibratory driving of sheet piles was modeled following the same steps used to model impact pile driving (Section 2.3.1). An American Piledriving Equipment APE Model 200T with Model 200 Universal Clamp was modeled driving a19.5-meter-long (64-foot-long), 0.95 cm (3/8 in) thick, Z-type sheet pile 9 m (30 feet) into the sediment in 9 m (30 ft) of water. The forcing function was modeled for a single cycle of the vibrating hammer using GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010). The finite difference model was used to compute the resulting pile vibrations from the stress wave that propagates down the sheet pile. The radiated sound waves were modeled as discrete point sources over the 18 m (60 ft) of the pile in the water and sediment (9 m [30 ft] water depth, 9 m [30 ft] penetration) with a vertical separation of 10 cm. The source level spectrum of the vibratory pile driving of a sheet pile for a cofferdam at the export cable landfall site are shown in Figure 9.

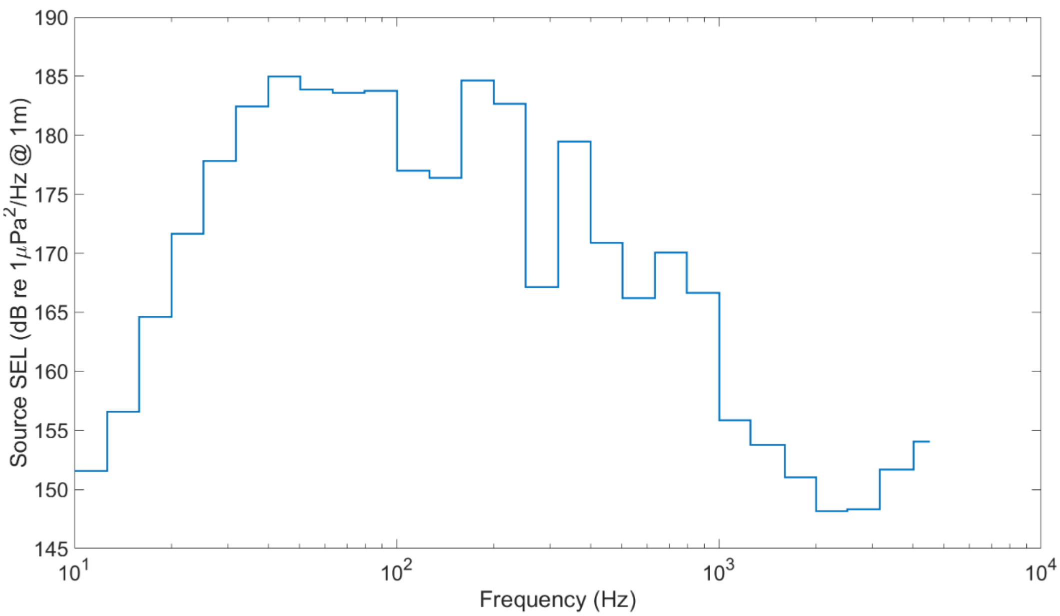

Figure 9. Decidecade-band spectral source levels, at 1 m, for cofferdam construction using vibratory pile driving.

2.3.3. Non-impulsive Sources: Dynamic Positioning Thrusters

The dominant underwater noise source on dynamically positioned vessels is due to cavitation on the propeller blades of the thrusters (e.g., Leggat et al. 1981). The noise power from the propellers is proportional to the number of blades, the propeller diameter, and the propeller tip speed. Spectral source levels can be estimated using formulas provided by Ross (1976) and Brown (1977). The proposed vessel for export cable installation is the *Ndurance*. The *Ndurance* is a 99-meter cable lay vessel with 30-meter beam and a 4.8-meter draft. The four (2 fore, 2 aft) azimuth thrusters and one bow thruster have a combined rated power of 5,050 kW (6,772 BHP). The source spectrum here was taken from JASCO source verification recordings of the *DSV Fu Lai*. *Fu Lai* is a 107-meter dynamically positioned support vessel with a breadth of 19 m and a loaded draft of 6.6 m (MacGillivray 2006). The vessel has 6 thrusters (3 fore and 3 aft) with propeller diameters between 2 m and 2.5 m. The source levels used assume operating power of 2,983 kW (4,000 BHP) on the *Ndurance* (Figure 10).

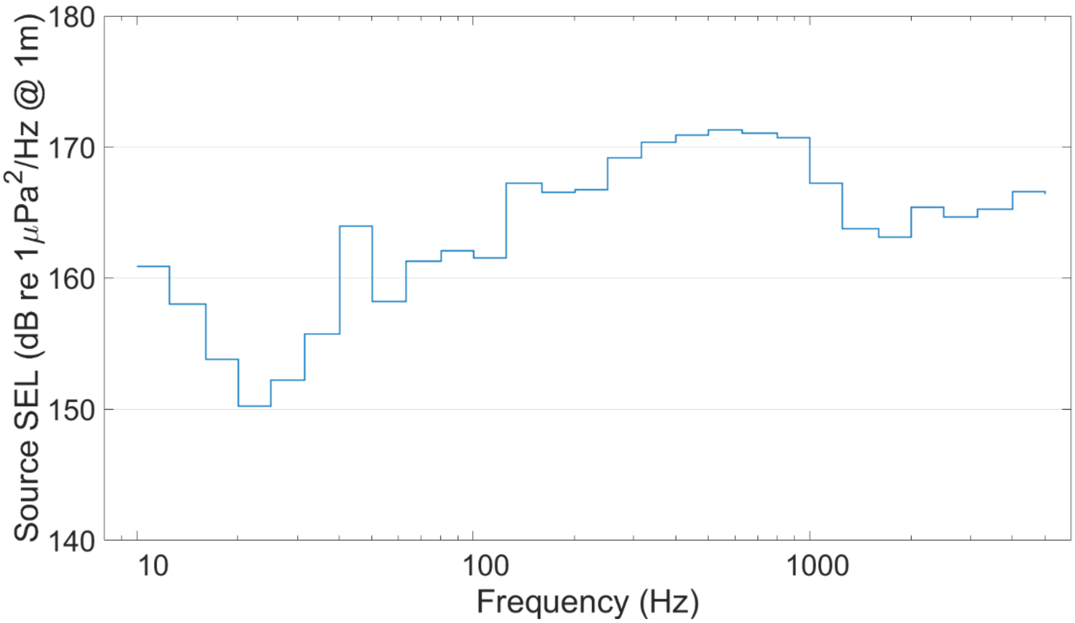

Figure 10. Decidecade-band spectral source levels, at 1 m, for thrusters from thrusters of a dynamic position vessel. Obtained from JASCO data of *DSV Fu Lai* vessel adjusted for anticipated energy rating of DP vessel.

2.3.4. Sound Propagation: Sound Energy

Transmission loss (i.e., sound propagation) can be predicted with JASCO's Marine Operations Noise Model (MONM). MONM computes received sound energy, the sound exposure level (L_E), for directional sources. MONM uses a wide-angle 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 solid 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). MONM's predictions have been validated against experimental data from several underwater acoustic measurement programs conducted by JASCO (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b).MONM accounts for the additional reflection loss at the seabed due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates site-specific environmental properties, such as bathymetry, underwater sound speed as a function of depth, and a geoacoustic profile the seafloor.

MONM treats frequency dependence by computing acoustic transmission loss at the center frequencies of 1/3-octave-bands. At each center frequency, the transmission loss is modeled as a function of depth and range from the source. Composite broadband received L_E are then computed by summing the received 1/3-octave-band levels across the modeled frequency range.

For computational efficiency, MONM and similar models such as PE-RAM, do not track temporal aspects of the propagating signal (as opposed to models that can output time-domain pressure signals, see Section 2.3.1.1). It is the total sound energy transmission loss that is calculated. For our purposes, that is equivalent to propagating the L_E acoustic metric. For continuous, steady-state signals L_p is readily obtained from the L_E.

2.3.5. Three-dimensional Sound Field

Acoustic fields in three dimensions are generated by modeling propagation loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D (Figure 11). These vertical radial planes are separated by an angular step size of Δθ, yielding N = 360°/Δθ planes.

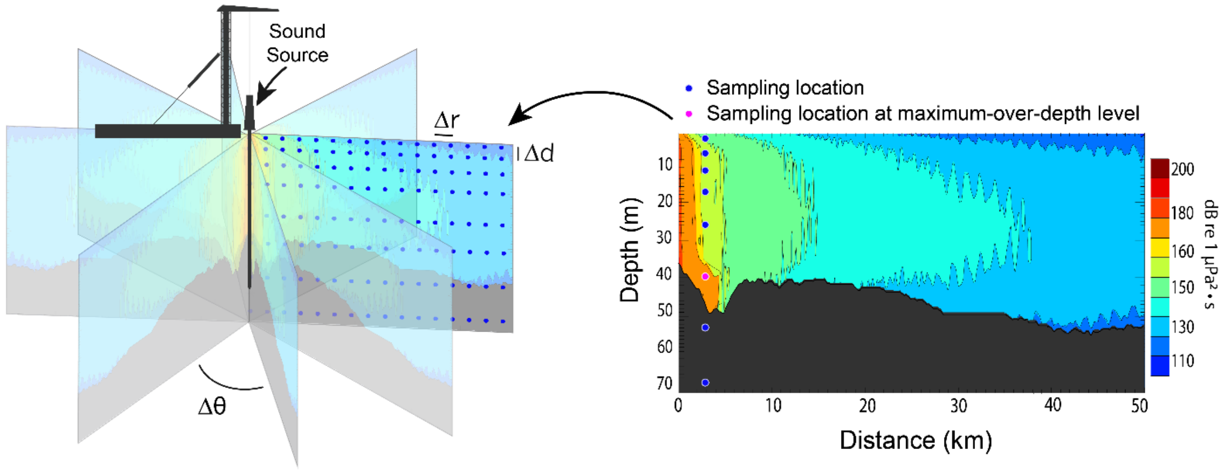

Figure 11. Modeled three-dimensional sound field (N×2-D method) and maximum-over-depth modeling approach. Sampling locations are shown as blue dots on both figures. On the right panel, the pink dot represents the sampling location where the sound level is maximum over the water column. This maximum-over-depth level is used in calculating distances to sound level thresholds for some marine animals.

2.3.6. Determining Ranges

A maximum-over depth approach is used to determine ranges to the defined thresholds (ranges to isopleths). That is, at each horizontal sampling range, the maximum received level that occurs within the water column is used as the value at that range. The ranges to a threshold typically differ along different radii and may not be continuous because sound levels may drop below threshold at some ranges and then exceed threshold at farther ranges. Figure 12 shows an example of an area with sound levels above threshold and two methods of reporting the injury or behavioral disruption range: (1) R_{max}, the maximum range at which the sound level was encountered in the modeled maximum-over-depth sound field, and (2) $R_{95\%}$, the maximum range at which the sound level was encountered after the 5% farthest such points were excluded. $R_{95\%}$ is used because, regardless of the shape of the maximum-over-depth footprint, the predicted range encompasses at least 95% of the horizontal area that would be exposed to sound at or above the specified level. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the heterogeneity of the acoustic environment. $R_{95\%}$ excludes ends of protruding areas or small isolated acoustic foci not representative of the nominal ensonification zone.

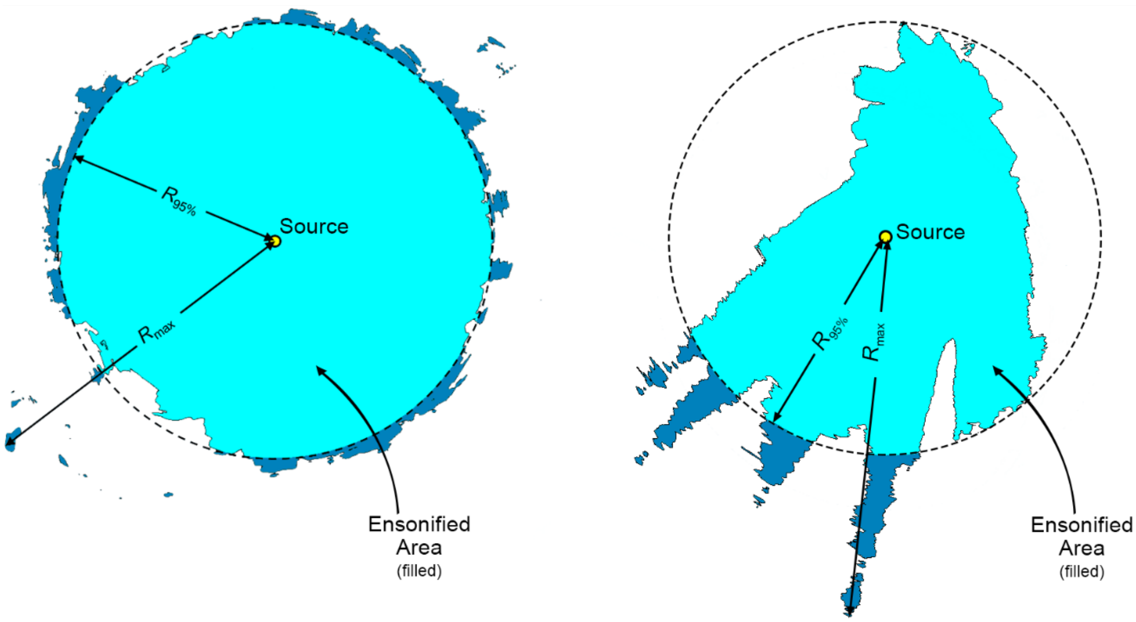

Figure 12.Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

2.3.6.1. Calculating the range for accumulated sound energy, L_E

The range to thresholds for accumulated sound energy, L_E, are found from the maximum-over-depth sound levels using the 95% ($R_{95\%}$, m) horizontal distances. The sound energy, L_E, accumulated over a specified time (e.g., 24 hours) is calculated by summing the single-strike sound energy, $L_{E,1\text{-strike}}$, over the number of strikes expected during that time period. The summation is expressed as:

$$L_E = L_{E,1\text{-strike}} + 10\log_{10}(N), \quad (1)$$

where N is the number of strikes.

After L_E for the number of strikes is calculated, the ranges to the specified thresholds are found.

2.4. Acoustic Criteria

To assess the potential impacts of the proposed construction-related impulse and continuous sounds, exposure criteria for sound levels that may negatively impact animals must first be established. The Marine Mammal Protection Act (MMPA) of 1972, as amended, prohibits causing injury or behavioral disruption of any marine mammal stock in the wild. In 2016, NOAA issued a Technical Guidance document (NMFS 2016) for assessing the effects of sound on marine mammal hearing. The Technical Guidance provides thresholds for the marine mammal functional hearing groups (Appendix D) to evaluate potential hearing loss, including the onset of permanent threshold shift (PTS) from temporary threshold shifts (TTS) (Table 6) (NMFS 2016). NOAA also provided guidance on associated weighting functions to account for the hearing frequency bands of marine mammals when applying the injury (Level A Take) criteria (Appendix D). The NOAA Guidance recommends dual criteria for assessing potentially injurious exposures, including peak, unweighted sound pressure (L_{pk}) and frequency-weighted cumulative sound exposure level (L_E). NOAA has not updated guidance for evaluating potential behavioral disruption (Level B Take). The current NMFS criteria for marine mammals is an unweighted rms sound pressure (L_p) of 160 SPL dB re 1 µPa.

In a cooperative effort between Federal and State transportation and resource agencies, interim criteria were developed to assess the potential for injury to fish exposed to pile driving sounds (Stadler and Woodbury 2009) (Table 7). For sea turtles, NMFS has considered injury onset beginning at an L_p of 180 dB re 1 µPa and behavioral response at an L_p of 175 dB re 1 µPa (Blackstock et al. 2018). These levels and behavioral response levels for fish were compiled and listed in Fisheries Hydroacoustic Working Group report (FHWG 2008), Table 7.

A technical report by an American National Standards Institute (ANSI)-registered committee (Popper et al. 2014) reviewed available data and suggested metrics and methods for estimating acoustic impacts for fish and sea turtles. Table 8 shows threshold levels suggested by Popper et al. (2014) for PTS for impulsive and continuous sounds. Their report does not define sound levels that may result in behavioral response, but does indicate a high likelihood of response near pile driving (tens of meters), moderate response at intermediate ranges (hundreds of meters), and low response far (thousands of meters) from the pile (Popper et al. 2014).

Injury and behavioral thresholds for sea turtles were developed for use by the US Navy (Finneran et al. 2017) based on exposure studies (e.g., McCauley et al. 2000). For sea turtles, dual acoustic thresholds (PK and SEL) have been suggested for PTS and TTS. The behavioral threshold provided in the GARFO acoustic tool (2019) is an SPL of 175 dB re 1 µPa (McCauley et al. 2000, Finneran et al. 2017) (Table 7).

Table 6. Summary of relevant PTS onset acoustic thresholds (NMFS 2016) for functional hearing groups LF is low-frequency cetaceans, MF is mid-frequency cetaceans, HF is high-frequency cetaceans, and PW is pinnipeds (Appendix D).

Hearing group	PTS onset thresholds* (received level; dB)	
	Impulsive	Non-impulsive
LF	$L_{pk,flat}$: 219 $L_{E,LF,24h}$: 183	$L_{E,LF,24hr}$: 199
MF	$L_{pk,flat}$: 230 $L_{E,MF,24h}$: 185	$L_{E,MF,24hr}$: 198
HF	$L_{pk,flat}$: 202 $L_{E,HF,24h}$: 155	$L_{E,HF,24hr}$: 173
PW	$L_{pk,flat}$: 218 $L_{E,PW,24h}$: 185	$L_{E,PW,24hr}$: 201

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure thresholds associated with impulsive sounds, these thresholds should also be considered.
L_{pk}, flat–peak sound pressure is flat weighted or unweighted and has a reference value of 1 µPa
L_E denotes cumulative sound exposure over a 24-hour period and has a reference value of 1 µPa^{2}s
The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting.

Table 7. Interim sea turtle and fish injury and behavioral acoustic thresholds currently used by NMFS GARFO and Bureau of Ocean Energy Management (BOEM) for impulsive pile driving.

Faunal group	Injury		TTS		Behavior
	L_{PK}	L_E	L_{PK}	L_E	L_p
Fish ≥2 g[a,b]	206	187	–	–	150
Fish <2 g[a,b]		183	–	–	
Sea turtles[c,d]	232	204	226	189	175

L_{PK} – peak sound pressure (dB re 1 µPa).
L_E – sound exposure level (dB re 1 µPa^2·s).

L_p – root mean square sound pressure (dB re 1 µPa).
TTS – temporary, recoverable hearing effects.
[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).
[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).
[c] Finneran (2017).
[d] McCauley et al. (2000).

Table 8. Acoustic metrics and thresholds for fish and sea turtles (Adapted from Popper et al. (2014)).

Group	Impulsive Sounds–Pile driving					Non-impulsive Sounds	
	Mortality or potential mortal injury		Recoverable Injury		TTS	Recoverable Injury	TTS
	L_E (dB)	L_{pk} (dB)	L_E (dB)	L_{pk} (dB)	L_E (dB)	$L_{pk, 48h}$ (dB)	$L_{pk, 12h}$ (dB)
Fish without swim bladder	>219	> 213	>216	> 213	>>186	--	--
Fish with swim bladder not involved in hearing	210	> 207	203	> 207	>186	--	--
Fish with swim bladder involved in hearing	207	> 207	203	> 207	186	170	158
Sea turtles	210	> 207	(N) High (I) Low (F) Low		(N) High (I) Low (F) Low	--	--
Eggs and larvae	>210	> 207	(N) Moderate (I) Low (F) Low		(N) Moderate (I) Low (F) Low	--	--

L_E = sound exposure level (dB re 1 µPa^2·s); L_{pk} = peak sound pressure (dB re 1 µPa); $L_{p,12hr}$ = root mean square sound pressure (dB re 1 µPa) for 12 hours continuous exposure; $L_{p, 48h}$ rms sound pressure (dB re 1 µPa) for 48 hours continuous exposure
TTS = temporary threshold shift., N = near (10s of meters), I = intermediate (100s of meters), and F = far (1000s of meters);
-- = not applicable

3. Results

Acoustic fields were modeled for the sound sources expected to contribute to the noise produced during construction of the wind farm. Impulsive noise from impact pile driving for installation of monopile foundations was modeled at two potential sites (P1 and P2 in Figure 1, Table 2), and using hammers from two manufacturers. Non-impulsive noise generated by DPS was modeled at two locations (C1 and C2 in Figure 1, Table 2) along the SFEC corridor. Non-impulsive noise resulting from vibratory pile driving for cofferdam installation was modeled at one location (CD in Figure 1, Table 2). The ranges to specific thresholds are reported for each scenario.

3.1. Threshold Ranges for Impulsive Sources: Impact Pile Driving

3.1.1. Marine Mammals

The ranges to injury and behavioral disruption threshold levels for marine mammals resulting from impact pile driving (each modeled using two different hammers, at two locations, and two seasons) are shown in Tables 9–18. Ranges for the dual criteria of peak sound pressure (L_{pk}) and accumulated sound exposure level (L_E) can be used to evaluate potential injury to marine mammals. Peak pressure is unweighted and used on a single exposure basis, that is, the ranges are independent of the number of strikes delivered to the pile. L_E, however, accumulates the sound energy over the duration of the exposure and the sound fields are weighted according to the functional hearing group. Ranges are shown for the number of strikes estimated to drive one 8 m monopile (2,400 strikes, Tables 9 & 10), ond 11 m monopile (4,500 strikes, Table 15; 8,000 strikes, Table 15. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).Table 15).

As with the peak pressure (L_{pk}) of the dual criteria for evaluating potential injury, the maximum sound pressure level (L_p) used to evaluate potential behavior is used on a one-time basis, so the range does not change with the number of pile strikes. Ranges to various unweighted sound pressure level thresholds were calculated for impact pile driving of an 8 m monopile (Tables 11 & 12) and 11 m monopile (Table 17). The current NMFS criteria for marine mammals is an unweighted sound pressure, L_p, of 160 SPL dB re 1 µPa. Following Wood et al. (2012), the hearing capability of the animals can be included in the behavioral assessment by weighting the sound fields (Southall et al. 2007) and using a stair-step function of different probabilities of response. The stair-step function uses the L_p thresholds 120, 140, 160, and 180 dB re 1 µPa. Ranges to the thresholds of the stair-step function were calculated for an 8 m monopile (Tables 13 & 14) and 11 m monopile (Table 18).

Predicted ranges assuming the use of noise attenuating systems, such as bubble curtains, are shown in Appendix E for an 8 m monopile and Appendix F for an 11 m monopile; each with broadband attenuation of 6, 10, and 12 dB. Appendix G has similar information for a difficult to drive 11 m monopile.

3.1.1.1. 8 m monopile foundation

Table 9. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	15,523				10,085				15,761				10,394			
	L_{pk}	**219**	33	52	64	78	33	52	64	78	33	52	64	78	33	52	64	78
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	158				100				158				158			
	L_{pk}	**230**	7	10	12	12	7	10	12	12	7	10	12	12	7	10	12	12
High-frequency cetaceans	$L_{E,24hr}$	**155**	10,228				7,651				10,073				7,601			
	L_{pk}	**202**	384	466	531	765	384	466	531	765	384	466	531	765	384	466	531	765
Phocid pinnipeds	$L_{E,24hr}$	**185**	2,944				2,757				2,970				2,750			
	L_{pk}	**218**	37	61	74	91	37	61	74	91	37	61	74	91	37	61	74	91

Table 10. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500
Low-frequency cetaceans	$L_{E,24hr}$	183	23,094				12,900				24,254				13,531			
	L_{pk}	219	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Mid-frequency cetaceans	$L_{E,24hr}$	185	255				180				255				250			
	L_{pk}	230	11	15	17	17	11	15	17	17	11	15	17	17	11	15	17	17
High-frequency cetaceans	$L_{E,24hr}$	155	15,873				10,408				15,234				10,427			
	L_{pk}	202	609	714	766	1,160	609	714	766	1,160	609	714	766	1,160	609	714	766	1,160
Phocid pinnipeds	$L_{E,24hr}$	185	4,763				4,030				4,617				3,922			
	L_{pk}	218	70	93	108	126	70	93	108	126	70	93	108	126	70	93	108	126

Table 11. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of an 8 m monopile using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	**120**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	80,339	97,064	--	--	23,560	25,505	30,673	38,971	95,203	--	--	--	26,216	30,075	36,231	43,890
	150	18,420	21,154	26,009	40,919	11,744	12,837	14,171	18,990	19,604	22,514	27,562	46,836	12,376	13,172	16,993	21,052
	160	5,689	7,385	8,923	11,909	4,943	5,900	7,170	8,970	5,489	7,375	9,003	12,368	4,900	5,763	7,257	9,345
	175	1,811	2,197	2,483	2,912	1,787	2,124	2,425	2,838	1,818	2,205	2,518	2,940	1,806	2,171	2,468	2,852
	180	1,001	1,334	1,651	2,065	1,000	1,331	1,619	2,025	1,026	1,324	1,677	2,103	1,013	1,360	1,655	2,065
	190	158	269	403	602	158	269	403	604	158	283	403	604	200	292	403	618

-- Range is greater than the extents of the modeled distance (100,000 m)

Table 12. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of an 8 m monopile using a Menck 3500S hammer at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
Unweighted	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	--	--	--	--	29,394	34,258	39,203	45,713	--	--	--	--	35,238	38,438	43,891	51,900
	150	24,608	27,670	41,857	64,409	13,438	15,982	18,987	21,871	26,449	35,671	47,727	71,031	15,340	18,340	20,890	23,930
	160	8,443	9,905	11,921	13,435	6,743	7,628	8,880	10,503	8,398	10,259	12,307	15,094	6,716	7,742	9,180	11,062
	175	4,368	4,827	6,046	7,927	4,056	4,507	5,012	6,196	4,320	4,801	5,743	7,849	4,031	4,482	4,966	6,027
	180	1,360	1,681	1,985	2,316	1,365	1,656	1,942	2,247	1,366	1,692	2,025	2,351	1,386	1,671	1,981	2,285
	190	269	381	522	696	269	403	550	716	283	381	522	700	292	403	550	716

-- Range is greater than the extents of the modeled distance (100,000 m)

Table 13. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of an 8 monopile using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								Hammer energy (kJ)							
		1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
LF	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	80,039	96,920	--	--	23,519	25,472	30,563	38,904	95,038	--	--	--	26,181	29,999	36,168	43,815
	160	5,640	7,350	8,896	11,863	4,924	5,854	7,140	8,945	5,450	7,333	8,960	12,343	4,883	5,720	7,220	9,306
	180	996	1,312	1,628	2,055	986	1,315	1,603	2,016	1,012	1,304	1,653	2,089	1,011	1,346	1,632	2,055
MF	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	53,456	65,443	99,504	>100,000	19,764	20,894	24,007	29,664	58,207	69,320	--	--	20,713	22,314	25,906	34,702
	160	3,603	4,075	4,802	7,504	3,335	3,662	4,472	5,530	3,494	3,971	4,740	7,354	3,310	3,613	4,410	5,378
	180	283	361	541	901	304	403	604	919	292	364	550	918	304	413	608	919
HF	120	--	--	--	--	94,711	98,155	--	--	--	--	--	--	99,359	--	--	--
	140	44,669	52,799	89,305	--	18,265	19,610	22,876	26,895	50,102	57,022	97,463	--	19,125	20,342	23,906	30,801
	160	3,122	3,422	4,383	5,831	3,050	3,210	4,008	4,916	3,150	3,335	4,262	5,615	3,034	3,233	3,939	4,827
	180	224	255	381	673	250	255	453	716	224	269	391	680	250	292	453	716
PW	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	70,597	83,354	--	--	22,065	23,386	26,391	35,772	79,894	96,421	--	--	23,684	25,873	31,935	39,776
	160	4,589	5,068	7,136	9,923	4,254	4,660	5,377	7,492	4,517	4,973	7,030	10,034	4,193	4,609	5,262	7,580
	180	541	743	1,011	1,471	585	762	1,026	1,471	541	743	990	1,481	583	762	1,044	1,501

-- Range is greater than the extents of the modeled distance (100,000 m)

Table 14. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of an 8 m monopile using a Menck 3500S hammer at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
LF	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	--	--	--	--	29,291	34,189	39,135	45,642	--	--	--	--	35,181	38,373	43,824	51,794
	160	8,415	9,863	11,885	13,408	6,720	7,606	8,856	10,481	8,373	10,224	12,274	14,954	6,688	7,715	9,155	11,037
	180	1,351	1,669	1,978	2,309	1,354	1,651	1,929	2,239	1,360	1,680	2,016	2,332	1,376	1,664	1,972	2,280
MF	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	95,809	--	--	--	23,573	25,257	30,151	37,760	--	--	--	--	25,586	27,182	35,009	41,440
	160	4,691	5,156	7,630	10,306	4,366	4,717	5,627	7,616	4,617	5,020	7,498	10,128	4,313	4,621	5,446	7,562
	180	510	652	901	1,282	559	680	950	1,300	510	652	922	1,301	559	697	930	1,324
HF	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	81,435	97,899	--	--	22,308	23,709	27,072	35,267	91,970	--	--	--	23,245	25,538	31,428	38,361
	160	4,250	4,618	6,201	8,750	3,816	4,279	4,970	6,657	4,117	4,540	5,905	8,615	3,758	4,205	4,871	6,613
	180	361	461	695	1,026	412	522	728	1,031	361	461	696	1,026	413	522	721	1,077
PW	120	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	140	--	--	--	--	25,951	28,887	36,118	42,179	--	--	--	--	30,434	34,750	40,048	47,092
	160	6,824	7,974	10,160	12,720	5,191	6,088	7,563	9,144	6,750	7,874	10,239	12,701	5,091	5,935	7,616	9,330
	180	901	1,141	1,471	1,840	943	1,163	1,460	1,820	922	1,151	1,487	1,882	934	1,160	1,486	1,861

-- Range is greater than the extents of the modeled distance (100,000 m)

3.1.1.2. 11 m monopile foundation

Table 15. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	183	19,305				12,276				20,697				13,386			
	L_{pk}	219	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Mid-frequency cetaceans	$L_{E,24hr}$	185	108				89				113				117			
	L_{pk}	230	3	5	7	9	3	5	7	9	3	4	6	8	3	4	6	8
High-frequency cetaceans	$L_{E,24hr}$	155	10,837				7,861				10,720				7,738			
	L_{pk}	202	522	626	907	1,551	522	626	907	1,551	524	607	1,005	1,539	524	607	1,005	1,539
Phocid pinnipeds	$L_{E,24hr}$	185	3,422				3,054				3,304				3,116			
	L_{pk}	218	35	50	73	101	35	50	73	101	30	47	74	100	30	47	74	100

Table 16. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of a diffcult 11 m monopile in 24 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	26,104				15,178				29,759				16,724			
	L_{pk}	**219**	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	197				134				204				197			
	L_{pk}	**230**	3	5	7	9	3	5	7	9	3	4	6	8	3	4	6	8
High-frequency cetaceans	$L_{E,24hr}$	**155**	16,565				10,444				16,086				10,401			
	L_{pk}	**202**	522	626	907	1,551	522	626	907	1,551	524	607	1,005	1,539	524	607	1,005	1,539
Phocid pinnipeds	$L_{E,24hr}$	**185**	4,944				4,245				4,774				4,130			
	L_{pk}	**218**	35	50	73	101	35	50	73	101	30	47	74	100	30	47	74	100

Table 17. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of an 11 m monopile using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	120	--	--	--	--	99,742	--	--	--	--	--	--	--	--	--	--	--
	140	64,605	73,717	99,487	--	24,616	26,089	31,634	37,964	79,290	92,728	--	--	79,290	31,862	36,921	43,007
	150	19,403	21,130	24,510	35,018	12,784	13,215	16,353	19,384	21,541	23,493	29,940	41,342	21,541	15,096	18,596	21,804
	160	7,459	8,382	10,135	12,481	6,107	7,111	8,223	9,801	7,503	8,633	10,794	12,746	7,503	7,194	8,480	10,499
	175	2,209	2,552	2,847	3,361	2,165	2,463	2,760	3,185	2,267	2,542	2,868	3,347	2,220	2,490	2,787	3,195
	180	1,446	1,749	2,049	2,490	1,393	1,692	1,981	2,415	1,453	1,744	2,057	2,500	1,398	1,682	1,962	2,430
	190	283	428	552	893	284	429	550	868	272	420	565	921	289	420	566	904

-- Range is greater than the extents of the modeled distance (100,000 m)

Table 18. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of an 11 monopile using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
LF	120	--	--	--	--	99,711	--	--	--	--	--	--	--	--	--	--	--
	140	64,411	73,475	99,396	--	24,566	26,038	31,541	37,886	78,893	92,428	--	--	28,280	31,759	36,841	42,908
	160	7,422	8,345	10,090	12,444	6,064	7,073	8,186	9,753	7,464	8,589	10,748	12,729	6,179	7,159	8,437	10,457
	180	1,429	1,737	2,028	2,473	1,376	1,680	1,965	2,405	1,448	1,723	2,032	2,489	1,393	1,667	1,942	2,421
MF	120	--	--	--	--	83,134	89,472	99,082	--	--	--	--	--	96,097	97,634	--	--
	140	36,412	40,310	54,987	83,459	17,487	18,351	20,953	23,864	41,007	45,684	61,380	96,564	18,997	20,083	22,719	26,325
	160	3,502	3,900	4,551	5,694	3,312	3,558	4,226	4,860	3,451	3,785	4,511	5,486	3,324	3,561	4,161	4,829
	180	316	385	522	860	341	388	581	865	303	388	539	844	330	411	590	877
HF	120	--	--	--	--	72,650	78,560	94,722	--	--	--	--	--	92,379	94,656	99,470	--
	140	28,692	33,486	44,466	68,595	14,364	15,413	18,954	21,937	33,142	36,988	50,454	73,866	15,767	17,395	20,173	23,230
	160	2,970	3,107	3,733	4,532	2,849	3,023	3,451	4,205	2,944	3,135	3,623	4,484	2,841	2,993	3,451	4,134
	180	184	209	342	500	189	215	368	556	180	206	322	506	206	228	363	564
PW	120	--	--	--	--	97,683	99,159	--	--	--	--	--	--	--	--	--	--
	140	50,508	57,548	80,686	--	21,515	22,550	25,288	31,176	58,927	67,554	96,930	>100,000	23,697	25,661	29,713	36,430
	160	4,993	5,704	7,524	9,392	4,607	4,922	6,005	7,593	4,939	5,569	7,503	9,879	4,592	4,902	6,014	7,702
	180	769	965	1,315	1,781	789	963	1,273	1,718	789	953	1,341	1,810	791	970	1,313	1,737

-- Range is greater than the extents of the modeled distance (100,000 m)

3.1.2. Fish and Sea Turtles

Weighting functions are not used to assess potential impacts to fish and sea turtles, and there is limited regulatory guidance for evaluation. The ANSI-accredited report by Popper et al. (2014) follows a similar approach as Southall et al. (2007) in suggesting the dual criteria of peak pressure and accumulated sound energy for evaluating potential injury. Similar to the results presented for marine mammals (Section 3.1.1), the ranges to potential injury and temporary threshold shifts for fish categories and sea turtles were calculated for an 8 m monopile (Tables 19 & 20) and an 11 m monopile (Table 23), assuming different hammers, two locations, and two seasons,. Earlier criteria, derived from Stadler and Woodbury (2009) use similar metrics but also include quantitative thresholds for evaluating potential behavioral disruption. Ranges to thresholds for fish based on the Stadler and Woodbury-derived criteria and ranges to thresholds for sea turtles based on the (Blackstock et al. 2018) criteria were calculated for an 8 m monopile (Tables 21 & 22) and an 11 m monopile (Table 24). As was done for the marine mammals, predicted ranges assuming the use of noise attenuation systems are shown in Appendix E for an 8 m monopile and Appendix F for an 11 m monopile; each with broadband attenuation of 6 and 12 dB.

3.1.2.1. 8 m monopile Foundation

Table 19. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	158				158				158				200			
	L_{pk}	213	90	111	130	167	90	111	130	167	90	111	130	167	90	111	130	167
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	875				912				873				918			
	L_{pk}	207	201	243	298	399	201	243	298	399	201	243	298	399	201	243	298	399
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,070				1,034				875				849			
	L_{pk}	207	201	243	298	399	201	243	298	399	201	243	298	399	201	243	298	399
Sea turtles (mortal injury)	$L_{E,24hr}$	210	875				912				873				918			
	L_{pk}	207	201	243	298	399	201	243	298	399	201	243	298	399	201	243	298	399
Eggs and larvae	$L_{E,24hr}$	210	875				912				873				918			
	L_{pk}	207	201	243	298	399	201	243	298	399	201	243	298	399	201	243	298	399
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	316				316				320				320			
	L_{pk}	213	90	111	130	167	90	111	130	167	90	111	130	167	90	111	130	167
Fish with swim bladder	$L_{E,24hr}$	203	2,316				2,219				2,401				2,300			
	L_{pk}	207	201	243	298	399	201	243	298	399	201	243	298	399	201	243	298	399
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	15,149				10,335				16,311				11,082			

Table 20. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	224				255				224				255			
	L_{pk}	213	133	186	216	256	133	186	216	256	133	186	216	256	133	186	216	256
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	1,150				1,151				1,166				1,171			
	L_{pk}	207	332	385	423	575	332	385	423	575	332	385	423	575	332	385	423	575
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,749				1,722				1,769				1,757			
	L_{pk}	207	332	385	423	575	332	385	423	575	332	385	423	575	332	385	423	575
Sea turtles (mortal injury)	$L_{E,24hr}$	210	1,150				1,151				1,166				1,171			
	L_{pk}	207	332	385	423	575	332	385	423	575	332	385	423	575	332	385	423	575
Eggs and larvae	$L_{E,24hr}$	210	1,150				1,151				1,166				1,171			
	L_{pk}	207	332	385	423	575	332	385	423	575	332	385	423	575	332	385	423	575
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	403				427				403				427			
	L_{pk}	213	133	186	216	256	133	186	216	256	133	186	216	256	133	186	216	256
Fish with swim bladder	$L_{E,24hr}$	203	2,991				2,800				3,007				2,822			
	L_{pk}	207	332	385	423	575	332	385	423	575	332	385	423	575	332	385	423	575
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	21,250				12,712				22,530				13,821			

Table 21. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	21,602				13,084				23,480				21,602			
	L_{pk}	206	222	279	336	455	222	279	336	455	222	279	336	455	222	279	336	455
Large fish	$L_{E,12hr}$	187	13,491				9,606				14,272				10,164			
	L_{pk}	206	222	279	336	455	222	279	336	455	222	279	336	455	222	279	336	455
Sea turtles	L_p	180	1,001	1,334	1,651	2,065	1,000	1,331	1,619	2,025	1,026	1,324	1,677	2,103	1,013	1,360	1,655	2,065
Small fish	L_p	150	18,420	21,154	26,009	40,919	11,744	12,837	14,171	18,990	19,604	22,514	27,562	46,836	12,376	13,172	16,993	21,052
Large fish	L_p	150	18,420	21,154	26,009	40,919	11,744	12,837	14,171	18,990	19,604	22,514	27,562	46,836	12,376	13,172	16,993	21,052
Blackstock et al. (2017)																		
Sea turtles	L_p	175	1,811	2,197	2,483	2,912	1,787	2,124	2,425	2,838	1,818	2,205	2,518	2,940	1,806	2,171	2,468	2,852
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	1601				1589				1610				1610			
	L_{pk}	232	7	10	12	12	7	10	12	12	7	10	12	12	7	10	12	12
Sea turtles - TTS	$L_{E,TU,24hr}$	189	9343				7433				9680				7518			
	L_{pk}	226	3	5	6	6	3	5	6	6	3	5	6	6	3	5	6	6

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

Table 22. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using a Menck 3500S hammer at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	30,192				16,129				35,312				17,820			
	L_{pk}	206	373	425	487	678	373	425	487	678	373	425	487	678	373	425	487	678
Large fish	$L_{E,12hr}$	187	18,931				11,753				20,020				12,744			
	L_{pk}	206	373	425	487	678	373	425	487	678	373	425	487	678	373	425	487	678
Sea turtles	L_p	180	1,360	1,681	1,985	2,316	1,365	1,656	1,942	2,247	1,366	1,692	2,025	2,351	1,386	1,671	1,981	2,285
Small fish	L_p	150	24,608	27,670	41,857	64,409	13,438	15,982	18,987	21,871	26,449	35,671	47,727	71,031	15,340	18,340	20,890	23,930
Large fish	L_p	150	24,608	27,670	41,857	64,409	13,438	15,982	18,987	21,871	26,449	35,671	47,727	71,031	15,340	18,340	20,890	23,930
Blackstock et al. (2017)																		
Sea turtles	L_p	175	2,266	2,552	2,850	3,169	2,205	2,483	2,777	3,060	2,302	2,571	2,862	3,175	2,239	2,512	2,790	3,061
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	2309				2197				2360				2235			
	L_{pk}	232	11	15	17	17	11	15	17	17	11	15	17	17	11	15	17	17
Sea turtles - TTS	$L_{E,TU,24hr}$	189	12830				9250				13656				9660			
	L_{pk}	226	5	7	9	8	5	7	9	8	5	7	9	8	5	7	9	8

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

3.1.2.2. 11 m monopile Foundation

Table 23. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	522				514				537				539			
	L_{pk}	213	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	2,017				1,931				2,024				1,915			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	2,882				2,712				2,974				2,737			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Sea turtles (mortal injury)	$L_{E,24hr}$	210	2,017				1,931				2,024				1,915			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Eggs and larvae	$L_{E,24hr}$	210	2,017				1,931				2,024				1,915			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	886				860				911				895			
	L_{pk}	213	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Fish with swim bladder	$L_{E,24hr}$	203	4,476				4,106				4,446				4,049			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	22,040				14,602				25,824				16,358			

Table 24. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 11 m monopile in 12 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	30,326				17,939				36,732				20,294			
	L_{pk}	206	266	332	497	738	266	332	497	738	269	320	535	733	269	320	535	733
Large fish	$L_{E,12hr}$	187	20,076				13,559				22,706				15,070			
	L_{pk}	206	266	332	497	738	266	332	497	738	269	320	535	733	269	320	535	733
Sea turtles	L_p	180	1,446	1,749	2,049	2,490	1,393	1,692	1,981	2,415	1,453	1,744	2,057	2,500	1,398	1,682	1,962	2,430
Small fish	L_p	150	19,403	21,130	24,510	35,018	12,784	13,215	16,353	19,384	21,541	23,493	29,940	41,342	13,196	15,096	18,596	21,804
Large fish	L_p	150	19,403	21,130	24,510	35,018	12,784	13,215	16,353	19,384	21,541	23,493	29,940	41,342	13,196	15,096	18,596	21,804
Blackstock et al. (2017)																		
Sea turtles	L_p	175	2,209	2,552	2,847	3,361	2,165	2,463	2,760	3,185	2,267	2,542	2,868	3,347	2,220	2,490	2,787	3,195
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	3465				3125				3400				3163			
	L_{pk}	232	1	2	2	3	1	2	2	3	1	1	2	2	1	1	2	2
Sea turtles - TTS	$L_{E,TU,24hr}$	189	14861				10781				16742				11691			
	L_{pk}	226	3	5	7	9	3	5	7	9	3	4	6	8	3	4	6	8

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

Table 25. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of a difficult 11 m monopile in 24 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	879				851				894				873			
	L_{pk}	213	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	2,816				2,674				2,850				2,678			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	3,944				3,591				3,862				3,574			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Sea turtles (mortal injury)	$L_{E,24hr}$	210	2,816				2,674				2,850				2,678			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Eggs and larvae	$L_{E,24hr}$	210	2,816				2,674				2,850				2,678			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	1,330				1,279				1,354				1,306			
	L_{pk}	213	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Fish with swim bladder	$L_{E,24hr}$	203	5,828				5,179				5,793				5,154			
	L_{pk}	207	230	290	432	634	230	290	432	634	228	276	458	631	228	276	458	631
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	29,364				17,618				35,624				19,933			

Table 26. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of a difficult 11 m monopile in 12 hours, using an IHC S-4000 hammer at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				***Summer***				***Winter***				***Summer***			
			Hammer energy (kJ)								***Hammer energy (kJ)***							
			1000	***1500***	***2500***	***4000***	***1000***	***1500***	***2500***	***4000***	***1000***	***1500***	***2500***	***4000***	***1000***	***1500***	***2500***	***4000***
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	42,920				21,353				50,025				24,663			
	L_{pk}	206	266	332	497	738	266	332	497	738	269	320	535	733	269	320	535	733
Large fish	$L_{E,12hr}$	187	26,037				16,502				31,843				18,588			
	L_{pk}	206	266	332	497	738	266	332	497	738	269	320	535	733	269	320	535	733
Sea turtles	L_p	180	1,446	1,749	2,049	2,490	1,393	1,692	1,981	2,415	1,453	1,744	2,057	2,500	1,398	1,682	1,962	2,430
Small fish	L_p	150	19,403	21,130	24,510	35,018	12,784	13,215	16,353	19,384	21,541	23,493	29,940	41,342	13,196	15,096	18,596	21,804
Large fish	L_p	150	19,403	21,130	24,510	35,018	12,784	13,215	16,353	19,384	21,541	23,493	29,940	41,342	13,196	15,096	18,596	21,804
Blackstock et al. (2017)																		
Sea turtles	L_p	175	2,209	2,552	2,847	3,361	2,165	2,463	2,760	3,185	2,267	2,542	2,868	3,347	2,220	2,490	2,787	3,195
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	4573				4156				4574				4089			
	L_{pk}	232	1	2	2	3	1	2	2	3	1	1	2	2	1	1	2	2
Sea turtles - TTS	$L_{E,TU,24hr}$	189	19609				13203				22106				14599			
	L_{pk}	226	3	5	7	9	3	5	7	9	3	4	6	8	3	4	6	8

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

3.2. Threshold Ranges for Non-impulsive Sources: Vibratory Pile Driving (Cofferdam Construction)

As with the impulsive sounds produced by impact pile driving, the ranges to thresholds for the non-impulsive sounds produced by vibratory hammering of sheet piles for cofferdam construction were calculated. Table 27 shows the ranges for potential injury due to accumulated sound energy, L_E, to marine mammal functional hearing groups around the cofferdam installation site. The current NMFS criteria for evaluating potential behavioral disruption in marine mammals is an unweighted sound pressure, L_p, of 120 SPL dB re 1 µPa. Table 28 shows the ranges to various thresholds starting at 120 SPL dB re 1 µPa. Though Wood et al. (2012) was developed for impulsive sounds, ranges for weighted sound fields (Southall et al. 2007) and using the stair-step L_p thresholds of 120, 140, 160, and 180 dB re 1 µPa are shown in Table 29 for comparison.

The only quantitative threshold that Popper et al. (2014) give for evaluating the impacts of non-impulsive (shipping) noise is for fish with swim bladders. Popper et al. (2014) does not give quantitative thresholds for other fish categories or sea turtles. The Stadler and Woodbury (2009) criteria were originally developed for impulsive sounds, but they have been used for non-impulsive sounds. The Stadler and Woodbury (2009) criteria L_p thresholds of 150 and 180 dB re 1 µPa, the Blackstock et al. (2018) criteria L_p thresholds of 175 dB re 1 µPa, and the Popper et al. (2014) criteria L_p thresholds of 158 and 170 dB re 1 µPa are included in Table 28.

Table 27. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to vibratory hammering of sheet pile.

Species group	Metric	Threshold (dB)	Winter			Summer		
			6 Hours	12 Hours	18 Hours	6 Hours	12 Hours	18 Hours
Low-frequency cetacean	$L_{E,24h}$	199	737	1,187	1,464	742	1,193	1,470
Mid-frequency cetacean	$L_{E,24h}$	198	0	0	0	0	0	0
High-frequency cetacean	$L_{E,24h}$	173	54	63	63	54	63	63
Phocid pinniped in water	$L_{E,24h}$	201	63	83	103	63	83	103

Table 28. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) for vibratory hammering of sheet pile.

Metric	Threshold (dB)	Winter	Summer
L_p	120	36,766	36,652
	140	3,305	3,299
	150	775	779
	158	238	238
	160	167	167
	170	63	63
	175	53	53
	180	31	31
	190	0	0

Table 29. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing groups due to vibratory hammering of sheet pile. LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Species	Metric	Threshold (dB)	Winter	Summer
LF	L_p	120	36,690	36,554
		140	3,284	3,282
		160	167	165
		180	0	31
MF	L_p	120	20,890	20,846
		140	1,504	1,510
		160	83	83
		180	0	0
HF	L_p	120	16,032	15,927
		140	1,099	1,108
		160	65	63
		180	0	0
PW	L_p	120	30,719	30,612
		140	2,440	2,429
		160	118	118
		180	0	0

3.3. Threshold Ranges for Non-impulsive Sources: Dynamic Positioning Thrusters

The ranges to thresholds for the non-impulsive sounds of the dynamic positioning thrusters were calculated. For the accumulating metric, L_E, ranges were calculated assuming the vessel is stationary for 24 hours. Table 30 shows the ranges for potential injury to marine mammal functional hearing groups along the SFEC corridor and interarray cable routes. The current NMFS criteria for evaluating potential behavioral disruption in marine mammals is an unweighted sound pressure, L_p, of 120 SPL dB re 1 µPa. Table 31 shows the ranges to various thresholds starting at 120 SPL dB re 1 µPa. As mentioned above, Wood et al. (2012) was developed for impulsive sounds, but for comparison ranges for weighted sound fields (Southall et al. 2007) and using the Wood et al. (20012) stair-step L_p thresholds of 120, 140,160, and 180 dB re 1 µPa are shown in Table 32 for comparison.

Again, the only quantitative threshold that Popper et al. (2014) give for evaluating the impacts of non-impulsive shipping noise is for fish with swim bladders, and the Stadler and Woodbury (2009) criteria were originally developed for impulsive sounds. The Stadler and Woodbury (2009) criteria L_p thresholds of 150, and 180 dB re 1 µPa, the Blackstock et al. (2018) criteria L_p thresholds of 175 dB re 1 µPa and, the Popper et al. (2014) criteria L_p thresholds of 158 and 170 dB re 1 µPa are found included in Table 31.

Table 30. Ranges ($R_{95\%}$ in meters) to injury thresholds for functional hearing group weighted (NMFS 2016) non-impulsive noise source of dynamically positioned vessel at two selected modeling locations C1 (open water) and C2 (land approach).

Hearing group	Metric	Threshold (dB)	C1		C2	
			Winter	*Summer*	*Winter*	*Summer*
Low-frequency cetaceans	$L_{E,24hr}$	199	79	112	112	112
Mid-frequency cetaceans	$L_{E,24hr}$	198	35	0	35	0
High-frequency cetaceans	$L_{E,24hr}$	173	56	100	71	103
Phocid pinnipeds	$L_{E,24hr}$	201	50	0	50	0

Table 31. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure level thresholds of dynamically positioned vessel at two selected modeling locations (C1 and C2).

Metric	Threshold (dB)	C1		C2	
		Winter	*Summer*	*Winter*	*Summer*
L_p	**120**	14,112	10,401	14,734	10,630
	140	673	862	855	1,066
	150	125	135	135	135
	158	56	25	56	25
	160	50	0	50	0
	170	0	0	0	0
	175	0	0	0	0
	180	0	0	0	0
	190	0	0	0	0

Table 32. Ranges ($R_{95\%}$ in meters) to functional hearing group weighted (Southall et al. 2007) sound pressure levels (L_p) threshold for dynamically positioned vessel at two selected modeling locations (C1 and C2).

Hearing group	Metric	Threshold (dB)	C1		C2	
			Winter	*Summer*	*Winter*	*Summer*
Low-frequency cetaceans	L_p	120	14,043	10,359	14,654	10,588
		140	673	828	851	1,063
		160	50	0	50	0
		180	0	0	0	0
Mid-frequency cetaceans	L_p	120	13,120	9,773	13,483	9,915
		140	480	693	675	807
		160	50	0	50	0
		180	0	0	0	0
High-frequency cetaceans	L_p	120	12,341	9,431	12,912	9,549
		140	451	667	586	738
		160	50	0	50	0
		180	0	0	0	0
Phocid pinnipeds	L_p	120	13,828	10,201	14,326	10,396
		140	567	736	762	1,026
		160	50	0	50	0
		180	0	0	0	0

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Appendix A. 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 make up one octave. One-third-octave-bands become wider with increasing frequency. See also octave.

absorption
The conversion of acoustic energy into heat.

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

azimuth
A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation, it is also called bearing.

bandwidth
The range of frequencies over which the context refers, e.g., acoustic signature or recording.

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.

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.

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).

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.

geoacoustic
Relating to the acoustic properties of the seabed.

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

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

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.

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

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

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).

propagation loss
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 transmission loss.

received level
The sound level measured at a receiver.

rms
root-mean-square.

rms sound pressure level (L_p)
The root-mean-square average of the instantaneous sound pressure as measured over some specified time interval. For continuous sound, the time interval is one second. See also sound pressure level (L_p) and 90% rms SPL.

shear wave
A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called secondary wave or S-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

sound exposure
Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second (Pa2·s) (ANSI S1.1-1994 R2004).

sound exposure level (L_E or SEL)
A measure related to the sound energy in one or more pulses. Unit: dB re 1 µPa2·s.

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

sound pressure level (L_p)
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:

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

Unless otherwise stated, L_p refers to the root-mean-square of the 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 pressure level measured 1 meter from a theoretical point source that radiates the same total sound power as the actual source. Unit: dB re 1 µPa @ 1 m

Appendix B. Summary of Study Assumptions

A summary of the assumptions used in this study, including inputs and the methods used for modeling are presented in Table B-1.

Table B-1. Summary of model inputs, assumptions and methods.

Parameter	Description
8 m Monopile Pile Driving Source Model	
Modeling method	Finite-difference structural model of pile vibration based on thin-shell theory; hammer forcing functions computed using GRLWEAP. Hammer above water.
Impact hammer model	IHC S4000
Ram weight	1977 kN (200 ton)[a]
Helmet weight	3234 kN (355 ton)[b]
Impact hammer energy	1000, 1500, 2500, 4000 kJ
Impact hammer model	Menck 3500T
Ram weight	1717 kN (175 ton)[a]
Helmet weight	1107 kN (113 ton)[a]
Impact hammer energy	1000, 1500, 2500, 3500 kJ
Modeled seabed penetration for each hammer energy	3 m (10 ft), 8 m (26 ft), 25 m (82 ft), 28 m (92 ft)
Strike rate (min^{-1})	30
Estimated number of strikes to drive pile at each energy	200, 800, 1000, 400
Number of piles per site per day	1
Pile length	85 m
Pile diameter	812.8 cm (320 in)
Pile Thickness	7.62 cm (3 in)
11 m Monopile Pile Driving Source Model	
Modeling method	Finite-difference structural model of pile vibration based on thin-shell theory; hammer forcing functions computed using GRLWEAP. Hammer above water.
Impact hammer model	IHC S4000
Ram weight	1977 kN (200 ton)[a]
Helmet weight	3234 kN (355 ton)[b]
Impact hammer energy	1000, 1500, 2500, 4000 kJ
Modeled seabed penetration for each hammer energy	6 m (19.7 ft), 23.5 m (77.1 ft), 41 m (134.5 ft), 45 m (147.6 ft)
Strike rate (min^{-1})	32
Estimated number of strikes to drive pile at each energy	500, 1000, 1500, 1500 (standard) 800, 1200, 3000, 3000 (difficult)
Number of piles per site per day	1
Pile length	97 m
Pile diameter	1097 cm (432 in)
Pile Thickness	10 cm (4 in)

Parameter	Description
Vibratory Pile Driving: Cofferdam	
Source modeling method	Scaled decidecade-band spectra based on operational power[4]
Vibratory hammer model	APE 200T
Clamp	Model 200 Universal Clamp
Sheet pile type	Z-Type
Sheet pile thickness	0.95 cm (3/8 in)
Sheet pile length	19.5 m (64 ft)
Pile penetration	9 m (30 ft)
Modeled Duration	6 h, 12 h, and 18 h
Dynamic Positioning System Source	
Source Modeling Method	Finite-difference structural model of pile vibration based on thin-shell theory; hammer forcing functions computed using GRLWEAP.
Surrogate Vessel	*DSV Fu Lai*
Measured Energy	3000 BHP
Number of thrusters	6
Draft	6.6 m
Modeled Vessel	*Ndurance*
Modeled Energy	4000 BHP
Number of thrusters	4
Draft	4.8 m
Modeled Duration	24 h
Environmental Parameters	
Sound Speed Profile	Sound speed profile from GDEM data averaged over region
Bathymetry	SRTM data combined with bathymetry data provided by client
Geoacoustics	Fine sand. Elastic seabed properties based on USGS East coast sediment analysis for modeling region.
Propagation Model	
Modeling method	Parabolic-equation propagation model with 2.5° azimuthal resolution; FWRAM full-waveform parabolic equation propagation model for 4 radials.
Source representation	Vertical line array
Frequency range	10-4000 Hz
Synthetic trace length	500 ms
Maximum modeled range	100 km

[a] Weight from IHC Sleeve XL spec sheet
[b] Weight from data provided by client (20170904_SFWF_Monopile_hammer_data.docx)
[c] Weight from GRLWEAP suggested helmet

Appendix C. Underwater Acoustics

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

C.1. Acoustic Metrics

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

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

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

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

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

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

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

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

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying L_p function. For short acoustic events, such as sonar pulses and marine mammal vocalizations, it is important to choose an appropriate time window that matches the duration of the signal. For in-air studies, when evaluating the perceived loudness of sounds with rapid amplitude variations in time, the time weighting function $g(t)$ is often set to a decaying exponential function that emphasizes more recent pressure signals. This function mimics the leaky integration nature of mammalian hearing. For example, human-based fast time-weighted L_p ($L_{p,fast}$) applies an exponential function with time constant 125 ms. A related simpler approach used in underwater acoustics sets $g(t)$ to a boxcar (unity amplitude) function of width 125 ms; the results can be referred to as $L_{p,\text{boxcar 125ms}}$. Another approach, historically used to evaluate L_p of impulsive signals underwater, defines $g(t)$ as a boxcar function with edges set to the times corresponding to 5% and 95% of the cumulative square pressure function encompassing the duration of an impulsive acoustic event. This calculation is applied individually to each impulse signal, and the results have been referred to as 90% SPL ($L_{p,90\%}$).

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

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

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

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

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

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

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

$$a_{pk} = \max(|\boldsymbol{a}(t)|). \quad \text{(C-6)}$$

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

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

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

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

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

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

C.2. One-third-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 better approximates real-world scenarios. 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 ith 1/3-octave-band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{i/10} , \quad \text{(C-9)}$$

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

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

The 1/3-octave-bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure C-1). In this report, the acoustic modeling spans from band −24 ($f_c(-24)$ = 0.004 kHz) to band 14 ($f_c(14)$ = 25 kHz).

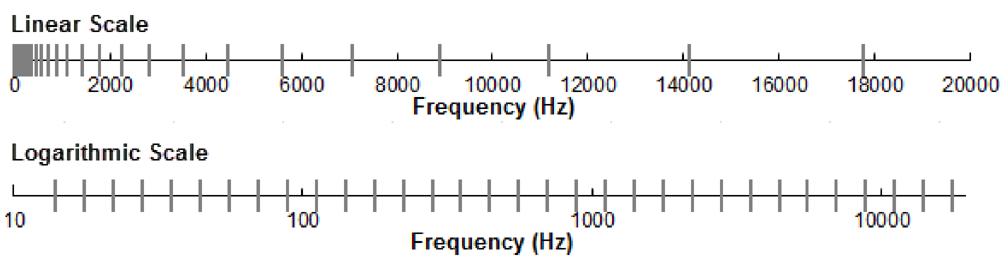

Figure C-1. One-third-octave-bands shown on a linear frequency scale and on a logarithmic scale.

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}:

$$L_b^{(i)} = 10 \log_{10} \left(\int_{f_{lo}}^{f_{hi}} S(f) df \right) , \quad \text{(C-11)}$$

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

$$\text{Broadband } L_p = 10 \log_{10} \sum_i 10^{L_b^{(i)}/10} , \quad \text{(C-12)}$$

Figure C-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 L_p is higher than the power spectrum, especially at higher frequencies. Acoustic modeling of 1/3-octave-bands require less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

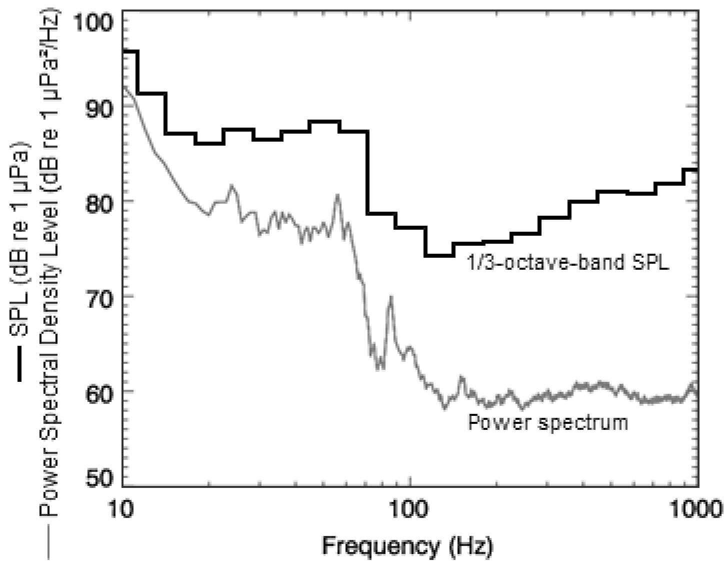

Figure C-2. A power spectrum and the corresponding 1/3-octave-band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

Appendix D. Auditory (Frequency) Weighting Functions

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

D.1. Southall et al. (2007) Marine Mammal Frequency Weighting Functions

Auditory weighting functions for marine mammals—called *M-weighting* functions—were proposed by Southall et al. (2007). Functions were defined for five hearing groups of marine mammals:

- Low-frequency cetaceans (LF)—mysticetes (baleen whales)
- Mid-frequency cetaceans (MF)—some odontocetes (toothed whales)
- High-frequency cetaceans (HF)—odontocetes specialized for using high-frequencies
- Pinnipeds in water—seals, sea lions, and walrus
- Pinnipeds in air (not addressed here)

The M-weighting functions have unity gain (0 dB) through the passband and their high and low frequency roll-offs are approximately –12 dB per octave. The amplitude response in the frequency domain of each M-weighting function is defined by:

$$G(f) = -20\log_{10}\left[\left(1+\frac{a^2}{f^2}\right)\left(1+\frac{f^2}{b^2}\right)\right] \tag{D-1}$$

where *G*(f) is the weighting function amplitude (in dB) at the frequency *f* (in Hz), and *a* and *b* are the estimated lower and upper hearing limits, respectively, which control the roll-off and passband of the weighting function. The parameters *a* and *b* are defined uniquely for each hearing group (Table D-1). The auditory weighting functions recommended by Southall et al. (2007) are shown in Figure D-1.

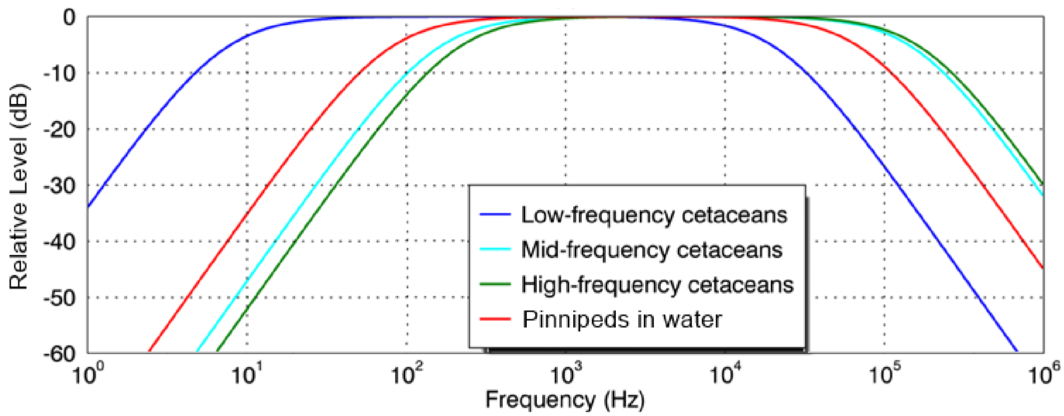

Figure D-1. Auditory weighting functions for functional marine mammal hearing groups as recommended by Southall et al. (2007).

Table D-1. Parameters for the auditory weighting functions recommended by Southall et al. (2007).

Hearing group	Southall et al. (2007)	
	a (Hz)	*b (Hz)*
Low-frequency cetaceans (LF)	7	22,000
Mid-frequency cetaceans (MF)	150	160,000
High-frequency cetaceans (HF)	200	180,000
Pinnipeds in water (PW)	75	75,000

D.2. Technical Guidance (NMFS 2016) Marine Mammal Frequency Weighting Functions

In 2015, a U.S. Navy technical report by Finneran (2015) recommended new auditory weighting functions. The overall shape of the auditory weighting functions is similar to human A-weighting functions, which follows the sensitivity of the human ear at low sound levels. The new frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right] \quad \text{(D-2)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2016). Table D-2 lists the frequency-weighting parameters for each hearing group; Figure D-2 shows the resulting frequency-weighting curves.

Table D-2. Parameters for the auditory weighting functions recommended by NMFS (2016).

Hearing group	*a*	*b*	f_{lo} (Hz)	f_{hi} (kHz)	*K* (dB)
Low-frequency cetaceans	1.0	2	200	19,000	0.13
Mid-frequency cetaceans	1.6	2	8,800	110,000	1.20
High-frequency cetaceans	1.8	2	12,000	140,000	1.36
Phocid pinnipeds in water	1.0	2	1,900	30,000	0.75
Otariid pinnipeds in water	2.0	2	940	25,000	0.64

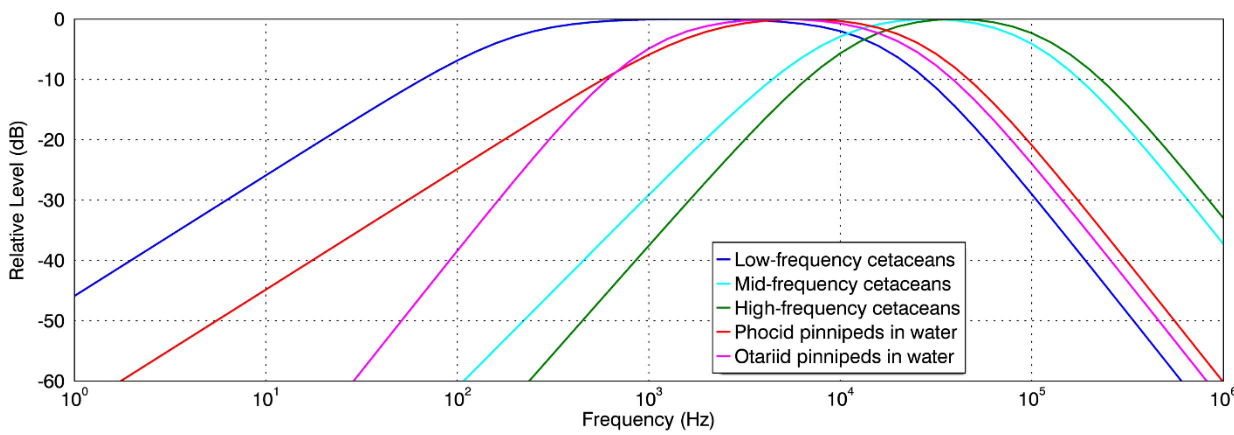

Figure D-2. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2016).

Appendix E. Threshold Ranges for One 8 m Monopile in 24 Hours with Attenuation

The following subsections present tables with the modeled ranges to injury and behavioral disruption threshold levels for marine mammals, fish, and sea turtles resulting from impact pile driving of one 8 m monopile assuming the use of noise attenuating systems, such as bubble curtains, resulting in a broadband reduction of 6 and 12 dB.

E.1. 6 dB Attenuation

E.1.1. Marine Mammals

Table E-1. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	7,325				5,950				7,218				5,903			
	L_{pk}	**219**	14	18	22	24	14	18	22	24	14	18	22	24	14	18	22	24
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	0				0				0				0			
	L_{pk}	**230**	3	5	6	6	3	5	6	6	3	5	6	6	3	5	6	6
High-frequency cetaceans	$L_{E,24hr}$	**155**	4,295				3,536				4,077				3,450			
	L_{pk}	**202**	156	220	252	357	156	220	252	357	156	220	252	357	156	220	252	357
Phocid pinnipeds	$L_{E,24hr}$	**185**	1,082				1,201				1,082				1,143			
	L_{pk}	**218**	15	20	24	33	15	20	24	33	15	20	24	33	15	20	24	33

Table E-2. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	10,224				7,653				10,155				7,629			
	L_{pk}	**219**	21	27	37	44	21	27	37	44	21	27	37	44	21	27	37	44
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	71				50				71				71			
	L_{pk}	**230**	5	7	9	8	5	7	9	8	5	7	9	8	5	7	9	8
High-frequency cetaceans	$L_{E,24hr}$	**155**	6,904				5,212				6,922				5,311			
	L_{pk}	**202**	269	347	383	494	269	347	383	494	269	347	383	494	269	347	383	494
Phocid pinnipeds	$L_{E,24hr}$	**185**	1,931				1,820				1,901				1,882			
	L_{pk}	**218**	24	36	51	53	24	36	51	53	24	36	51	53	24	36	51	53

Table E-3. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 6 dB of attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	**120**	--	--	--	--	68,467	77,010	96,492	--	--	--	--	--	90,391	95,011	--	--
	140	27,127	34,957	48,251	82,856	14,656	17,680	20,368	24,079	33,634	40,306	55,911	96,988	17,483	19,900	22,549	26,976
	150	9,263	10,987	12,905	19,244	7,341	8,436	9,794	12,191	9,416	11,498	12,950	20,359	7,424	8,732	10,438	12,584
	160	3,400	4,094	4,653	6,271	3,242	3,798	4,356	5,123	3,400	4,050	4,610	6,031	3,227	3,748	4,320	5,078
	175	860	1,188	1,458	1,901	900	1,180	1,450	1,856	863	1,209	1,487	1,960	890	1,204	1,464	1,914
	180	403	570	778	1,097	403	570	765	1,101	403	570	783	1,097	403	586	791	1,123
	190	71	112	112	224	71	112	112	206	71	100	112	212	100	112	158	224

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-4. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using a Menck 3500S hammer with 6 dB of attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
Unweighted	120	--	--	--	--	95,239	98,983	--	--	--	--	--	--	99,687	--	--	--
	140	45,850	56,172	86,849	>100,000	19,815	21,634	24,133	27,501	53,221	64,571	98,325	>100,000	21,916	23,800	26,834	34,170
	150	12,702	13,358	19,431	23,800	9,325	10,478	12,125	13,150	12,732	15,118	20,397	25,692	9,808	11,113	12,543	14,124
	160	4,368	4,827	6,046	7,927	4,056	4,507	5,012	6,196	4,320	4,801	5,743	7,849	4,031	4,482	4,966	6,027
	175	1,208	1,484	1,811	2,136	1,217	1,476	1,773	2,072	1,217	1,504	1,850	2,171	1,242	1,501	1,812	2,110
	180	570	757	996	1,254	585	763	1,005	1,251	566	762	1,005	1,273	586	781	1,011	1,275
	190	112	112	158	250	112	112	158	255	112	112	158	269	112	158	200	292

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-5. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
LF	120	--	--	--	--	68,288	76,771	96,397	--	--	--	--	--	90,272	94,943	--	--
	140	27,102	34,825	48,096	82,524	14,625	17,648	20,336	24,036	33,530	40,194	55,753	96,808	17,437	19,859	22,522	26,920
	160	3,380	4,070	4,630	6,216	3,221	3,762	4,334	5,102	3,377	4,021	4,596	5,968	3,213	3,716	4,303	5,059
	180	381	570	762	1,070	391	570	762	1,082	381	570	763	1,079	403	570	776	1,092
MF	120	--	--	--	--	55,365	59,301	76,842	98,805	--	--	--	--	66,052	74,610	94,164	--
	140	20,943	23,208	33,192	55,395	12,108	12,783	14,698	19,996	20,861	23,575	36,342	59,654	12,394	12,817	16,831	21,011
	160	2,342	2,527	2,933	3,670	2,264	2,482	2,828	3,400	2,329	2,563	2,909	3,610	2,314	2,496	2,847	3,359
	180	100	112	180	300	112	112	200	320	100	112	180	292	112	150	212	320
HF	120	--	--	--	--	51,589	55,012	68,866	95,368	--	--	--	--	58,819	64,976	89,972	99,712
	140	18,611	20,612	27,204	45,866	11,038	11,877	13,271	18,533	18,227	20,435	27,259	51,073	11,228	12,204	13,452	19,366
	160	2,040	2,246	2,640	3,158	1,992	2,184	2,602	3,081	2,062	2,264	2,654	3,178	2,023	2,209	2,607	3,081
	180	71	100	112	224	50	100	112	250	71	71	112	224	71	112	150	250
PW	120	--	--	--	--	62,479	68,896	91,112	--	--	--	--	--	81,962	90,738	98,164	
	140	24,340	27,155	41,763	71,970	13,136	14,356	18,347	22,250	26,015	33,019	47,421	83,124	13,556	16,933	20,066	24,333
	160	2,850	3,106	3,670	4,691	2,752	3,010	3,409	4,365	2,830	3,121	3,609	4,629	2,789	3,006	3,381	4,327
	180	180	250	361	608	180	255	403	640	180	269	361	602	212	292	400	650

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-6. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using a Menck 3500S hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
LF	120	--	--	--	--	95,094	98,949	--	--	--	--	--	--	99,616	--	--	--
	140	45,719	55,962	86,494	--	19,780	21,595	24,091	27,438	53,060	64,327	98,199	--	21,866	23,753	26,792	34,109
	160	4,357	4,813	6,004	7,904	4,048	4,499	5,000	6,157	4,313	4,786	5,703	7,816	4,014	4,470	4,954	5,993
	180	559	752	990	1,250	570	762	1,000	1,250	559	752	996	1,250	583	776	1,001	1,273
MF	120	--	--	--	--	72,858	85,001	99,172	--	--	--	--	--	92,664	96,468	--	--
	140	29,800	37,184	57,398	94,210	14,193	17,117	20,165	23,353	33,846	41,015	61,032	--	15,070	17,865	21,199	25,278
	160	2,878	3,084	3,717	4,607	2,768	2,995	3,444	4,261	2,843	3,102	3,667	4,522	2,804	2,971	3,395	4,186
	180	158	224	300	472	158	250	335	539	158	224	300	461	200	250	336	522
HF	120	--	--	--	--	65,675	75,346	95,852	--	--	--	--	--	87,257	93,493	99,967	--
	140	26,252	31,641	47,001	79,467	13,112	14,271	18,744	22,128	26,438	34,448	52,009	89,717	13,148	14,900	19,531	23,052
	160	2,568	2,811	3,200	4,150	2,550	2,712	3,102	3,712	2,608	2,777	3,200	4,045	2,546	2,751	3,109	3,653
	180	112	141	224	335	112	150	255	381	112	158	224	320	142	200	250	400
PW	120	--	--	--	--	87,890	96,223	--	--	--	--	--	--	97,237	--	--	--
	140	39,797	47,363	73,714	--	17,848	19,651	22,350	25,604	44,978	54,314	86,706	--	19,632	21,287	24,532	29,321
	160	3,540	4,082	4,710	6,115	3,306	3,691	4,385	5,011	3,466	4,000	4,650	5,781	3,301	3,651	4,344	4,930
	180	316	427	585	832	354	461	636	854	316	427	570	814	354	474	641	863

-- Range is greater than the extents of the modeled distance (100,000 m)

E.1.2. Fish and Sea Turtles

Table E-7. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	100				100				71				112			
	L_{pk}	213	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	403				427				403				427			
	L_{pk}	207	133	186	216	256	133	186	216	256	133	186	216	256	133	186	216	256
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	695				716				696				716			
	L_{pk}	207	133	186	216	256	133	186	216	256	133	186	216	256	133	186	216	256
Sea turtles (mortal injury)	$L_{E,24hr}$	210	403				427				403				427			
	L_{pk}	207	133	186	216	256	133	186	216	256	133	186	216	256	133	186	216	256
Eggs and larvae	$L_{E,24hr}$	210	403				427				403				427			
	L_{pk}	207	133	186	216	256	133	186	216	256	133	186	216	256	133	186	216	256
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	141				141				112				158			
	L_{pk}	213	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Fish with swim bladder	$L_{E,24hr}$	203	1,315				1,320				1,345				1,350			
	L_{pk}	207	133	186	216	256	133	186	216	256	133	186	216	256	133	186	216	256
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	10,311				7,858				10,622				7,983			

Table E-8. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	90				79				79				79			
	L_{pk}	213	6	6	9	18	6	7	9	10	19	37	60	70	20	40	62	71
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	320				316				266				261			
	L_{pk}	207	13	29	45	50	13	29	40	40	58	84	130	150	59	86	140	160
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	535				526				443				445			
	L_{pk}	207	13	29	45	50	13	29	40	40	58	84	130	150	59	86	140	160
Sea turtles (mortal injury)	$L_{E,24hr}$	210	320				316				266				261			
	L_{pk}	207	13	29	45	50	13	29	40	40	58	84	130	150	59	86	140	160
Eggs and larvae	$L_{E,24hr}$	210	320				316				266				261			
	L_{pk}	207	13	29	45	50	13	29	40	40	58	84	130	150	59	86	140	160
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	112				112				112				112			
	L_{pk}	213	6	6	9	18	6	7	9	10	19	37	60	70	20	40	62	71
Fish with swim bladder	$L_{E,24hr}$	203	1,075				1,061				836				828			
	L_{pk}	207	13	29	45	50	13	29	40	40	58	84	130	150	59	86	140	160
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	5,736				5,265				5,244				4,973			

Table E-9. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	10,701				8,207				11,180				8,475			
	L_{pk}	206	98	126	146	209	98	126	146	209	98	126	146	209	98	126	146	209
Large fish	$L_{E,12hr}$	187	7,114				6,004				7,092				6,004			
	L_{pk}	206	98	126	146	209	98	126	146	209	98	126	146	209	98	126	146	209
Sea turtles	L_p	180	403	570	778	1,097	403	570	765	1,101	403	570	783	1,097	403	586	791	1,123
Small fish	L_p	150	9,263	10,987	12,905	19,244	7,341	8,436	9,794	12,191	9,416	11,498	12,950	20,359	7,424	8,732	10,438	12,584
Large fish	L_p	150	9,263	10,987	12,905	19,244	7,341	8,436	9,794	12,191	9,416	11,498	12,950	20,359	7,424	8,732	10,438	12,584
Blackstock et al. (2017)																		
Sea turtles	L_p	175	860	1,188	1,458	1,901	900	1,180	1,450	1,856	863	1,209	1,487	1,960	890	1,204	1,464	1,914
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	626				640				610				650			
	L_{pk}	232	3	5	6	6	3	5	6	6	3	5	6	6	3	5	6	6
Sea turtles - TTS	$L_{E,TU,24hr}$	189	5012				4438				4897				4361			
	L_{pk}	226	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

Table E-10. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using a Menck 3500S hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	14,662				9,984				15,527				10,554			
	L_{pk}	206	146	211	238	285	146	211	238	285	146	211	238	285	146	211	238	285
Large fish	$L_{E,12hr}$	187	9,205				7,250				9,319				7,318			
	L_{pk}	206	146	211	238	285	146	211	238	285	146	211	238	285	146	211	238	285
Sea turtles	L_p	180	570	757	996	1,254	585	763	1,005	1,251	566	762	1,005	1,273	586	781	1,011	1,275
Small fish	L_p	150	12,702	13,358	19,431	23,800	9,325	10,478	12,125	13,150	12,732	15,118	20,397	25,692	9,808	11,113	12,543	14,124
Large fish	L_p	150	12,702	13,358	19,431	23,800	9,325	10,478	12,125	13,150	12,732	15,118	20,397	25,692	9,808	11,113	12,543	14,124
Blackstock et al. (2017)																		
Sea turtles	L_p	175	1,208	1,484	1,811	2,136	1,217	1,476	1,773	2,072	1,217	1,504	1,850	2,171	1,242	1,501	1,812	2,110
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	962				996				985				996			
	L_{pk}	232	5	7	9	8	5	7	9	8	5	7	9	8	5	7	9	8
Sea turtles - TTS	$L_{E,TU,24hr}$	189	6671				5691				6704				5644			
	L_{pk}	226	2	3	4	4	2	3	4	4	2	3	4	4	2	3	4	4

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

E.2. 10 dB Attenuation

E.2.1. Marine Mammals

Table E-11. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
Low-frequency cetaceans	$L_{E,24hr}$	183	4,547				3,999				4,406				3,929			
	L_{pk}	219	8	11	15	15	8	11	15	15	8	11	15	15	8	11	15	15
Mid-frequency cetaceans	$L_{E,24hr}$	185	0				0				0				50			
	L_{pk}	230	3	3	4	4	3	3	4	4	3	3	4	4	3	3	4	4
High-frequency cetaceans	$L_{E,24hr}$	155	2,300				1,981				2,307				1,991			
	L_{pk}	202	103	128	158	195	103	128	158	195	103	128	158	195	103	128	158	195
Phocid pinnipeds	$L_{E,24hr}$	185	500				585				500				600			
	L_{pk}	218	9	13	16	16	9	13	16	16	9	13	16	16	9	13	16	16

Table E-12. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer with 10 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500
Low-frequency cetaceans	$L_{E,24hr}$	183	6,295				5,354				6,250				5,220			
	L_{pk}	219	13	17	20	20	13	17	20	20	13	17	20	20	13	17	20	20
Mid-frequency cetaceans	$L_{E,24hr}$	185	0				0				0				50			
	L_{pk}	230	3	4	5	5	3	4	5	5	3	4	5	5	3	4	5	5
High-frequency cetaceans	$L_{E,24hr}$	155	3,453				3,056				3,287				2,960			
	L_{pk}	202	154	189	253	305	154	189	253	305	154	189	253	305	154	189	253	305
Phocid pinnipeds	$L_{E,24hr}$	185	863				854				828				860			
	L_{pk}	218	15	20	22	22	15	20	22	22	15	20	22	22	15	20	22	22

Table E-13. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	**120**	--	--	--	--	49,994	54,451	64,153	88,636	--	--	--	--	57,399	64,024	84,991	97,624
	140	18,420	21,154	26,009	40,919	11,744	12,837	14,171	18,990	19,604	22,514	27,562	46,836	12,376	13,172	16,993	21,052
	150	5,689	7,385	8,923	11,909	4,943	5,900	7,170	8,970	5,489	7,375	9,003	12,368	4,900	5,763	7,257	9,345
	160	2,683	2,997	3,363	4,290	2,583	2,909	3,218	3,962	2,677	3,008	3,360	4,243	2,620	2,936	3,210	3,922
	175	461	658	873	1,235	461	680	901	1,221	461	671	873	1,253	475	680	901	1,242
	180	158	269	403	602	158	269	403	604	158	283	403	604	200	292	403	618
	190	0	0	71	112	0	0	71	112	0	0	71	112	50	50	100	112

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-14. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using a Menck 3500S hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
Unweighted	**120**	--	--	--	--	62,554	70,138	90,124	99,709	--	--	--	--	80,945	91,476	97,913	--
	140	24,608	27,670	41,857	64,409	13,438	15,982	18,987	21,871	26,449	35,671	47,727	71,031	15,340	18,340	20,890	23,930
	150	8,443	9,905	11,921	13,435	6,743	7,628	8,880	10,503	8,398	10,259	12,307	15,094	6,716	7,742	9,180	11,062
	160	3,100	3,491	4,168	4,769	3,005	3,312	3,835	4,443	3,108	3,476	4,117	4,718	3,010	3,298	3,773	4,403
	175	667	885	1,140	1,414	680	901	1,141	1,409	671	894	1,142	1,422	694	906	1,166	1,423
	180	269	381	522	696	269	403	550	716	283	381	522	700	292	403	550	716
	190	0	50	100	112	0	71	100	112	0	71	100	112	50	100	112	142

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-15. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								Hammer energy (kJ)							
		1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
LF	120	--	--	--	--	49,917	54,350	64,019	88,410	--	--	--	--	57,297	63,860	84,704	97,555
	140	18,352	21,110	25,971	40,809	11,715	12,823	14,119	18,947	19,544	22,459	27,455	46,725	12,355	13,149	16,950	21,009
	160	2,667	2,982	3,351	4,262	2,570	2,899	3,202	3,941	2,663	2,995	3,343	4,216	2,608	2,923	3,195	3,897
	180	158	269	400	602	158	269	400	602	158	269	400	602	200	292	403	602
MF	120	--	--	--	--	41,378	44,181	52,194	66,886	--	--	--	--	45,590	49,090	60,203	88,939
	140	11,850	12,832	19,361	26,869	8,554	9,326	11,394	13,252	11,905	12,832	19,266	27,038	8,541	9,433	11,766	13,573
	160	1,550	1,789	2,202	2,723	1,530	1,769	2,163	2,658	1,553	1,818	2,241	2,729	1,563	1,811	2,173	2,680
	180	0	0	100	112	0	0	100	141	0	0	71	112	50	50	112	200
HF	120	--	--	--	--	38,720	41,102	48,967	61,256	--	--	--	--	42,238	45,007	54,943	79,177
	140	10,492	11,449	14,931	23,879	7,708	8,344	10,389	12,845	10,325	11,500	13,620	23,989	7,608	8,288	10,532	12,855
	160	1,262	1,458	1,906	2,442	1,278	1,443	1,879	2,372	1,250	1,460	1,914	2,452	1,298	1,458	1,914	2,413
	180	0	0	50	112	0	0	0	112	0	0	0	100	50	50	50	112
PW	120	--	--	--	--	46,500	49,910	58,997	79,595	--	--	--	--	52,808	57,130	73,619	95,381
	140	13,424	18,054	23,366	34,942	10,353	11,363	12,941	17,103	14,120	18,919	23,873	39,668	10,718	11,998	13,086	18,493
	160	2,127	2,440	2,761	3,298	2,084	2,358	2,691	3,160	2,171	2,451	2,766	3,289	2,109	2,404	2,711	3,162
	180	100	112	158	292	100	112	158	304	71	112	180	300	112	158	200	316

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-16. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using a Menck 3500S hammer with 10 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
LF	120	--	--	--	--	62,435	69,973	89,900	99,671	--	--	--	--	80,642	91,358	97,845	>100,000
	140	24,534	27,615	41,755	64,192	13,410	15,670	18,950	21,837	26,399	35,544	47,609	70,788	15,243	18,290	20,851	23,879
	160	3,092	3,473	4,151	4,759	3,000	3,302	3,818	4,430	3,102	3,466	4,104	4,707	3,004	3,290	3,759	4,391
	180	269	381	515	680	269	403	539	707	269	381	515	695	292	403	541	711
MF	120	--	--	--	--	50,867	55,300	67,931	91,882	--	--	--	--	57,923	65,829	89,754	98,346
	140	18,289	20,912	27,059	41,701	11,073	12,166	13,329	17,781	18,289	20,901	27,261	46,873	11,355	12,446	13,819	18,885
	160	2,136	2,393	2,754	3,152	2,110	2,312	2,680	3,065	2,187	2,371	2,750	3,171	2,110	2,358	2,704	3,057
	180	71	112	141	224	100	112	150	255	71	100	141	224	112	112	200	250
HF	120	--	--	--	--	47,601	51,397	61,885	84,525	--	--	--	--	53,239	58,463	80,681	96,300
	140	13,252	18,459	24,065	36,420	10,103	11,031	12,894	15,599	13,169	18,130	24,226	39,512	10,190	11,238	12,897	17,151
	160	1,844	2,072	2,460	2,903	1,812	2,026	2,404	2,795	1,858	2,100	2,486	2,865	1,856	2,055	2,430	2,818
	180	50	71	112	141	0	71	112	158	0	71	100	158	50	100	112	200
PW	120	--	--	--	--	57,516	63,118	81,233	98,505	--	--	--	--	70,166	83,066	95,697	>100,000
	140	22,438	25,135	36,043	53,265	12,807	13,234	17,226	20,241	23,300	26,255	40,579	59,681	12,907	14,287	18,676	21,962
	160	2,693	2,952	3,303	4,105	2,632	2,850	3,166	3,701	2,706	2,930	3,290	4,025	2,646	2,863	3,167	3,655
	180	150	180	269	403	158	206	304	461	150	180	283	412	181	212	304	461

-- Range is greater than the extents of the modeled distance (100,000 m)

E.2.2. Fish and Sea Turtles

Table E-17. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	0				0				0				50			
	L_{pk}	213	18	24	29	32	18	24	29	32	18	24	29	32	18	24	29	32
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	141				141				141				158			
	L_{pk}	207	44	69	84	103	44	69	84	103	44	69	84	103	44	69	84	103
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	255				255				269				292			
	L_{pk}	207	44	69	84	103	44	69	84	103	44	69	84	103	44	69	84	103
Sea turtles (mortal injury)	$L_{E,24hr}$	210	141				141				141				158			
	L_{pk}	207	44	69	84	103	44	69	84	103	44	69	84	103	44	69	84	103
Eggs and larvae	$L_{E,24hr}$	210	141				141				141				158			
	L_{pk}	207	44	69	84	103	44	69	84	103	44	69	84	103	44	69	84	103
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	0				50				0				71			
	L_{pk}	213	18	24	29	32	18	24	29	32	18	24	29	32	18	24	29	32
Fish with swim bladder	$L_{E,24hr}$	203	559				559				559				559			
	L_{pk}	207	44	69	84	103	44	69	84	103	44	69	84	103	44	69	84	103
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	5,286				4,639				5,170				4,572			

Table E-18. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	0				0				0				50			
	L_{pk}	213	28	36	49	58	28	36	49	58	28	36	49	58	28	36	49	58
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	180				180				180				212			
	L_{pk}	207	84	107	124	145	84	107	124	145	84	107	124	145	84	107	124	145
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	335				361				320				361			
	L_{pk}	207	84	107	124	145	84	107	124	145	84	107	124	145	84	107	124	145
Sea turtles (mortal injury)	$L_{E,24hr}$	210	180				180				180				212			
	L_{pk}	207	84	107	124	145	84	107	124	145	84	107	124	145	84	107	124	145
Eggs and larvae	$L_{E,24hr}$	210	180				180				180				212			
	L_{pk}	207	84	107	124	145	84	107	124	145	84	107	124	145	84	107	124	145
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	71				71				71				100			
	L_{pk}	213	28	36	49	58	28	36	49	58	28	36	49	58	28	36	49	58
Fish with swim bladder	$L_{E,24hr}$	203	695				716				696				716			
	L_{pk}	207	84	107	124	145	84	107	124	145	84	107	124	145	84	107	124	145
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	6,709				5,680				6,710				5,625			

Table E-19. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using an IHC S-4000 hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	7,114				6,004				7,092				6,004			
	L_{pk}	206	49	80	98	120	49	80	98	120	49	80	98	120	49	80	98	120
Large fish	$L_{E,12hr}$	187	4,721				4,235				4,618				4,176			
	L_{pk}	206	49	80	98	120	49	80	98	120	49	80	98	120	49	80	98	120
Sea turtles	L_p	180	158	269	403	602	158	269	403	604	158	283	403	604	200	292	403	618
Small fish	L_p	150	5,689	7,385	8,923	11,909	4,943	5,900	7,170	8,970	5,489	7,375	9,003	12,368	4,900	5,763	7,257	9,345
Large fish	L_p	150	5,689	7,385	8,923	11,909	4,943	5,900	7,170	8,970	5,489	7,375	9,003	12,368	4,900	5,763	7,257	9,345
Blackstock et al. (2017)																		
Sea turtles	L_p	175	461	658	873	1,235	461	680	901	1,221	461	671	873	1,253	475	680	901	1,242
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	316				304				320				300			
	L_{pk}	232	2	3	4	4	2	3	4	4	2	3	4	4	2	3	4	4
Sea turtles - TTS	$L_{E,TU,24hr}$	189	3110				2899				3108				2927			
	L_{pk}	226	3	5	6	6	3	5	6	6	3	5	6	6	3	5	6	6

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

Table E-20. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using a Menck 3500S hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	9,205				7,250				9,319				7,318			
	L_{pk}	206	92	123	142	166	92	123	142	166	92	123	142	166	92	123	142	166
Large fish	$L_{E,12hr}$	187	6,050				5,197				5,979				5,121			
	L_{pk}	206	92	123	142	166	92	123	142	166	92	123	142	166	92	123	142	166
Sea turtles	L_p	180	269	381	522	696	269	403	550	716	283	381	522	700	292	403	550	716
Small fish	L_p	150	8,443	9,905	11,921	13,435	6,743	7,628	8,880	10,503	8,398	10,259	12,307	15,094	6,716	7,742	9,180	11,062
Large fish	L_p	150	8,443	9,905	11,921	13,435	6,743	7,628	8,880	10,503	8,398	10,259	12,307	15,094	6,716	7,742	9,180	11,062
Blackstock et al. (2017)																		
Sea turtles	L_p	175	667	885	1,140	1,414	680	901	1,141	1,409	671	894	1,142	1,422	694	906	1,166	1,423
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	495				502				495				510			
	L_{pk}	232	2	3	4	4	2	3	4	4	2	3	4	4	2	3	4	4
Sea turtles - TTS	$L_{E,TU,24hr}$	189	4316				3892				4197				3831			
	L_{pk}	226	5	7	9	8	5	7	9	8	5	7	9	8	5	7	9	8

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

E.3. 12 dB Attenuation

E.3.1. Marine Mammals

Table E-21. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	3,491				3,158				3,354				3,190			
	L_{pk}	**219**	6	8	11	11	6	8	11	11	6	8	11	11	6	8	11	11
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	0				0				0				0			
	L_{pk}	**230**	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3
High-frequency cetaceans	$L_{E,24hr}$	**155**	1,476				1,345				1,432				1,364			
	L_{pk}	**202**	78	97	120	148	78	97	120	148	78	97	120	148	78	97	120	148
Phocid pinnipeds	$L_{E,24hr}$	**185**	320				335				320				350			
	L_{pk}	**218**	7	10	12	12	7	10	12	12	7	10	12	12	7	10	12	12

Table E-22. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer with 12 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	4,998				4,350				4,835				4,262			
	L_{pk}	**219**	10	13	15	15	10	13	15	15	10	13	15	15	10	13	15	15
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	0				0				0				0			
	L_{pk}	**230**	2	3	4	4	2	3	4	4	2	3	4	4	2	3	4	4
High-frequency cetaceans	$L_{E,24hr}$	**155**	2,476				2,180				2,476				2,159			
	L_{pk}	**202**	117	143	192	231	117	143	192	231	117	143	192	231	117	143	192	231
Phocid pinnipeds	$L_{E,24hr}$	**185**	570				673				570				680			
	L_{pk}	**218**	11	15	17	17	11	15	17	17	11	15	17	17	11	15	17	17

Table E-23. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	120	--	--	--	--	43,694	47,568	55,038	69,967	--	--	--	--	49,199	54,475	65,291	91,432
	140	13,081	17,331	21,364	27,536	10,130	11,412	12,836	15,540	13,218	18,583	22,603	35,324	10,689	12,191	13,131	18,315
	150	4,728	5,560	7,341	9,816	4,400	4,925	5,811	7,645	4,680	5,402	7,306	10,177	4,360	4,899	5,671	7,779
	160	2,331	2,693	2,973	3,540	2,277	2,600	2,884	3,362	2,376	2,693	2,983	3,523	2,309	2,642	2,907	3,353
	175	320	500	652	962	320	500	658	955	320	500	652	982	354	500	667	971
	180	112	158	255	427	112	180	255	430	112	180	269	427	158	212	292	447
	190	0	0	0	71	0	0	0	71	0	0	0	71	50	50	50	112

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-24. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using a Menck 3500S hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
Unweighted	120	--	--	--	--	53,822	58,996	70,948	92,985	--	--	--	--	62,847	72,371	92,105	98,881
	140	20,769	23,470	28,003	43,422	12,610	13,130	15,455	19,234	21,812	25,145	35,867	49,903	12,814	14,261	18,157	21,092
	150	6,750	8,011	9,758	12,105	5,246	6,402	7,533	8,917	6,705	8,000	10,103	12,382	5,179	6,309	7,628	9,192
	160	2,777	3,052	3,440	4,140	2,706	2,952	3,260	3,800	2,789	3,050	3,422	4,093	2,722	2,962	3,259	3,747
	175	472	650	850	1,100	500	652	860	1,107	461	650	851	1,110	500	658	873	1,124
	180	180	269	361	500	180	269	381	515	180	269	361	502	200	292	391	522
	190	0	0	50	100	0	0	50	100	0	0	0	71	50	50	71	112

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-25. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								Hammer energy (kJ)							
		1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
LF	120	--	--	--	--	43,615	47,476	54,928	69,798	--	--	--	--	49,099	54,374	65,117	91,299
	140	13,072	17,295	21,319	27,493	10,100	11,379	12,822	15,416	13,189	18,515	22,546	35,204	10,651	12,163	13,105	18,265
	160	2,311	2,680	2,957	3,516	2,259	2,583	2,865	3,353	2,358	2,677	2,972	3,506	2,301	2,621	2,890	3,336
	180	112	158	255	424	112	180	255	427	112	158	269	427	158	206	292	430
MF	120	--	--	--	--	36,015	38,306	45,458	56,004	--	--	--	--	39,455	42,143	50,764	67,422
	140	9,348	10,622	12,971	21,227	7,118	7,832	9,611	12,276	9,168	10,636	12,956	21,270	7,058	7,781	9,771	12,516
	160	1,170	1,401	1,812	2,385	1,209	1,395	1,803	2,305	1,163	1,412	1,855	2,369	1,210	1,422	1,844	2,355
	180	0	0	0	112	0	0	0	112	0	0	0	100	50	50	50	112
HF	120	--	--	--	--	33,326	35,659	42,269	52,138	--	--	--	--	36,523	38,823	46,409	59,814
	140	7,983	8,968	12,000	19,043	5,890	6,847	8,610	11,185	7,853	8,812	11,960	18,739	5,720	6,823	8,582	11,412
	160	901	1,077	1,512	2,081	939	1,118	1,492	2,050	919	1,110	1,512	2,103	922	1,134	1,504	2,059
	180	0	0	0	71	0	0	0	71	0	0	0	71	50	50	50	100
PW	120	--	--	--	--	40,364	43,502	50,819	63,353	--	--	--	--	44,814	48,777	58,354	84,105
	140	11,951	12,967	18,712	25,598	8,688	9,668	11,494	13,231	12,134	12,978	19,331	26,300	8,820	10,151	12,112	14,182
	160	1,756	2,070	2,433	2,926	1,726	2,010	2,352	2,822	1,769	2,102	2,435	2,921	1,761	2,059	2,401	2,850
	180	50	100	112	206	50	100	112	250	0	71	112	206	50	112	158	224

-- Range is greater than the extents of the modeled distance (100,000 m)

Table E-26. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using a Menck 3500S hammer with 12 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*	*1000*	*1500*	*2500*	*3500*
LF	120	--	--	--	--	53,718	58,878	70,785	92,799	--	--	--	--	62,703	72,171	92,000	98,806
	140	20,729	23,448	27,887	43,306	12,596	13,121	15,351	19,197	21,745	24,906	35,756	49,754	12,802	14,200	18,106	21,053
	160	2,766	3,044	3,423	4,130	2,702	2,942	3,252	3,783	2,780	3,041	3,408	4,077	2,712	2,957	3,251	3,731
	180	158	269	361	500	180	269	381	510	180	269	361	500	200	292	391	515
MF	120	--	--	--	--	44,181	47,833	56,592	71,394	--	--	--	--	49,048	53,956	68,538	91,899
	140	12,821	13,665	21,609	27,788	9,289	10,358	12,401	13,743	12,820	13,595	21,775	30,550	9,363	10,580	12,587	14,550
	160	1,753	2,001	2,404	2,815	1,746	1,950	2,332	2,710	1,761	2,001	2,385	2,779	1,768	1,998	2,371	2,750
	180	0	71	112	141	0	71	112	158	0	71	100	158	50	100	112	200
HF	120	--	--	--	--	41,141	44,666	52,638	64,670	--	--	--	--	45,031	49,301	60,615	86,116
	140	11,454	12,766	19,410	25,947	8,336	9,205	11,317	13,052	11,497	12,770	19,091	26,153	8,274	9,222	11,547	13,052
	160	1,432	1,692	2,102	2,511	1,422	1,671	2,080	2,499	1,450	1,681	2,136	2,550	1,451	1,665	2,074	2,487
	180	0	0	71	112	0	0	71	112	0	0	71	112	50	50	100	112
PW	120	--	--	--	--	49,718	54,008	64,301	85,357	--	--	--	--	56,781	63,416	85,836	96,656
	140	17,905	20,605	26,012	38,122	11,212	12,377	13,292	17,506	18,549	21,117	26,604	42,871	11,764	12,613	14,345	19,035
	160	2,355	2,593	2,935	3,331	2,277	2,532	2,826	3,182	2,342	2,625	2,912	3,306	2,331	2,550	2,850	3,189
	180	112	141	180	269	112	141	206	300	112	141	180	292	142	158	212	300

-- Range is greater than the extents of the modeled distance (100,000 m)

E.3.2. Fish and Sea Turtles

Table E-27. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using an IHC S-4000 hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	0				0				0				0			
	L_{pk}	213	14	18	22	24	14	18	22	24	14	18	22	24	14	18	22	24
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	112				112				112				112			
	L_{pk}	207	33	52	64	78	33	52	64	78	33	52	64	78	33	52	64	78
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	158				158				158				200			
	L_{pk}	207	33	52	64	78	33	52	64	78	33	52	64	78	33	52	64	78
Sea turtles (mortal injury)	$L_{E,24hr}$	210	112				112				112				112			
	L_{pk}	207	33	52	64	78	33	52	64	78	33	52	64	78	33	52	64	78
Eggs and larvae	$L_{E,24hr}$	210	112				112				112				112			
	L_{pk}	207	33	52	64	78	33	52	64	78	33	52	64	78	33	52	64	78
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	0				0				0				50			
	L_{pk}	213	14	18	22	24	14	18	22	24	14	18	22	24	14	18	22	24
Fish with swim bladder	$L_{E,24hr}$	203	381				381				381				391			
	L_{pk}	207	33	52	64	78	33	52	64	78	33	52	64	78	33	52	64	78
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	4,226				3,846				4,137				3,798			

Table E-28. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 8 m monopile in 24 hours, using a Menck 3500S hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500	1000	1500	2500	3500
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	0				0				0				0			
	L_{pk}	213	21	27	37	44	21	27	37	44	21	27	37	44	21	27	37	44
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	141				141				112				158			
	L_{pk}	207	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	224				255				224				255			
	L_{pk}	207	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Sea turtles (mortal injury)	$L_{E,24hr}$	210	141				141				112				158			
	L_{pk}	207	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Eggs and larvae	$L_{E,24hr}$	210	141				141				112				158			
	L_{pk}	207	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	0				0				0				0			
	L_{pk}	213	21	27	37	44	21	27	37	44	21	27	37	44	21	27	37	44
Fish with swim bladder	$L_{E,24hr}$	203	500				502				495				510			
	L_{pk}	207	64	81	94	110	64	81	94	110	64	81	94	110	64	81	94	110
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	5,456				4,708				5,314				4,633			

Table E-29. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using an IHC S-4000 hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	5,864				5,102				5,776				5,032			
	L_{pk}	206	37	61	74	91	37	61	74	91	37	61	74	91	37	61	74	91
Large fish	$L_{E,12hr}$	187	3,798				3,447				3,710				3,426			
	L_{pk}	206	37	61	74	91	37	61	74	91	37	61	74	91	37	61	74	91
Sea turtles	L_p	180	112	158	255	427	112	180	255	430	112	180	269	427	158	212	292	447
Small fish	L_p	150	4,728	5,560	7,341	9,816	4,400	4,925	5,811	7,645	4,680	5,402	7,306	10,177	4,360	4,899	5,671	7,779
Large fish	L_p	150	4,728	5,560	7,341	9,816	4,400	4,925	5,811	7,645	4,680	5,402	7,306	10,177	4,360	4,899	5,671	7,779
Blackstock et al. (2017)																		
Sea turtles	L_p	175	320	500	652	962	320	500	658	955	320	500	652	982	354	500	667	971
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	212				206				224				206			
	L_{pk}	232	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sea turtles - TTS	$L_{E,TU,24hr}$	189	2413				2309				2452				2365			
	L_{pk}	226	3	5	6	6	3	5	6	6	3	5	6	6	3	5	6	6

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

Table E-30. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 8 m monopile in 12 hours, using a Menck 3500S hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	7,474				6,175				7,428				6,153			
	L_{pk}	206	70	93	108	126	70	93	108	126	70	93	108	126	70	93	108	126
Large fish	$L_{E,12hr}$	187	4,850				4,301				4,732				4,224			
	L_{pk}	206	70	93	108	126	70	93	108	126	70	93	108	126	70	93	108	126
Sea turtles	L_p	180	180	269	361	500	180	269	381	515	180	269	361	502	200	292	391	522
Small fish	L_p	150	6,750	8,011	9,758	12,105	5,246	6,402	7,533	8,917	6,705	8,000	10,103	12,382	5,179	6,309	7,628	9,192
Large fish	L_p	150	6,750	8,011	9,758	12,105	5,246	6,402	7,533	8,917	6,705	8,000	10,103	12,382	5,179	6,309	7,628	9,192
Blackstock et al. (2017)																		
Sea turtles	L_p	175	472	650	850	1,100	500	652	860	1,107	461	650	851	1,110	500	658	873	1,124
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	361				320				361				320			
	L_{pk}	232	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1
Sea turtles - TTS	$L_{E,TU,24hr}$	189	3394				3120				3371				3112			
	L_{pk}	226	5	7	9	8	5	7	9	8	5	7	9	8	5	7	9	8

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

Appendix F. Threshold Ranges for One 11 m Monopile in 24 Hours with Attenuation

The following subsections present tables with the modeled ranges to injury and behavioral disruption threshold levels for marine mammals, fish, and sea turtles resulting from impact pile driving of one 11 m monopile assuming the use of noise attenuating systems, such as bubble curtains, resulting in a broadband reduction of 6 and 12 dB. These results assume 4,500 strikes to drive a monopile (Table 4).

F.1. 6 dB Attenuation

F.1.1. Marine Mammals

Table F-1. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
Low-frequency cetaceans	$L_{E,24hr}$	183	9,843				7,716				10,163				7,830			
	L_{pk}	219	8	13	17	23	8	13	17	23	8	11	15	21	8	11	15	21
Mid-frequency cetaceans	$L_{E,24hr}$	185	40				28				40				64			
	L_{pk}	230	1	2	2	3	1	2	2	3	1	1	2	2	1	1	2	2
High-frequency cetaceans	$L_{E,24hr}$	155	4,582				3,622				4,291				3,551			
	L_{pk}	202	196	241	373	543	196	241	373	543	195	239	388	539	195	239	388	539
Phocid pinnipeds	$L_{E,24hr}$	185	1,368				1,330				1,432				1,370			
	L_{pk}	218	10	15	20	27	10	15	20	27	9	13	18	25	9	13	18	25

Table F-2. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 6 dB of attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	120	--	--	--	--	65,809	70,784	86,447	98,691	--	--	--	--	85,150	90,541	97,029	--
	140	26,639	33,072	42,449	56,813	17,370	18,750	21,146	24,121	35,080	39,244	49,326	69,280	19,513	21,071	23,591	27,484
	150	10,721	11,908	13,158	18,520	8,589	9,419	10,879	12,720	11,480	12,508	15,321	20,897	8,937	10,019	11,702	13,145
	160	4,246	4,659	5,466	7,466	3,971	4,405	4,894	6,218	4,162	4,679	5,347	7,520	3,929	4,380	4,876	6,332
	175	1,279	1,568	1,883	2,299	1,253	1,526	1,820	2,228	1,327	1,637	1,915	2,332	1,280	1,560	1,856	2,272
	180	553	877	1,100	1,519	585	849	1,065	1,471	566	885	1,101	1,481	592	867	1,074	1,485
	190	113	144	181	321	113	144	181	306	108	144	184	326	134	162	198	326

-- Range is greater than the extents of the modeled distance (100,000 m)

Table F-3. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								Hammer energy (kJ)							
		1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
LF	120	--	--	--	--	65,658	70,606	86,185	98,645	--	--	--	--	84,878	90,384	96,972	--
	140	26,551	32,935	42,303	56,614	17,338	18,698	21,098	24,077	34,969	39,116	49,157	69,000	19,464	21,016	23,529	27,409
	160	4,230	4,637	5,425	7,423	3,947	4,388	4,875	6,154	4,139	4,661	5,304	7,479	3,905	4,361	4,857	6,256
	180	546	868	1,083	1,503	577	844	1,051	1,459	563	877	1,092	1,465	583	860	1,065	1,468
MF	120	--	--	--	--	48,282	50,592	57,998	70,381	--	--	--	--	54,495	57,518	70,398	91,431
	140	17,019	18,434	22,652	27,409	10,926	11,620	12,942	14,896	17,438	19,164	23,548	33,959	11,357	12,180	13,171	17,532
	160	2,330	2,481	2,854	3,304	2,263	2,435	2,758	3,172	2,295	2,512	2,816	3,321	2,283	2,448	2,766	3,149
	180	117	134	179	260	117	141	180	297	113	134	179	256	134	160	197	295
HF	120	--	--	--	--	44,336	46,256	52,664	62,047	--	--	--	--	48,935	51,580	60,341	79,418
	140	12,828	13,153	19,486	24,016	9,467	10,107	11,692	13,086	12,848	13,161	19,729	24,862	9,672	10,371	12,176	13,326
	160	1,900	2,046	2,391	2,814	1,840	1,977	2,339	2,723	1,863	2,108	2,405	2,773	1,893	2,016	2,365	2,750
	180	57	89	122	170	57	89	126	171	45	85	120	161	72	108	142	185
PW	120	--	--	--	--	57,411	60,991	72,143	91,948	--	--	--	--	68,613	75,223	92,102	98,635
	140	22,933	24,129	31,788	44,490	13,181	14,190	17,685	20,681	24,262	26,583	38,258	51,702	14,523	17,069	19,868	22,896
	160	3,113	3,444	4,159	4,845	3,003	3,244	3,802	4,528	3,161	3,404	4,068	4,824	3,025	3,242	3,786	4,500
	180	234	341	494	780	256	350	494	800	228	323	482	792	268	342	511	797

-- Range is greater than the extents of the modeled distance (100,000 m)

F.1.2. Fish and Sea Turtles

Table F-4. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	161				161				161				181			
	L_{pk}	213	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	886				860				911				895			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,360				1,311				1,421				1,359			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Sea turtles (mortal injury)	$L_{E,24hr}$	210	886				860				911				895			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Eggs and larvae	$L_{E,24hr}$	210	886				860				911				895			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	286				284				291				301			
	L_{pk}	213	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Fish with swim bladder	$L_{E,24hr}$	203	2,238				2,125				2,310				2,214			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	12,117				9,476				13,501				10,022			

Table F-5. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 11 m monopile in 12 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	16,514				11,729				18,543				12,988			
	L_{pk}	206	95	122	187	290	95	122	187	290	94	120	183	271	94	120	183	271
Large fish	$L_{E,12hr}$	187	11,000				8,914				11,968				9,291			
	L_{pk}	206	95	122	187	290	95	122	187	290	94	120	183	271	94	120	183	271
Sea turtles	L_p	180	553	877	1,100	1,519	585	849	1,065	1,471	566	885	1,101	1,481	592	867	1,074	1,485
Small fish	L_p	150	10,721	11,908	13,158	18,520	8,589	9,419	10,879	12,720	11,480	12,508	15,321	20,897	8,937	10,019	11,702	13,145
Large fish	L_p	150	10,721	11,908	13,158	18,520	8,589	9,419	10,879	12,720	11,480	12,508	15,321	20,897	8,937	10,019	11,702	13,145
Blackstock et al. (2017)																		
Sea turtles	L_p	175	1,279	1,568	1,883	2,299	1,253	1,526	1,820	2,228	1,327	1,637	1,915	2,332	1,280	1,560	1,856	2,272
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	1665				1584				1682				1575			
	L_{pk}	232	1	2	2	3	1	2	2	3	1	2	2	2	1	2	2	2
Sea turtles - TTS	$L_{E,TU,24hr}$	189	8307				6989				8524				7066			
	L_{pk}	226	2	4	5	7	2	4	5	7	2	4	5	7	2	4	5	7

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

F.2. 10 dB Attenuation

F.2.1. Marine Mammals

Table F-6. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	183	6,519				5,646				6,566				5,606			
	L_{pk}	219	3	5	7	9	3	5	7	9	3	5	7	9	3	5	7	9
Mid-frequency cetaceans	$L_{E,24hr}$	185	20				20				20				45			
	L_{pk}	230	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
High-frequency cetaceans	$L_{E,24hr}$	155	2,329				2,025				2,330				2,009			
	L_{pk}	202	92	119	174	243	92	119	174	243	91	116	178	240	91	116	178	240
Phocid pinnipeds	$L_{E,24hr}$	185	628				703				638				721			
	L_{pk}	218	4	7	9	12	4	7	9	12	4	5	8	11	4	5	8	11

Table F-7. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	**120**	--	--	--	--	50,168	53,201	60,862	73,305	--	--	--	--	57,637	61,619	74,078	92,372
	140	19,403	21,130	24,510	35,018	12,784	13,215	16,353	19,384	21,541	23,493	29,940	41,342	13,196	15,096	18,596	21,804
	150	7,459	8,382	10,135	12,481	6,107	7,111	8,223	9,801	7,503	8,633	10,794	12,746	6,230	7,194	8,480	10,499
	160	3,044	3,476	4,110	4,840	2,958	3,287	3,792	4,538	3,101	3,422	4,013	4,824	2,989	3,267	3,745	4,531
	175	697	922	1,240	1,716	689	955	1,223	1,665	714	935	1,315	1,703	718	938	1,265	1,655
	180	283	428	552	893	284	429	550	868	272	420	565	921	289	420	566	904
	190	40	82	108	156	40	89	113	156	40	85	108	152	64	102	128	172

-- Range is greater than the extents of the modeled distance (100,000 m)

Table F-8. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								Hammer energy (kJ)							
		1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
LF	120	--	--	--	--	50,073	53,080	60,741	73,126	--	--	--	--	57,505	61,466	73,839	92,238
	140	19,350	21,064	24,451	34,884	12,767	13,196	16,005	19,335	21,477	23,415	29,749	41,193	13,171	14,996	18,532	21,743
	160	3,031	3,445	4,085	4,814	2,948	3,257	3,757	4,522	3,091	3,404	3,989	4,802	2,980	3,243	3,720	4,511
	180	272	412	546	888	283	412	540	863	267	408	560	913	286	405	564	899
MF	120	--	--	--	--	36,646	38,485	43,880	50,889	--	--	--	--	40,476	42,643	48,789	58,113
	140	10,388	11,176	13,002	18,797	7,828	8,485	9,904	11,819	10,536	11,510	13,048	19,670	7,857	8,600	10,334	12,358
	160	1,664	1,800	2,146	2,543	1,580	1,740	2,076	2,506	1,669	1,836	2,214	2,580	1,552	1,773	2,093	2,533
	180	40	57	100	144	40	57	102	146	40	45	89	144	64	83	122	165
HF	120	--	--	--	--	33,140	34,843	39,790	46,172	--	--	--	--	36,497	38,190	43,713	51,579
	140	8,400	9,057	11,287	13,180	6,606	7,088	8,445	10,180	8,279	8,997	11,486	13,220	6,531	7,091	8,450	10,472
	160	1,122	1,335	1,716	2,088	1,122	1,295	1,643	2,021	1,159	1,341	1,793	2,177	1,165	1,338	1,673	2,044
	180	28	28	45	89	28	28	45	89	28	28	45	89	45	60	64	117
PW	120	--	--	--	--	44,138	46,606	52,970	62,419	--	--	--	--	49,521	52,758	61,177	78,389
	140	13,289	17,020	20,599	25,037	10,649	11,515	12,864	14,720	15,054	18,351	22,252	28,811	11,254	12,189	13,239	17,667
	160	2,419	2,660	2,980	3,608	2,374	2,585	2,883	3,362	2,421	2,655	3,033	3,556	2,375	2,607	2,901	3,361
	180	134	161	206	379	141	161	224	377	134	161	204	379	156	181	241	389

-- Range is greater than the extents of the modeled distance (100,000 m)

F.2.2. Fish and Sea Turtles

Table F-9. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	89				102				89				120			
	L_{pk}	213	11	17	22	30	11	17	22	30	11	15	20	28	11	15	20	28
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	451				457				428				448			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	721				710				738				730			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Sea turtles (mortal injury)	$L_{E,24hr}$	210	451				457				428				448			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Eggs and larvae	$L_{E,24hr}$	210	451				457				428				448			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	144				144				144				162			
	L_{pk}	213	11	17	22	30	11	17	22	30	11	15	20	28	11	15	20	28
Fish with swim bladder	$L_{E,24hr}$	203	1,360				1,311				1,421				1,359			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	8,455				7,156				8,699				7,241			

Table F-10. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 11 m monopile in 12 hours, using an IHC S-4000 hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	11,000				8,914				11,968				9,291			
	L_{pk}	206	46	66	96	133	46	66	96	133	40	62	98	132	40	62	98	132
Large fish	$L_{E,12hr}$	187	7,790				6,645				7,883				6,737			
	L_{pk}	206	46	66	96	133	46	66	96	133	40	62	98	132	40	62	98	132
Sea turtles	L_p	180	283	428	552	893	284	429	550	868	272	420	565	921	289	420	566	904
Small fish	L_p	150	7,459	8,382	10,135	12,481	6,107	7,111	8,223	9,801	7,503	8,633	10,794	12,746	6,230	7,194	8,480	10,499
Large fish	L_p	150	7,459	8,382	10,135	12,481	6,107	7,111	8,223	9,801	7,503	8,633	10,794	12,746	6,230	7,194	8,480	10,499
Blackstock et al. (2017)																		
Sea turtles	L_p	175	697	922	1,240	1,716	689	955	1,223	1,665	714	935	1,315	1,703	718	938	1,265	1,655
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	878				868				896				886			
	L_{pk}	232	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
Sea turtles - TTS	$L_{E,TU,24hr}$	189	5775				5080				5742				5052			
	L_{pk}	226	1	2	2	3	1	2	2	3	1	2	2	2	1	2	2	2

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

F.3. 12 dB Attenuation

F.3.1. Marine Mammals

Table F-11. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	5,437				4,675				5,303				4,644			
	L_{pk}	**219**	2	4	5	7	2	4	5	7	2	4	5	7	2	4	5	7
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	20				20				20				45			
	L_{pk}	**230**	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
High-frequency cetaceans	$L_{E,24hr}$	**155**	1,640				1,662				1,634				1,354			
	L_{pk}	**202**	70	90	132	184	70	90	132	184	69	88	135	182	69	88	135	182
Phocid pinnipeds	$L_{E,24hr}$	**185**	428				442				428				448			
	L_{pk}	**218**	3	5	7	9	3	5	7	9	3	4	6	8	3	4	6	8

Table F-12. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	**120**	--	--	--	--	44,439	47,094	53,337	62,558	--	--	--	--	50,249	53,618	61,852	77,717
	140	14,365	17,652	21,193	25,609	11,391	12,424	13,225	17,139	17,764	19,961	23,552	33,044	12,188	12,835	15,111	19,273
	150	5,785	7,023	8,380	10,587	5,020	5,824	7,093	8,591	5,734	7,046	8,625	11,351	5,017	5,790	7,176	8,950
	160	2,765	3,003	3,451	4,299	2,689	2,916	3,255	4,067	2,763	3,056	3,409	4,265	2,685	2,950	3,246	4,022
	175	500	690	904	1,334	500	684	932	1,287	500	703	931	1,354	520	707	924	1,312
	180	184	281	405	689	184	283	412	675	189	279	402	702	201	298	400	690
	190	28	45	80	122	28	45	82	122	28	45	80	122	60	64	102	142

-- Range is greater than the extents of the modeled distance (100,000 m)

Table F-13. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								Hammer energy (kJ)							
		1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
LF	120	--	--	--	--	44,348	46,999	53,222	62,430	--	--	--	--	50,136	53,504	61,706	77,431
	140	14,254	17,613	21,128	25,560	11,355	12,389	13,206	17,095	17,696	19,901	23,477	32,932	12,159	12,814	15,012	19,222
	160	2,758	2,991	3,423	4,282	2,680	2,905	3,230	4,041	2,751	3,045	3,391	4,240	2,675	2,937	3,229	4,001
	180	184	267	397	683	184	279	388	671	184	268	394	694	200	287	393	680
MF	120	--	--	--	--	30,280	33,329	38,244	44,535	--	--	--	--	35,315	37,074	42,446	49,741
	140	8,273	8,983	11,123	13,106	6,616	7,125	8,469	10,148	8,216	9,032	11,470	13,240	6,583	7,160	8,592	10,588
	160	1,271	1,454	1,807	2,204	1,230	1,378	1,747	2,151	1,242	1,468	1,839	2,245	1,240	1,405	1,782	2,163
	180	28	28	57	113	28	28	57	113	28	40	45	102	60	64	83	128
HF	120	--	--	--	--	26,461	27,565	34,499	40,095	--	--	--	--	30,424	33,206	37,894	44,161
	140	6,648	7,335	8,967	11,524	5,060	5,460	7,035	8,609	6,534	7,215	8,896	11,730	4,951	5,317	7,044	8,672
	160	824	981	1,332	1,765	859	963	1,290	1,708	829	995	1,337	1,822	848	1,009	1,333	1,753
	180	20	20	28	45	20	20	28	45	20	20	28	45	45	45	60	64
PW	120	--	--	--	--	38,672	40,932	46,618	54,200	--	--	--	--	43,334	45,758	52,823	63,158
	140	12,000	12,854	17,057	21,198	9,183	9,909	11,540	12,997	12,432	12,947	18,405	22,998	9,556	10,480	12,207	13,650
	160	2,090	2,299	2,663	3,061	2,020	2,220	2,588	2,970	2,104	2,331	2,660	3,109	2,034	2,270	2,612	2,982
	180	102	126	161	228	102	128	161	247	89	128	161	228	122	144	181	261

-- Range is greater than the extents of the modeled distance (100,000 m)

F.3.2. Fish and Sea Turtles

Table F-14. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	63				63				63				90			
	L_{pk}	213	8	13	17	23	8	13	17	23	8	11	15	21	8	11	15	21
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	286				284				291				301			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	522				514				537				539			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Sea turtles (mortal injury)	$L_{E,24hr}$	210	286				284				291				301			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Eggs and larvae	$L_{E,24hr}$	210	286				284				291				301			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	113				117				117				134			
	L_{pk}	213	8	13	17	23	8	13	17	23	8	11	15	21	8	11	15	21
Fish with swim bladder	$L_{E,24hr}$	203	1,068				1,043				1,084				1,050			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	7,080				6,152				7,112				6,222			

Table F-15. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 11 m monopile in 12 hours, using an IHC S-4000 hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	9,248				7,650				9,655				7,836			
	L_{pk}	206	35	50	73	101	35	50	73	101	30	47	74	100	30	47	74	100
Large fish	$L_{E,12hr}$	187	6,473				5,736				6,511				5,715			
	L_{pk}	206	35	50	73	101	35	50	73	101	30	47	74	100	30	47	74	100
Sea turtles	L_p	180	184	281	405	689	184	283	412	675	189	279	402	702	201	298	400	690
Small fish	L_p	150	5,785	7,023	8,380	10,587	5,020	5,824	7,093	8,591	5,734	7,046	8,625	11,351	5,017	5,790	7,176	8,950
Large fish	L_p	150	5,785	7,023	8,380	10,587	5,020	5,824	7,093	8,591	5,734	7,046	8,625	11,351	5,017	5,790	7,176	8,950
Blackstock et al. (2017)																		
Sea turtles	L_p	175	500	690	904	1,334	500	684	932	1,287	500	703	931	1,354	520	707	924	1,312
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	600				572				603				564			
	L_{pk}	232	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
Sea turtles - TTS	$L_{E,TU,24hr}$	189	4670				4250				4676				4162			
	L_{pk}	226	1	2	2	3	1	2	2	3	1	2	2	2	1	2	2	2

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

Appendix G. Threshold Ranges for One Difficult to Drive 11 m Monopile in 24 Hours with Attenuation

The following subsections present tables with the modeled ranges to injury and behavioral disruption threshold levels for marine mammals, fish, and sea turtles resulting from impact pile driving of one difficult to drive 11 m monopile assuming the use of noise attenuating systems, such as bubble curtains, resulting in a broadband reduction of 6, 10, and 12 dB. These results assume 8,000 strikes to drive a monopile (Table 5).

G.1. 6 dB Attenuation

G.1.1. Marine Mammals

Table G-1. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one difficult to drive 11 m monopile in 24 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	183	13,218				9,549				14,043				9,999			
	L_{pk}	219	8	13	17	23	8	13	17	23	8	11	15	21	8	11	15	21
Mid-frequency cetaceans	$L_{E,24hr}$	185	63				45				63				64			
	L_{pk}	230	1	2	2	3	1	2	2	3	1	1	2	2	1	1	2	2
High-frequency cetaceans	$L_{E,24hr}$	155	6,853				5,257				6,879				5,267			
	L_{pk}	202	196	241	373	543	196	241	373	543	195	239	388	539	195	239	388	539
Phocid pinnipeds	$L_{E,24hr}$	185	2,138				1,963				2,207				2,026			
	L_{pk}	218	10	15	20	27	10	15	20	27	9	13	18	25	9	13	18	25

Table G-2. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 6 dB of attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	120	--	--	--	--	65,809	70,784	86,447	98,691	--	--	--	--	85,150	90,541	97,029	--
	140	26,639	33,072	42,449	56,813	17,370	18,750	21,146	24,121	35,080	39,244	49,326	69,280	19,513	21,071	23,591	27,484
	150	10,721	11,908	13,158	18,520	8,589	9,419	10,879	12,720	11,480	12,508	15,321	20,897	8,937	10,019	11,702	13,145
	160	4,246	4,659	5,466	7,466	3,971	4,405	4,894	6,218	4,162	4,679	5,347	7,520	3,929	4,380	4,876	6,332
	175	1,279	1,568	1,883	2,299	1,253	1,526	1,820	2,228	1,327	1,637	1,915	2,332	1,280	1,560	1,856	2,272
	180	553	877	1,100	1,519	585	849	1,065	1,471	566	885	1,101	1,481	592	867	1,074	1,485
	190	113	144	181	321	113	144	181	306	108	144	184	326	134	162	198	326

-- Range is greater than the extents of the modeled distance (100,000 m)

Table G-3. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
LF	120	--	--	--	--	65,658	70,606	86,185	98,645	--	--	--	--	84,878	90,384	96,972	--
	140	26,551	32,935	42,303	56,614	17,338	18,698	21,098	24,077	34,969	39,116	49,157	69,000	19,464	21,016	23,529	27,409
	160	4,230	4,637	5,425	7,423	3,947	4,388	4,875	6,154	4,139	4,661	5,304	7,479	3,905	4,361	4,857	6,256
	180	546	868	1,083	1,503	577	844	1,051	1,459	563	877	1,092	1,465	583	860	1,065	1,468
MF	120	--	--	--	--	48,282	50,592	57,998	70,381	--	--	--	--	54,495	57,518	70,398	91,431
	140	17,019	18,434	22,652	27,409	10,926	11,620	12,942	14,896	17,438	19,164	23,548	33,959	11,357	12,180	13,171	17,532
	160	2,330	2,481	2,854	3,304	2,263	2,435	2,758	3,172	2,295	2,512	2,816	3,321	2,283	2,448	2,766	3,149
	180	117	134	179	260	117	141	180	297	113	134	179	256	134	160	197	295
HF	120	--	--	--	--	44,336	46,256	52,664	62,047	--	--	--	--	48,935	51,580	60,341	79,418
	140	12,828	13,153	19,486	24,016	9,467	10,107	11,692	13,086	12,848	13,161	19,729	24,862	9,672	10,371	12,176	13,326
	160	1,900	2,046	2,391	2,814	1,840	1,977	2,339	2,723	1,863	2,108	2,405	2,773	1,893	2,016	2,365	2,750
	180	57	89	122	170	57	89	126	171	45	85	120	161	72	108	142	185
PW	120	--	--	--	--	57,411	60,991	72,143	91,948	--	--	--	--	68,613	75,223	92,102	98,635
	140	22,933	24,129	31,788	44,490	13,181	14,190	17,685	20,681	24,262	26,583	38,258	51,702	14,523	17,069	19,868	22,896
	160	3,113	3,444	4,159	4,845	3,003	3,244	3,802	4,528	3,161	3,404	4,068	4,824	3,025	3,242	3,786	4,500
	180	234	341	494	780	256	350	494	800	228	323	482	792	268	342	511	797

-- Range is greater than the extents of the modeled distance (100,000 m)

G.1.2. Fish and Sea Turtles

Table G-4. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	272				279				272				287			
	L_{pk}	213	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	1,330				1,279				1,354				1,306			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,942				1,869				1,960				1,881			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Sea turtles (mortal injury)	$L_{E,24hr}$	210	1,330				1,279				1,354				1,306			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Eggs and larvae	$L_{E,24hr}$	210	1,330				1,279				1,354				1,306			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	509				502				519				524			
	L_{pk}	213	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Fish with swim bladder	$L_{E,24hr}$	203	3,157				2,913				3,189				2,975			
	L_{pk}	207	81	104	153	234	81	104	153	234	81	103	157	217	81	103	157	217
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	16,036				11,528				18,142				12,725			

Table G-5. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 11 m monopile in 12 hours, using an IHC S-4000 hammer with 6 dB attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	***1500***	***2500***	***4000***	***1000***	***1500***	***2500***	***4000***	***1000***	***1500***	***2500***	***4000***	***1000***	***1500***	***2500***	***4000***
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	21,414				14,328				24,995				16,036			
	L_{pk}	206	95	122	187	290	95	122	187	290	94	120	183	271	94	120	183	271
Large fish	$L_{E,12hr}$	187	14,533				10,698				16,276				11,652			
	L_{pk}	206	95	122	187	290	95	122	187	290	94	120	183	271	94	120	183	271
Sea turtles	L_p	180	553	877	1,100	1,519	585	849	1,065	1,471	566	885	1,101	1,481	592	867	1,074	1,485
Small fish	L_p	150	10,721	11,908	13,158	18,520	8,589	9,419	10,879	12,720	11,480	12,508	15,321	20,897	8,937	10,019	11,702	13,145
Large fish	L_p	150	10,721	11,908	13,158	18,520	8,589	9,419	10,879	12,720	11,480	12,508	15,321	20,897	8,937	10,019	11,702	13,145
Blackstock et al. (2017)																		
Sea turtles	L_p	175	1,279	1,568	1,883	2,299	1,253	1,526	1,820	2,228	1,327	1,637	1,915	2,332	1,280	1,560	1,856	2,272
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	2211				2122				2295				2211			
	L_{pk}	232	1	2	2	3	1	2	2	3	1	2	2	2	1	2	2	2
Sea turtles - TTS	$L_{E,TU,24hr}$	189	10684				8607				11515				8940			
	L_{pk}	226	2	4	5	7	2	4	5	7	2	4	5	7	2	4	5	7

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

G.2. 10 dB Attenuation

G.2.1. Marine Mammals

Table G-6. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one difficult to drive 11 m monopile in 24 hours, using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	8,692				7,017				8,681				7.080			
	L_{pk}	**219**	3	5	7	9	3	5	7	9	3	5	7	9	3	5	7	9
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	20				28				20				60			
	L_{pk}	**230**	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
High-frequency cetaceans	$L_{E,24hr}$	**155**	3,627				3,119				3,514				2,993			
	L_{pk}	**202**	92	119	174	243	92	119	174	243	91	116	178	240	91	116	178	240
Phocid pinnipeds	$L_{E,24hr}$	**185**	1,051				1,143				1,050				1,075			
	L_{pk}	**218**	4	7	9	12	4	7	9	12	4	5	8	11	4	5	8	11

Table G-7. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	**120**	--	--	--	--	50,168	53,201	60,862	73,305	--	--	--	--	57,637	61,619	74,078	92,372
	140	19,403	21,130	24,510	35,018	12,784	13,215	16,353	19,384	21,541	23,493	29,940	41,342	13,196	15,096	18,596	21,804
	150	7,459	8,382	10,135	12,481	6,107	7,111	8,223	9,801	7,503	8,633	10,794	12,746	6,230	7,194	8,480	10,499
	160	3,044	3,476	4,110	4,840	2,958	3,287	3,792	4,538	3,101	3,422	4,013	4,824	2,989	3,267	3,745	4,531
	175	697	922	1,240	1,716	689	955	1,223	1,665	714	935	1,315	1,703	718	938	1,265	1,655
	180	283	428	552	893	284	429	550	868	272	420	565	921	289	420	566	904
	190	40	82	108	156	40	89	113	156	40	85	108	152	64	102	128	172

-- Range is greater than the extents of the modeled distance (100,000 m)

Table G-8. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 10 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
LF	120	--	--	--	--	50,073	53,080	60,741	73,126	--	--	--	--	57,505	61,466	73,839	92,238
	140	19,350	21,064	24,451	34,884	12,767	13,196	16,005	19,335	21,477	23,415	29,749	41,193	13,171	14,996	18,532	21,743
	160	3,031	3,445	4,085	4,814	2,948	3,257	3,757	4,522	3,091	3,404	3,989	4,802	2,980	3,243	3,720	4,511
	180	272	412	546	888	283	412	540	863	267	408	560	913	286	405	564	899
MF	120	--	--	--	--	36,646	38,485	43,880	50,889	--	--	--	--	40,476	42,643	48,789	58,113
	140	10,388	11,176	13,002	18,797	7,828	8,485	9,904	11,819	10,536	11,510	13,048	19,670	7,857	8,600	10,334	12,358
	160	1,664	1,800	2,146	2,543	1,580	1,740	2,076	2,506	1,669	1,836	2,214	2,580	1,552	1,773	2,093	2,533
	180	40	57	100	144	40	57	102	146	40	45	89	144	64	83	122	165
HF	120	--	--	--	--	33,140	34,843	39,790	46,172	--	--	--	--	36,497	38,190	43,713	51,579
	140	8,400	9,057	11,287	13,180	6,606	7,088	8,445	10,180	8,279	8,997	11,486	13,220	6,531	7,091	8,450	10,472
	160	1,122	1,335	1,716	2,088	1,122	1,295	1,643	2,021	1,159	1,341	1,793	2,177	1,165	1,338	1,673	2,044
	180	28	28	45	89	28	28	45	89	28	28	45	89	45	60	64	117
PW	120	--	--	--	--	44,138	46,606	52,970	62,419	--	--	--	--	49,521	52,758	61,177	78,389
	140	13,289	17,020	20,599	25,037	10,649	11,515	12,864	14,720	15,054	18,351	22,252	28,811	11,254	12,189	13,239	17,667
	160	2,419	2,660	2,980	3,608	2,374	2,585	2,883	3,362	2,421	2,655	3,033	3,556	2,375	2,607	2,901	3,361
	180	134	161	206	379	141	161	224	377	134	161	204	379	156	181	241	389

-- Range is greater than the extents of the modeled distance (100,000 m)

G.2.2. Fish and Sea Turtles

Table G-9. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	144				144				1444				160			
	L_{pk}	213	11	17	22	30	11	17	22	30	11	15	20	28	11	15	20	28
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	705				690				725				717			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,182				1,138				1,207				1,121			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Sea turtles (mortal injury)	$L_{E,24hr}$	210	705				690				725				717			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Eggs and larvae	$L_{E,24hr}$	210	705				690				725				717			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	213				216				213				228			
	L_{pk}	213	11	17	22	30	11	17	22	30	11	15	20	28	11	15	20	28
Fish with swim bladder	$L_{E,24hr}$	203	1,942				1,869				1,960				1,881			
	L_{pk}	207	33	57	76	115	33	57	76	115	33	53	75	115	33	53	75	115
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	10,761				8,744				11,694				9,132			

Table G-10. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 11 m monopile in 12 hours, using an IHC S-4000 hammer with 10 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000	1000	1500	2500	4000
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	14,533				10,698				16,277				11,652			
	L_{pk}	206	46	66	96	133	46	66	96	133	40	62	98	132	40	62	98	132
Large fish	$L_{E,12hr}$	187	9,856				8,130				10,554				8,380			
	L_{pk}	206	46	66	96	133	46	66	96	133	40	62	98	132	40	62	98	132
Sea turtles	L_p	180	283	428	552	893	284	429	550	868	272	420	565	921	289	420	566	904
Small fish	L_p	150	7,459	8,382	10,135	12,481	6,107	7,111	8,223	9,801	7,503	8,633	10,794	12,746	6,230	7,194	8,480	10,499
Large fish	L_p	150	7,459	8,382	10,135	12,481	6,107	7,111	8,223	9,801	7,503	8,633	10,794	12,746	6,230	7,194	8,480	10,499
Blackstock et al. (2017)																		
Sea turtles	L_p	175	697	922	1,240	1,716	689	955	1,223	1,665	714	935	1,315	1,703	718	938	1,265	1,655
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	1354				1301				1431				1365			
	L_{pk}	232	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
Sea turtles - TTS	$L_{E,TU,24hr}$	189	7435				6339				7479				6425			
	L_{pk}	226	1	2	2	3	1	2	2	3	1	2	2	2	1	2	2	2

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g

G.3. 12 dB Attenuation

G.3.1. Marine Mammals

Table G-11. Ranges ($R_{95\%}$ in meters) to injury thresholds (NMFS 2016) for marine mammal functional hearing groups due to impact hammering of one difficult to drive 11 m monopile in 24 hours, using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Low-frequency cetaceans	$L_{E,24hr}$	**183**	7,035				6,002				7,040				6,004			
	L_{pk}	**219**	2	4	5	7	2	4	5	7	2	4	5	7	2	4	5	7
Mid-frequency cetaceans	$L_{E,24hr}$	**185**	20				20				20				45			
	L_{pk}	**230**	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
High-frequency cetaceans	$L_{E,24hr}$	**155**	2,460				2,210				2,447				2,141			
	L_{pk}	**202**	70	90	132	184	70	90	132	184	69	88	135	182	69	88	135	182
Phocid pinnipeds	$L_{E,24hr}$	**185**	751				761				784				779			
	L_{pk}	**218**	3	5	7	9	3	5	7	9	3	4	6	8	3	4	6	8

Table G-12. Ranges ($R_{95\%}$ in meters) to unweighted sound pressure levels (L_p) due to impact hammering of a monopile using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2).

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Unweighted	**120**	--	--	--	--	44,439	47,094	53,337	62,558	--	--	--	--	50,249	53,618	61,852	77,717
	140	14,365	17,652	21,193	25,609	11,391	12,424	13,225	17,139	17,764	19,961	23,552	33,044	12,188	12,835	15,111	19,273
	150	5,785	7,023	8,380	10,587	5,020	5,824	7,093	8,591	5,734	7,046	8,625	11,351	5,017	5,790	7,176	8,950
	160	2,765	3,003	3,451	4,299	2,689	2,916	3,255	4,067	2,763	3,056	3,409	4,265	2,685	2,950	3,246	4,022
	175	500	690	904	1,334	500	684	932	1,287	500	703	931	1,354	520	707	924	1,312
	180	184	281	405	689	184	283	412	675	189	279	402	702	201	298	400	690
	190	28	45	80	122	28	45	82	122	28	45	80	122	60	64	102	142

-- Range is greater than the extents of the modeled distance (100,000 m)

Table G-13. Ranges ($R_{95\%}$ in meters) to sound pressure levels (L_p) weighted (Southall et al. 2007) for marine mammal hearing group due to impact hammering of a monopile using an IHC S-4000 hammer with 12 dB attenuation at two selected modeling locations (P1 and P2). LF is low-frequency cetacean, MF is mid-frequency cetacean, HF is high-frequency cetacean, PW is Phocid pinniped in water.

Hearing group	Threshold (dB)	P1								P2							
		Winter				Summer				Winter				Summer			
		Hammer energy (kJ)								*Hammer energy (kJ)*							
		1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
LF	120	--	--	--	--	44,348	46,999	53,222	62,430	--	--	--	--	50,136	53,504	61,706	77,431
	140	14,254	17,613	21,128	25,560	11,355	12,389	13,206	17,095	17,696	19,901	23,477	32,932	12,159	12,814	15,012	19,222
	160	2,758	2,991	3,423	4,282	2,680	2,905	3,230	4,041	2,751	3,045	3,391	4,240	2,675	2,937	3,229	4,001
	180	184	267	397	683	184	279	388	671	184	268	394	694	200	287	393	680
MF	120	--	--	--	--	30,280	33,329	38,244	44,535	--	--	--	--	35,315	37,074	42,446	49,741
	140	8,273	8,983	11,123	13,106	6,616	7,125	8,469	10,148	8,216	9,032	11,470	13,240	6,583	7,160	8,592	10,588
	160	1,271	1,454	1,807	2,204	1,230	1,378	1,747	2,151	1,242	1,468	1,839	2,245	1,240	1,405	1,782	2,163
	180	28	28	57	113	28	28	57	113	28	40	45	102	60	64	83	128
HF	120	--	--	--	--	26,461	27,565	34,499	40,095	--	--	--	--	30,424	33,206	37,894	44,161
	140	6,648	7,335	8,967	11,524	5,060	5,460	7,035	8,609	6,534	7,215	8,896	11,730	4,951	5,317	7,044	8,672
	160	824	981	1,332	1,765	859	963	1,290	1,708	829	995	1,337	1,822	848	1,009	1,333	1,753
	180	20	20	28	45	20	20	28	45	20	20	28	45	45	45	60	64
PW	120	--	--	--	--	38,672	40,932	46,618	54,200	--	--	--	--	43,334	45,758	52,823	63,158
	140	12,000	12,854	17,057	21,198	9,183	9,909	11,540	12,997	12,432	12,947	18,405	22,998	9,556	10,480	12,207	13,650
	160	2,090	2,299	2,663	3,061	2,020	2,220	2,588	2,970	2,104	2,331	2,660	3,109	2,034	2,270	2,612	2,982
	180	102	126	161	228	102	128	161	247	89	128	161	228	122	144	181	261

-- Range is greater than the extents of the modeled distance (100,000 m)

G.3.2. Fish and Sea Turtles

Table G-14. Ranges ($R_{95\%}$ in meters) to thresholds for fish and sea turtle groups (Popper et al. 2014) due to impact hammering of one 11 m monopile in 24 hours, using an IHC S-4000 hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2).

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	108				113				108				128			
	L_{pk}	213	8	13	17	23	8	13	17	23	8	11	15	21	8	11	15	21
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	509				502				519				524			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	879				851				894				873			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Sea turtles (mortal injury)	$L_{E,24hr}$	210	509				502				519				524			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Eggs and larvae	$L_{E,24hr}$	210	509				502				519				524			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	161				161				161				179			
	L_{pk}	213	8	13	17	23	8	13	17	23	8	11	15	21	8	11	15	21
Fish with swim bladder	$L_{E,24hr}$	203	1,545				1,496				1,610				1,518			
	L_{pk}	207	25	43	58	87	25	43	58	87	25	40	57	87	25	40	57	87
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	9,048				7,517				9,352				7,676			

Table G-15. Ranges (R95% in meters) to thresholds for fish (FHWG 2008) and sea turtle groups (Blackstock et al. 2017) due to impact hammering of one 11 m monopile in 12 hours, using an IHC S-4000 hammer with 12 dB of attenuation at two selected modeling locations (P1 and P2). The duration of pile driving will be <12 hours per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	P1								P2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								*Hammer energy (kJ)*							
			1000	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*	*1000*	*1500*	*2500*	*4000*
FHWG (2008)																		
Small fish	$L_{E,12hr}$	183	11,766				9,337				13,018				9,813			
	L_{pk}	206	35	50	73	101	35	50	73	101	30	47	74	100	30	47	74	100
Large fish	$L_{E,12hr}$	187	8,271				7,017				8,504				7,105			
	L_{pk}	206	35	50	73	101	35	50	73	101	30	47	74	100	30	47	74	100
Sea turtles	L_p	180	184	281	405	689	184	283	412	675	189	279	402	702	201	298	400	690
Small fish	L_p	150	5,785	7,023	8,380	10,587	5,020	5,824	7,093	8,591	5,734	7,046	8,625	11,351	5,017	5,790	7,176	8,950
Large fish	L_p	150	5,785	7,023	8,380	10,587	5,020	5,824	7,093	8,591	5,734	7,046	8,625	11,351	5,017	5,790	7,176	8,950
Blackstock et al. (2017)																		
Sea turtles	L_p	175	500	690	904	1,334	500	684	932	1,287	500	703	931	1,354	520	707	924	1,312
Finneran et al. (2017)																		
Sea turtles - PTS	$L_{E,TU,24hr}$	204	972				972				981				960			
	L_{pk}	232	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
Sea turtles - TTS	$L_{E,TU,24hr}$	189	6126				5426				6225				5407			
	L_{pk}	226	1	2	2	3	1	2	2	3	1	2	2	2	1	2	2	2

Small fish are defined as having a total mass of < 2 g
Large fish are defined as having a total mass of ≥ 2 g