Revolution Wind Underwater Acoustic Analysis

Impact Pile Driving during Turbine Foundation Installation

Submitted to:
Revolution Wind, LLC

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This report supports both BOEM and NOAA Fisheries MMPA permit processes. Results presented here are preliminary and have not been subject to NOAA Fisheries Office of Protected Resources (OPR) review as part of the MMPA process. NOAA Fisheries OPR may request changes that lead to revised results. A final report will be provided to BOEM upon completion of the NOAA Fisheries review process and in advance of publication of the Draft Environmental Impact Statement (EIS).

Executive Summary

Revolution Wind, LLC (Revolution Wind), a 50/50 joint venture between Ørsted North America Inc. (Ørsted NA) and Eversource Investment LLC (Eversource), proposes to construct, own, and operate the Revolution Wind Farm (RWF) in the designated Bureau of Ocean Energy Management (BOEM) Renewable Energy Lease Area OCS-A 0486 (Lease Area, Figure 1). RWF includes up to 100 foundations consisting of wind turbine generators (WTG), and two offshore substations (OSS), and inter-array cables (IAC) connecting the WTG and OSS. The WTG will each be supported by a 12 m diameter monopile foundation, while the OSS will either be supported by a 15 m monopile foundation or a jacketed foundation with four, 4 m piles. Installation of inter-array and export cables will require the use of a dynamically positioned (DP) cable lay vessel.

Underwater noise associated with the construction of the RWF will predominantly result from impact pile driving of the monopile or jacket foundations. Other secondary sources of sound include DP vessel thrusters used during cable installation and vessel propulsion during transit.

WTG monopile foundations consisting of a single 12 m diameter pile were modeled at two representative locations in the lease area. OSS monopile and jacketed foundations were also modeled at two proposed locations. Forcing functions for impact pile driving were computed for each pile type using GRLWEAP 2010 (GRLWEAP, Pile Dynamics 2010). The resulting forcing functions were used as inputs to JASCO's impact pile driving source models to characterize the acoustic source. Acoustic sound fields were estimated using JASCO's Marine Operations Noise model (MONM) and Full Wave Range Dependent Acoustic Model (FWRAM). To account for the likely minimum sound reduction resulting from noise abatement systems (NAS) such as bubble curtains, the modeling study included a hypothetical broadband attenuation level of 10 dB for all impact pile driving acoustic modeling results. The 10 dB level was conservatively chosen as an achievable sound reduction level when one NAS is in use during pile driving, and is based on a recent analysis of NAS (Bellmann et al. 2020).

DP thruster noise from the vessel used to install cable along the potential export cable corridor and inter-array cable routes was qualitatively assessed.

Results of the acoustic modeling of piling activities are presented as single strike radial distances to a series of nominal sound pressure levels (SPL), sound exposure levels (SEL), and zero-to-peak pressure levels (PK) with 10 dB attenuation applied. Acoustic radial distance tables are provided in Appendix G for the highest hammer energy for each pile type for both summer and winter sound speed profiles and reported for different frequency weighting functions.

The JASCO Animal Simulation Model Including Noise (JASMINE) was used to estimate the radial distances from the piling source within which 95% of the simulated animals (animats) were exposed above relevant cumulative SEL injury thresholds. Exposure-based radial distances are most relevant for monitoring and mitigation planning and to estimate the number of animals exposed to regulatory-defined acoustic thresholds. Exposure-based radial distances ($ER_{95\%}$) are reported for each of the three pile types and for each species, based on both summer and winter sound speed profiles. NAS mitigation was considered in the exposure-based range estimates by attenuating the sound fields simulated animats were exposed to by 0, 6, 10, and 15 dB. The varying attenuation levels were included for comparison purposes.

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1. Introduction

Revolution Wind, LLC (Revolution Wind), a 50/50 joint venture between Ørsted North America Inc. (Ørsted NA) and Eversource Investment LLC (Eversource), proposes to construct, own, and operate the Revolution Wind Farm (RWF) in the designated Bureau of Ocean Energy Management (BOEM) Renewable Energy Lease Area OCS-A 0486 (Lease Area, Figure 1). RWF includes up to 100 foundations consisting of wind turbine generators (WTG), and two offshore substations (OSS), and inter-array cables (IAC) connecting the WTG and OSS. The WTG will each be supported by a 12 m diameter monopile foundation, while the OSS will either be supported by a 15 m monopile foundation or a jacketed foundation with four, 4 m piles. Installation of inter-array and export cables will require the use of a dynamically positioned (DP) cable lay vessel.

JASCO Applied Sciences (JASCO) modeled underwater noise likely to be generated during impact pile driving during wind turbine installation for inclusion in the COP. The objectives of this modeling study were to predict the radial distances to regulatory-defined acoustic thresholds that are associated with potential injury (Level A Take) or behavioral disruption (Level B Take), and to use the results of animal movement and exposure modeling to estimate exposure ranges ($ER_{95\%}$).

1.1. Modeling Scope and Assumptions

Underwater noise associated with the construction of the RWF will predominantly result from impact pile driving of the monopile or jacket foundations. Other secondary sources of sound include DP vessel thrusters used during cable installation and vessel propulsion during transit. Impact pile driving produces impulsive sounds while thrusters produce non-impulsive sound (NMFS 2018).

Results of the acoustic modeling of piling activities are presented as single strike radial distances to a series of nominal sound pressure levels (SPL), sound exposure levels (SEL), and zero-to-peak pressure levels (PK) with 10 dB attenuation applied. Acoustic radial distance tables are provided in Appendix G for the highest hammer energy for each pile type for both summer and winter sound speed profiles and reported for different frequency weighting functions.

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Appendix B summarizes project and study assumptions. Some of the project data were provided by Deepwater Wind South Fork, LLC (DWSF) for the South Fork acoustic modeling study (Denes et al. 2018) 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 are reported using metric.

1.1.1. Impact Pile Driving

WTG monopile foundations consisting of a single 12 m diameter pile were modeled at two representative locations in the lease area (L024_002 and L024_114 in Figure 1 and Table 1). WTG monopile foundations are assumed to be vertical and driven to a penetration depth of 40 m (130 ft). OSS monopile foundations consisting of a single, 15 m diameter pile, were modeled at two proposed locations in the lease area (OSS1 and OSS2 in Figure 1 and Table 1). OSS monopile foundations are driven to a penetration depth of 50 m (164 ft). OSS jacket foundations consisting of four, 4 m diameter piles were modeled at the same two proposed locations in the lease area (OSS1 and OSS2 in Figure 1 and Table 1). Jacket foundation piles are driven to a penetration depth of 70 m (223 ft). The estimated number of strikes required to drive all pile types to completion was provided by Revolution Wind.

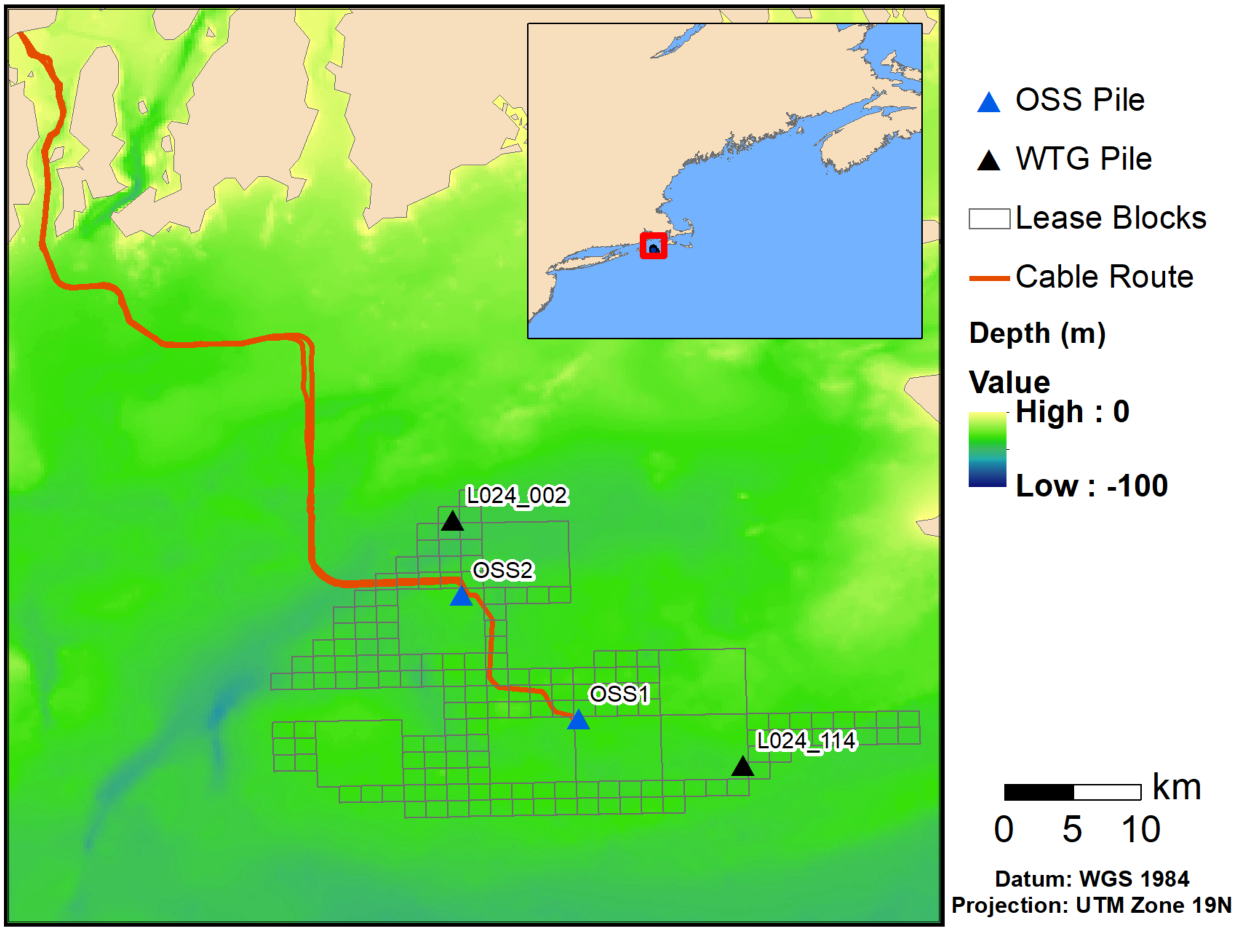

Figure 1. Map showing the representative locations used in acoustic modeling. Black and blue triangles show the modeling locations for impact pile driving for WTG and OSS piles proposed for the Revolution Wind Farm. A proposed cable route is shown in red.

Table 1. Locations for acoustic modeling of WTG and OSS foundations.

Model site	Location (UTM Zone 19N)		Water depth (m)	Sources	Source type
	Easting	Northing			
L024-002	320793.48	4569669.5	41.3	Monopile	Impulsive
L024-114	336403.93	4551413.2	36.8		
OSS 1	327480.00	4554999.69	34.2	Monopile and Jacketed Foundations	Impulsive
OSS 2	321190.00	4564259.69	34.4		

1.1.2. Secondary Sound Sources

While impulsive pile driving is considered the primary sound source during wind farm construction, there are several other potential anthropogenic sound sources associated with offshore project construction and operation. These sources were not quantitatively modeled because the potential acoustic impact of these sound sources is expected to be much less than primary sound sources associated with pile foundation installation. A qualitative consideration of secondary sound sources is discussed in this section.

Anthropogenic sounds from vessel traffic associated with the project are likely to be similar in frequency characteristics and sound levels to existing commercial traffic in the region. Vessel sound, including DP thruster and propulsion noise, would be associated with cable installation vessels and operations, piling installation vessels, and general transit to/from the installation locations during construction and operation. Potential sound impacts from cable installation are expected to derive primarily from the vessel(s) laying the cable.

During a similar type of underwater construction activity, Robinson et al. (2011) measured sound levels radiated from marine aggregate dredgers, mainly trailing suction hopper dredges, during normal operation. Robinson et al. (2011) concluded that because of the operation of the propulsion system, noise radiated at less than 500 Hertz (Hz) is similar to that of a merchant vessel “traveling at modest speed (i.e., between 8 and 16 knots)” (for self-propelled dredges). During dredging operations, additional sound energy generated by the impact and abrasion of the sediment passing through the draghead, suction pipe, and pump, is radiated in the 1–2 kHz frequency band. These acoustic components would not be present during cable lay operations, so these higher frequency sounds are not anticipated. Additionally, field studies conducted offshore New Jersey, Virginia, and Alaska show that noise generated by using vibracores and drilling boreholes diminishes below the NMFS Level B harassment thresholds (120 dB for continuous sound sources) relatively quickly and is unlikely to cause harassment to marine mammals (NMFS 2009, Reiser et al. 2010, 2011, TetraTech 2014). Based on these studies, sounds from cable laying activities are anticipated to be comparable to potential Project vessel noise impacts from offshore construction activities.

During construction, it is estimated that multiple vessels may operate concurrently at or in close proximity to the RWF. Some of these vessels may maintain their position using DP thrusters during pile driving or other construction activities. The dominant underwater sound source on DP vessels arises from cavitation on the propeller blades of the thrusters (Leggat et al. 1981). The noise power from the propellers is proportional to the number of blades, propeller diameter, and propeller tip speed. Sound levels generated by vessels under DP are dependent on the operational state and weather conditions. Zykov et al. (2013) and McPherson et al. (2019) report a maximum broadband SPL for numerous vessels with varying propulsion power under DP of up to 192 decibel (dB) re 1 micro Pascal (μPa) (for a pipe-laying vessel in deep water). All vessels emit sound from propulsion systems while in transit. Non-Project vessel traffic in the vicinity of the RWF includes recreational vessels, fishing vessels, cargo vessels, tankers, passenger vessels, and others. As such, marine mammals, fish, and sea turtles in the general region are regularly subjected to vessel activity and would potentially be habituated to the associated underwater noise as a result of this exposure (BOEM 2014). Because noise from vessel traffic associated with construction activities is likely to be similar to background vessel traffic noise, potential risk of impacts from vessel noise to marine mammals is expected to be low relative to the risk of impact from pile-driving sound.

2. Methods

2.1. Acoustic Environment

The proposed RWF is located in a continental shelf environment characterized by predominantly sandy seabed sediments. Water depths in the construction area vary between 30-45 m. From May through October, the average temperature of the upper 10–15 m of the water column is higher, resulting in an increased surface layer sound speed. This creates a downward refracting environment in which propagating sound interacts with the seafloor more than in a well-mixed environment. Increased wind mixing combined with a decrease in solar energy in November and December results in a sound speed profile that is more uniform with depth. Separate acoustic propagation model runs were conducted for both average summer and average winter sound speed profiles. See Appendix F.1 for more details on the environmental parameters used in acoustic propagation and exposure modeling.

2.2. Modeling Locations

Acoustic propagation modeling for WTG monopiles was conducted at two locations, L024-002 in the northwest section of the proposed WF area and L024-114 in the southeast (black triangles in Figure 1). Two types of offshore substation (OSS) foundations (jacketed and monopile) were modeled at three proposed installation locations within the RWF to represent possible sound fields for the construction area. The water depth at the site locations was extracted from the bathymetry file provided by DWSF for the South Fork acoustic modeling study (Denes et al. 2018) (Figure 1).

2.3. Impact Pile Driving

2.3.1. Schedule

Revolution Wind is proposing to install up to 100, 12 m WTG monopile foundations and two offshore substations, which may use either a 15 m monopile foundation or a jacketed foundation comprised of four, 4 m piles, in the RWF area. Hammer energy schedules for each of the three modeled pile types are provided in Tables 2–4. As a way of validating the acoustic modeling for this study, single-strike SEL received levels at 750 m from the driven pile were determined from the calculated 3-D sound fields (see Appendices E, F, and G) and compared to the institute für technische und angewandte (itap) forecast (Appendix H).

Table 2. Hammer energy schedule for 12 m WTG monopile installation. Total strike count is 6,500 and total penetration depth is 40 m.

Energy level (kilojoule [kJ])	Strike count	Pile penetration (m)	Modeled strike rate (min^{-1})
1,000	500	8	30
2,000	1,000	5	
3,000	2,000	12	
4,000	3,000	15	

Table 3. Hammer energy schedule for 15 m OSS monopile installation. Total strike count is 11,500 and total penetration depth is 50 m.

Energy level (kilojoule [kJ])	Strike count	Pile penetration (m)	Modeled strike rate (min^{-1})
1,000	500	12	30
2,000	1,000	8	
3,000	2,000	10	
4,000	8,000	20	

Table 4. Hammer energy schedule for 4 m OSS jacketed foundation installation. Total strike count is 11,000 and total penetration depth is 70 m.

Energy level (kilojoule [kJ])	Strike count	Pile penetration (m)	Modeled strike rate (min^{-1})
500	500	15	30
1,000	1,000	10	
1,500	1,500	13	
2,000	8,000	32	

2.3.2. Source Modeling

Piles deform when driven with impact hammers, creating a bulge that travels down the pile and radiates sound into the surrounding air, water, and seabed. This sound may be received as a direct transmission from the sound source to biological receivers (such as marine mammals, sea turtles, and fish) through the water, or as the result of reflected paths from the surface, or re-radiated into the water from the seabed (Figure 2). Sound transmission depends on many environmental parameters, such as the sound speeds in water and substrates, and sound production parameters of the pile and how it is driven, including the pile material, size (length, diameter, and thickness) and the type and energy of the hammer. JASCO's model assumes a pile being driven directly into the sediment. For some construction, jacket foundation pin piles may be driven with the piles already installed through the foundation pile sleeves. The additional structure is predicted to add up to 2.5 dB of acoustic energy to the sound field (Bellmann et al. 2020). Further, to ensure a conservative impact estimate from the 15 m OSS monopiles, a 2 dB safety factor was added to the analyzed sound fields.

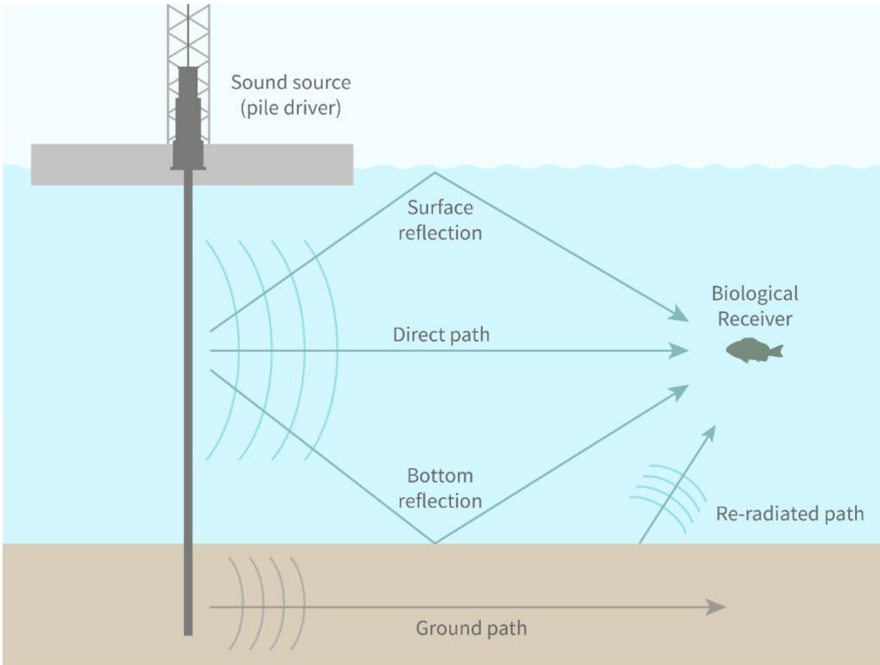

Figure 2. Sound propagation paths associated with impact pile driving (adapted from Buehler et al. 2015).

NAS mitigation was considered in this study by attenuating the sound fields by 0, 6, 10, and 15 dB to calculate for comparison, the exposure-based radial distances to regulatory-defined acoustic thresholds. These reductions may be achieved with various proven technologies. For additional details see Section 2.3.4 and Appendix E.

Forcing functions were computed for each pile type using GRLWEAP 2010 (GRLWEAP, Pile Dynamics 2010). The model assumed direct contact between the hammers, helmets, and piles (i.e., no cushion material) (Figures 3–5). The forcing functions serve as the inputs to JASCO's impact pile driving source models used to estimate equivalent acoustic source characteristics detailed in Appendix E. Decidecade spectral source levels for each pile type, hammer energy, and modeled location for both summer and winter sound speed profiles are shown in Figures 6–13.

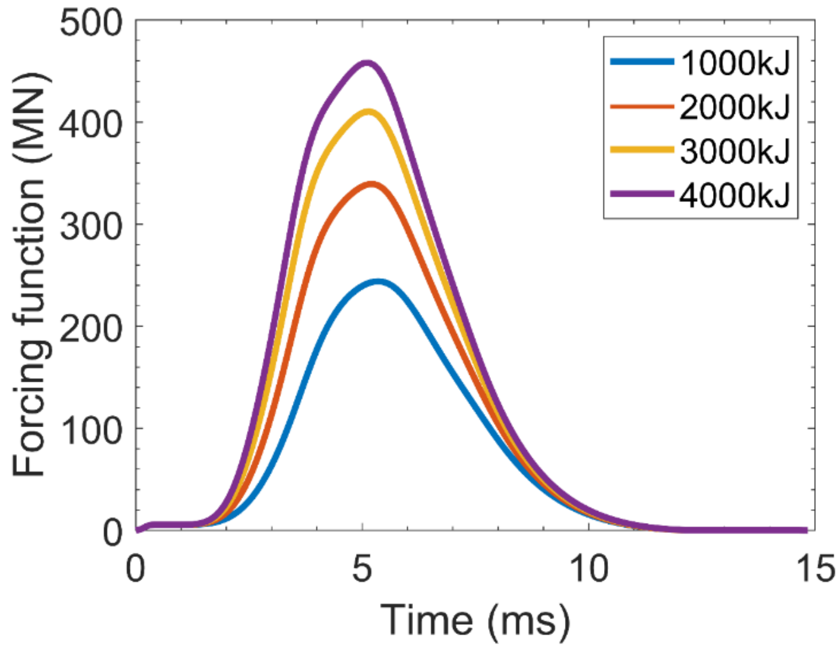

Figure 3. Modeled forcing functions versus time for the IHC S-4000 impact hammer for a 12 m monopile as a function of hammer energy.

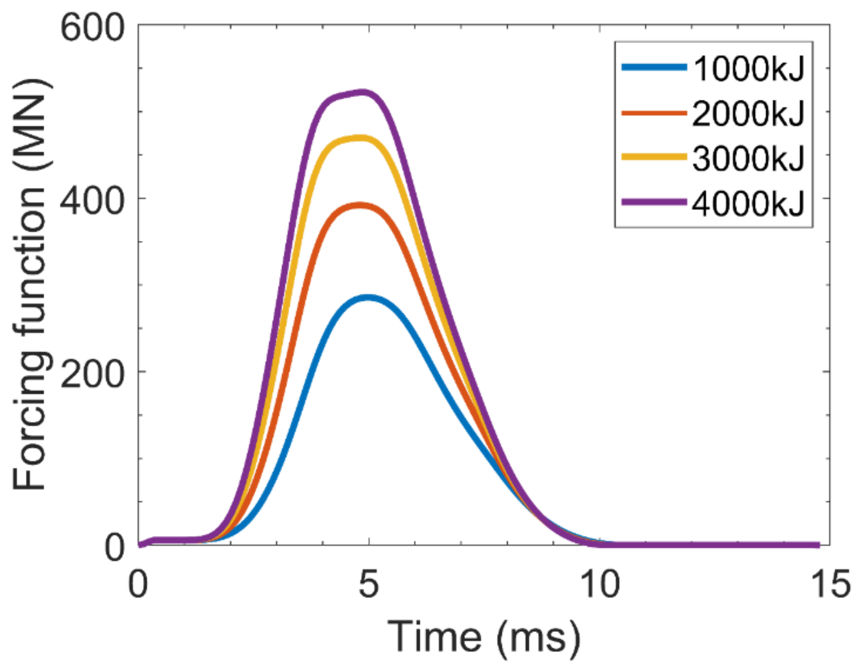

Figure 4. Modeled forcing functions versus time for the IHC S-4000 impact hammer for a 15 m monopile as a function of hammer energy.

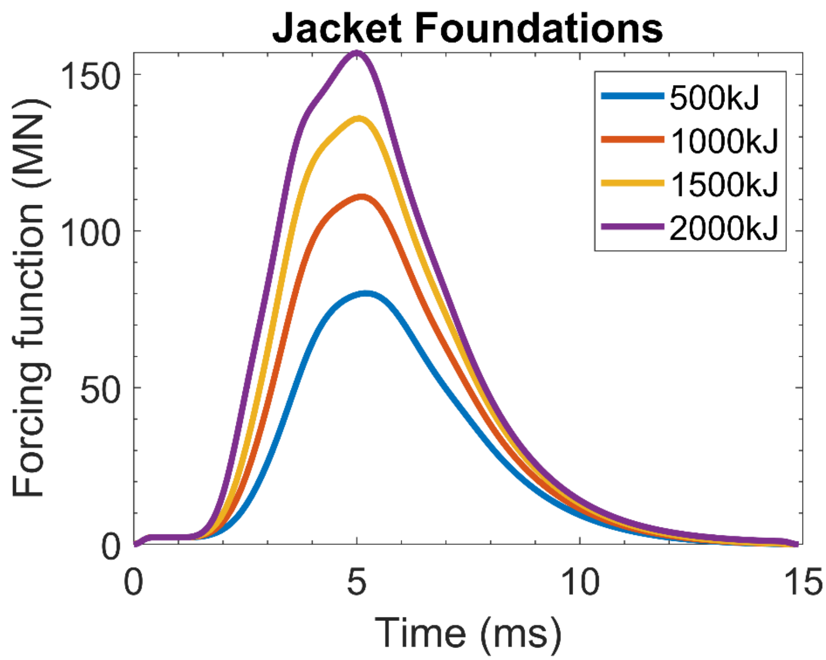

Figure 5. Modeled forcing functions versus time for the IHC S-2300 impact hammer for a 4 m pin pile as a function of hammer energy.

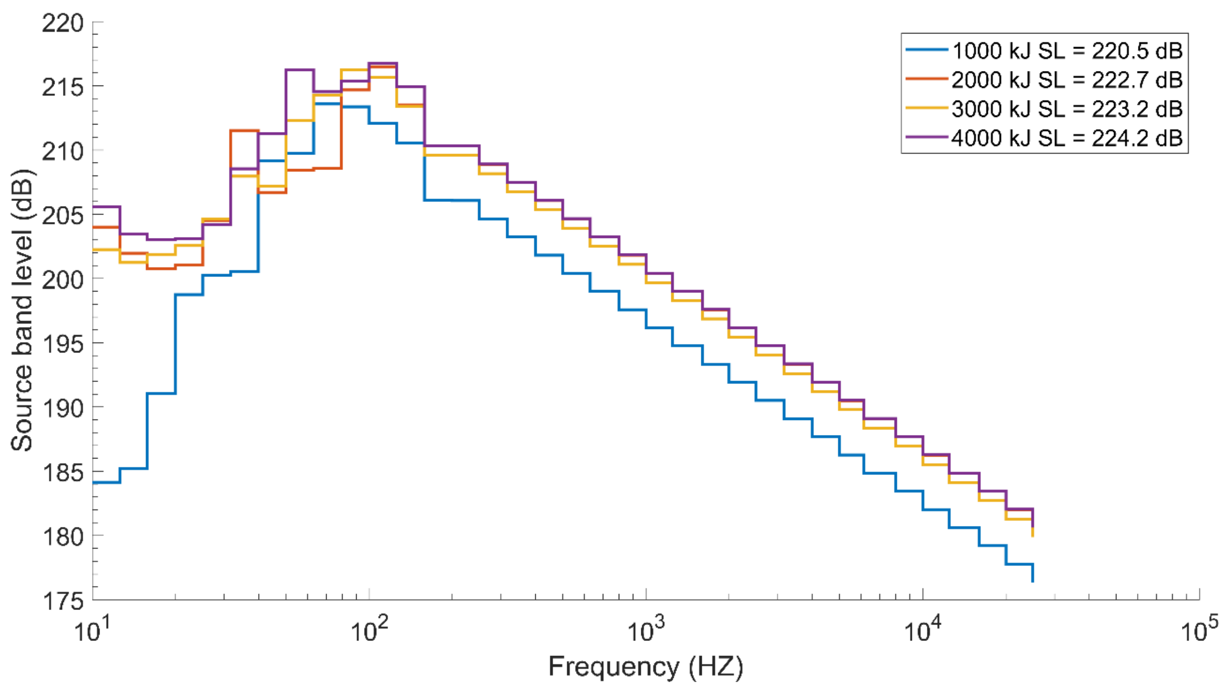

Figure 6. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-002 with a summer sound speed profile.

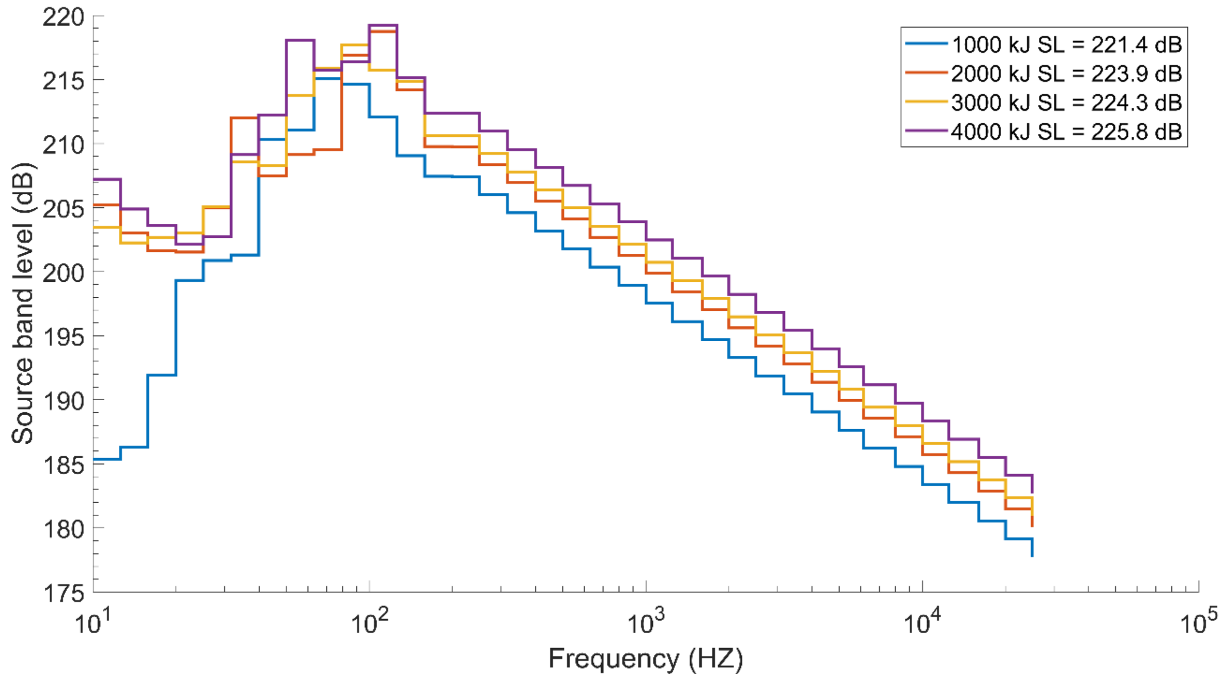

Figure 7. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-002 with a winter sound speed profile.

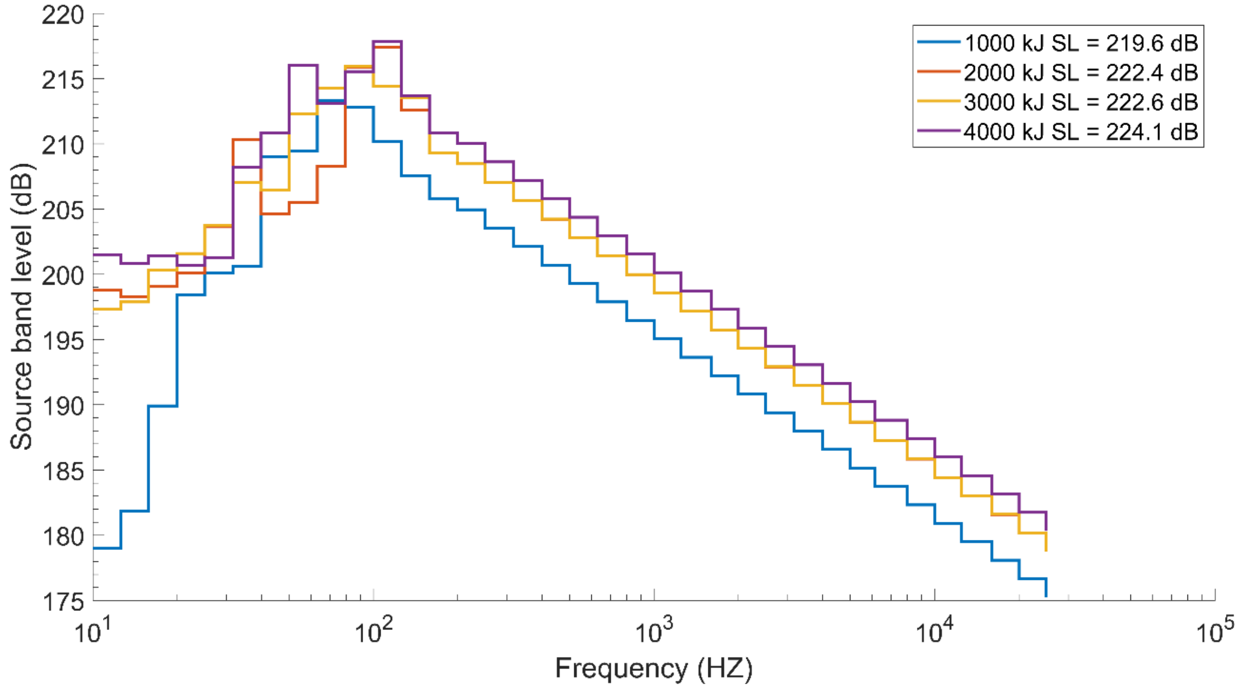

Figure 8. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-114 with a summer sound speed profile.

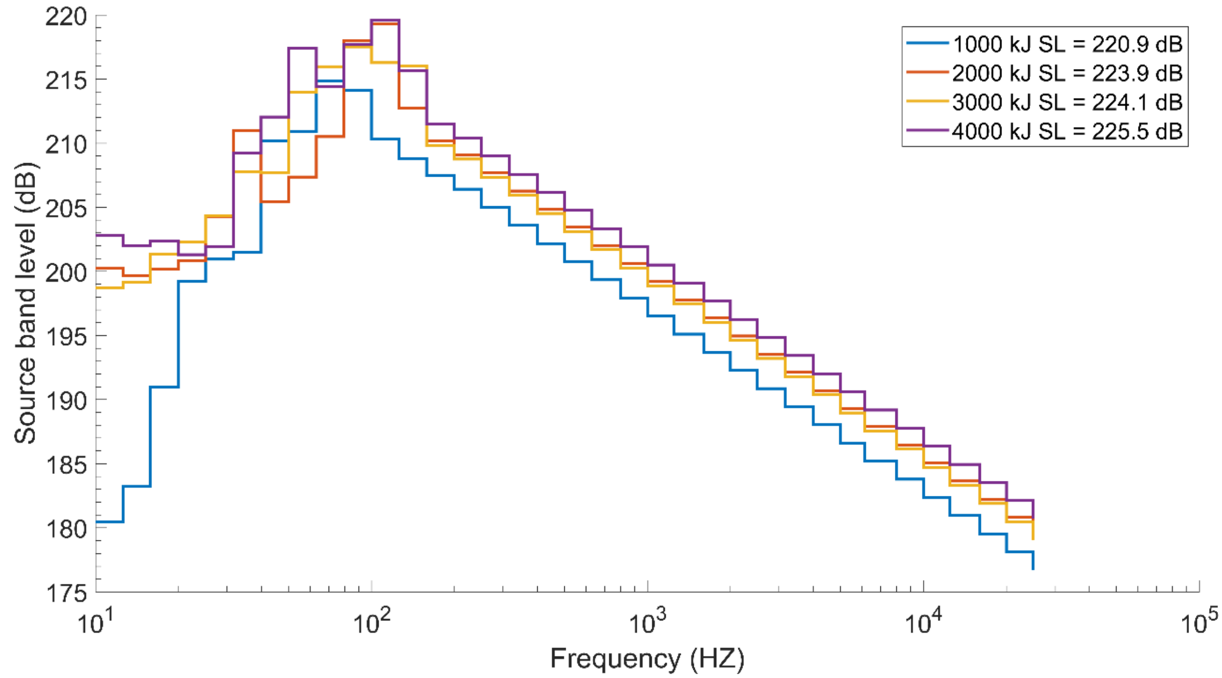

Figure 9. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-114 with a winter sound speed profile.

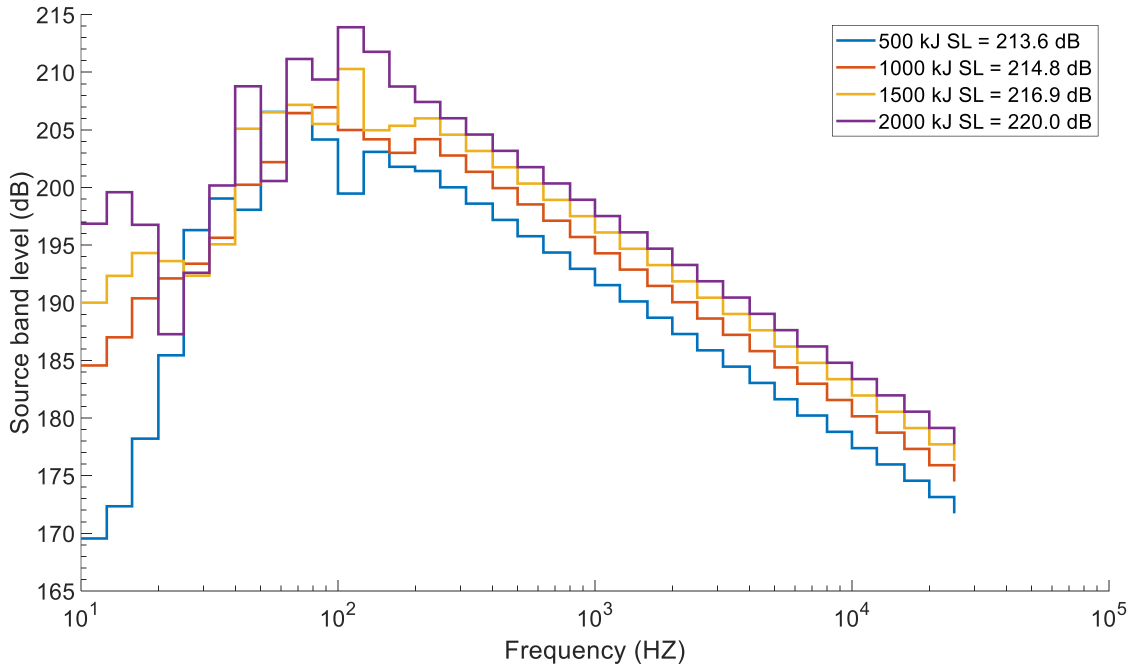

Figure 10. Decidecade band spectral source levels for a pin pile (4 m) installation using an IHC S-2300 hammer with a summer sound speed profile.

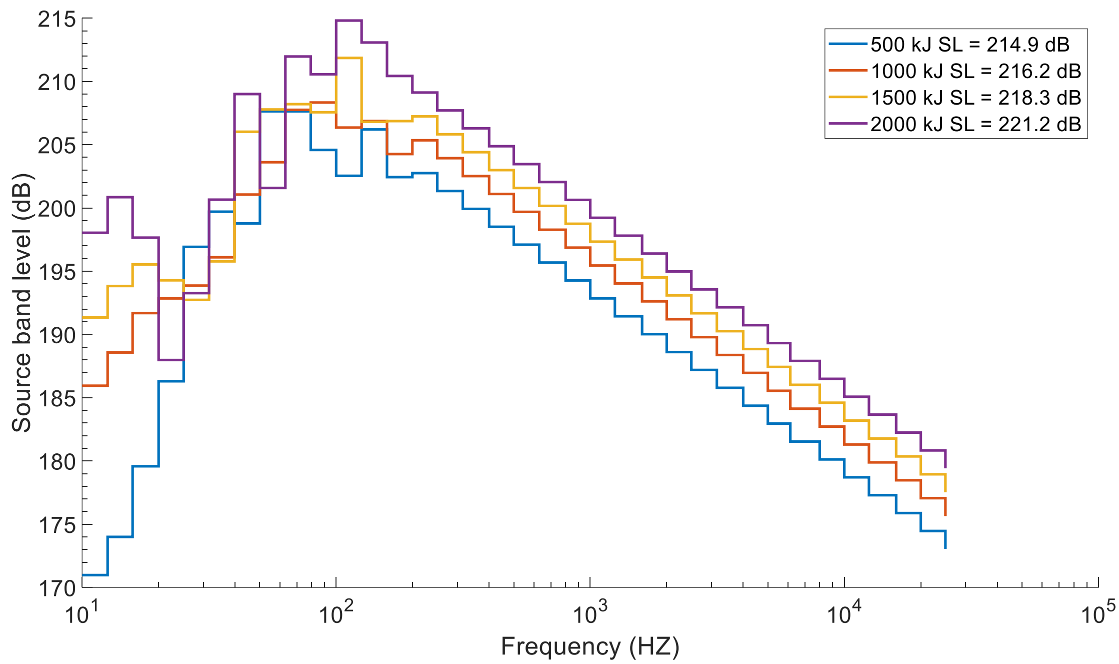

Figure 11. Decidecade band spectral source levels for a pin pile (4 m) installation using an IHC S-2300 hammer with a winter sound speed profile.

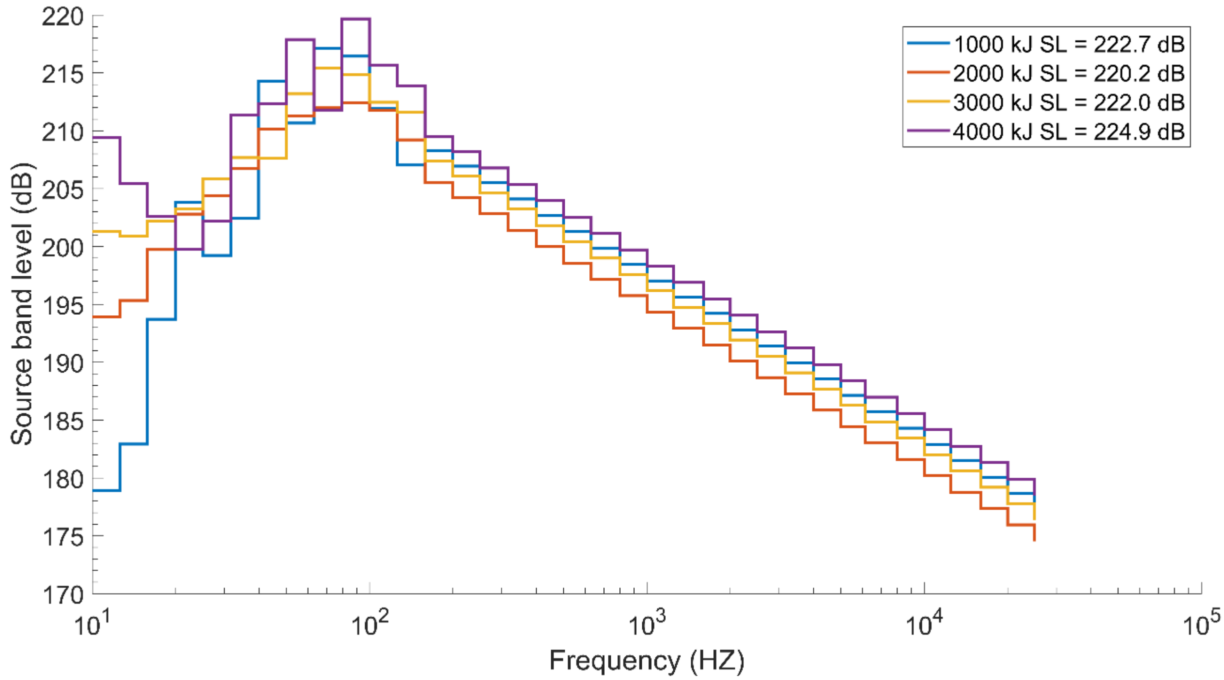

Figure 12. Decidecade band spectral source levels for monopile (15 m) installation using an IHC S-4000 hammer with a summer sound speed profile.

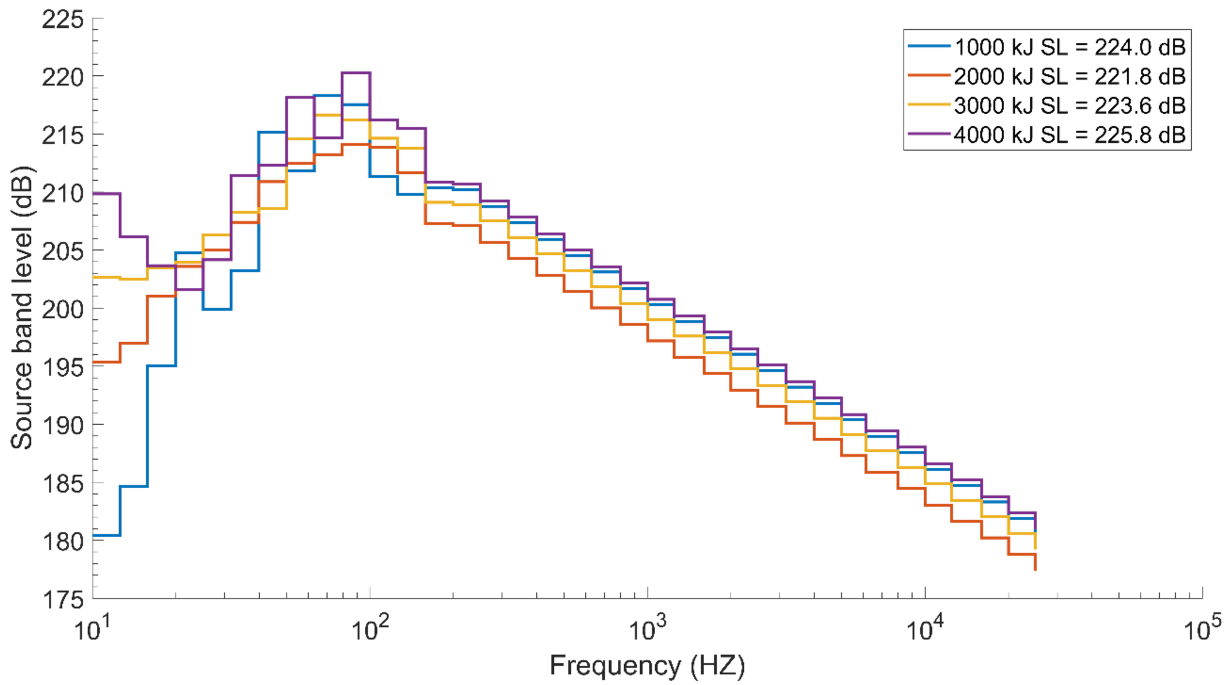

Figure 13. Decidecade band spectral source levels for monopile (15 m) installation using an IHC S-4000 hammer with a winter sound speed profile.

2.3.3. Sound Propagation

Acoustic propagation modeling was conducted using JASCO's Marine Operations Noise Model (MONM) and Full Wave Range Dependent Acoustic Model (FWRAM) that both combine the outputs of the source model with the spatial and temporal environmental context (e.g., location, oceanographic conditions, and seabed type) to estimate sound fields. The lower frequency bands were modeled using MONM and FWRAM, which are based on the parabolic equation (PE) method of acoustic propagation modeling. The higher frequencies were modeled using MONM-Bellhop, which is a Gaussian beam ray theoretic acoustic propagation model. See Appendix F for a more detailed description of propagation modeling. A comparison of unweighted, broadband received levels at 750m was made between the computed sound fields in this study and forecasted levels for monopiles from the itap empirical model (Bellman et al. 2020) (Appendix H).

2.3.4. Noise Mitigation

Noise abatement systems (NAS) are often used to decrease the sound levels in the water near a source by inserting a local impedance change that acts as a barrier to sound transmission. Attenuation by impedance change can be achieved through a variety of technologies, including bubble curtains, evacuated sleeve systems (e.g., IHC-Noise Mitigation System (NMS)), encapsulated bubble systems, or Helmholtz resonators, such as the AdBm NMS and HydroSound Dampers (HSDs). The effectiveness of each system is frequency dependent and may be influenced by local environmental conditions such as current and depth. For example, the size of the bubbles determines the effective frequency band of an air bubble curtain, with larger bubbles needed for lower frequencies.

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). A California Department of Transportation (CalTrans) study tested several small, single bubble curtain systems and found that the best attenuation systems resulted in 10–15 dB of attenuation. (Buehler et al. 2015) concluded that attenuation greater than 10 dB could not be reliably predicted from single, small bubble curtains because sound transmitted through the seabed and re-radiated into the water column is the dominant source of sound in the water for bubble curtains deployed immediately around (within 10 m) the pile (Buehler et al. 2015).

A recent analysis of NASs measured during impact driving of large piles (up to 8 m) by Bellmann et al. (2020) provides expected performance for common NAS configurations. Measurements with a single bubble curtain and an air supply of 0.3 m^3/min.m resulted in 7 to 11 dB of broadband attenuation for optimized systems in up to 40 m water depth. Increased air flow (0.5 m^3/min.m) may improve the attenuation level up to 11 to 13 dB (M. Bellmann, personal communication, 2019). Double bubble curtains add another local impedance change with optimized systems in up to 40 m water depth was measured to achieve 15 to 16 dB of broadband attenuation. The IHC-NMS can provide 15 to 17 dB of attenuation (for piles <8 m diameter). Other NASs such as the AdBm NMS achieved 6 to 8 dB (M. Bellmann, personal communication, 2019) and HSDs were measured at 10 to 12 dB attenuation (Bellmann 2020). Systems may be deployed in series to achieve higher levels of attenuation.

For this study, 10 dB broadband attenuation was conservatively chosen as an achievable reduction of sound levels produced during pile driving when one NAS is in use, noting that a 10 dB decrease means the sound energy level is reduced by 90%. For exposure-based radial distance estimation, several levels of attenuation were included for comparison purposes.

2.4. Acoustic Criteria–Marine Mammals

The Marine Mammal Protection Act (MMPA) prohibits the take of marine mammals. The term “take” is defined as: to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal. MMPA regulations define harassment in two categories relevant to the Project construction and operations. These are:

- **Level A**: Any act of pursuit, torment, or annoyance that has the potential to injure a marine mammal or marine mammal stock in the wild, and
- **Level B**: Any act of pursuit, torment, or annoyance that has the potential to disturb a marine mammal or marine mammal stock in the wild by disrupting behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but that does not have the potential to injure a marine mammal or marine mammal stock in the wild (16 U.S.C. 1362).

To assess the potential impacts of the underwater sound in the RWF, it is necessary to first establish the acoustic exposure criteria used by United States regulators to estimate marine mammal takes. In 2016, National Oceanographic and Atmospheric Administration (NOAA) Fisheries issued a Technical Guidance document that provides acoustic thresholds for onset of PTS in marine mammal hearing for most sound sources, which was updated in 2018 (NMFS 2016, 2018). The Technical Guidance document also recognizes two main types of sound sources: impulsive and non-impulsive. Non-impulsive sources are further broken down into continuous or intermittent categories.

NOAA Fisheries also provided guidance on the use of weighting functions when applying Level A harassment criteria. The Technical Guidance recommends the use of a dual criterion for assessing Level A exposures, including a peak (unweighted/flat) sound level metric (PK) and a cumulative SEL metric with frequency weighting. Both acoustic criteria and weighting function application are divided into functional hearing groups (low-, mid-, and high-frequency for cetaceans) that species are assigned to, based on their respective hearing ranges. The acoustic analysis applies the most recent sound exposure criteria utilized by the NOAA Fisheries to estimate acoustic harassment (NMFS 2018).

Sound levels thought to elicit disruptive behavioral response are described using the SPL metric (NMFS and NOAA 2005). NOAA Fisheries currently uses behavioral response thresholds of 160 dB re 1 µPa for impulsive sounds and 120 dB re 1 µPa for non-impulsive sounds for all marine mammal species (NMFS 2018), based on observations of mysticetes (Malme et al. 1983a, 1984, Richardson et al. 1986, 1990). Alternative thresholds used in acoustic assessments include a graded probability of response approach and take into account the frequency-dependence of animal hearing sensitivity (Wood et al. 2012b). The 160 dB threshold is used in this assessment as per NOAA guidance (2019).

The publication of ISO 18405 Underwater Acoustics–Terminology (ISO 2017) provided a dictionary of underwater bioacoustics (the previous standard was ANSI S1.1-2013 R2013). In the remainder of this report, we follow the definitions and conventions of ISO (2017) except where stated otherwise (Table 5).

Table 5. Summary of relevant acoustic terminology used in this report.

Metric	NOAA (NMFS 2018)	This report (ISO 2017)	
		Main text	Tables/ Equations
Sound pressure level	n/a	SPL	L_p
Peak pressure level	PK	PK	L_{pk}
Cumulative sound exposure level	SEL_{cum}	SEL	L_E

*The SEL_{cum} metric as used by the NMFS describes the sound energy received by a biological receptor over a period of 24 hr. Accordingly, following the ISO standard, this will be denoted as SEL in this report, except for in tables and equations where L_E will be used.

2.4.1. Marine Mammal Hearing Groups

Current data and predictions show that marine mammal species differ in their hearing capabilities, in absolute hearing sensitivity as well as frequency band of hearing (Richardson et al. 1995, Wartzok and Ketten 1999, Southall et al. 2007, Au and Hastings 2008). While hearing measurements are available for a small number of species based on captive animal studies, there are no direct measurements of many odontocetes or any mysticetes. As a result, hearing ranges for many odontocetes are grouped with similar species, and predictions for mysticetes are based on other methods including: anatomical studies and modeling (Houser et al. 2001, Parks et al. 2007, Tubelli et al. 2012, Cranford and Krysl 2015); vocalizations (see reviews in Richardson et al. 1995, Wartzok and Ketten 1999, Au and Hastings 2008); taxonomy; and behavioral responses to sound (Dahlheim and Ljungblad 1990, see review in Reichmuth et al. 2007). In 2007, Southall et al. proposed that marine mammals be divided into hearing groups. This division was updated in 2016 and 2018 by the NMFS using more recent best available science (Table 6).

Southall et al. (2019) published an updated set of Level A sound exposure criteria (i.e., for onset of TTS and PTS in marine mammals). While the authors propose a new nomenclature and classification for the marine mammal functional hearing groups, the proposed thresholds and weighting functions do not differ in effect from those proposed by NMFS (2018). The new hearing groups proposed by Southall et al. (2019) have not yet been adopted by NOAA. The NOAA (2018) hearing groups presented in Table 6 are used in this analysis.

Table 6. Marine mammal hearing groups (NMFS Sills et al. 2014, 2018).

Hearing group	Generalized hearing range*
Low-frequency (LF) cetaceans (mysticetes or baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (odontocetes: delphinids, beaked whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (other odontocetes)	275 Hz to 160 kHz
Phocid pinnipeds in water (PPW)	50 Hz to 39 kHz

* The generalized hearing range for all species within a group. Individual hearing will vary.

2.4.2. Marine Mammal Auditory Weighting Functions

The potential for anthropogenic sounds to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear well, unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency. Auditory (frequency) weighting functions reflect an animal's ability to hear a sound (Nedwell and Turnpenny 1998, Nedwell et al. 2007). Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS thresholds expressed in metrics that consider what is known about marine mammal hearing (e.g., SEL (L_E)) (Southall et al. 2007, Erbe et al. 2016, Finneran 2016). Marine mammal auditory weighting functions for all hearing groups (Table 6) published by Finneran (2016) are included in the NMFS (2018) Technical Guidance for use in conjunction with corresponding PTS (Level A) onset acoustic criteria (Table 7).

The application of marine mammal auditory weighting functions emphasizes the importance of taking measurements and characterizing sound sources in terms of their overlap with biologically important frequencies (e.g., frequencies used for environmental awareness, communication, and the detection of predators or prey), and not only the frequencies that are relevant to achieving the objectives of the sound producing activity (i.e., context of sound source; NMFS 2018).

2.4.3. Injury Exposure Criteria

Injury to the hearing apparatus of a marine mammal may result from a fatiguing stimulus measured in terms of SEL, which considers the sound level and duration of the exposure signal. Intense sounds may also damage hearing independent of duration, so an additional metric of peak pressure (PK) is also used to assess acoustic exposure injury risk. A PTS in hearing may be considered injurious, but there are no published data on the sound levels that cause PTS in marine mammals. There are data that indicate the received sound levels at which temporary threshold shift (TTS) occurs, and PTS onset may be extrapolated from TTS onset level and an assumed growth function (Southall et al. 2007). The NMFS (2018) criteria incorporate the best available science to estimate PTS onset in marine mammals from sound energy accumulated over 24 hr (SEL), or very loud, instantaneous peak sound pressure levels. These dual threshold criteria of SEL and PK may be used to calculate marine mammal exposures (Table 7). If a non-impulsive sound has the potential to exceed the peak sound pressure level thresholds associated with impulsive sounds, these thresholds are considered.

Table 7. Summary of relevant PTS onset acoustic thresholds (received level; dB) for marine mammal hearing groups (NMFS 2018).

Hearing group	Impulsive*		Non-impulsive
	Unweighted L_{pk} (dB re 1 µPa)	Weighted $L_{E,24hr}$ (dB re 1 µPa^{2}s)	Weighted $L_{E,24hr}$ (dB re 1 µPa^{2}s)
Low-frequency (LF) cetaceans	219	183	199
Mid-frequency (MF) cetaceans	230	185	198
High-frequency (HF) cetaceans	202	155	173
Phocid seals in water (PW)	218	185	201

* Dual metric acoustic thresholds for impulsive sounds: Use the results with the largest isopleth to calculate PTS onset. If a non-impulsive sound has the potential to exceed the impulsive peak sound pressure level thresholds, these thresholds are considered.

2.4.4. Behavioral Disruption Exposure Criteria

Numerous studies on marine mammal behavioral responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioral reactions. It is recognized that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison and Frankel 2012). Because of the complexity and variability of marine mammal behavioral responses to acoustic exposure, the NMFS has not yet released technical guidance on behavioral thresholds for calculating animal exposures (NMFS 2018). The NMFS currently uses a step function to assess behavioral impact (NOAA 2005). A 50% probability of inducing behavioral responses at an SPL of 160 dB re 1 µPa was derived from the HESS (1999) report, which was based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1983b, Malme et al. 1984). The HESS team recognized that behavioral responses to sound may occur at lower levels, but substantial responses were only likely to occur above an SPL of 140 dB re 1 µPa.

An extensive review of behavioral responses to sound was undertaken by Southall et al. (2007, their Appendix B). Southall et al. (2007) found varying responses for most marine mammals between an SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions. In 2012, Wood et al. proposed a graded probability of response for impulsive sounds using a frequency weighted SPL metric. Wood et al. (2012a) also designated behavioral response categories for sensitive species (including harbor porpoises and beaked whales) and for migrating mysticetes.

Table 8. Level B exposure criteria used in this analysis. Probability of behavioral response frequency-weighted sound pressure level (SPL, dB re 1 µPa). Probabilities are not additive. Adapted from Wood et al. (2012).

Marine mammal group	Probability of response to frequency weighted L_p (dB re 1 µPa)			
	120	140	160	180
Beaked whales and harbor porpoises	50%	90%		
Migrating mysticete whales	10%	50%	90%	
All other species		10%	50%	90%

2.5. Acoustic Criteria–Fish and Sea Turtles

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 impact pile driving sounds (Stadler and Woodbury 2009) (Table 9). 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 injury and behavioral response levels for fish were compiled and listed in Greater Atlantic Regional Fisheries Office's acoustics tool (GARFO 2016).

Table 9. Acoustic metrics and thresholds for fish and sea turtles (from Stadler and Woodbury 2009, GARFO 2016, Blackstock et al. (2018)).

Fish group	Injury		Behavior	
	$L_{E,12h}$ (dB)	L_{pk} (dB)	L_p (dB)	L_p (dB)
Fish	187 [a]	206 [a]	--	150 [b]
Sea turtles	--	--	180 [b]	175 [c]

Thresholds for fish are for individuals with a total mass of ≥2 g
L_{pk} = peak sound pressure (dB re 1 µPa); L_p = root mean square of the sound pressure (dB re 1 µPa); $L_{E,12hr}$ = cumulative sound exposure level over 12 hr (dB re 1 µPa^2·s)
-- indicates not applicable
a = Stadler and Woodbury (2009)
b = GARFO (2016)
c = Blackstock et al. (2018)

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 10 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 impact 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).

Table 10. Acoustic metrics and thresholds for fish and sea turtles (Adapted from Popper et al. 2014).

Group	Impulsive sounds–impact 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)	$L_{p,\,48hr}$ (dB)	$L_{p,\,12hr}$ (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 µPa²·s); L_{pk} = peak sound pressure (dB re 1 µPa); $L_{p,12hr}$ = root mean square sound pressure (dB re 1 µPa) for 12 hr continuous exposure; $L_{p,\,48hr}$ rms sound pressure (dB re 1 µPa) for 48 hr continuous exposure
TTS = temporary threshold shift., N = near (10s of meters), I = intermediate (100s of meters), and F = far (1000s of meters)
-- indicates not applicable
> indicates great than; >> indicates much greater than

Noise from impact pile driving may cause temporary, localized displacement of sea turtles. McCauley et al. (2000) suggest that sea turtles display behavior indicative of avoidance within 1 km (0.62 miles) of an operating seismic vessel. Above SPL 175 dB re 1µPa, McCauley et al. (2000) described sea turtle behavior as erratic, indicating that they were agitated. The researchers observed increasing swimming behavior with increasing received sound level, concluding that 175 dB re 1µPa rms was the point at which sea turtles exhibit avoidance behavior. Acoustic measurements during pile-driving events in the construction of the Block Island Wind Farm measured peak pressure levels of 188 dB at 500 m (1,640 ft) from the source (Miller and Potty 2017). It is likely that sea turtles avoid this area if they exhibit similar behavioral patterns to those observed by McCauley et al. (2000).

The NMFS criteria (SPL of 180 dB re 1 µPa), the Popper et al. (2014) criteria, and the Blackstock et al. (2018) Navy criteria were evaluated in this analysis.

2.6. Estimating Monitoring Zones for Mitigation

Monitoring zones for mitigating acoustic impacts to marine species are estimated using animal movement and exposure modeling. The range to the closest point of approach (CPA) for each of the species-specific animats (simulated animals) during a simulation is recorded and then the CPA range that accounts for 95% of the animats that receive sound levels exceeding an acoustic impact threshold is determined (Figure 14). The $ER_{95\%}$ (95% Exposure Range) is the horizontal distance that includes 95% of the CPAs of animats exceeding a given impact threshold. $ER_{95\%}$ is reported for marine mammals and sea turtles. If used as an exclusion zone, keeping animals farther away from the source than the $ER_{95\%}$ will reduce exposure estimates by 95%.

Unlike marine mammals and sea turtles for which animal movement modeling was performed, fish were considered static (not moving) receivers so exposure ranges were not calculated. Instead, the acoustic ranges to fish impact criteria thresholds were calculated by determining the isopleths at which received sound level thresholds could be exceeded (Appendix F.5).

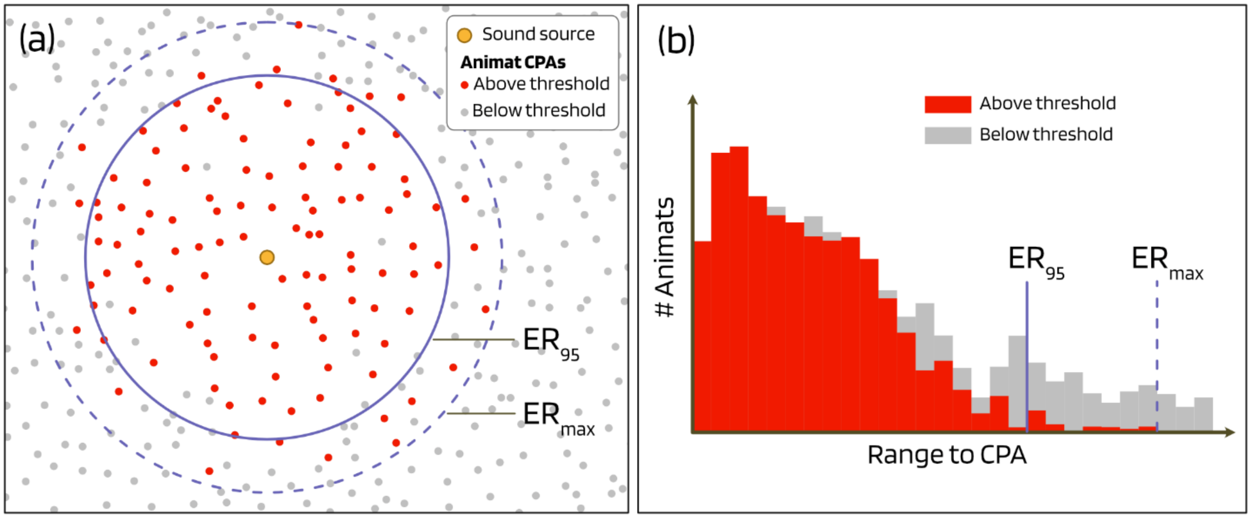

Figure 14. Example distribution of animat closest points of approach (CPAs). Panel (a) shows the horizontal distribution of animats near a sound source. Panel (b) shows a stacked bar plot of the distribution of ranges to animat CPAs. The 95% and maximum Exposure Ranges ($ER_{95\%}$ and ER_{max}) are indicated in both panels.

3. Results

Radial distances to exposure criteria thresholds are often reported for monitoring and mitigation purposes and can be calculated using either sound propagation models or animal movement models. For each sound level threshold, the maximum acoustic range (R_{max}) and the 95% range ($R_{95\%}$) were calculated. R_{max} is the distance to the farthest occurrence of the threshold level, at any depth. $R_{95\%}$ for a sound level is the radius of a circle, centered on the source, encompassing 95% of the sound at levels above threshold. Using $R_{95\%}$ reduces the sensitivity to extreme outlying values (the farthest 5% of ranges). A more detailed description of this calculation approach is found in Appendix F.5.

Appendix G provides summaries of single strike acoustic radial distances to a series of nominal sound level thresholds for SPL, SEL, and PK with 10 dB mitigation applied to pile driving sound levels.

For exposure-based radial distance estimates ($ER_{95\%}$), animal movement modeling is used to estimate ranges to regulatory-defined acoustic thresholds for marine mammals and turtles for all three pile types (Section 3.1). Results based on both summer and winter sound speed profiles are reported. NAS mitigation was considered by attenuating the sound fields in the simulations by 0, 6, 10, and 15 dB.

3.1. Exposure-based Radial Distance Estimates for Impact Pile Driving

The following subsections contain tables of exposure-based ranges ($ER_{95\%}$) calculated for Level A sound exposure thresholds (SEL) and peak thresholds (PK), as well as Level B exposure thresholds (SPL) described in Sections 2.4 and 2.5.

3.1.1. Marine Mammals

Exposure-based ranges ($ER_{95\%}$) to Level A SEL and PK acoustic thresholds are presented for WTG monopile and OSS monopile and jacketed foundations (Table 11 - 22). Ranges to Level B unweighted SPL acoustic thresholds (NOAA 2005) and m-weighted SPL acoustic thresholds (Wood et al. 2012) are also included. Results are presented for both seasons (summer and winter) and for broadband mitigation of 0, 6, 10, and 15 dB attenuation for comparison purposes.

Table 11. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the WTG monopile foundations (L024-002 and L024-114) during the summer.

Species	Injury								Behavior							
	L_E (NMFS 2018)				L_{pk} (NMFS 2018) ‡				L_p (NMFS 2005)				L_p (Wood et al. 2012)			
	Attenuation (dB)								Attenuation (dB)							
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Low-frequency cetaceans																
Fin whale* (Sei whale*†)	3.75	2.04	1.17	0.44	0.086	0.012	0.005	0.002	5.69	4.08	3.70	2.90	5.82	4.13	3.71	2.89
Minke whale	2.72	1.26	0.44	0.11	0.086	0.012	0.005	0.002	5.60	4.06	3.67	2.88	5.76	4.09	3.69	2.88
Humpback whale	5.49	3.26	2.13	1.09	0.086	0.012	0.005	0.002	5.73	4.13	3.72	2.99	5.87	4.16	3.74	2.98
NARW*	3.72	2.01	1.26	0.53	0.086	0.012	0.005	0.002	5.75	4.12	3.72	2.92	5.82	4.17	3.74	2.91
Mid-frequency cetaceans																
Atlantic spotted dolphin	0.01	<0.01	<0.01	0	0.004	0.002	0	0	5.69	4.08	3.70	2.92	4.00	3.09	2.17	1.11
Atlantic white sided dolphin	<0.01	0	0	0	0.004	0.002	0	0	5.62	4.06	3.73	2.89	3.93	3.07	2.13	1.15
Common dolphin	<0.01	0	0	0	0.004	0.002	0	0	6.01	4.35	3.89	2.91	4.12	3.03	2.25	1.05
Risso's dolphin	0.01	<0.01	0	0	0.004	0.002	0	0	5.74	4.12	3.71	2.95	3.97	3.11	2.16	1.17
Bottlenose dolphin	0.08	0.01	<0.01	0	0.004	0.002	0	0	5.95	4.25	3.76	3.05	4.07	3.27	2.20	1.08
High-frequency cetaceans																
Harbor porpoise	3.86	2.39	1.54	0.69	0.84	0.39	0.2	0.123	5.76	4.15	3.76	2.95	31.30	24.13	19.58	14.75
Pinnipeds in water																
Gray seal	1.66	0.44	0.08	0.01	0.095	0.015	0.006	0.003	5.92	4.25	3.87	3.12	4.80	3.90	3.24	2.07
Harbor seal	1.61	0.60	0.10	0.01	0.095	0.015	0.006	0.003	5.88	4.15	3.79	2.94	4.68	3.83	3.29	2.08

* Listed as Endangered under the ESA
† Fin whale used as a surrogate for sei whale behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 12. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the WTG monopile foundations (L024-002 and L024-114) during the winter.

Species	Injury								Behavior							
	L_E (NMFS 2018)				L_{pk} (NMFS 2018) ‡				L_p (NMFS 2005)				L_p (Wood et al. 2012)			
	Attenuation (dB)								Attenuation (dB)							
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Low-frequency cetaceans																
Fin whale* (Sei whale*†)	10.03	4.30	2.35	0.90	0.091	0.012	0.005	0.002	9.73	5.76	4.08	3.39	9.92	5.88	4.11	3.40
Minke whale	7.27	2.81	1.38	0.32	0.091	0.012	0.005	0.002	9.43	5.67	4.03	3.40	9.66	5.74	4.06	3.41
Humpback whale	17.02	7.23	4.18	1.87	0.091	0.012	0.005	0.002	9.59	5.80	4.10	3.46	9.85	5.90	4.14	3.46
NARW*	9.72	4.36	2.42	0.90	0.091	0.012	0.005	0.002	9.68	5.80	4.11	3.41	9.94	5.86	4.14	3.42
Mid-frequency cetaceans																
Atlantic spotted dolphin	0.01	<0.01	<0.01	0	0.004	0.002	0	0	9.56	5.76	4.10	3.42	5.84	3.62	3.05	1.75
Atlantic white sided dolphin	<0.01	0	0	0	0.004	0.002	0	0	9.59	5.78	4.05	3.40	5.82	3.63	3.06	1.78
Common dolphin	0.06	0	0	0	0.004	0.002	0	0	10.78	6.22	4.35	3.43	6.25	3.62	3.02	1.86
Risso's dolphin	0.02	<0.01	<0.01	0	0.004	0.002	0	0	9.77	5.90	4.12	3.44	6.01	3.69	3.14	1.73
Bottlenose dolphin	0.23	0.01	0.01	0	0.004	0.002	0	0	10.26	6.28	4.31	3.63	6.52	3.75	3.28	1.94
High-frequency cetaceans																
Harbor porpoise	7.83	4.03	2.53	1.22	0.86	0.39	0.21	0.113	9.90	5.93	4.16	3.50	47.23	45.06	42.78	42.13
Pinnipeds in water																
Gray seal	3.23	0.95	0.26	0.02	0.102	0.014	0.006	0.003	10.20	6.10	4.29	3.60	8.47	4.61	3.77	3.03
Harbor seal	3.31	1.08	0.34	0.05	0.102	0.014	0.006	0.003	9.96	5.98	4.24	3.48	8.40	4.50	3.71	3.07

* Listed as Endangered under the ESA
† Fin whale used as a surrogate for sei whale behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 13. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS monopile foundation (OSS1 and OSS2) during the summer.

Species	Injury								Behavior							
	L_E (NMFS 2018)				L_{pk} (NMFS 2018) ‡				L_p (NMFS 2005)				L_p (Wood et al. 2012)			
	Attenuation (dB)								Attenuation (dB)							
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Low-frequency cetaceans																
Fin whale* (Sei whale*†)	4.08	2.23	1.27	0.61	0.076	0.013	0.006	0.003	6.62	4.46	4.03	3.24	6.79	4.52	4.06	3.25
Minke whale	2.95	1.34	0.72	0.15	0.076	0.013	0.006	0.003	6.59	4.45	3.92	3.27	6.76	4.47	3.93	3.27
Humpback whale	6.30	3.99	2.49	1.18	0.076	0.013	0.006	0.003	6.54	4.56	3.83	3.41	6.78	4.58	3.90	3.40
NARW*	3.82	2.18	1.38	0.55	0.076	0.013	0.006	0.003	6.72	4.56	3.90	3.29	6.85	4.58	3.95	3.29
Mid-frequency cetaceans																
Atlantic spotted dolphin	0.02	0	0	0	0.005	0.002	0	0	6.61	4.53	3.97	3.33	4.01	3.28	2.28	1.27
Atlantic white sided dolphin	0	0	0	0	0.005	0.002	0	0	6.26	4.41	3.87	3.26	3.95	3.15	2.24	1.23
Common dolphin	0	0	0	0	0.005	0.002	0	0	6.50	4.65	4.14	3.51	4.14	3.25	2.29	0
Risso's dolphin	0.02	0	0	0	0.005	0.002	0	0	6.53	4.56	4.03	3.28	4.10	3.25	2.23	1.29
Bottlenose dolphin	0.05	<0.01	<0.01	0	0.005	0.002	0	0	6.73	4.58	3.98	3.42	4.18	3.34	2.43	1.18
High-frequency cetaceans																
Harbor porpoise	4.00	2.33	1.47	0.72	0.54	0.32	0.26	0.09	6.71	4.57	3.98	3.38	27.63	20.52	17.61	14.81
Pinnipeds in water																
Gray seal	2.00	0.59	0.26	0.01	0.082	0.16	0.007	0.004	6.85	4.58	4.12	3.45	5.22	4.04	3.53	2.31
Harbor seal	1.65	0.56	0.23	0.03	0.082	0.16	0.007	0.004	6.63	4.64	3.84	3.38	5.31	3.86	3.44	2.29

* Listed as Endangered under the ESA
† Fin whale used as a surrogate for sei whale behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 14. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS monopile foundation (OSS1 and OSS2) during the winter.

Species	Injury								Behavior							
	L_E (NMFS 2018)				L_{pk} (NMFS 2018)				L_p (NMFS 2005)				L_p (Wood et al. 2012)			
	Attenuation (dB)								Attenuation (dB)							
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Low-frequency cetaceans																
Fin whale* (Sei whale*†)	10.05	4.45	2.52	0.92	0.078	0.013	0.006	0.003	10.37	6.50	4.44	3.63	10.59	6.57	4.45	3.65
Minke whale	7.14	2.97	1.44	0.31	0.078	0.013	0.006	0.003	10.35	6.54	4.45	3.53	10.51	6.58	4.48	3.57
Humpback whale	14.95	7.83	5.01	2.13	0.078	0.013	0.006	0.003	10.55	6.51	4.49	3.54	10.72	6.52	4.51	3.55
NARW*	10.30	4.34	2.36	1.09	0.078	0.013	0.006	0.003	10.50	6.57	4.51	3.58	10.69	6.69	4.54	3.60
Mid-frequency cetaceans																
Atlantic spotted dolphin	0.02	0	0	0	0.005	0.002	0	0	10.29	6.56	4.54	3.55	6.00	3.58	3.17	1.83
Atlantic white sided dolphin	0	0	0	0	0.005	0.002	0	0	10.57	6.26	4.41	3.52	5.85	3.57	3.01	1.77
Common dolphin	0	0	0	0	0.005	0.002	0	0	10.07	6.38	4.46	3.53	6.26	3.54	3.10	1.91
Risso's dolphin	0.02	0	0	0	0.005	0.002	0	0	10.81	6.41	4.56	3.62	5.95	3.70	3.17	1.77
Bottlenose dolphin	0.08	<0.01	<0.01	0	0.005	0.002	0	0	10.66	6.73	4.64	3.64	6.26	3.65	3.22	1.97
High-frequency cetaceans																
Harbor porpoise	7.61	3.69	2.26	1.05	0.62	0.32	0.26	0.095	10.57	6.60	4.54	3.56	47.54	43.80	42.07	41.50
Pinnipeds in water																
Gray seal	2.91	0.93	0.40	0.01	0.087	0.016	0.007	0.004	10.83	6.61	4.57	3.78	8.86	4.84	3.84	3.18
Harbor seal	3.02	1.12	0.33	0.06	0.087	0.016	0.007	0.004	10.60	6.69	4.64	3.81	9.16	4.70	3.83	3.11

* Listed as Endangered under the ESA
† Fin whale used as a surrogate for sei whale behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 15. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS jacketed foundations (OSS1 and OSS2) during the summer.

Species	Injury								Behavior							
	L_E (NMFS 2018)				L_{pk} (NMFS 2018) ‡				L_p (NMFS 2005)				L_p (Wood et al. 2012)			
	Attenuation (dB)								Attenuation (dB)							
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Low-frequency cetaceans																
Fin whale* (Sei whale*†)	5.06	2.89	1.66	0.83	0.016	0.003	0	0	5.68	3.94	3.54	2.66	5.81	4.00	3.56	2.68
Minke whale	3.54	1.85	1.03	0.32	0.016	0.003	0	0	5.59	3.96	3.55	2.64	5.75	4.05	3.57	2.64
Humpback whale	7.18	4.59	3.02	1.55	0.016	0.003	0	0	5.79	4.01	3.64	2.73	5.87	4.06	3.67	2.74
NARW*	4.89	2.74	1.68	0.76	0.016	0.003	0	0	5.81	3.94	3.56	2.64	5.94	4.00	3.58	2.63
Mid-frequency cetaceans																
Atlantic spotted dolphin	0.02	0.02	0	0	0	0	0	0	5.68	3.92	3.61	2.66	3.96	3.31	2.35	1.32
Atlantic white sided dolphin	0.02	0.02	0	0	0	0	0	0	5.66	3.96	3.59	2.70	4.01	3.30	2.30	1.31
Common dolphin	0	0	0	0	0	0	0	0	5.12	4.13	3.52	2.71	4.13	3.29	2.35	0
Risso's dolphin	0.03	0.02	<0.01	0	0	0	0	0	5.64	4.02	3.56	2.61	4.07	3.35	2.35	1.34
Bottlenose dolphin	0.66	0.04	0.04	0.01	0	0	0	0	5.79	4.22	3.75	2.73	4.19	3.53	2.55	1.40
High-frequency cetaceans																
Harbor porpoise	5.38	3.38	2.39	1.42	0.24	0.077	0.047	0.023	5.88	4.06	3.68	2.67	31.01	22.50	18.95	16.06
Pinnipeds in water																
Gray seal	2.88	1.24	0.61	0.10	0.02	0.004	0	0	5.86	4.13	3.73	2.75	5.05	3.90	3.23	2.19
Harbor seal	3.20	1.37	0.82	0.20	0.02	0.004	0	0	5.68	3.95	3.64	2.67	4.97	3.85	3.34	2.15

* Listed as Endangered under the ESA
† Fin whale used as a surrogate for sei whale behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 16. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS jacketed foundations (OSS1 and OSS2) during the winter.

Species	Injury								Behavior							
	L_E (NMFS 2018)				L_{pk} (NMFS 2018) ‡				L_p (NMFS 2005)				L_p (Wood et al. 2012)			
	Attenuation (dB)								Attenuation (dB)							
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Low-frequency cetaceans																
Fin whale* (Sei whale*†)	24.89	10.82	5.39	2.09	0.016	0.003	0	0	10.99	6.01	3.97	3.30	11.24	6.04	4.00	3.31
Minke whale	19.37	6.87	3.06	0.98	0.016	0.003	0	0	10.93	5.99	3.94	3.32	11.30	6.04	3.99	3.32
Humpback whale	27.68	16.21	9.04	4.04	0.016	0.003	0	0	11.39	6.03	3.95	3.37	11.55	6.11	3.98	3.37
NARW*	24.04	10.75	5.47	1.93	0.016	0.003	0	0	11.00	5.95	3.97	3.37	11.15	5.99	4.00	3.39
Mid-frequency cetaceans																
Atlantic spotted dolphin	0.02	0.02	0	0	0	0	0	0	11.35	6.02	3.87	3.31	7.82	3.77	3.29	2.09
Atlantic white sided dolphin	0.14	0.02	0	0	0	0	0	0	11.26	6.01	3.97	3.35	7.82	3.84	3.31	2.12
Common dolphin	0	0	0	0	0	0	0	0	10.55	6.28	4.12	3.51	7.86	3.95	3.51	2.22
Risso's dolphin	0.12	0.02	<0.01	0	0	0	0	0	11.60	6.09	3.99	3.35	7.99	3.81	3.33	2.15
Bottlenose dolphin	1.34	0.25	0.04	0.01	0	0	0	0	12.46	6.41	4.26	3.48	8.43	4.01	3.48	2.15
High-frequency cetaceans																
Harbor porpoise	16.39	8.47	4.99	2.53	0.24	0.078	0.048	0.024	11.70	6.20	4.05	3.41	49.17	47.30	44.30	42.01
Pinnipeds in water																
Gray seal	8.84	3.12	1.33	0.33	0.021	0.004	0	0	12.00	6.23	4.13	3.48	10.64	4.99	3.76	3.01
Harbor seal	10.20	3.51	1.51	0.38	0.021	0.004	0	0	11.76	6.15	4.01	3.40	10.44	4.92	3.65	3.04

* Listed as Endangered under the ESA
† Fin whale used as a surrogate for sei whale behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

3.1.2. Sea Turtles

Similar to the results presented for marine mammals (Section 3.1.1), Level A and Level B exposure-based ranges ($ER_{95\%}$) for sea turtles were calculated for WTG and OSS foundations for two seasons, and for broadband mitigation of 0, 6, 10, and 15 dB attenuation (Tables 17 to 22).

Table 17. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the WTG monopile foundations (L024-002 and L024-114) during the summer.

Species	Injury												Behavior			
	L_E (210 dB)				L_{pk} (207 dB) ‡				L_p (180 dB)				L_p (175 dB)			
	Attenuation (dB)												Attenuation (dB)			
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Leatherback turtle*	0.40	0.09	<0.01	<0.01	0.5	0.181	0.106	0.055	1.65	0.79	0.39	0.16	2.74	1.58	0.85	0.39
Loggerhead turtle	0.42	0.11	0.02	<0.01	0.5	0.181	0.106	0.055	1.85	0.86	0.42	0.18	3.01	1.70	0.99	0.42
Kemp's ridley turtle*†	0.42	0.11	0.02	<0.01	0.5	0.181	0.106	0.055	1.85	0.86	0.42	0.18	3.01	1.70	0.99	0.42

* Listed as Endangered under the ESA
† Loggerhead turtle used as a surrogate for Kemp's ridley turtle behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 18. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the WTG monopile foundation (L024-002 and L024-114) during the winter.

Species	Injury												Behavior			
	L_E (210 dB)				L_{pk} (207 dB) ‡				L_p (180 dB)				L_p (175 dB)			
	Attenuation (dB)												Attenuation (dB)			
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Leatherback turtle*	1.13	0.19	<0.01	<0.01	0.42	0.147	0.113	0.054	2.48	1.06	0.57	0.20	3.37	2.10	1.35	0.57
Loggerhead turtle	0.88	0.13	0.02	0.02	0.42	0.147	0.113	0.054	2.75	1.29	0.66	0.25	3.47	2.43	1.47	0.66
Kemp's ridley turtle*†	0.88	0.13	0.02	0.02	0.42	0.147	0.113	0.054	2.75	1.29	0.66	0.25	3.47	2.43	1.47	0.66

* Listed as Endangered under the ESA
† Loggerhead turtle used as a surrogate for Kemp's ridley turtle behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 19. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS monopile foundation (OSS1 and OSS2) during the summer.

Species	Injury												Behavior			
	L_E (210 dB)				L_{pk} (207 dB) ‡				L_p (180 dB)				L_p (175 dB)			
	Attenuation (dB)												Attenuation (dB)			
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Leatherback turtle*	0.68	0.04	0.04	0	0.37	0.154	0.09	0.56	2.03	1.18	0.68	0.28	2.95	1.88	1.17	0.68
Loggerhead turtle	1.05	0.28	0	0	0.37	0.154	0.09	0.56	2.37	1.23	0.78	0.28	3.40	2.16	1.34	0.78
Kemp's ridley turtle*†	1.05	0.28	0	0	0.37	0.154	0.09	0.56	2.37	1.23	0.78	0.28	3.40	2.16	1.34	0.78

* Listed as Endangered under the ESA
† Loggerhead turtle used as a surrogate for Kemp's ridley turtle behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 20. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS monopile foundation (OSS1 and OSS2) during the winter.

Species	Injury												Behavior			
	L_E (210 dB)				L_{pk} (207 dB) ‡				L_p (180 dB)				L_p (175 dB)			
	Attenuation (dB)												Attenuation (dB)			
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Leatherback turtle*	1.27	0.48	0.04	0	0.35	0.143	0.072	0.055	2.76	1.54	0.75	0.39	3.49	2.42	1.65	0.75
Loggerhead turtle	1.12	0.28	0	0	0.35	0.143	0.072	0.055	2.99	1.52	0.91	0.42	3.63	2.64	1.75	0.91
Kemp's ridley turtle*†	1.12	0.28	0	0	0.35	0.143	0.072	0.055	2.99	1.52	0.91	0.42	3.63	2.64	1.75	0.91

* Listed as Endangered under the ESA
† Loggerhead turtle used as a surrogate for Kemp's ridley turtle behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 21. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS jacketed foundations (OSS1 and OSS2) during the summer.

Species	Injury												Behavior			
	L_E (210 dB)				L_{pk} (207 dB) ‡				L_p (180 dB)				L_p (175 dB)			
	Attenuation (dB)												Attenuation (dB)			
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Leatherback turtle*	0.84	0.05	0	0	0.086	0.041	0.023	0.06	1.42	0.60	0.34	0.09	2.34	1.23	0.76	0.34
Loggerhead turtle	0.80	0.16	0	0	0.086	0.041	0.023	0.06	1.54	0.73	0.39	0.16	2.71	1.50	0.87	0.39
Kemp's ridley turtle*†	0.80	0.16	0	0	0.086	0.041	0.023	0.06	1.54	0.73	0.39	0.16	2.71	1.50	0.87	0.39

* Listed as Endangered under the ESA
† Loggerhead turtle used as a surrogate for Kemp's ridley turtle behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

Table 22. Exposure ranges ($ER_{95\%}$) in km to injury (SEL and PK) and behavioral (SPL) acoustic thresholds for the OSS jacketed foundations (OSS1 and OSS2) during the winter.

Species	Injury												Behavior			
	L_E (210 dB)				L_{pk} (207 dB) ‡				L_p (180 dB)				L_p (175 dB)			
	Attenuation (dB)												Attenuation (dB)			
	0	6	10	15	0	6	10	15	0	6	10	15	0	6	10	15
Leatherback turtle*	1.16	0.52	0.02	0	0.088	0.042	0.024	0.006	1.99	0.97	0.58	0.20	3.15	1.85	1.18	0.58
Loggerhead turtle	1.25	0.25	0.16	0	0.088	0.042	0.024	0.006	2.37	1.08	0.59	0.16	3.41	2.09	1.25	0.59
Kemp's ridley turtle*†	1.25	0.25	0.16	0	0.088	0.042	0.024	0.006	2.37	1.08	0.59	0.16	3.41	2.09	1.25	0.59

* Listed as Endangered under the ESA
† Loggerhead turtle used as a surrogate for Kemp's ridley turtle behavioral definition
‡ Peak ranges are calculated directly from acoustic modeling (Appendix G.3)

3.2. Acoustic Threshold Ranges for Impact Pile Driving: Fish

Radial distances to regulatory defined acoustic thresholds (Section 2.5) are presented for fish for WTG monopile and OSS monopile and jacketed foundations (Tables 23 to 28), at two locations for two seasons with 10 dB attenuation.

Table 23. Ranges ($R_{95\%}$ in meters) to thresholds for fish (GARFO 2016) due to impact hammering of two 12 m monopile in 12 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
GARFO (2016)																		
Small fish	$L_{E,12hr}$	183	12,003				6,967				11,190				6,351			
	L_{pk}	206	41	70	94	115	50	69	88	89	49	67	88	105	51	66	82	99
Large fish	$L_{E,12hr}$	187	8,717				5,420				7,997				4,968			
	L_{pk}	206	41	70	94	115	50	69	88	89	49	67	88	105	51	66	82	99
Small fish	L_p	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805
Large fish	L_p	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805

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 24. Ranges ($R_{95\%}$ in meters) to thresholds for fish groups (Popper et al. 2014) due to impact hammering of two 12 m monopile in 24 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114).

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	89				72				108				82			
	L_{pk}	213	5	14	11	18	5	15	11	12	5	14	12	18	5	15	12	18
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	494				330				512				354			
	L_{pk}	207	21	48	85	106	21	60	80	81	29	59	78	97	41	58	73	91
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	805				581				838				580			
	L_{pk}	207	21	48	85	106	21	60	80	81	29	59	78	97	41	58	73	91
	L_{pk}	207	21	48	85	106	21	60	80	81	29	59	78	97	41	58	73	91
Eggs and larvae	$L_{E,24hr}$	210	494				330				512				354			
	L_{pk}	207	21	48	85	106	21	60	80	81	29	59	78	97	41	58	73	91
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	161				128				184				144			
	L_{pk}	213	5	14	11	18	5	15	11	12	5	14	12	18	5	15	12	18
Fish with swim bladder	$L_{E,24hr}$	203	1,509				1056				1619				1056			
	L_{pk}	207	21	48	85	106	21	60	80	81	29	59	78	97	41	58	73	91
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	9437				5805				8712				5300			

Table 25. Ranges ($R_{95\%}$ in meters) to thresholds for fish (Popper et al. 2014) due to impact hammering of one 15 m monopile in 24 hr, using an IHC S-4000 hammer at two selected modeling locations (OSS1 and OSS2). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	OSS1								OSS2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	240				188				243				189			
	L_{pk}	213	10	10	12	19	10	10	12	19	10	10	12	19	10	10	12	19
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	1,024				840				1,054				860			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,528				1,184				1,583				1,243			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Eggs and larvae	$L_{E,24hr}$	210	1,024				840				1,054				860			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	400				301				412				340			
	L_{pk}	213	10	10	12	19	10	10	12	19	10	10	12	19	10	10	12	19
Fish with swim bladder	$L_{E,24hr}$	203	2,443				1,871				2,513				1,951			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	9,964				6,286				11,733				7,310			

Table 26. Ranges ($R_{95\%}$ in meters) to thresholds for fish (GARFO 2016) due to impact hammering of one 15 m monopile in 12 hr, using an IHC S-4000 hammer at two selected modeling locations (OSS1 and OSS2). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	OSS1								OSS2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
Small fish	$L_{E,12hr}$	183	12,550				7,317				14,609				8,542			
	L_{pk}	206	47	67	84	99	47	66	78	93	47	67	84	99	47	66	78	93
Large fish	$L_{E,12hr}$	187	9,275				5,943				10,940				6,895			
	L_{pk}	206	47	67	84	99	47	66	78	93	47	67	84	99	47	66	78	93
Small fish	L_p	150	7,128	7,160	8,149	9,221	5,082	4,620	5,114	5,959	8,417	8,389	9,561	10,888	5,781	5,063	5,786	6,921
Large fish	L_p	150	7,128	7,160	8,149	9,221	5,082	4,620	5,114	5,959	8,417	8,389	9,561	10,888	5,781	5,063	5,786	6,921

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 27. Ranges ($R_{95\%}$ in meters) to thresholds for fish (Popper et al. 2014) due to impact hammering of four 4 m jacket foundation piles in 24 hr, using an IHC S-2300 hammer at two selected modeling locations (OSS1 and OSS2). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	OSS1								OSS2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			500	1000	1500	2000	500	1000	1500	2000	500	1000	1500	2000	500	1000	1500	2000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	121				100				121				102			
	L_{pk}	213	2	3	4	6	2	3	4	6	2	3	4	6	2	3	4	6
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	583				412				594				426			
	L_{pk}	207	5	9	13	24	6	10	13	23	5	9	13	24	6	10	13	23
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	932				707				950				717			
	L_{pk}	207	5	9	13	24	6	10	13	23	5	9	13	24	6	10	13	23
Eggs and larvae	$L_{E,24hr}$	210	583				412				594				426			
	L_{pk}	207	5	9	13	24	6	10	13	23	5	9	13	24	6	10	13	23
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	200				164				204				164			
	L_{pk}	213	2	3	4	6	2	3	4	6	2	3	4	6	2	3	4	6
Fish with swim bladder	$L_{E,24hr}$	203	1,677				1,165				1,726				1,217			
	L_{pk}	207	5	9	13	24	6	10	13	23	5	9	13	24	6	10	13	23
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	10,783				5,537				12,528				6,273			

Table 28. Ranges ($R_{95\%}$ in meters) to thresholds for fish (GARFO 2016) due to impact hammering of four 4 m jacket foundation piles in 12 hr, using an IHC S-2300 hammer at two selected modeling locations (OSS1 and OSS2). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	OSS1								OSS2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			500	1000	1500	2000	500	1000	1500	2000	500	1000	1500	2000	500	1000	1500	2000
GARFO (2016)																		
Small fish	$L_{E,12hr}$	183	14,540				6,676				16,795				7,704			
	L_{pk}	206	7	11	16	28	7	11	43	27	7	11	16	28	7	11	43	27
Large fish	$L_{E,12hr}$	187	9,762				5,215				11,357				5,846			
	L_{pk}	206	7	11	16	28	7	11	43	27	7	11	16	28	7	11	43	27
Small fish	L_p	150	4,851	6,063	7,442	9,745	3,954	4,140	4,379	5,256	5,258	6,788	8,687	11,345	4,074	4,231	4,694	5,871
Large fish	L_p	150	4,851	6,063	7,442	9,745	3,954	4,140	4,379	5,256	5,258	6,788	8,687	11,345	4,074	4,231	4,694	5,871

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

4. Discussion

This study predicted underwater sound levels associated with the installation of piles supporting WTG and OSS foundations, including monopiles and jacket foundations, for the RWF.

The single-strike ranges to a series of nominal sound levels for impact pile driving were calculated by first computing the forcing functions for each pile type using GRLWEAP 2010 and then estimating an equivalent point source using JASCO's impact pile driving source models. JASCO's MONM and FWRAM were then used to generate predicted sound fields. Ranges to regular isopleth levels were extracted from the sound fields. A comparison of the RWF modeled sound fields was made with a forecasting, empirical model (itap) that predicts pile driving sound levels at 750 m from the pile. The modeled sound fields at 750 m and the empirically-based forecast were within 3 dB for all hammer energy levels. The good agreement demonstrates consistency between the two approaches.

The results from the animal movement and exposure modeling were used to estimate exposure-based ranges ($ER_{95\%}$). Exposure ranges are reported for each of the three pile types and for each species, based on both summer and winter sound speed profiles. As anticipated, radial distances estimated using the winter sound speed profile were consistently larger than those estimated using the summer sound speed profile. $ER_{95\%}$ for the WTG and OSS monopiles cannot be directly compared since they are the result of multiple convergent factors, including an installation schedule of 2 piles per day for the WTG piles and 1 pile per day for the OSS piles. Additionally, the OSS monopiles were modeled using a greater number of strikes and a larger pile diameter, which likely results in more energy coupling into the water column.

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Appendix A. Glossary

1/3-octave
One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band
Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave band increases with increasing center frequency.

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

absorption
The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

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

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

Auditory frequency weighting (auditory weighting function, frequency-weighting function)
The process of band-pass filtering sounds to reduce the importance of inaudible or less-audible frequencies for individual species or groups of species of aquatic mammals (ISO 2017). One example is M-weighting introduced by Southall et al. (2007) to describe "Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds".

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

boxcar averaging
A signal smoothing technique that returns the averages of consecutive segments of a specified width.

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.

cavitation
A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

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

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

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

decade
Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade
One-tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one-third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a “one-third octave”.

decidecade band
Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing center frequency.

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).

delphinid
Family of oceanic dolphins, or Delphinidae, composed of approximately thirty extant species, including dolphins, porpoises, and killer whales.

ensonified
Exposed to sound.

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.

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

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

high-frequency (HF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for hearing high frequencies.

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.

low-frequency (LF) cetacean
The functional cetacean hearing group that represents mysticetes (baleen whales) specialized for hearing low frequencies.

mid-frequency (MF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for mid-frequency hearing.

Monte Carlo simulation
The method of investigating the distribution of a non-linear multi-variate function by random sampling of all of its input variable distributions.

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

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

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

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

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

parabolic equation (PE) 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.

particle acceleration
The rate of change of particle velocity. Unit: meter per second squared (m/s^2). Symbol: *a*.

particle velocity
The physical speed of a particle in a material moving back and forth in the direction of the pressure wave. Unit: meter per second (m/s). Symbol: v.

peak pressure level (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).

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

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

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

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

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 (RL)
The sound level measured (or that would be measured) at a defined location.

rms
root-mean-square.

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

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

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

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

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

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 μPa^2:

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

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90% sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

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

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

spectral density level
The decibel level ($10 \cdot \log_{10}$) of the spectral density of a given parameter such as SPL or SEL, for which the units are dB re 1 μPa^2/Hz and dB re 1 $\mu Pa^2 \cdot s$/Hz, respectively.

spectrum
An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

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

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

Appendix B. Summary of Study Assumptions

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

Parameter	Description
12 m WTG Monopile Impact 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)
Helmet weight	3234 kN (330 ton)
Impact hammer energy	1000, 2000, 3000, 4000 kJ
Modeled seabed penetration for each hammer energy	6 m, 11 m, 23 m, 38 m
Final seabed penetration for each hammer energy	8 m, 13 m, 25 m, 40 m
Final pile seabed penetration	40 m
Penetration rate for each hammer energy (mm/bl)	10, 5, 6, 5
Pile self-settling penetration	3 m
Strike rate (min^{-1})	30
Estimated number of strikes to drive pile at each energy	500, 1000, 2000, 3000
Total number of strikes per pile	6500
Expected duration to drive one pile	~220 min
Number of piles per site per day	2–3
Pile length	110 m
Pile diameter	12 m
Pile Thickness	16 cm
Monopile modeled locations (ID, easting, northing, water depth)	L024-002, 320793.48, 4569669.5, 41.3 L024-114, 336403.93, 4551413.22, 36.8
15 m OSS Monopile Impact 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 (202 ton)
Helmet weight	3234 kN (330 ton)
Impact hammer energy	1000, 2000, 3000, 4000 kJ
Modeled seabed penetration for each hammer energy	10 m, 18 m, 28 m, 48 m
Final seabed penetration for each hammer energy	12 m, 20 m, 30 m, 50 m
Final pile seabed penetration	50 m
Penetration rate for each hammer energy (mm/bl)	18, 8, 5, 2.5

Parameter	Description
Pile self-settling penetration	3 m
Strike rate (min^{-1})	30
Estimated number of strikes to drive pile at each energy	500, 1000, 2000, 8000
Total number of strikes per pile	11500
Expected duration to drive one pile	~380 min
Number of piles per site per day	0.5–1
Pile length	120 m
Pile diameter	15 m
Pile Thickness	20 cm
Monopile modeled locations (ID, easting, northing, water depth)	OSS1, 327480.00, 4554999.69, 34.18 OSS2, 321190.00, 4564259.69, 34.42 OSS(Backup), 321190.00, 4558703.69, 33.49
4 m OSS Jacket Foundation Pin Impact 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 S2300
Ram weight	1130 kN (115 ton)
Helmet weight	711 kN (73 ton)
Impact hammer energy	500, 1000, 1500, 2000 kJ
Modeled seabed penetration for each hammer energy	13 m, 23 m, 36 m, 68 m
Final seabed penetration for each hammer energy	15 m, 25 m, 38 m, 70 m
Final pile seabed penetration	70 m
Penetration rate for each hammer energy (mm/bl)	29, 10, 8.67, 4
Pile self-settling penetration	0.5 m
Strike rate (min^{-1})	30
Estimated number of strikes to drive pile at each energy	500, 1000, 1500, 8000
Total number of strikes per pile	11000
Expected duration to drive one pile	~360 min
Number of piles per site per day	3–4
Pile length	85 m
Pile diameter	4 m
Pile thickness	8 cm
Monopile modeled locations (ID, easting, northing, water depth)	OSS1, 327480.00, 4554999.69, 34.18 OSS2, 321190.00, 4564259.69, 34.42 OSS(Backup), 321190.00, 4558703.69, 33.49
Environmental Parameters	
Sound Speed Profile	Sound speed profile from GDEM data averaged over region
Bathymetry	SRTM data combined with bathymetry data provided by client

Parameter	Description
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 (PE) propagation model for 4 radials.
Source representation	Vertical line array
Frequency range	10-2000 Hz extrapolated to 63000 Hz (frequency and range dependent absorption applied to propagation loss from 2000 Hz estimates for higher frequencies)
Synthetic trace length	1000 ms
Maximum modeled range	70 km

Appendix C. Underwater Acoustics

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 airguns, impact 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 (PK or $L_{p,pk}$; 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, $p(t)$:

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \tag{C-1}$$

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 an acoustic event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure (PK-PK or $L_{p,pk\text{-}pk}$; 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, $p(t)$:

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

The sound pressure level (SPL or 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 SPL always refers to an rms pressure level and therefore not instantaneous pressure:

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

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 SPL ($L_{p,\mathrm{fast}}$) 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 $L_{p,\mathrm{boxcar\ 125ms}}$. 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 (SEL or L_E; dB re 1 µPa²·s) is the time-integral of the squared acoustic pressure over a duration (T):

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

where T_0 is a reference time interval of 1 s. SEL 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 pulsed sounds, SEL can be calculated by summing the SEL of the N individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the N individual events:

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

Because the SPL(T_{90}) and SEL are both computed from the integral of square pressure, these metrics are related numerically by the following expression, which depends only on the duration of the time window T:

$$L_p = L_E - 10\log_{10}(T) \tag{C-6}$$

$$L_{p90} = L_\mathrm{E} - 10\log_{10}(T_{90}) - 0.458 \tag{C-7}$$

where the 0.458 dB factor accounts for the 10% of pulse SEL missing from the SPL(T_{90}) integration time window.

Energy equivalent SPL (L_{eq}; dB re 1 µPa) denotes the SPL of a stationary (constant amplitude) sound that generates the same SEL as the signal being examined, $p(t)$, over the same time period, T:

$$L_\mathrm{eq} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)\,dt \middle/ p_0^2\right) \tag{C-8}$$

The equations for SPL and the energy-equivalent SPL are numerically identical. Conceptually, the difference between the two metrics is that the SPL is typically computed over short periods (typically of 1 s or less) and tracks the fluctuations of a non-steady acoustic signal, whereas the L_{eq} reflects the average SPL of an acoustic signal over time periods typically of 1 min to several hours.

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

C.2. Decidecade Band Analysis

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

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are approximately one-tenth of a decade wide and often referred to as 1/3-octave-bands. Each octave represents a doubling in sound frequency. The center frequency of the *i*th band, $f_{\mathrm{c}}(i)$, is defined as

$$f_{\mathrm{c}}(i) = 10^{\frac{i}{10}}\,\mathrm{kHz} \tag{C-9}$$

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

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

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure C-1). The acoustic modeling spans from band 1 (f_c (1) = 10 Hz) to band 44 (f_c (44) = 25 kHz).

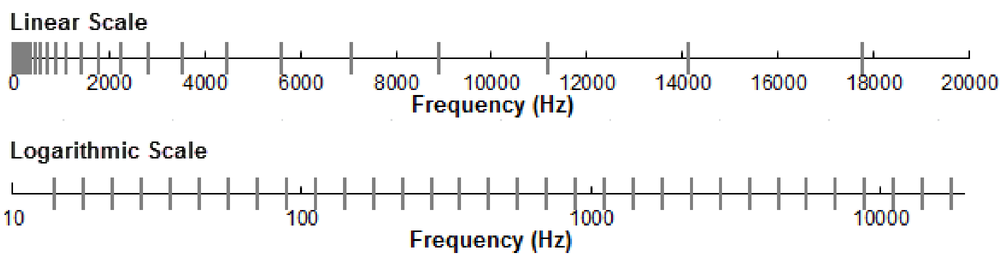


Figure C-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

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

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

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

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

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

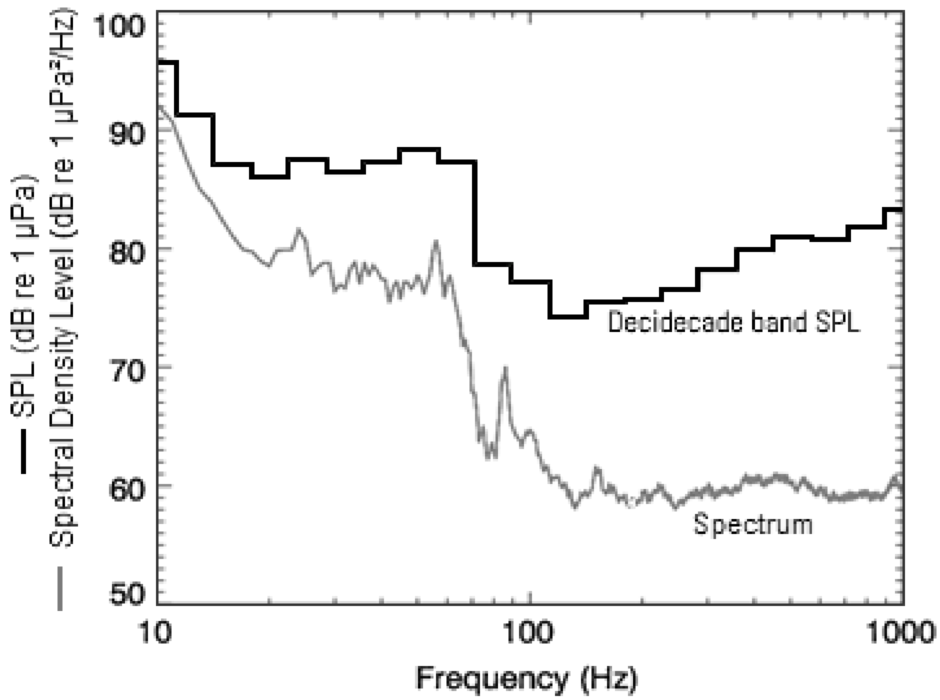


Figure C-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

Appendix 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 SPL sound fields for gauging potential behavioral disruption. The Technical Guidance issued by NMFS (2018) 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). These M-weighting functions are applied in a similar way as A-weighting for noise level assessments for humans. 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). Figure D-1 shows the auditory weighting functions recommended by Southall et al. (2007).

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

Hearing group	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

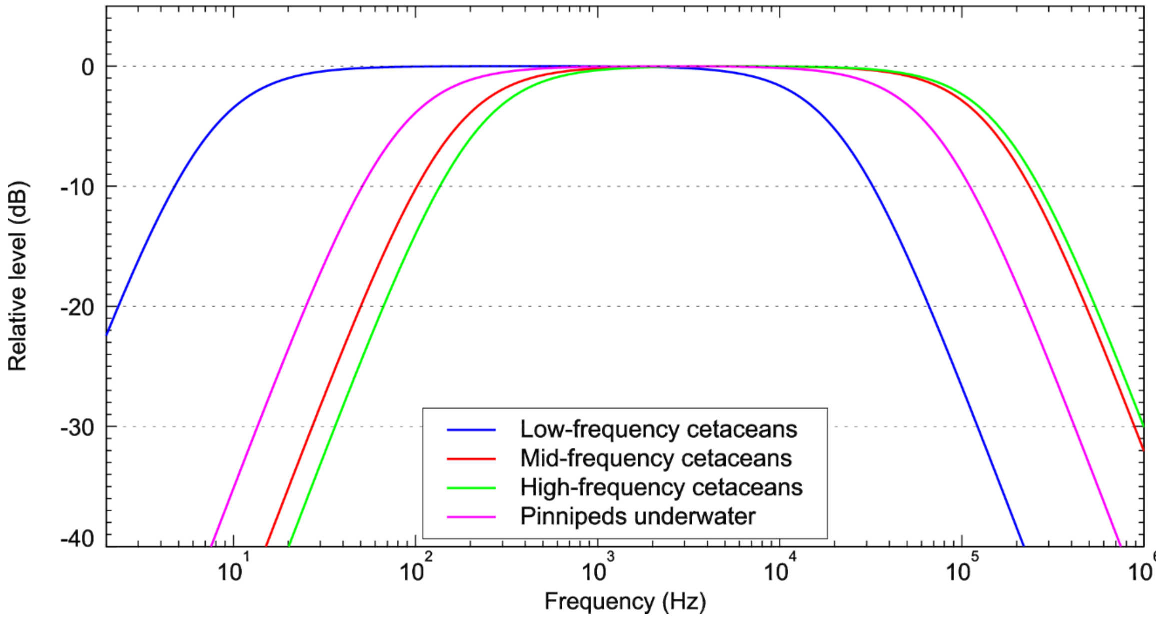


Figure D-1. Auditory weighting functions for functional marine mammal hearing groups as recommended by Southall et al. (2007).

D.2. Technical Guidance (NMFS 2018) Marine Mammal Frequency Weighting Functions

In 2015, a US 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:

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

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively), phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2018). 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 (2018).

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

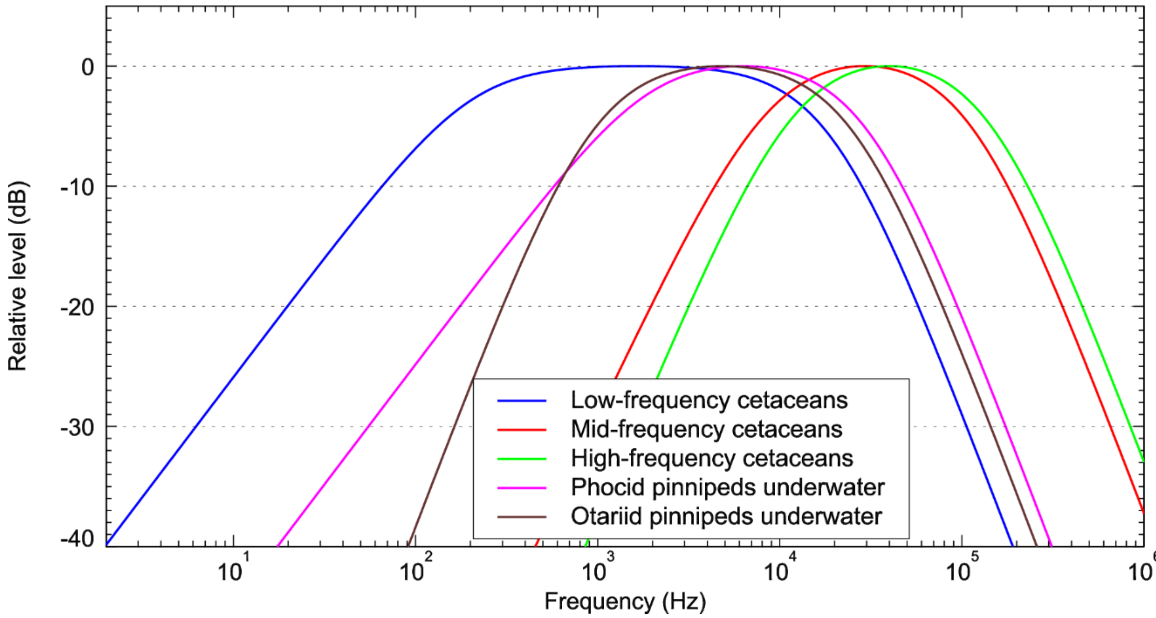


Figure D-2. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2018).

Appendix E. Pile Driving Source Model

A physical model of pile vibration and near-field sound radiation is used to calculate source levels of piles. The physical model employed in this study computes the underwater vibration and sound radiation of a pile by solving the theoretical equations of motion for axial and radial vibrations of a cylindrical shell. These equations of motion are solved subject to boundary conditions, which describe the forcing function of the hammer at the top of the pile and the soil resistance at the base of the pile (Figure E-1). Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretized using the finite difference (FD) method and are solved on a discrete time and depth mesh.

To model the sound emissions from the piles, the force of the impact pile driving hammers also had to be modeled. The force at the top of each pile was computed using the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010), which includes a large database of simulated hammers—both impact and vibratory—based on the manufacturer's specifications. The forcing functions from GRLWEAP were used as inputs to the FD model to compute the resulting pile vibrations.

The sound radiating from the pile itself is simulated using a vertical array of discrete point sources. The point sources are centered on the pile axis. 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 the water at the pile wall. The sound field propagating away from the vertical source array is then calculated using a time-domain acoustic propagation model (see Appendix F.4). MacGillivray (2014) describes the theory behind the physical model in more detail.

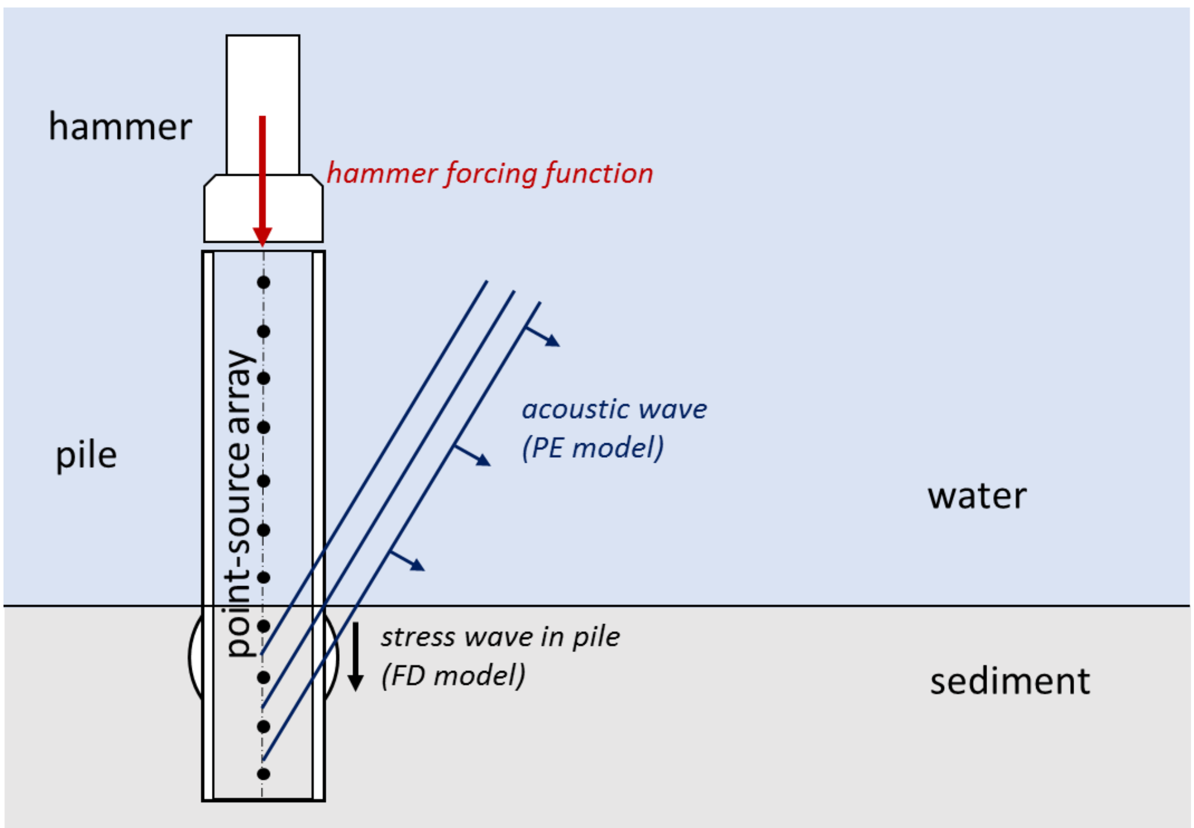


Figure E-1. Physical model geometry for impact driving of a cylindrical pile (vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves that the pile wall radiates.

Appendix F. Sound Propagation Modeling

F.1. Environmental Parameters

F.1.1. Bathymetry

A bathymetry grid for the acoustic propagation model was compiled based on data provided by Deepwater Wind South Fork, LLC (DWSF, Denes et al. 2018) and Shuttle Radar Topography Mission (SRTM) referred to as SRTM-TOPO15+ (Becker et al. 2009).

F.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 (Denes et al. 2018). The dominant soil type is expected to be sand. Table F-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 F-1. Estimated geoacoustic properties used for modeling, as a function of depth. Within an indicated depth range, the parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm^3)	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	1.2–2.1		
>100			2,604	2.1		

F.1.3. Sound Speed Profile

The speed of sound in sea-water is a function of temperature, salinity and pressure (depth) (Coppens 1981). Sound velocity profiles were obtained from the US Navy's Generalized Digital Environmental Model (GDEM; NAVO 2003). The sound speed profiles change little with depth near the proposed construction area (Figure F-1). The months of April through October are weakly downwardly refracting (Figure F-1) leading to more interaction with the seabed 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 seabed. The absolute velocity of November and December is greater than January, February, and March. For this study, a representative sound speed profile for the summer months and the winter months are both used to produce results for comparison.

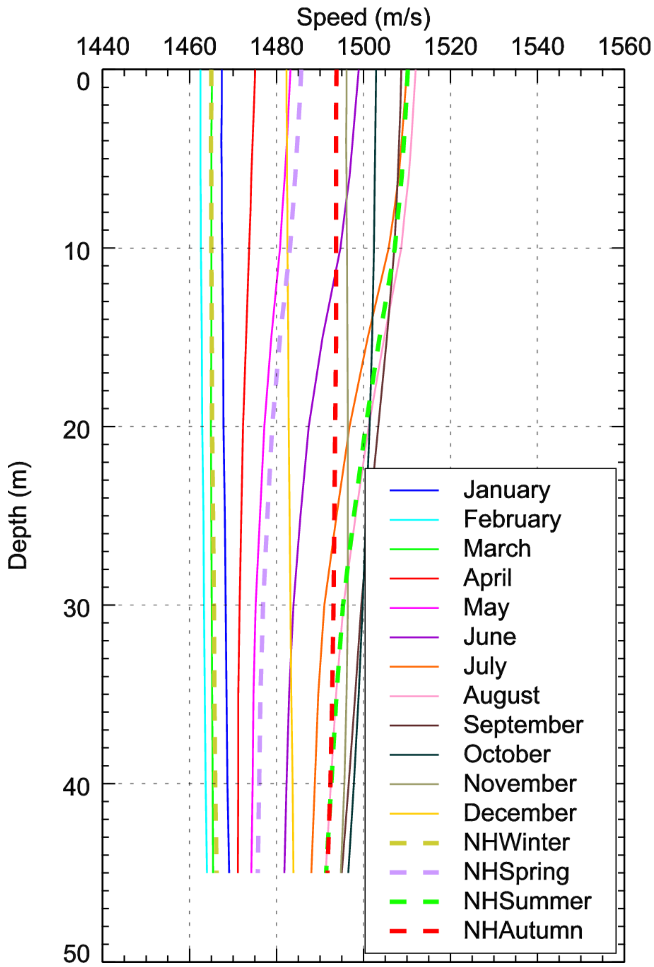


Figure F-1. Month and seasonal average sound velocity profiles in proposed construction area.

F.2. Propagation Loss

The propagation of sound through the environment can be modeled by predicting the acoustic propagation loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, and absorbed scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic energy source level ($L_{S,E}$), expressed in dB re 1 µPa²m²s, and energy propagation loss ($N_{PL,E}$), in units of dB, at a given frequency are known, then the received level ($L_{E,p}$) at a receiver location can be calculated in dB re 1 µPa²s by:

$$L_{E,p}(\theta,r) = L_{S,E}(\theta) - N_{PL,E}(\theta,r), \tag{F-1}$$

where θ defines the specific direction, and r is the range of the receiver from the source.

F.3. Sound Propagation with MONM

Underwater sound propagation (i.e., transmission loss) at frequencies of 10 Hz to 2 kHz was predicted with JASCO's Marine Operations Noise Model (MONM). MONM computes received per-pulse SEL for directional impulsive sources, and SEL over 1 s for non-impulsive sources, at a specified source depth. MONM computes acoustic propagation via a wide-angle parabolic equation (PE) solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). The PE method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed, which results from 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 the following site-specific environmental properties: a bathymetric grid of the modeled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

MONM computes acoustic fields in three dimensions by modeling transmission 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. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding N = 360°/$\Delta\theta$ number of planes (Figure F-2).

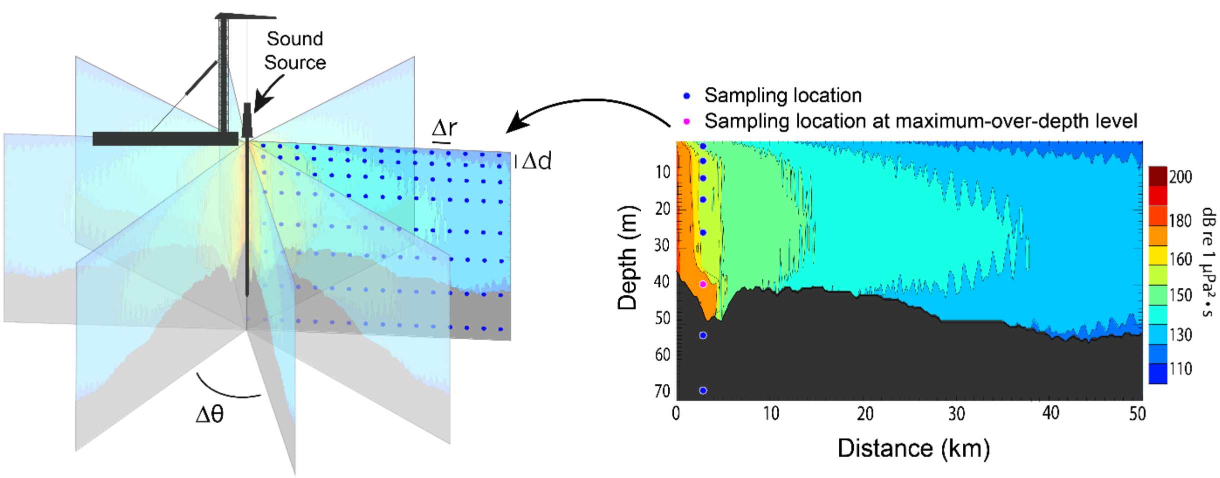


Figure F-2. Modeled three-dimensional sound field (N×2-D method) and maximum-over-depth modeling approach. Sampling locations are shown as blue dots on both figures. On the right panel, the pink dot represents the sampling location where the sound level is maximum over the water column. This maximum-over-depth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

F.4. Sound Propagation with FWRAM

For impulsive sounds from impact pile driving, time-domain representations of the pressure waves generated in the water are required for calculating SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterize vertical directivity effects in the near-field zone. For this study, synthetic pressure waveforms were computed using FWRAM, which is a time-domain acoustic model based on the same wide-angle PE algorithm as MONM. FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments, and it takes the same environmental inputs as MONM (bathymetry, water sound speed profile, and seabed geoacoustic profile). Unlike MONM, FWRAM computes pressure waveforms via Fourier synthesis of the modeled acoustic transfer function in closely spaced frequency bands. FWRAM employs the array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012).

Synthetic pressure waveforms were modeled over the frequency range 10–2048 Hz, inside a 1 s window (e.g., Figure F-3). The synthetic pressure waveforms were post-processed, after applying a travel time correction, to calculate standard SPL and SEL metrics versus range and depth from the source.

Besides providing direct calculations of the peak pressure level and SPL, the synthetic waveforms from FWRAM can also be used to convert the SEL values from MONM to SPL.

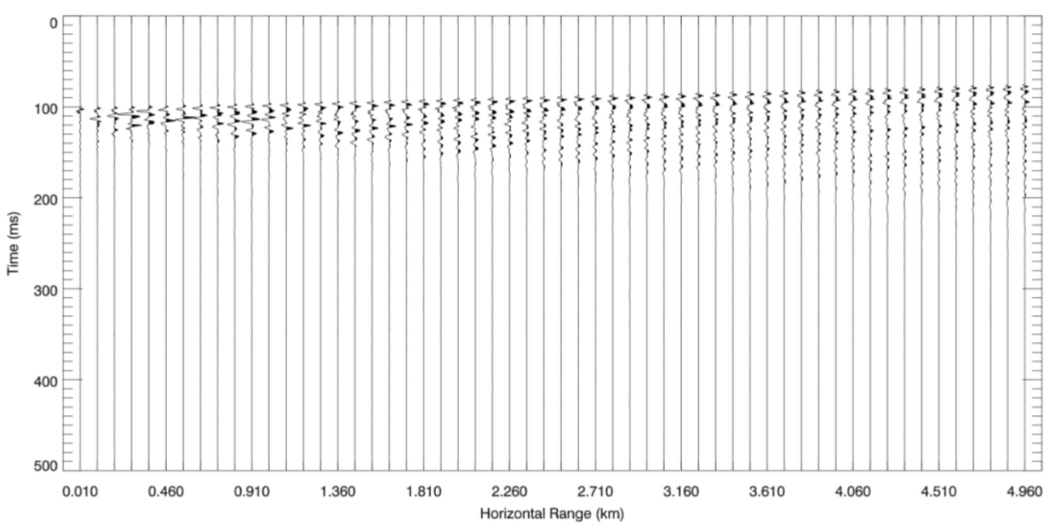
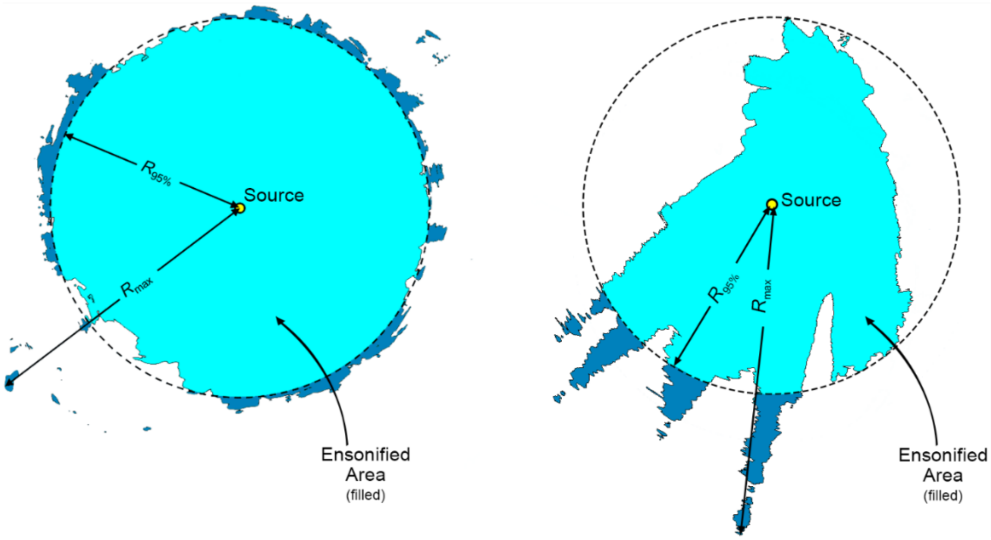


Figure F-3. Example of synthetic pressure waveforms computed by FWRAM for at multiple range offsets. Receiver depth is 35 m and the amplitudes of the pressure traces have been normalised for display purposes.

F.5. Estimating Radial Distance to Acoustic Thresholds

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 F-4 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 is considered to 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.



(a) (b)

Figure F-4. 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}.

F.6. Model Validation Information

Predictions from JASCO's propagation models (MONM and FWRAM) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including the United States and Canadian Arctic, Canadian and southern United States waters, Greenland, Russia and Australia (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, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al. 2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities which have included internal validation of the modeling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016).

Appendix G. Acoustic Radial Distances for Impact Pile Driving

G.1. Single-strike SPL Acoustic Ranges

Table G-1. Distance (in km) to per-strike SPL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	-	-	-	-	-	-	-	-	-	-
190	0.089	0.089	0.089	0.089	-	-	-	-	0.028	0.028
180	0.5	0.481	0.495	0.472	0.108	0.108	0.072	0.072	0.221	0.215
170	2.184	1.967	2.18	1.945	0.616	0.58	0.393	0.362	1.16	1.075
160	4.107	3.833	4.098	3.825	2.548	2.235	2.125	1.771	3.569	3.282
150	6.433	5.805	6.43	5.794	4.274	4.098	4.108	3.869	5.196	4.696
140	11.851	9.842	11.832	9.828	7.941	7.1	7.357	6.311	9.803	8.685
130	19.551	16.34	19.546	16.31	15.587	12.5	14.156	11.333	18.229	14.776
120	30.35	25.66	30.349	25.635	26.49	21.389	25.177	19.884	28.975	24.007

- dashes indicate that thresholds are not reached

Table G-2. Distance (in km) to per-strike SPL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.02	0.02	0.02	0.02	-	-	-	-	-	-
190	0.122	0.122	0.12	0.117	0.02	0.02	-	-	0.045	0.045
180	0.728	0.671	0.723	0.662	0.134	0.128	0.082	0.082	0.344	0.328
170	2.96	2.741	2.937	2.724	0.901	0.82	0.625	0.563	1.968	1.713
160	4.601	4.271	4.586	4.26	3.453	3.24	3.046	2.772	3.978	3.785
150	11.732	9.758	11.732	9.741	6.964	6.007	5.38	4.776	9.713	8.222
140	34.632	29.234	34.612	29.177	25.809	20.302	21.022	17.282	31.13	25.93
130	49.469	41.18	49.469	41.18	49.469	41.178	49.469	41.178	49.469	41.18
120	49.469	41.257	49.469	41.257	49.469	41.256	49.469	41.255	49.469	41.257

- dashes indicate that thresholds are not reached

Table G-3. Distance (in km) to per-strike SPL isopleths for OSS jacketed foundations at Site OSS2 at a hammer energy of 2000 kJ, computed for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
190	0.073	0.072	0.064	0.063	0.001	0.001	0.001	0.001	0.04	0.04
180	0.393	0.368	0.389	0.364	0.122	0.121	0.085	0.084	0.221	0.212
170	1.737	1.609	1.726	1.599	0.618	0.589	0.502	0.462	1.129	1.043
160	3.889	3.739	3.887	3.732	2.6	2.356	2.121	1.947	3.382	3.205
150	6.386	5.871	6.366	5.858	4.324	4.165	4.167	4.004	5.289	4.848
140	11.831	10.477	11.74	10.465	8.918	8.117	8.024	7.311	10.692	9.519
130	19.009	15.77	18.992	15.759	15.636	13.405	14.516	12.531	17.417	14.875
120	26.615	21.192	26.609	21.184	24.279	19.246	22.885	18.472	25.816	20.511

Table G-4. Distance (in km) to per-strike SPL isopleths for OSS jacketed foundations at Site OSS2 at a hammer energy of 2000 kJ, computed for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
190	0.1	0.09	0.1	0.08	0.021	0.021	0.001	0.001	0.045	0.045
180	0.553	0.518	0.549	0.51	0.146	0.144	0.117	0.108	0.306	0.297
170	2.471	2.253	2.46	2.235	0.962	0.911	0.697	0.635	1.684	1.523
160	4.305	4.098	4.299	4.092	3.556	3.36	3.247	3.029	3.928	3.774
150	13.11	11.345	13.104	11.326	8.876	7.479	6.992	6.14	11.803	9.94
140	35.942	28.881	35.942	28.846	35.362	25.755	35.054	23.273	35.378	27.79
130	49.47	39.724	49.47	39.724	49.47	39.723	49.47	39.725	49.47	39.724
120	49.47	40.052	49.47	40.05	49.47	40.05	49.47	40.046	49.47	40.053

Table G-5. Distance (in km) to per-strike SPL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ, computed for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.029	0.029	0.029	0.029	0.001	0.001	0.001	0.001	0.001	0.001
190	0.162	0.157	0.157	0.152	0.001	0.001	0.001	0.001	0.045	0.045
180	0.82	0.764	0.801	0.744	0.135	0.128	0.085	0.083	0.306	0.297
170	2.568	2.384	2.556	2.369	0.662	0.621	0.444	0.412	1.482	1.376
160	4.254	4.1	4.247	4.093	2.582	2.379	2.068	1.843	3.76	3.545
150	7.497	6.921	7.479	6.898	4.304	4.162	4.091	3.935	5.809	5.328
140	12.488	11.079	12.476	11.059	8.625	7.857	7.414	6.795	10.831	9.763
130	19.099	15.894	19.072	15.88	14.991	12.871	13.54	11.841	17.315	14.722
120	26.465	20.89	26.448	20.879	22.902	18.487	21.667	17.578	25.25	20.013

Table G-6. Distance (in km) to per-strike SPL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ, computed for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.029	0.029	0.029	0.029	0.001	0.001	0.001	0.001	0.001	0.001
190	0.181	0.172	0.179	0.17	0.021	0.021	0.001	0.001	0.064	0.063
180	1.005	0.937	0.985	0.924	0.153	0.145	0.1	0.1	0.424	0.397
170	3.214	3.024	3.208	3.005	0.938	0.877	0.581	0.545	1.994	1.836
160	5.12	4.698	5.081	4.671	3.393	3.216	2.853	2.597	4.021	3.838
150	12.252	10.888	12.236	10.864	6.8	6.056	5.064	4.622	10.161	9.028
140	28.829	22.922	28.829	22.892	22.794	18.395	20.832	16.082	27.053	21.174
130	49.47	39.843	49.47	39.844	49.47	39.88	49.47	39.906	49.47	39.853
120	49.47	40.018	49.47	40.018	49.47	40.018	49.47	40.023	49.47	40.017

G.2. Single-strike SEL Acoustic Ranges

Table G-7. Distance (in km) to per-strike SEL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (Southall et al. 2007, NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	-	-	-	-	-	-	-	-	-	-
190	-	-	-	-	-	-	-	-	-	-
180	0.117	0.117	0.028	0.028	-	-	-	-	-	-
170	0.597	0.555	0.189	0.184	-	-	-	-	-	-
160	2.472	2.185	0.956	0.882	-	-	-	-	0.108	0.108
150	5.437	4.851	3.369	3.069	0.06	0.06	0.028	0.028	0.668	0.621
140	9.801	8.618	7.383	6.62	0.316	0.297	0.156	0.152	2.797	2.357
130	16.745	14.26	13.534	11.422	2.003	1.547	1.172	1.066	6.586	5.646
120	26.686	22.726	23.849	19.574	4.852	3.827	3.619	2.827	13.132	10.295

- dashes indicate that thresholds are not reached

Table G-8. Distance (in km) to per-strike SEL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	-	-	-	-	-	-	-	-	-	-
190	0.028	0.028	-	-	-	-	-	-	-	-
180	0.146	0.144	0.04	0.04	-	-	-	-	-	-
170	0.852	0.8	0.272	0.268	-	-	-	-	0.02	0.02
160	3.507	3.15	1.636	1.409	-	-	-	-	0.134	0.128
150	9.612	7.81	5.723	5.154	0.1	0.1	0.028	0.028	1	0.773
140	25.799	20.453	18.279	15.137	0.481	0.418	0.242	0.206	4.566	3.997
130	49.469	40.87	49.469	40.487	2.478	2.167	1.434	1.124	19.779	14.549
120	49.469	41.239	49.469	41.239	9.091	6.975	5.603	4.326	49.469	41.17

- dashes indicate that thresholds are not reached

Table G-9. Distance (in km) to per-strike SEL isopleths for OSS jacketed foundations at Site OSS2 at a hammer energy of 2000 kJ, computed for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	-	-	-	-	-	-
190	0.001	0.001	0.001	0.001	-	-	-	-	-	-
180	0.085	0.084	0.029	0.029	-	-	-	-	0.001	0.001
170	0.474	0.447	0.185	0.181	0.001	0.001	0.001	0.001	0.021	0.021
160	1.981	1.852	0.958	0.881	0.001	0.001	0.001	0.001	0.127	0.126
150	5.281	4.783	3.282	3.022	0.064	0.063	0.029	0.029	0.766	0.714
140	10.21	9.209	7.994	7.317	0.568	0.386	0.213	0.204	3.222	2.675
130	16.835	14.227	14.37	12.383	2.07	1.967	1.486	1.059	7.602	6.563
120	24.968	19.634	22.312	18.14	5.58	4.52	3.845	3.278	13.409	11.615

- dashes indicate that thresholds are not reached

Table G-10. Distance (in km) to per-strike SEL isopleths for OSS jacketed foundations at Site OSS2 at a hammer energy of 2000 kJ, computed for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	-	-	-	-	-	-
190	0.001	0.001	0.001	0.001	-	-	-	-	0.001	0.001
180	0.108	0.108	0.045	0.045	-	-	-	-	0.001	0.001
170	0.655	0.62	0.251	0.243	0.001	0.001	0.001	0.001	0.029	0.029
160	2.849	2.628	1.562	1.436	0.001	0.001	0.001	0.001	0.153	0.146
150	9.616	8.706	6.729	5.793	0.1	0.09	0.064	0.064	1.066	0.905
140	28.143	22.541	26.772	19.441	0.684	0.549	0.323	0.301	5.559	4.671
130	49.47	39.817	49.47	39.84	3.733	2.435	1.946	1.518	28.431	19.752
120	49.47	40.022	49.47	40.023	11.335	8.887	6.448	5.165	49.47	39.719

- dashes indicate that thresholds are not reached

Table G-11. Distance (in km) to per-strike SEL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ, computed for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.029	0.029	0.029	0.029	0.001	0.001	0.001	0.001	0.001	0.001
190	0.162	0.157	0.157	0.152	0.001	0.001	0.001	0.001	0.045	0.045
180	0.82	0.764	0.801	0.744	0.135	0.128	0.085	0.083	0.306	0.297
170	2.568	2.384	2.556	2.369	0.662	0.621	0.444	0.412	1.482	1.376
160	4.254	4.1	4.247	4.093	2.582	2.379	2.068	1.843	3.76	3.545
150	7.497	6.921	7.479	6.898	4.304	4.162	4.091	3.935	5.809	5.328
140	12.488	11.079	12.476	11.059	8.625	7.857	7.414	6.795	10.831	9.763
130	19.099	15.894	19.072	15.88	14.991	12.871	13.54	11.841	17.315	14.722
120	26.465	20.89	26.448	20.879	22.902	18.487	21.667	17.578	25.25	20.013

Table G-12. Distance (in km) to per-strike SEL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ, computed for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.029	0.029	0.029	0.029	0.001	0.001	0.001	0.001	0.001	0.001
190	0.181	0.172	0.179	0.17	0.021	0.021	0.001	0.001	0.064	0.063
180	1.005	0.937	0.985	0.924	0.153	0.145	0.1	0.1	0.424	0.397
170	3.214	3.024	3.208	3.005	0.938	0.877	0.581	0.545	1.994	1.836
160	5.12	4.698	5.081	4.671	3.393	3.216	2.853	2.597	4.021	3.838
150	12.252	10.888	12.236	10.864	6.8	6.056	5.064	4.622	10.161	9.028
140	28.829	22.922	28.829	22.892	22.794	18.395	20.832	16.082	27.053	21.174
130	49.47	39.843	49.47	39.844	49.47	39.88	49.47	39.906	49.47	39.853
120	49.47	40.018	49.47	40.018	49.47	40.018	49.47	40.023	49.47	40.017

- dashes indicate that thresholds are not reached

G.3. Single-strike Peak Acoustic Radial Distances

Table G-13. Distance (in km) to PK isopleths at the highest hammer energy for each of the pile types using a summer sound speed profile. All ranges are reported assuming a 10 dB broadband attenuation.

PK	Ranges (km)		
	WTG Monopile Foundation	*OSS Monopile Foundation*	*OSS Jacketed Foundation*
230	-	-	-
219	0.005	0.006	0.004
218	0.006	0.007	0.005
216	0.010	0.011	0.007-
213	0.018	0.019	0.018
210	0.072	0.071	0.028-
207	0.095	0.090	0.042
202	0.178	0.260	0.087

- dashes indicate that thresholds are not reached

Table G-14. Distance (in km) to PK isopleths at the highest hammer energy for each of the pile types using a winter sound speed profile. All ranges are reported assuming a 10 dB broadband attenuation.

PK	Ranges (km)		
	WTG Monopile Foundation	*OSS Monopile Foundation*	*OSS Jacketed Foundation*
230	-	-	-
219	0.005	0.006	0.004
218	0.006	0.007	0.005
216	0.010	0.010	0.007
213	0.018	0.019	0.018
210	0.074	0.072	0.028
207	0.101	0.095	0.042
202	0.200	0.260	0.088

- dashes indicate that thresholds are not reached

G.4. Impact pile driving per pile SEL ranges

G.4.1. Summer

Table G-15. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one WTG 12 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (L024-002 and L024-114).

Hearing group	Threshold (dB)	L024-002 Attenuation level (dB)				L024-114 Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	9.065	6.27	4.656	2.952	8.458	5.904	4.476	2.868
Mid-frequency cetaceans	185	0.595	0.122	0.08	0.028	0.564	0.146	0.089	0.028
High-frequency cetaceans	155	6.756	4.6	3.42	2.246	6.61	4.532	3.447	2.174
Phocid pinnipeds	185	2.985	1.471	0.81	0.3	3.03	1.601	0.844	0.326
Sea turtles	210	1.598	0.679	0.33	0.161	1.62	0.679	0.354	0.161

Table G-16. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one OSS 15 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (OSS1 and OSS2).

Hearing group	Threshold (dB)	OSS1 Attenuation level (dB)				OSS2 Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	9.252	6.768	5.324	3.774	10.603	7.835	5.97	4.032
Mid-frequency cetaceans	185	0.605	0.184	0.09	0.029	0.689	0.206	0.09	0.029
High-frequency cetaceans	155	7.08	4.968	3.846	2.517	7.608	5.401	4.048	2.758
Phocid pinnipeds	185	3.542	1.983	1.141	0.604	3.81	2.058	1.154	0.582
Sea turtles	210	2.493	1.329	0.84	0.397	2.585	1.394	0.86	0.397

Table G-17. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of four, 4 m jacket foundation pin piles in 24 hours, using an IHC S-2300 hammer with attenuation at two selected modeling locations (OSS1 and OSS2).

Hearing group	Threshold (dB)	OSS1 Attenuation level (dB)				OSS2 Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	10.074	7.255	5.639	3.903	11.348	8.36	6.406	4.233
Mid-frequency cetaceans	185	1.007	0.534	0.165	0.083	1.036	0.395	0.19	0.083
High-frequency cetaceans	155	8.333	6.069	4.732	3.38	8.977	6.531	5.121	3.617
Phocid pinnipeds	185	4.472	2.542	1.604	0.781	4.78	2.701	1.62	0.787
Sea turtles	210	2.212	1.106	0.682	0.272	2.298	1.154	0.683	0.282

G.4.2. Winter

Table G-18. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one WTG 12 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (L024-002 and L024-114).

Hearing group	Threshold (dB)	L024-002				L024-114			
		Attenuation level (dB)				Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	24.415	13.061	8.663	4.847	28.108	12.369	8.109	4.768
Mid-frequency cetaceans	185	0.511	0.206	0.089	0.028	0.594	0.184	0.102	0.028
High-frequency cetaceans	155	13.885	7.94	5.246	2.709	14.363	8.028	5.404	3.226
Phocid pinnipeds	185	4.907	2.226	1.134	0.428	5.205	2.302	1.165	0.475
Sea turtles	210	2.261	0.955	0.494	0.201	2.35	0.988	0.512	0.224

Table G-19. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one OSS 15 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (OSS1 and OSS2).

Hearing group	Threshold (dB)	OSS1				OSS2			
		Attenuation level (dB)				Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	31.061	13.98	9.489	5.948	28.983	16.273	11.121	6.646
Mid-frequency cetaceans	185	0.754	0.241	0.142	0.064	0.72	0.253	0.119	0.063
High-frequency cetaceans	155	15.856	8.88	5.941	3.36	16.353	9.437	6.475	3.706
Phocid pinnipeds	185	6.462	2.7	1.547	0.688	6.72	2.773	1.583	0.698
Sea turtles	210	3.284	1.715	1.024	0.477	3.484	1.767	1.054	0.491

Table G-20. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of four, 4 m jacket foundation pin piles in 24 hours, using an IHC S-2300 hammer with attenuation at two selected modeling locations (OSS1 and OSS2).

Hearing group	Threshold (dB)	OSS1				OSS2			
		Attenuation level (dB)				Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	40.895	23.141	13.39	7.488	39.716	24.761	15.426	8.743
Mid-frequency cetaceans	185	1.464	0.557	0.261	0.117	1.481	0.546	0.277	0.102
High-frequency cetaceans	155	23.454	13.402	9.117	5.336	23.336	14.004	9.558	5.564
Phocid pinnipeds	185	10.741	4.581	2.47	1.081	11.511	4.672	2.382	1.103
Sea turtles	210	3.12	1.487	0.869	0.384	3.233	1.543	0.888	0.394

Appendix H. itap Comparison

itap GmbH is a German agency accredited for measuring and forecasting sound levels produced during impact pile driving for installations such as wind farms (see below/attachment). Sound level predictions were made using itap's empirical model to forecast single-strike SEL at 750 m from the pile (results supplied by Ørsted). itap's empirical forecasting model was created by compiling and fitting numerous measurements at 750 m for a variety of pile dimensions, hammer types and hammer energy levels, and at several locations (though primarily in the North Sea). The itap model is based on the 95th percentile of the single-strike SEL measurement. That is, the SEL value used to generate the model was the level inclusive of 95% of the single-strike measurements at a given hammer energy level (the highest 5% of single-strike SEL measurements were discarded). Because the itap model forecasts mean values from aggregated measurements, application to specific pile driving scenarios may be expected to differ to some degree from the forecast.

As a way of validating the acoustic modeling for this study, single-strike SEL received levels at 750 m from the driven pile were determined from the calculated 3-D sound fields (see Appendices E, F, and G) and compared to the itap forecast (Tables H-1, H-2, and H-3). itap's model forecasts the 95th percentile of SEL values while the acoustic modeling in this study results in an estimate of a median value (50th percentile), so the levels calculated for this study at 750 m are expected to be lower than the forecasted levels. All values were rounded to the nearest dB.

Table H-1 shows that the single- strike SEL levels at 750 m predicted in this study compare well with the itap forecast. At lower hammer energy levels this study's predicted received levels are lower than the itap forecast, and at higher hammer energy levels the predicted received levels are greater than the forecast levels. It is likely that the pile penetration depth accounts for this trend. When more of the pile has penetrated into the seabed, the pile as a sound source has a larger radiating area in the water and substrate and produces more sound energy. In this study, lower hammer energy levels at the start of pile driving when little of the pile has penetrated into the substrate. Within the itap model, measurements from all hammer energy levels represent a range of pile penetration depths such that measurements of lower hammer energy strikes include piles near full penetration and driven with smaller hammers, which may produce louder sounds.

Table H-1. Broadband single-strike SEL (dB re 1 µPa^2·s) comparison of WTG monopile foundation modeled sound field with itap (Bellmann et al. 2020) at 750 m.

Source location/Season	Hammer energy (kJ			
	1000 kJ	2000 kJ	3000 kJ	4000 kJ
itap (12 m)	*179*	*181*	*183*	*184*
L024-002, Summer	179	181	182	183
L024-114, Summer	181	184	184	185
L024-002, Winter	179	181	182	183
L024-114, Winter	180	184	184	185

Table H-2. Broadband single-strike SEL (dB re 1 µPa^2·s) comparison of OSS monopile modeled sound field with itap (Bellmann et al. 2020) at 750 m.

Source location/Season	Hammer energy (kJ			
	1000 kJ	2000 kJ	3000 kJ	4000 kJ
itap (15 m)	*180*	*182*	*184*	*185*
OSS1, Summer	181	179	181	184
OSS2, Summer	183	181	183	185
OSS1, Winter	181	179	181	184
OSS2, Winter	183	181	183	185

Table H-3. Broadband single-strike SEL (dB re 1 µPa^2·s) comparison of OSS jacket foundation pin pile modeled sound field with itap (Bellmann et al. 2020) at 750 m.

Source location/Season	Hammer energy (kJ			
	500 kJ	1000 kJ	1500 kJ	2000 kJ
itap (4 m)	*173*	*175*	*177*	*178*
OSS1, Summer	173	174	176	179
OSS2, Summer	175	176	178	181
OSS1, Winter	173	174	176	179
OSS2, Winter	175	176	178	181

H.1. itap Description and Qualifications

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INSTITUT FÜR TECHNISCHE UND ANGEWANDTE PHYSIK GMBH

Messstelle nach §29b BImSchG

für Geräusche

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Qualification and References of the *itap GmbH*

Dear Mr. Matej Simurda,

as requested, please find below a short description / biography of the *itap GmbH*. In case you need more detailed information, please feel free to contact me.

Short description of the *itap GmbH*

Graduates from the Carl von Ossietzky University of Oldenburg founded the Institute of Technical and Applied Physics (itap) in 1992 (https://www.itap.de/en/). As the demand for technical-scientific services rose, the institute was transferred into an independent limited liability company in 1995.

Meanwhile, the company can look on 25 years business experience, during which new areas of activity opened up constantly. Over time, different physical problems were dealt with; the focus however always was in the field of technical acoustics. To be named hereby in particular: our sustainable activities in the field of immission (pollution) control onshore as well as our pioneering role in the investigation of underwater noise with the aim to protect marine life.

Qualification and certification

The *itap GmbH* is a notified measuring agency in Germany according to §29b BImSchG (Federal Control of Pollution Act) and has an accredited quality management system (QMS) according to the ISO/IEC 17025 for emission and immission (pollution) measurements of sounds and vibrations (accreditation in accordance with the DAkkS – German accreditation body – for measurements and forecasts of underwater noise (impulse and continuous noise), the immission (pollution) protection module sounds and vibrations, as well as noise in the workplace).

Technical references: underwater noise

The itap GmbH was involved in all German Offshore Windfarm (OWF) construction projects since 2008, by predicting the estimated pile-driving noise during construction, consultancy services regarding noise measurements and noise mitigation strategies, as well as measuring ambient and pile-driving noise during the construction phase and operational noise of Offshore Wind Turbine Generators after completion of construction works.

Within a Research and Development (R&D) project the technical information system for underwater noise MarinEARS (Marine Explorer and Registry of Sound https://marinears.bsh.de) was designed in cooperation with the German regulatory authority BSH (Bundesamt für Seeschifffahrt und Hydrographie). All quality checked and post-processed underwater noise measurement data from 2012 till 2020 for German OWF projects within MarinEARS were provided by the *itap GmbH*. The technical field report regarding the experiences with impact pile-driving noise as well as the application of noise mitigation measures of this R&D project is available in German and English version at our homepage: https://www.itap.de/en/news/field-report-pile-driving-noise-published/.

Furthermore, the *itap GmbH* was also involved in OWF construction projects in Belgium, The Netherlands, Denmark, Sweden, United Kingdom and Taiwan, providing underwater noise predictions and consultancy services as well as performing underwater noise measurements.

The *Itap GmbH* has measured underwater noise during use of all available noise mitigation measures (noise mitigation systems as well as noise abatement systems) for offshore constructions worldwide under offshore conditions (offshore reliable and state-of-the-art noise mitigation measures as well as prototypes in accordance to DIN SPEK 45653 (2017)).

Besides the main task domain of underwater noise in connection with OWF construction projects (pile-driving noise), the *itap GmbH* predicts and measures underwater noise of all kinds of maritime activities. Such as for offshore projects like cable or pipe laying activities, cable fault detection, any acoustical surveys (e. g. sonar operations), clearance of unexploded ordnances (UXO), detonations or decommissioning of any offshore constructions, vessel based noise as well as for costal projects (e. g. within harbor facilities).

Services: underwater noise

Consultancy: The *itap GmbH* provides consultancy services related to the full scope of underwater noise predictions and measurements (especially related to Offshore Wind Farms). In recent years, our experience in Europe has expanded and extended beyond Europe to the United States of America, Taiwan and Australia. Due to our pioneering role in this field and the associated 20 years of experience in Europe, we can offer a wide range of consulting services. Such as preparation of noise mitigation concepts, selection of suitable noise mitigation measures, support within approval procedures and contact to local authorities.

Underwater noise prognosis: In recent years, our portfolio of underwater noise prediction services regarding pile driving noise has grown to meet a variety of different local regulatory requirements for various noise mitigation values throughout Europe and Taiwan and to assist the environmental impact assessment by species specific underwater noise modelling like in UK, Australia and the USA. The *itap GmbH* is able to perform underwater noise prognosis for various noise sources regarding impulsiveness and continuous noise according to national guidelines and project-specific requirements of the local approval authorities and respective local environmental conditions.

For underwater noise prognosis we are using our extensive experiences within this domain. Based on this, we have developed two models for underwater noise prediction:

1) Impulsiveness underwater noise model: Our validated pile-driving noise model based on measured values over the last 20 years within more than 35 pcs OWF and more than 30 pcs single foundation projects (empirical approach). With this pile-driving model, mitigated as well as unmitigated pile-driving noise can be predicted (broadband as well as frequency depending).
   This model also contains the empirical approach of Soloway and Dahl (2014) as well as own measured data during UXO clearance activities and detonations.
2) Continuous noise model: *Itap GmbH* also developed a model for continuous noise activities like vessel based construction projects (pipe and cable laying projects as well as operational noise from Offshore Wind Turbine Generator). However, this model will currently be extended to vibro-piling activities based on measured data as well.

Underwater noise measurements: At the beginning of the underwater noise measurements with regard to OWFs in 2000, there was no measurement device commercially available on the market, so the decision was made to develop an own system. The benefit of our own developed and constructed devices is that we can adapt our measurement devices to a variety of special requirements regarding amplitude and frequency range (from ambient noise till noise during UXO clearance from 20 Hz up to 200 kHz). Furthermore, the mooring systems for our measurement devices are self-constructed and can be adapted to the local environmental conditions easily. During the last 20 years we have been able to gain a lot of experience with different measurements under different environmental conditions.

All measurement devices of *itap GmbH* are fulfilling the requirements of national and international standards (e. g. BSH, 2011; ISO 18406) and the calibration is performed in accordance to ISO/IEC 17025 (2018).

Research and Development: Due the special expertise in the field of technical acoustics the *itap GmbH* has participated in various research projects dealing with underwater noise (https://www.itap.de/en/research-projects/). E. g. in the field of underwater sound propagation, further development of noise mitigation measures and the evaluation of the impact of underwater noise on marine mammals.

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Appendix I. Animal Movement and Exposure Modeling for Radial Distance Calculation

Animal movement and exposure modeling can be used to estimate potential species-specific exposure-based radial distances from a source as an alternative to acoustic ranges within which animals are assumed to be exposed to a regulatory-defined sound level threshold. Sound sources move as do animals. The sound fields may be complex, and the sound received by an animal is a function of where the animal is at any given time. To a reasonable approximation, the location of the sound source(s) is known, and acoustic modeling can be used to predict the 3-D sound field. The location and movement of animals within the sound field, however, is unknown. Realistic animal movement within the sound field can be simulated. Repeated random sampling (Monte Carlo method simulating many animals within the operations area) is used to estimate the sound exposure history of the population of simulated animals during the operation.

Monte Carlo methods provide a heuristic approach for determining the probability distribution function (PDF) of complex situations, such as animals moving in a sound field. The probability of an event's occurrence is determined by the frequency with which it occurs in the simulation. The greater the number of random samples, in this case the more simulated animals (animats), the better the approximation of the PDF. Animats are randomly placed, or seeded, within the simulation boundary at a specified density (animats/km^2). Higher densities provide a finer PDF estimate resolution but require more computational resources. To ensure good representation of the PDF, the animat density is set as high as practicable allowing for computation time. The animat density is much higher than the real-world density to ensure good representation of the PDF.

Several models for marine mammal movement have been developed (Ellison et al. 1987, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another based on probabilities determined from measured swimming behavior. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of participating in foraging, play, rest, or travel. Attractions and aversions to variables like anthropogenic sounds and different depth ranges can be included in the models.

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was based on the open-source marine mammal movement and behavior model (3MB, Houser 2006) and used to predict the exposure of animats (virtual marine mammals and sea turtles) to sound arising from sound sources in simulated representative surveys. Inside JASMINE, the sound source location mimics the movement of the source vessel through the proposed survey pattern. Animats are programmed to behave like the marine animals likely to be present in the survey area. The parameters used for forecasting realistic behaviors (e.g., diving, foraging, aversion, and surface times.) are determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. An individual animat's modeled sound exposure levels are summed over the total simulation duration, such as 24 hr or the entire simulation, to determine its total received energy, and then compared to the assumed threshold criteria.

JASMINE uses the same animal movement algorithms as the 3MB model (Houser, 2006), but has been extended to be directly compatible with MONM and FWRAM acoustic field predictions, for inclusion of source tracks, and importantly for animats to change behavioral states based on time and space dependent modeled variables such as received levels for aversion behavior.

I.1. Animal Movement Parameters

JASMINE uses previously measured behavior to forecast behavior in new situations and locations. The parameters used for forecasting realistic behavior are determined (and interpreted) from marine species studies (e.g., tagging studies). Each parameter in the model is described as a probability distribution. When limited or no information is available for a species parameter, a Gaussian or uniform distribution may be chosen for that parameter. For the Gaussian distribution, the user determines the mean and standard deviation of the distribution from which parameter values are drawn. For the uniform distribution, the user determines the maximum and minimum distribution from which parameter values are drawn. When detailed information about the movement and behavior of a species is available, a user-created distribution vector, including cumulative transition probabilities, may be used (referred to here as a vector model; Houser 2006). Different sets of parameters can be defined for different behavior states. The probability of an animat starting out in or transitioning into a given behavior state can in turn be defined in terms of the animat's current behavioral state, depth, and the time of day. In addition, each travel parameter and behavioral state has a termination function that governs how long the parameter value or overall behavioral state persists in simulation.

The parameters used in JASMINE describe animal movement in both the vertical and horizontal planes. The parameters relating to travel in these two planes are briefly described below. JASCO maintains species-specific choices of values for the behavioral parameters used in this study. The parameter values are available for limited distribution upon request.

Travel sub-models

- **Direction**– determines an animat's choice of direction in the horizontal plane. Sub-models are available for determining the heading of animats, allowing for movement to range from strongly biased to undirected. A random walk model can be used for behaviors with no directional preference, such as feeding and playing. In a random walk, all bearings are equally likely at each parameter transition time step. A correlated random walk can be used to smooth the changes in bearing by using the current heading as the mean of the distribution from which to draw the next heading and standard deviation equal to the perturbation. An additional variant of the correlated random walk is available that includes a directional bias for use in situations where animals have a preferred absolute direction, such as migration. A user-defined vector of directional probabilities can also be input to control animat heading. For more detailed discussion of these parameters, see Houser (2006) and Houser and Cross (1999).
- **Travel rate**–defines an animat's rate of travel in the horizontal plane. When combined with vertical speed and dive depth, the dive profile of the animat is produced.

Dive sub-models

- **Ascent rate**–defines an animat's rate of travel in the vertical plane during the ascent portion of a dive.
- **Descent rate**–defines an animat's rate of travel in the vertical plane during the descent portion of a dive.
- **Depth**–defines an animat's maximum dive depth.
- **Bottom following**–determines whether an animat returns to the surface once reaching the ocean floor, or whether it follows the contours of the bathymetry.
- **Reversals**–determines whether multiple vertical excursions occur once an animat reaches the maximum dive depth. This behavior is used to emulate the foraging behavior of some marine mammal species at depth. Reversal-specific ascent and descent rates may be specified.
- **Surface interval**–determines the duration an animat spends at, or near, the surface before diving again.

I.1.1. Exposure Integration Time

The interval over which acoustic exposure (L_E) should be integrated and maximal exposure (L_p) determined is not well defined. Both Southall et al. (2007) and the NMFS (2018) recommend a 24 hr baseline accumulation period, but state that there may be situations where this is not appropriate (e.g., a high-level source and confined population). Resetting the integration after 24 hr can lead to overestimating the number of individual animals exposed because individuals can be counted multiple times during an operation. The type of animal movement engine used in this study simulates realistic movement using swimming behavior collected over relatively short periods (hours to days) and does not include large-scale movement such as migratory circulation patterns. Therefore, the simulation time is limited to a few weeks, the approximate scale of the collected data (Houser 2006). For this study, one-week simulations (i.e., 7 days) were modeled for each scenario.

Ideally, a simulation area is large enough to encompass the entire range of a population so that any animal that approaches the survey area during an operation is included. However, there are limits to the simulation area, and computational overhead increases with area. For practical reasons, the simulation area is limited in this analysis to a maximum distance of 200 km (124.2 miles) from the WF. In the simulation, every animat that reaches a border is replaced by another animat entering at the opposing border—e.g., an animat crossing the northern border of the simulation is replaced by one entering the southern border at the same longitude. When this action places the animat in an inappropriate water depth, the animat is randomly placed on the map at a depth suited to its species definition. This approach maintains a consistent animat density and allows for longer integration periods with finite simulation areas.