Underwater Acoustic Assessment

South Thomson Barge Landing Development

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Prepared for

ROTTNEST ISLAND AUTHORITY

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Acronyms and Abbreviations

°C	degree Celsius
°F	degree Fahrenheit
dB	decibel
dB re 1 µPa	decibels referenced at one micropascal
dBSea	Software for the prediction of underwater noise in a variety of environments
dB/km	decibels per kilometer
HF	high frequency
Hz	hertz
ISO	International Organization for Standardization
kHz	kilohertz
km	kilometers
LF	low frequency
L_E	sound exposure level
$L_{E,24hr}$	24-hour cumulative sound exposure level
$L_{p,rms}$	root-mean-squared sound pressure level
$L_{p,pk}$	peak sound pressure
m/s	meters per second
MF	mid-frequency
MMPA	Marine Mammal Protection Act
NMFS	National Marine Fisheries Service
ppt	parts per thousand
Project	Thomson Bay South Development Project
PK	peak sound pressure level
PTS	permanent threshold shift
RIA	Rottnest Island Authority
RPS	RPS Group
rms	root-mean-square
SEL	sound exposure level
SELcum	cumulative sound exposure level
SPL	sound pressure level
Tetra Tech	Tetra Tech, Inc.

TTS	temporary threshold shift
μPa	micropascal

1.0 INTRODUCTION

1.1 Overview of the South Thomson Barge Landing Development

The Rottnest Island Authority (RIA) proposes the South Thomson Barge Landing Development (Project), situated around the former Army Groyne on Rottnest Island (the site), approximately 30 kilometers (km) west of Perth, Western Australia. The development project is to:

- Facilitate increasing demand for commercial marine services arising from planned infrastructure works;
- Manage barge and logistical movement away from the settlement areas; and
- Improve visitor experience and reduce safety risk.

As part of the Project, the RIA will be constructing a rock armor (breakwater) over the existing army groyne and a 100-meter extension, with a 40-meter concrete deck on steel piles (contingency ferry jetty).

1.2 Scope

Tetra Tech Inc. (Tetra Tech) was contracted to model and assess the sources of underwater noise generated during the construction and installation of the Project. The objective of this modeling assessment was to predict the ranges to acoustic thresholds of marine mammals, sea turtles, and fish, and the potential injury and behavioral acoustic exposures of marine mammals and sea turtles during construction of the Project including impact and vibratory pile driving activities. This report includes information relevant to the assessment of specific noise-producing construction-related activities and their potential to impact protected marine animals that may occur in the Project Study Area, which includes a modeling area extending 5 km away from the piling locations.

2.0 ACOUSTIC METRICS AND TERMINOLOGY

This section outlines some of the relevant concepts in acoustics to help the non-specialist reader best understand the modeling assessment and results presented in this report. Sound is the result of mechanical vibrations traveling through a fluid medium such as air or water. These vibrations constitute waves that generate a time-varying pressure disturbance oscillating above and below the ambient pressure.

It is important to note that underwater sound levels are not equivalent to in-air sound levels, with which most readers would be more familiar. An underwater sound pressure level (SPL or L_p) of 150 decibels (dB) referenced to 1 micropascal (re 1 µPa) is not equivalent to an in-air sound pressure level of 150 dB re 20 µPa due to the differences in density and speed of sound between water and air, and the different reference pressures that are used to calculate the dB levels, i.e., 1 µPa for water and 20 µPa for air. Underwater sound levels can be presented either as overall broadband levels or as frequency-dependent levels showing the frequency content of a source. Broadband values present the total sound pressure level of a given sound source within a specified frequency bandwidth. Sometimes it is preferable to use frequency-dependent sound levels to characterize spectral content of a sound source and/or identify narrowband sources such as one-third octave band levels, which are one-third of an octave wide, wherein octave refers to a factor 2 increase in sound frequency.

The sound level estimates presented in this modeling study are expressed in terms of several metrics and apply the use of exposure durations to allow for interpretation relative to potential biological impacts on marine life. The National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) issued a Technical Guidance that provides acoustical thresholds and defines the threshold metrics (NMFS 2018). The International Organization for Standardization (ISO) 18405 Underwater Acoustics – Terminology (ISO 2017) provided a dictionary of underwater bioacoustics for standardized terminology. Table 1 provides a summary of the relevant metrics from both NMFS (2018) and ISO (2017) that are used within this report.

Table 1. Summary of Acoustic Terminology

Metric	NMFS (2018)	ISO (2017)		Reference Value
		Main Text	Equations and Tables	
Sound Pressure Level	SPL	SPL	L_p	dB re 1 µPa
Peak Sound Pressure Level	PK	L_{pk}	$L_{p,pk}$	dB re 1 µPa
Cumulative Sound Exposure Level	SEL_{cum} 1/	SEL	L_E	dB re 1 µPa²·s

Note:
1/ NMFS (2018) describes the cumulative sound exposure level (SEL_{cum}) metric over an accumulation period of 24 hours. Following the ISO standard, this will be identified as SEL in the text and $L_{E,24h}$ will be used in tables and equations of this report with the accumulation period identified.

This report follows the ISO (2017) standard terminology and symbols for the sound metrics unless stated otherwise. Below are descriptions of the relevant metrics and concepts that should help frame the discussion of acoustics in this document. The majority of the information in the following sections provides further insight into how data and modeling results have been presented in accordance with regulatory reporting requirements and established criteria.

Peak sound pressure (PK or L_{pk} or $L_{p,pk}$; dB re 1 µPa) is the maximum instantaneous noise level over a given event and is calculated using the level of the squared sound pressure from zero-to-peak within the wave. The peak sound pressure level is commonly used as a descriptor for impulsive sound sources. At high intensities, the L_{pk} can be a valid criterion for assessing whether a sound is potentially injurious; however, since it does not take into account the pulse duration or bandwidth of a signal, it is not a good indicator of loudness or potential for masking effects. The L_{pk} can be calculated using the formula in Equation 1. Impulses are characterized by a relatively rapid rise from ambient pressure to a maximal pressure value followed by a decay period that may include a period of diminishing, oscillating maximal and minimal pressures.

$$L_{p,pk} = 10\, log_{10} \left[\frac{max(|p^2(t)|)}{p_0^2}\right]\ dB \qquad (1)$$

Sound pressure level (SPL_{rms} or $L_{p,rms}$; dB re 1 µPa) is the root-mean-square (rms) sound pressure level in a stated frequency band over a specified time window. It is important to note that SPL herewith refers to a rms pressure level and therefore not instantaneous pressure. The SPL is calculated by taking the square root of the average of the square of the pressure waveform over the duration of the time period. The SPL is also known as the quadratic mean and is a statistical measure of the magnitude of a varying quantity. Given a measurement of the time-varying sound pressure from a given sound source, the SPL is computed according to the formula in Equation 2 where p^2 is the mean squared sound pressure and p_0^2 is the reference value of mean-square sound pressure, which is 1 μPa^2.

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

Sound exposure level (SEL or L_E; dB re 1 $\mu Pa^2 \cdot s$) is similar to the SPL but further specifies the sound pressure over a specified time interval or event, for a specified frequency range. The SEL for a single event is calculated by taking the time integral of the squared sound pressure, E_p, over the full event duration as shown in Equation 3:

$$L_E = 10\,log_{10}\left(\int_{T_{100}} p^2(t)dt/T_0 p_0^2\right)\ dB \tag{3}$$

The SEL represents the total acoustic energy received at a given location. Unless otherwise stated, SELs for impulsive noise sources presented in this report, i.e., impact hammer pile-driving, refer to a single pulse. In addition, SEL can be calculated as a cumulative metric over periods with multiple acoustic events. In the case of impulsive sources like impact piling, SEL describes the summation of energy for the entire impulse normalized to 1 second and can be expanded to represent the summation of energy from multiple pulses. The latter is written SEL_{cum} denoting that it represents the cumulative sound exposure level. Sound exposure level is often used in the assessment of marine mammal and fish injury/physiological impacts over a 24-hour time period. The SEL_{cum} (dB re 1 $\mu Pa^2 \cdot s$) can be computed by summing (in linear units) the SEL of N individual events as shown in Equation 4:

$$L_{E,N} = 10\,log_{10}\left(\sum_{i=1}^{N} 10^{\frac{SEL_i}{10}}\right)\ dB \tag{4}$$

3.0 SOUND PROPAGATION IN SHALLOW WATERS

3.1 Seawater Absorption

Absorption in the underwater environment involves conversion of acoustic energy into heat and thereby represents a true loss of acoustic energy to the water. The primary causes of absorption have been attributed to several processes including viscosity, thermal conductivity, and chemical reactions involving ions in the seawater. The absorption of sound energy by water linearly reduces the sound level with range and is given by an absorption coefficient in units of decibels per kilometer (dB/km). The attenuation coefficient is calculated from empirical equations and increases with the square of frequency. For example, for typical open-ocean values (temperature of 50 degrees Fahrenheit (°F) [10 degrees Celsius (°C)], pH of 8.0, and a salinity of 35 practical salinity units, the equations presented by Francois and Garrison (1982a and 1982b) yield the following values for attenuation due to seawater absorption: 0.001 dB/km at 100 hertz (H”), 0.06 dB/km at 1 kilohertz (kHz), 0.96 dB/km at 10 kHz, and 33.6 dB/km at 100 kHz. Thus, low frequencies are favored for long-range propagation. Seawater absorption was accounted for in the acoustic modeling according to the Fisher and Simmons (1977) calculation methodology. Site-specific sound speed profile information was used, resulting in a site-specific sound attenuation rate.

3.2 Scattering and Reflection

Scattering of sound from the surface and bottom boundaries, and from other objects, is difficult to quantify as it is site specific. However, it is valuable in characterizing and understanding the received sound field. Reflection, refraction, and diffraction from gas bubbles and other inhomogeneities in the propagating medium serve to scatter sound and will affect propagation loss, even in relatively calm waters. If boundaries are present, whether “real” like the surface of the sea or “internal” like changes in the physical characteristics of the water, sound propagation is affected. The received acoustic intensity depends on the losses due to the path length as well as the amount of energy reflected from each interface. Multiple reflections may occur as the sound reflects alternately from the sea floor and the sea surface, resulting in constructive and/or destructive interference patterns. Reflections occurring between the sea floor and sea surface are accounted for in the Project acoustic modeling analysis.

Changes in direction of the sound due to variation in sound speed are known as refraction. The speed of sound is not constant with depth and range but depends on the temperature, pressure, and salinity. Of the three factors, the greatest impact on sound velocity is temperature. The change in the direction of the sound wave due to changes in sound speed can produce many complex sound paths. When there is a negative temperature gradient, sound speed decreases with depth, and sound rays bend sharply downward. At some horizontal distance from the sound source, there are regions of low sound intensity where sound rays do not reach, which are known as shadow zones. Variability in sound speed can also produce surface ducts and sound channels that can trap acoustic energy and enable long-distance propagation with minimal losses; for example, the Sound Fixing and Ranging channel, also known as the deep sound channel, acts as an acoustic waveguide and has been used for ocean surveillance and attributed toward increased communication ranges for marine mammals such as fin whales.

Since the inhomogeneities in water are very small compared to the wavelength of the sound signals, this attenuation effect will mostly contribute when the signals encounter changes in bathymetries and propagate through the sea floor and the subsurface. For variable bathymetries, the calculation complexity increases as individual portions of the signal are scattered differently. However, if the acoustic wavelength is much greater than the scale of the seabed non-uniformities, as is most often the case for low-frequency sounds, then the effect of scattering on propagation loss becomes somewhat less important than other factors. Also, scattering loss occurring at the surface due to wave action increases at higher sea states. For reflection from the sea surface, it is assumed that the surface is smooth. While a rough sea surface would increase scattering and transmission loss at higher frequencies, the scale of surface roughness is insufficient to have a significant effect on sound propagation in the near field relative to the source.

3.3 Seabed Absorption

Seabed sediment characteristics influence propagation loss in shallow water due to the repeated reflections and scattering at the water/sea floor interface. For underwater acoustic analysis, shallow water is typically defined as water depths less than 656 feet (200 meters). Depending on the sediment properties, sound may be absorbed or reflected. For example, fine-grained silt and clay absorb sound efficiently, while sand, gravel, and bedrock are more reflective. To model these effects, the most important parameters to consider are the sediment density, sound speed, and acoustic attenuation.

The acoustic properties of different sediment types display a much greater range of variation than the acoustic properties of seawater. A good understanding of these properties and their spatial variation is useful for accurate modeling. Oftentimes it is challenging to obtain site-specific data characterizing the sea floor; however, based on the provided Project data and regional geological mapping, the Project area consists of sand and shell debris (Department of Mines, Industry Regulation and Safety, 2020). Based on geotechnical site investigation, the planned dredging depth for the Project shows a surficial carbonate sand layer overlying a carbonate rock, which is thought to be Tamala limestone (in2Dredging 2024). Therefore, sand and gravel were used as sediment inputs for the underwater acoustic model. Further details pertaining to sediment characteristics are provided in Section 5.4, and in Appendix B, Underwater Sound Propagation Modeling Methodology.

3.4 Cut-off Frequency

Sound propagation in shallow water is essentially a normal mode where a sound wave moves sinusoidally and has its own frequency and the sound channel is an acoustic waveguide. Each mode is a standing wave in the vertical direction that propagates in the horizontal direction at a frequency-dependent speed. Each mode has a cut-off frequency, below which no sound propagation is possible. The cut-off frequency is determined based on the type of bottom material and water column depth. This limiting frequency can also be calculated if the speed of sound in the sediment ($C_{sediment}$) is known (Au and Hastings 2008) and seasonal temperature variation of the speed of sound of the seawater (C_{water}) is known using the following Equation 5:

$$f_c = \frac{C_{water}}{4h} / \sqrt{1 - (C_{water})^2/(C_{sediment})^2} \tag{5}$$

Where: f_c = critical frequency
C_{water} = speed of sound of water
$C_{sediment}$ = speed of sound in sediment
h = water depth in the direction of sound propagation

The speed of sound in sediment is higher than in water. In water, it is approximated at 1,500 meters/second (m/s). Values for speed of sound in sediment in the Project Study Area range from 1,526 m/s to 1,530 m/s. Sound traveling in shallower regions of the Project Study Area will be subject to a higher cut-off frequency and a greater attenuation rate than sound propagating in deeper regions.

Figure 1 graphically presents the cut-off frequency for different bottom material types (represented as separate lines on the figure) plotted as a function of water depth (x-axis) and cut-off frequency (y-axis). As shown, at an approximate water depth of 13 feet (4 meters) and a sea bottom consisting of predominantly rock, which represents the Project Study Area, the cut-off frequency would be expected to occur at approximately 0.08 kHz. For the Project acoustic modeling analysis, the concept of cut-off frequency is incorporated into the modeling calculations through the characterization of sediment properties within the seabed.

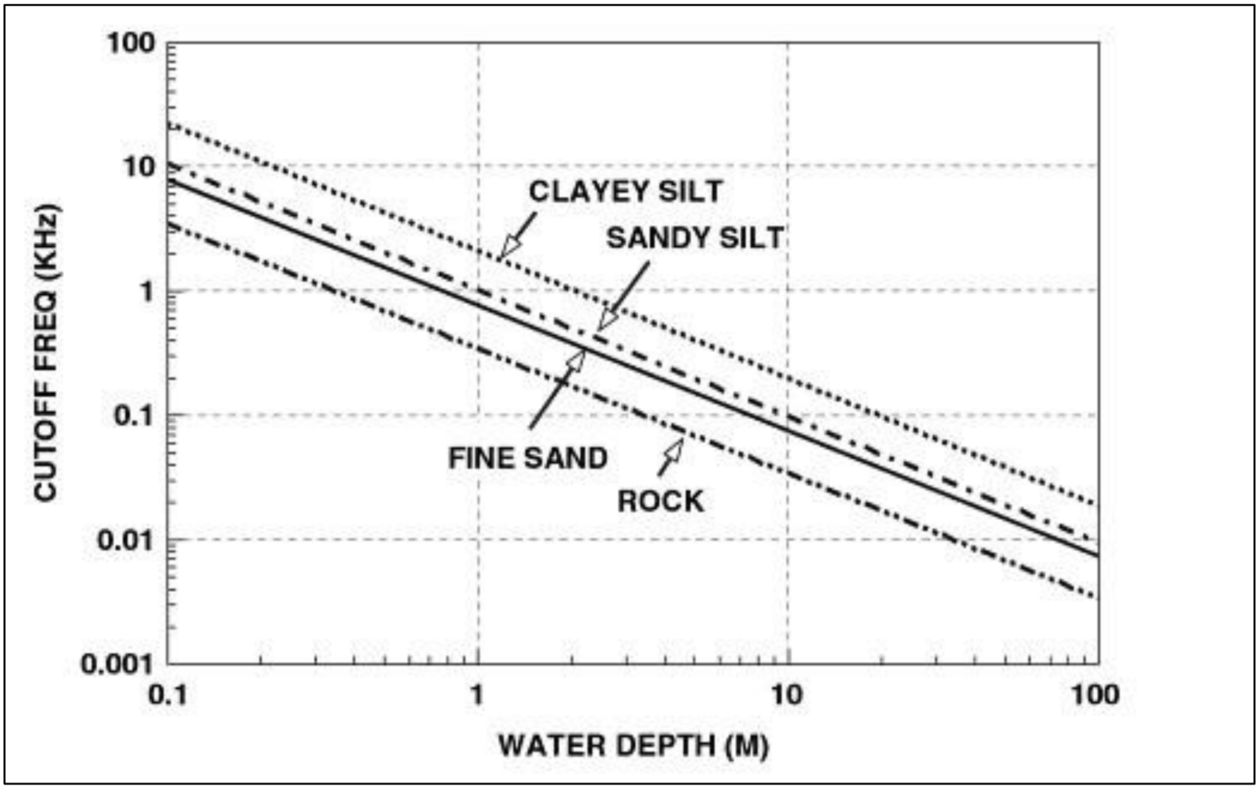

Figure 1. Cut-off Frequencies for Different Bottom Materials (Au and Hastings 2008)

4.0 MARINE FAUNA ASSESSMENT CRITERIA

National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) provided guidance for assessing the impacts of anthropogenic sound on marine mammals under their regulatory jurisdiction, which includes whales, dolphins, porpoises, seals, and sea lions, and updated this guidance in 2018 (NMFS 2018). The guidance specifically defines marine mammal hearing groups; develops auditory weighting functions; and identifies the received levels, or acoustic threshold levels, above which individual marine mammals are predicted to experience changes in their hearing sensitivity (permanent threshold shift [PTS] or temporary threshold shift [TTS]) for acute, incidental exposure to underwater sound. Under this guidance, any occurrence of PTS constitutes a Level A, or injury, take. The sound emitted by man-made sources may induce TTS or PTS in an animal in two ways: (1) peak sound pressure levels ($L_{p,pk}$) may cause damage to the inner ear, and (2) the accumulated sound energy the animal is exposed to (SEL) over the entire duration of a discrete or repeated noise exposure has the potential to induce auditory damage if it exceeds the relevant threshold levels.

Research showed that the frequency content of the sound would play a role in causing damage. Sound outside the hearing range of the animal would be unlikely to affect its hearing, while the sound energy within the hearing range could be harmful. Under the NMFS (2018) guidance, recognizing that marine mammal species do not have equal hearing capabilities, five hearing groups of marine mammals are defined as follows:

- *Low-frequency (LF) Cetaceans*—this group consists of the baleen whales (mysticetes) with a collective generalized hearing range of 7 Hz to 35 kHz.
- *Mid-frequency (MF) Cetaceans*—includes most of the dolphins, all toothed whales except for *Kogia* spp., and all the beaked and bottlenose whales with a generalized hearing range of approximately 150 Hz to 160 kHz (renamed high-frequency cetaceans by Southall et al. [2019] because their best hearing sensitivity occurs at frequencies of several tens of kHz or higher).
- *High-frequency (HF) Cetaceans*—incorporates all the true porpoises, the river dolphins, plus *Kogia* spp., *Cephalorhynchid* spp. (genus in the dolphin family Delphinidae), and two species of *Lagenorhynchus* (Peale's and hourglass dolphins) with a generalized hearing range estimated from 275 Hz to 160 kHz (renamed very high-frequency cetaceans by Southall et al. (2019) since some species have best sensitivity at frequencies exceeding 100 kHz).
- *Phocids Underwater*—consists of true seals with a generalized underwater hearing range from 50 Hz to 86 kHz (renamed Phocids carnivores in water by Southall et al. [2019]).
- *Otariids Underwater*—includes sea lions and fur seals with a generalized underwater hearing range from 60 Hz to 39 kHz (termed Other marine carnivores in water by Southall et al. [2019] and includes otariids, as well as walrus [Family Odobenide], polar bear [*Ursus maritimus*], and sea and marine otters [Family Mustelidae]).

Within these generalized hearing ranges, the ability to hear sounds varies with frequency, as demonstrated by examining audiograms of hearing sensitivity (NMFS 2018; Southall et al. 2019). To reflect higher noise sensitivities at specific frequencies, auditory weighting functions were developed for each functional hearing group that reflected the best available data on hearing ability (composite audiograms), susceptibility to noise-induced hearing loss, impacts of noise on hearing, and data on equal latency (NMFS 2018). These weighting functions are applied to individual sound received levels to reflect the susceptibility of each hearing group to noise-induced threshold shifts, which is not the same as the range of best hearing (Figure 2).

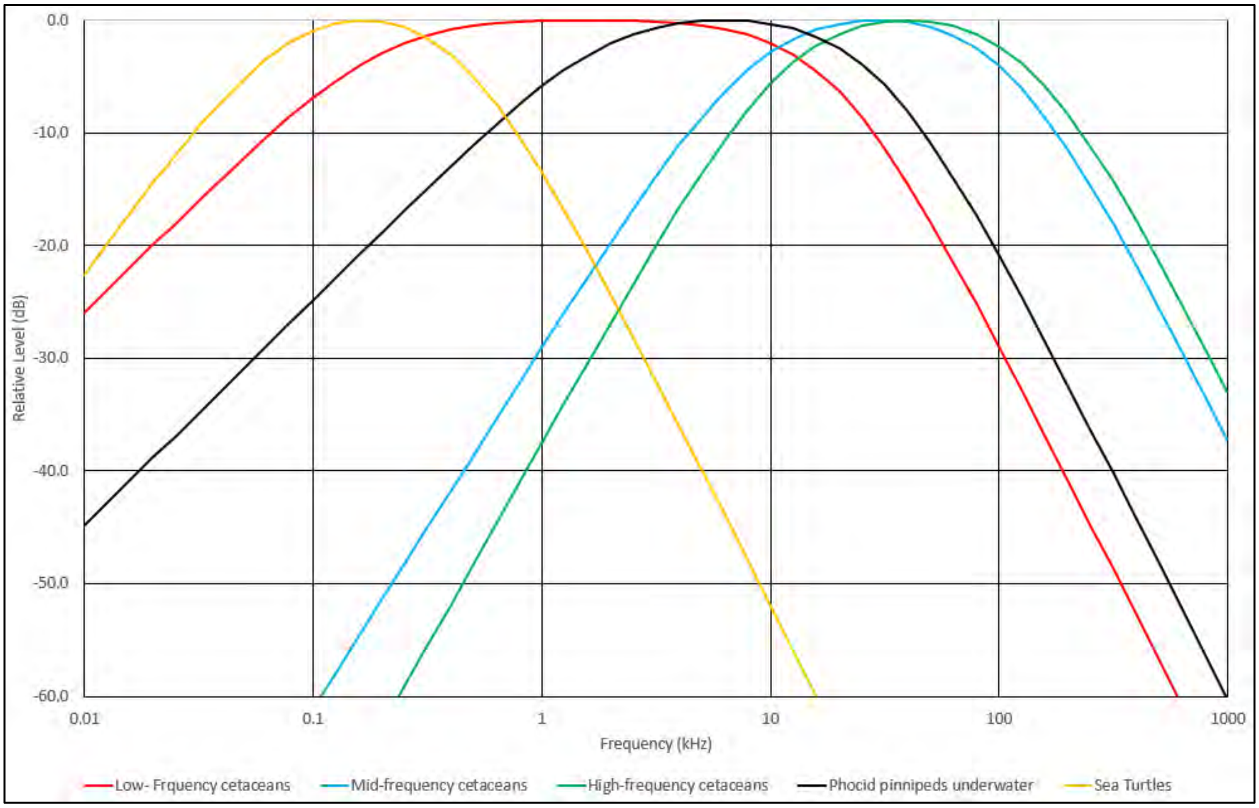

Figure 2. Auditory Weighting Functions for Cetaceans (Low-frequency, Mid-frequency, and High-frequency Species), Pinnipeds in Water from NMFS (2018)

NMFS (2018) defined acoustic threshold levels at which PTS and TTS are predicted to occur for each hearing group for impulsive and non-impulsive signals, which are presented in terms of dual metrics: SEL and $L_{p,pk}$. The Level B harassment thresholds are also provided in Table 2 and were revised by NMFS as interim criteria in 2023.

NMFS anticipates behavioral response for sea turtles from impulsive sources such as impact pile-driving to occur at SPL_{rms} 175 dB, which has elicited avoidance behavior of sea turtles (Table 3; NMFS 2023b; Finneran et al. 2017). There is limited information available on the effects of noise on sea turtles, and the hearing capabilities of sea turtles are still poorly understood. In addition, the U.S. Navy introduced a weighting filter appropriate for sea turtle impact evaluation in their 2017 document titled "Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)." That weighting has been applied to impulsive criterion for PTS (204 dB SEL), impulsive criterion for TTS (189 dB SEL), and non-impulsive criteria for TTS (200 dB SEL and 226 dB $L_{p,pk}$) and PTS (220 dB SEL and 232 dB $L_{p,pk}$). The weighting for sea turtles is presented in Figure 2.

In a cooperative effort between federal and state agencies, interim criteria were developed to assess the potential for injury to fishes exposed to pile-driving sounds. These noise injury thresholds have been established by the Fisheries Hydroacoustic Working Group, which was assembled and subsequently by NMFS as presented in Table 3.

Table 2. Acoustic Threshold Levels for Marine Mammals

Hearing Groups	Impulsive Sounds			Non-Impulsive Sounds		
	PTS Onset	TTS Onset	Behavior	PTS Onset	TTS Onset	Behavior
Low-frequency cetaceans	219 dB ($L_{p,pk}$) 183 ($L_{E,LF,24h}$)	213 dB ($L_{p,pk}$) 168 dB ($L_{E,LF,24h}$)	160 dB (L_p)	199 dB ($L_{E,LF,24h}$)	179 dB ($L_{E,LF,24h}$)	120 dB ($L_{p,rms}$)
Mid-frequency cetaceans	230 dB ($L_{p,pk}$) 185 dB ($L_{E,MF,24h}$)	224 dB ($L_{p,pk}$) 170 dB ($L_{E,MF,24h}$)		198 dB ($L_{E,MF,24h}$)	178 dB ($L_{E,MF,24h}$)	
High-frequency cetaceans	202 dB ($L_{p,pk}$) 155 dB ($L_{E,HF,24h}$)	196 dB ($L_{p,pk}$) 140 dB ($L_{E,HF,24h}$)		173 dB ($L_{E,HF,24h}$)	153 dB ($L_{E,HF,24h}$)	
Phocid pinnipeds underwater	218 dB ($L_{p,pk}$) 185 dB ($L_{E,PW,24h}$)	212 dB ($L_{p,pk}$) 170 dB ($L_{E,PW,24h}$)		201 dB ($L_{E,PW,24h}$)	181 dB ($L_{E,PW,24h}$)	
Otariid pinnipeds underwater	232 dB ($L_{p,pk}$) 203 dB ($L_{E,OW,24h}$)	226 dB ($L_{p,pk}$) 188 dB ($L_{E,OW,24h}$)		219 dB ($L_{E,OW,24h}$)	199 dB ($L_{E,OW,24h}$)	

Sources: Southall et al. (2019); NMFS (2018, 2023a)

$L_{E,24h}$ = cumulative sound exposure level over a 24-hour period (dB re 1 μPa^2·s);
$L_{p,pk}$ = peak sound pressure level (dB re 1 μPa);
L_p = root mean square sound pressure level (dB re 1 μPa)

Table 3. Acoustic Threshold Levels for Fishes and Sea Turtles

Hearing Group	Impulsive Signals		Non-impulsive Signals		Behavior (Impulsive and Non-impulsive)
	Injury	TTS Onset	Injury	TTS Onset	
Fishes	206 dB ($L_{p,pk}$) 187 dB ($L_{E,24h}$)	–	–	–	150 dB ($L_{p,rms}$)
Sea Turtles	232 dB ($L_{p,pk}$) 204 dB ($L_{E,TUW,24h}$)	226 dB ($L_{p,pk}$) 189 dB ($L_{E,TUW,24h}$)	220 dB ($L_{E,TUW,24h}$)	200 dB ($L_{E,TUW,24h}$)	175 dB ($L_{p,rms}$)

Sources: Stadler and Woodbury (2009); NMFS (2018, 2023b); Finneran et al. (2017)

$L_{E,24h}$ = cumulative sound exposure level over a 24-hour period (dB re 1 μPa^2·s);
$L_{p,pk}$ = peak sound pressure level (dB re 1 μPa);
L_p = root mean square sound pressure level (dB re 1 μPa)

A Working Group organized under the American National Standards Institute-Accredited Standards Committee S3, Subcommittee 1, Animal Bioacoustics, also developed sound exposure guidelines for fish and sea turtles (Table 4; Popper et al. 2014). They identified three types of fishes depending on how they might be affected by underwater sound. The categories include fishes with no swim bladder or other gas chamber (e.g., flounders, dab, and other flatfishes); fishes with swim bladders in which hearing does not involve the swim bladder or other gas volume (e.g., salmonids); and fishes with a swim bladder that is involved in hearing (e.g., channel catfish).

Table 4. Acoustic Threshold Levels for Fish, Impulsive and Non-Impulsive

Hearing Groups	Impulsive Sounds			Non-Impulsive Sounds	
	Mortality and Potential Mortal Injury	Recoverable Injury	TTS	Recoverable Injury	TTS
Fishes without swim bladders	> 213 dB ($L_{p,pk}$) > 219 dB ($L_{E,24h}$)	> 213 dB ($L_{p,pk}$) > 216 dB ($L_{E,24h}$)	> 186 dB ($L_{E,24h}$)	–	–
Fishes with swim bladder not involved in hearing	207 dB ($L_{p,pk}$) 210 dB ($L_{E,24h}$)	207 dB ($L_{p,pk}$) 203 dB ($L_{E,24h}$)	>186 dB ($L_{E,24h}$)	–	–
Fishes with swim bladder involved in hearing	207 dB ($L_{p,pk}$) 207 dB ($L_{E,24h}$)	207 dB ($L_{p,pk}$) 203 dB ($L_{E,24h}$)	186 dB ($L_{E,24h}$)	170 dB ($L_{p,rms}$)	158 dB ($L_{p,rms}$)
Eggs and larvae	207 dB ($L_{p,pk}$) 210 dB ($L_{E,24h}$)	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	–	–

Sources: Popper et al. (2014), NMFS 2023b, Finneran et al. (2017)

$L_{E,24h}$ = cumulative sound exposure over a 24-hour period (dB re 1 μPa^2·s);
$L_{p,pk}$ = peak sound pressure (dB re 1 μPa);
L_p = root mean square sound pressure (dB re 1 μPa)
PTS = permanent threshold shift;
N = near (10s of meters);
I = intermediate (100s of meters);
F = far (1000s of meters);
– = not applicable

5.0 UNDERWATER NOISE MODELING METHODOLOGY

Underwater acoustic model simulations were conducted for primary noise-generating activities occurring during Project construction and operation. The following subsections describe the modeling calculations approach, modeled scenarios, and model input values. Please refer to Appendix B for additional details on the modeling principles and assumptions.

5.1 Sound Propagation Model

Underwater sound propagation modeling was completed using dBSea, a software developed by Marshall Day Acoustics for the prediction of underwater noise in a variety of environments. The model is built by importing bathymetry data and placing noise sources in the environment. Each source can consist of equipment chosen from either the standard or user-defined databases. Noise mitigation methods may also be included. The user has control over the seabed and water properties including sound speed profile, temperature, salinity, and current. Noise levels are calculated to the extent of the bathymetry area. To examine results in more detail, levels may be plotted in cross sections, or a detailed spectrum may be extracted at any point in the calculation area. Levels are calculated in third octave bands from 12.5 Hz to 20 kHz. Please refer to Appendix B for additional details on the modeling principles and assumptions.

5.2 Modeling Environment

The accuracy of underwater noise modeling results is largely dependent on the sound source characteristics and the accuracy of the intrinsically dynamic data inputs and assumptions used to describe the medium between the path and receiver, including sea surface conditions, water column, and sea bottom. Depending on the sound source under review, it was approximated as a point source or a line source, composed of multiple points, extending downward into the water column. Furthermore, determining sound emissions for the various sources are based on a combination of factors, including known properties (e.g., hammer energy) as well as consulting empirical data. The exact information required can never be obtained for all possible modeling situations, particularly for long-range acoustic modeling of temporally varying sound sources where uncertainties in model inputs increase at greater propagation distances from the source. Model input variables incorporated into the calculations are further described in the following subsections.

5.3 Bathymetry

For geometrically shallow water (i.e., less than 200 meters), sound propagation is dominated by boundary effects. Bathymetry data represent the three-dimensional nature of the subaqueous land surface and was provided by the client (DoT 2020). The bathymetry is imported into the model and sets the extents for displaying modeled received sound levels; therefore, prior to selecting the bathymetry, coverage test model runs are conducted to determine the anticipated distance to the lowest relevant underwater acoustic threshold values.

5.4 Sediment Characteristics

Sediment type (e.g., hard rock, sand, mud, clay) directly impacts the speed of sound since it is a part of the medium in which the sound propagates. The sea floor composition in the Project area is expected to be predominantly sand and shell substrate (RPS 2019). The geoacoustic properties with information on the compositional data of the surficial sediments were informed by estimated geophysical and geotechnical data. The sediment layers and the geoacoustic properties used in the modeling analysis of the impact piling are defined in Table 5.

Table 5. Geoacoustic Properties of Sub-bottom Sediments as a Function of Depth

Seabed Layer (m)	Material	Geoacoustic Properties
0 to 2	Sand	Cp = 1650 m/s αs (dB/λ) = 0.8 dB/ λ ρ = 1900 kg/m3
2 to 10	Gravel	Cp = 1800 m/s αs (dB/λ) = 0.6 dB/ λ ρ = 2000 kg/m3

5.5 Seasonal Sound Speed Profiles

The speed of sound in sea water depends on the temperature T (°C), salinity S (parts per thousand [ppt]), and depth D (meters), and can be described using sound speed profiles. Often, a homogeneous or mixed layer of constant velocity is present in the first few meters. It corresponds to the mixing of superficial water through surface agitation. There can also be other features such as a surface channel, which corresponds to sound velocity increasing from the surface down. This channel is often due to a shallow isothermal layer appearing in winter conditions but can also be caused by water that is very cold at the surface. In a negative sound gradient, the sound speed decreases with depth, which results in sound refracting downward, which may result in increased bottom losses with distance from the source. In a positive sound gradient as predominantly present in the winter season, sound speed increases with depth and the sound is refracted upward, which can aid in long-distance sound propagation. Pile-driving will take place in the daytime. For the construction modeling scenarios, the average of the February and June sound speed profiles was used. The speed of sound profile information was obtained using the NOAA Sound Speed Manager software incorporating the World Ocean Atlas 2018 extension algorithms (Garcia et al. 2019). Additional details pertaining to the sound speed profile sensitivity analysis conducted for the Project can be found in Appendix B.

5.6 Threshold Range Calculations

To determine the ranges to the defined threshold isopleths, a maximum received level-over-depth approach was used. This approach uses the maximum received level that occurs within the water column at each horizontal sampling point. Both the R_{max} and the $R_{95\%}$ ranges were calculated for each of the regulatory thresholds. The R_{max} is the maximum range in the model at which the sound level calculated. The $R_{95\%}$ is the maximum range at which a sound level was calculated excluding 5% of the R_{max}. The $R_{95\%}$ excludes major outliers or protruding areas associated with the underwater acoustic modeling environment. Regardless of shape of the calculated isopleths the predicted range encompasses at least 95 percent of the horizontal area that would be exposed to sound at or above the specified level. All ranges to injury thresholds presented in his report are presented in terms of the $R_{95\%}$ range.

6.0 ACOUSTIC MODELING SCENARIOS

The Project is in a conceptual phase and as such the engineering details of the piling are not confirmed. Using the current design information, the P1 location was selected for modeling pile-driving acoustical impacts as it is farthest offshore compared to the other piling locations and represents expected worst-case conditions, for example, where propagation would occur through gaps in existing barriers (such as the breakwaters) and for the deepest water conditions. Table 6 and Figure 3 shows the piling locations.

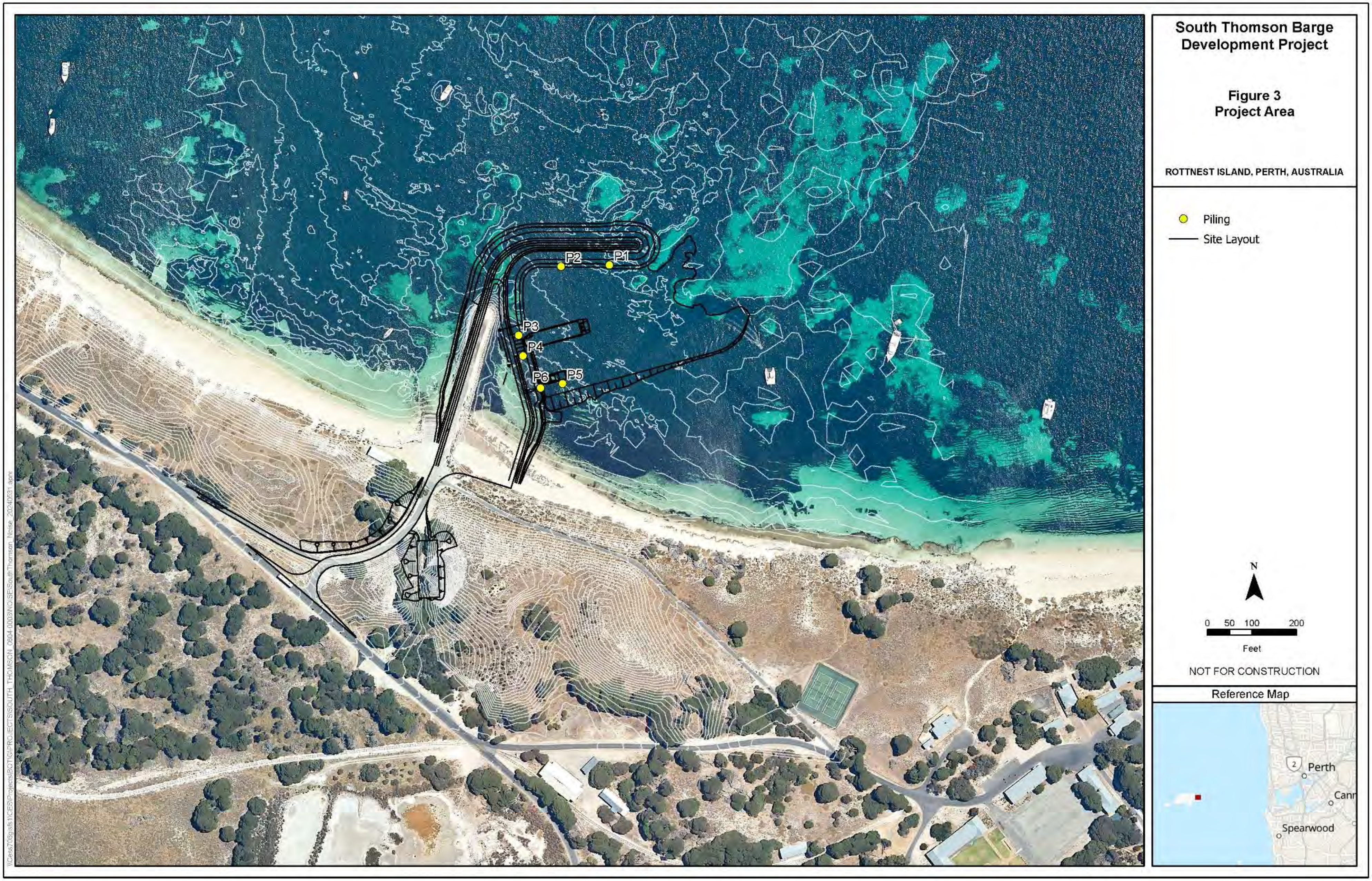

Figure 3. Project Area

Table 6. Piling Coordinates

Piling Locations	Coordinates (UTM Zone 50H)
P1	363112.00 m E, 6458542.00 m S
P2	363079.00 m E, 6458541.00 m S
P3	363050.00 m E, 6458494.00 m S
P4	363053.00 m E, 6458480.00 m S
P5	363080.00 m E, 6458461.00 m S
P6	363065.00 m E, 6458458.00 m S

The representative acoustic modeling scenarios were derived from descriptions of the expected construction activities. The modeled scenarios were chosen to reflect where potential underwater noise impacts of marine species were anticipated and include impact hammer and vibratory hammer associated with pile installation. As discussed above, all modeling scenarios occur at a representative location, which was selected so that the effects of sound propagation at the range of water column depths occurring within the project area could be best observed.

A summary of construction scenarios included in the underwater acoustic modeling analysis is provided in Table 7. The pile diameters selected for the impact pile driving modeling scenarios were based on maximum Project design considerations provided by the RIA. The subsections that follow provide more detailed information about the parameters used to model the noise sources associated with each scenario.

Table 7. Underwater Acoustic Modeling Scenarios

Scenario	Description	Location (UTM Coordinates)	Maximum Hammer Energy (kilojoule)	Total Hammer Blows / Duration[1/]	Source Level
1	Impact pile driving installation, diameter: 24 inches	363112 m, 6458542 m	70	2,838	211 $L_{p,pk}$ 183 $L_{E,ss}$ 193 L_p
2	Vibratory hammer pile installation, diameter: 24 inches	363112 m, 6458542 m	N/A	120 minutes	159 $L_{E,1sec}$

Note:
1/ The total number of blows and duration represents the installation of two piles per day.

Propagation modeling was conducted using the maximum projected blow energy to calculate L_{pk} and SPL; however, a soft start and pile progression were also incorporated into the model to calculate SEL for each pile scenario as shown in Table 8.

Table 8. Impact Pile-Driving Progression Summary

Pile Diameter	Hammer Energy (kilojoule)	Duration (minutes)[1/]	Blows per Minute[2/]	Total Number of Blows[1/]
24 inches	10	18	52	936
	30	10	48	484
	50	10	54	536
	70	18	49	882

Notes:
1/ The total number of blows and duration represents the installation of two piles per day.
2/ Value rounded to the nearest whole number.

6.1 Underwater Noise Generated by Impact Pile Driving

Impact pile driving involves weighted hammers that pile drive foundations into the sea floor. Different methods for lifting the weight associated with the pile driver include hydraulic, steam, or diesel. The acoustic energy is created upon impact; the energy travels into the water along different paths: (1) from the top of the pile where the hammer hits, through the air, into the water; (2) from the top of the pile, down the pile, radiating into the air while traveling down the pile, from air into water; (3) from the top of the pile, down the pile, radiating directly into the water from the length of pile below the waterline; and (4) down the pile radiating into the ground, traveling through the ground and radiating back into the water. Near the pile, acoustic energy arrives from different paths with different associated stage and time lags, which creates a pattern of destructive and constructive interference. Further away from the pile, the water- and seafloor-born energy are the dominant pathways. The underwater noise generated by a pile-driving strike depends primarily on the following factors:

- The impact energy and type of pile-driving hammer;
- The size and type of the pile;
- Water depth; and
- Subsurface hardness in which the pile is being driven.

The acoustic energy radiated into the aquatic environment by a struck pile is directly correlated to the kinetic energy that the impact hammer imparts to it. Engineering considerations about pile penetration and load-bearing capacity dictate that the impact hammer energy must be matched to the pile and to the resistance of the underlying substrate (Parola 1970). Greater hammer impact energy is required for larger diameter piles to achieve the desired load bearing capacity. The water depth also has a strong influence on the acoustic energy propagation in the water column. As water depth increases, the farther the sound will propagate. The site P1, presented in Table 6, has a depth of 4 meters which is representative of the project area where pile driving is expected to occur.

The 24-inch pile driving scenario was modeled using a vertical array of sources spaced at a 0.5-meter array, distributing the sound emissions from pile driving throughout the water column. The vertical array was assigned third-octave band sound characteristics adjusted for site-specific parameters discussed above including expected hammer energy and number of blows. Third octave band center frequencies from 12.5 Hz up to 20 kHz were used in the modeling. The spectra used in the modeling is shown below in Figure 4. This spectrum is based data for similar pile diameters and is scaled to the broadband source levels presented in Table 7, which is based on empirical and measurement data.

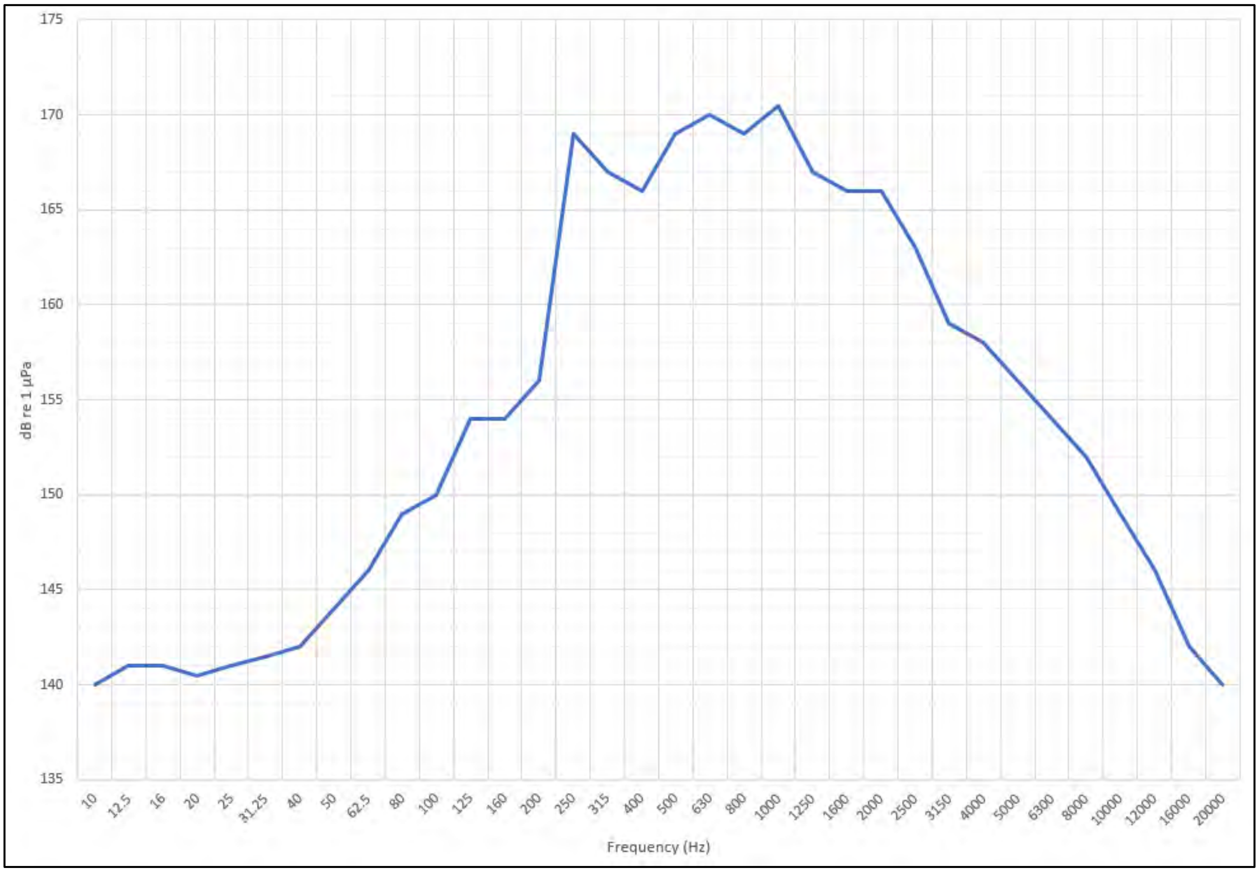

Figure 4. Impact Pile Driving Spectral Source Level

6.2 Underwater Noise Generated by Vibratory Pile Driving

A vibratory hammer will be used for the installation of new piles. Vibratory hammers install piling into the ground by applying a rapidly alternating force to the pile. This is generally accomplished by rotating eccentric weights about shafts. Each rotating eccentric produces a force acting in a single plane and directed toward the centerline of the shaft. The weights are set off-center of the axis of rotation by the eccentric arm. If only one eccentric arm is used, in one revolution, force will be exerted in all directions giving the system significant lateral whip. To avoid this problem, the eccentric arms are paired so the lateral forces cancel each other, leaving only axial force for the pile.

In general, vibratory pile-driving is less noisy than impact pile-driving. Modeling was accomplished using one-third-octave band vibratory hammer source levels from measurements of a similar pile diameter and adjusted to the broadband source levels presented in Table 7. The frequency distribution of the vibratory hammer for pile installation is displayed in Figure 5.

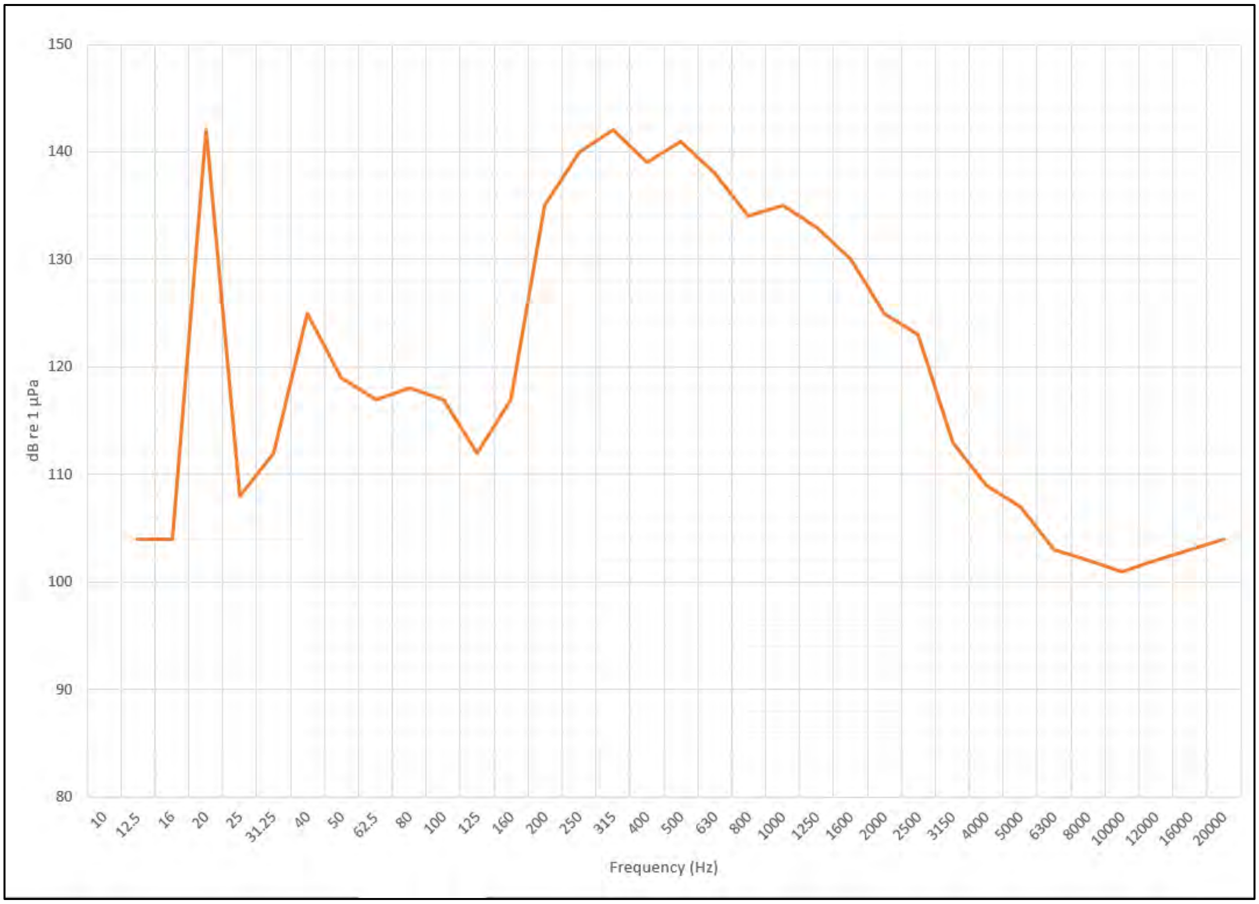

Figure 5. Vibratory Hammer Spectral Source Level

7.0 MODEL RESULTS

As indicated earlier, applying site-specific parameters related to the marine environment and Project sound source characteristics, acoustic modeling was completed using dBSea to assess distances to the various acoustic threshold levels identified in Section 4.0. The analyzed modeling scenarios as described in Table 9 include the following:

- Scenario 1: Impact pile-driving installation for a 24-inch-diameter pile
- Scenario 2: Vibratory hammer installation for a 24-inch-diameter pile

These activities were modeled at a representative location within the Project Study Area. The underwater acoustic modeling results of each of the scenarios are provided in the sections below. Results are presented without mitigation.

Appendix A summarizes the R_{95} distances for the L_{pk} ($L_{p,pk}$), SPL ($L_{p,rms}$), and SEL ($L_{E,24hr}$) metrics. The results of the analysis will be used to inform development of the Project and mitigation measures that will be applied during construction of the Project, in consultation with appropriate regulatory agencies. The Project will obtain the necessary permits to address potential impacts to marine mammals, sea turtles, and other fisheries resources and will establish appropriate and practicable mitigation and monitoring measures through discussions with regulatory agencies. Figure 6 and

Figure 7 show the unweighted and unmitigated underwater received sound pressure levels for each scenario. Underwater sound pressure level ranges are displayed in 5 dB increments and sound propagation characteristics are shown, as applicable, throughout the Project Study Area and beyond.

7.1 Impact Pile Driving Results

7.1.1 Marine Mammal Injury and Behavioral Onset Results

The results for marine mammal injury and behavioral onset for the impact pile driving scenarios are shown in Table 9. The results display trends that are expected, such as increasingly reduced distances as greater levels of noise mitigation are applied. In addition, the smallest distances to thresholds were observed for the L_{pk} acoustic thresholds while the largest distances were observed for the 160 dB SPL_{rms} for the marine mammal behavioral criteria. The largest distance was modeled to be 84 meters corresponding to the 160 dB SPL_{rms} marine mammal behavioral criterion without mitigation for the impact installation of the 24-inch-diameter pile.

Table 9. Marine Mammal Injury and Behavioral Onset Criteria Threshold Distances (meters) for Impact Pile-Driving

Impact Hammer Energy: 70 kJ, Pile Diameter: 24 inches					
Hearing Group	Metric	PTS		TTS	
		Threshold (dB)	Distance (meters)	Threshold (dB)	Distance (meters)
Low-frequency cetaceans	$L_{E,24hr}$ 1/,3/,4/	183	73	168	404
	$L_{p,pk}$ 1/,3/,4/	219	-6/	213	-6/
Mid-frequency cetaceans	$L_{E,24hr}$ 1/,3/,4/	185	-6/	170	36
	$L_{p,pk}$ 1/,3/,4/	230	-6/	224	-6/
High-frequency cetaceans	$L_{E,24hr}$ 1/,3/,4/	155	73	140	500
	$L_{p,pk}$ 1/,3/,4/	202	8	196	18
Phocid pinnipeds	$L_{E,24hr}$ 1/,3/,4/	185	38	170	139
	$L_{p,pk}$ 1/,3/,4/	218	-6/	212	-6/
Otariid pinnipeds	$L_{E,24hr}$ 1/,3/,4/	203	-6/	188	25
	$L_{p,pk}$ 1/,3/,4/	232	-6/	226	-6/
All Marine Mammals	$L_{p,rms}$ 2/,5/	160	84	-	-

Notes:
1/ NMFS 2018
2/ NMFS 2023a
3/ Permanent Threshold Shift (PTS) Onset
4/ Temporary Threshold Shift (TTS) Onset
5/ Behavioral Disturbance
6/ The threshold level is greater than the source level; therefore, distances are not generated.

7.1.2 Fish Injury and Behavioral Onset Results

The results for fish injury and behavioral onset results for fish with no swim bladder, fish with a swim bladder not involved in hearing, fish with swim bladder involved in hearing, eggs and larvae, small fish, and large fish are shown in Table 10. All distance to threshold values were low (i.e., less than 100 meters) except for the distance to the 150 dB SPL_{rms} behavioral threshold criteria. The largest distance was modeled to be 348 meters corresponding to the 150 dB SPL_{rms} fish behavioral criterion without mitigation for the impact installation of the 24-inch-diameter pile.

Table 10. Fish Injury and Behavioral Onset Criteria Threshold Distances (meters) for Impact Pile Driving

Impact Hammer, Energy: 70 kJ, Pile Diameter: 24 inches			
Hearing Group	Metric	Threshold (dB)	Distance (meters)
Fish: no swim bladder	$L_{E,24hr}$ [1/,2/]	219	-[6/]
	$L_{p,pk}$ [1/,2/]	213	-[6/]
Fish: swim bladder is not involved in hearing	$L_{E,24hr}$ [1/,2/]	210	-[6/]
	$L_{p,pk}$ [1/,2/]	207	-[6/]
Fish: swim bladder involved in hearing	$L_{E,24hr}$ [1/,2/]	207	4
	$L_{p,pk}$ [1/,2/]	207	-[6/]
Eggs and larvae	$L_{E,24hr}$ [1/,2/]	210	-[6/]
	$L_{p,pk}$ [1/,2/]	207	-[6/]
Small fish	$L_{E,24hr}$ [3/,4/]	183	76
	$L_{p,pk}$ [3/,4/]	206	2
	L_p [5/]	150	348
Large fish	$L_{E,24hr}$ [3/,4/]	187	52
	$L_{p,pk}$ [3/,4/]	206	2
	$L_{p,rms}$ [5/]	150	348

Notes:
[1] Popper et al. 2014
[2] Mortality and Potential Mortal Injury
[3] Stadler and Woodbury 2009
[4] Small fish are fish less than 2 grams in weight. Large fish are 2 grams or larger.

[6] The threshold level is greater than the source level; therefore, distances are not generated.

7.1.3 Sea Turtle Injury and Behavioral Onset Results

The results for sea turtle injury and behavioral onset results are shown in Table 11. All distance to threshold values were low (i.e., less than 50 meters). The largest distance was modeled to be 37 meters corresponding to the 175 dB SPL_{rms} marine mammal behavioral criterion without mitigation for the impact installation of the 24-inch-diameter pile.

Table 11. Sea Turtle Injury and Behavioral Onset Criteria Threshold Distances (meters) for Impact Pile Driving

Impact Hammer, Energy: 70 kJ, Pile Diameter: 24 inches			
Hearing Group	Metric	Threshold (dB)	Distance (meters)
Sea Turtle Temporary Threshold Shift	$L_{E,24hr}$ [1/,3/]	189	30
	$L_{p,pk}$ [1/,3/]	226	-[4/]
Sea Turtle Permanent Threshold Shift	$L_{E,24hr}$ [1/,3/]	204	3
	$L_{p,pk}$ [1/,3/]	232	-[4/]
Sea Turtle Behavioral	$L_{p,rms}$ [2/,3/]	175	37

Impact Hammer, Energy: 70 kJ, Pile Diameter: 24 inches			
Hearing Group	Metric	Threshold (dB)	Distance (meters)

Notes:
1/ NMFS 2018
2/ NMFS 2023b
3/ Finneran et al. 2017
4/ The threshold level is greater than the source level; therefore, distances are not generated.
kJ = kilojoule

7.2 Vibratory Hammer Pile Installation Results

7.2.1 Marine Mammal Injury and Behavioral Onset Results

The results for marine mammal injury and behavioral onset for the vibratory hammer pile installation scenarios are shown in Table 12. The smallest distances to thresholds were observed for the SEL acoustic thresholds while the largest distances were observed for the 120 dB SPL_{rms} marine mammal criteria. The largest distance was modeled to be 167 meters corresponding to the 120 dB SPL_{rms} criterion without mitigation for the vibratory installation of the 24-inch pile diameter.

Table 12. Marine Mammal Injury and Behavioral Onset Criteria Threshold Distances (meters) for Vibratory Hammer Pile Installation

Vibratory Hammer, Pile Diameter: 24 inches					
		PTS		TTS	
Hearing Group	Metric	Threshold (dB)	Distance (meters)	Threshold (dB)	Distance (meters)
Low-frequency cetaceans	$L_{E,24hr}$ 1/,3/,4/	199	-6/	179	19
Mid-frequency cetaceans	$L_{E,24hr}$ 1/,3/,4/	198	-6/	178	-6/
High-frequency cetaceans	$L_{E,24hr}$ 1/,3/,4/	173	-6/	153	-6/
Phocid pinnipeds	$L_{E,24hr}$ 1/,3/,4/	201	-6/	181	-6/
Otariid pinnipeds underwater	$L_{E,24hr}$ 1/,3/,4/	219	-6/	199	-6/
All Marine Mammals	$L_{p,rms}$ 2/,5/	120	167	-	-

Notes:
1/ NMFS 2018
2/ NMFS 2023a
3/ Permanent Threshold Shift (PTS) Onset
4/ Temporary Threshold Shift (TTS) Onset
5/ Behavioral Disturbance
6/ The threshold level is greater than the source level; therefore, distances are not generated.

7.2.2 Fish Injury and Behavioral Onset Results

The results for fish injury and behavioral onset results for small fish and large fish are shown in Table 13. All distance to threshold values were low (i.e., less than 50 meters). The largest distance of 21 meters occurred for unmitigated distance to the 183 dB SEL acoustic threshold for the vibratory installation of the 24-inch pile diameter.

Table 13. Fish Injury and Behavioral Onset Criteria Threshold Distances (meters) for Vibratory Hammer Pile Installation

Vibratory Hammer, Pile Diameter: 24 inches			
Hearing Group	Metric	Threshold (dB)	Distance (meters)
Small fish	$L_{E,24hr}$ 3/,4/	183	16
	L_p 5/	150	6
Large fish	$L_{E,24hr}$ 3/,4/	187	21
	$L_{p,rms}$ 5/	150	6

Notes:
1/ Popper et al. 2014
2/ Mortality and Potential Mortal Injury
3/ Stadler and Woodbury 2009
4/ Small fish are fish less than 2 grams in weight. Large fish are 2 grams or larger.

7.2.3 Sea Turtle Injury and Behavioral Onset Results

The results for sea turtle injury and behavioral onset results are shown in Table 14. There were not associated distances because the thresholds are greater than the source level.

Table 14. Sea Turtle Injury and Behavioral Onset Criteria Threshold Distances (meters) for Vibratory Hammer Pile Installation

Vibratory Hammer, Pile Diameter: 24 inches			
Hearing Group	Metric	Threshold (dB)	Distance (meters)
Sea Turtle Temporary Threshold Shift	$L_{E,24hr}$ 1/,3/	200	-4/
Sea Turtle Permanent Threshold Shift	$L_{E,24hr}$ 1/,3/	220	-4/
All Sea Turtles	$L_{p,rms}$ 2/,3/	175	-4/

Notes:
1/ NMFS 2018
2/ NMFS 2023b
3/ Finneran et al. 2017
4/ The threshold level is greater than the source level; therefore, distances are not generated.

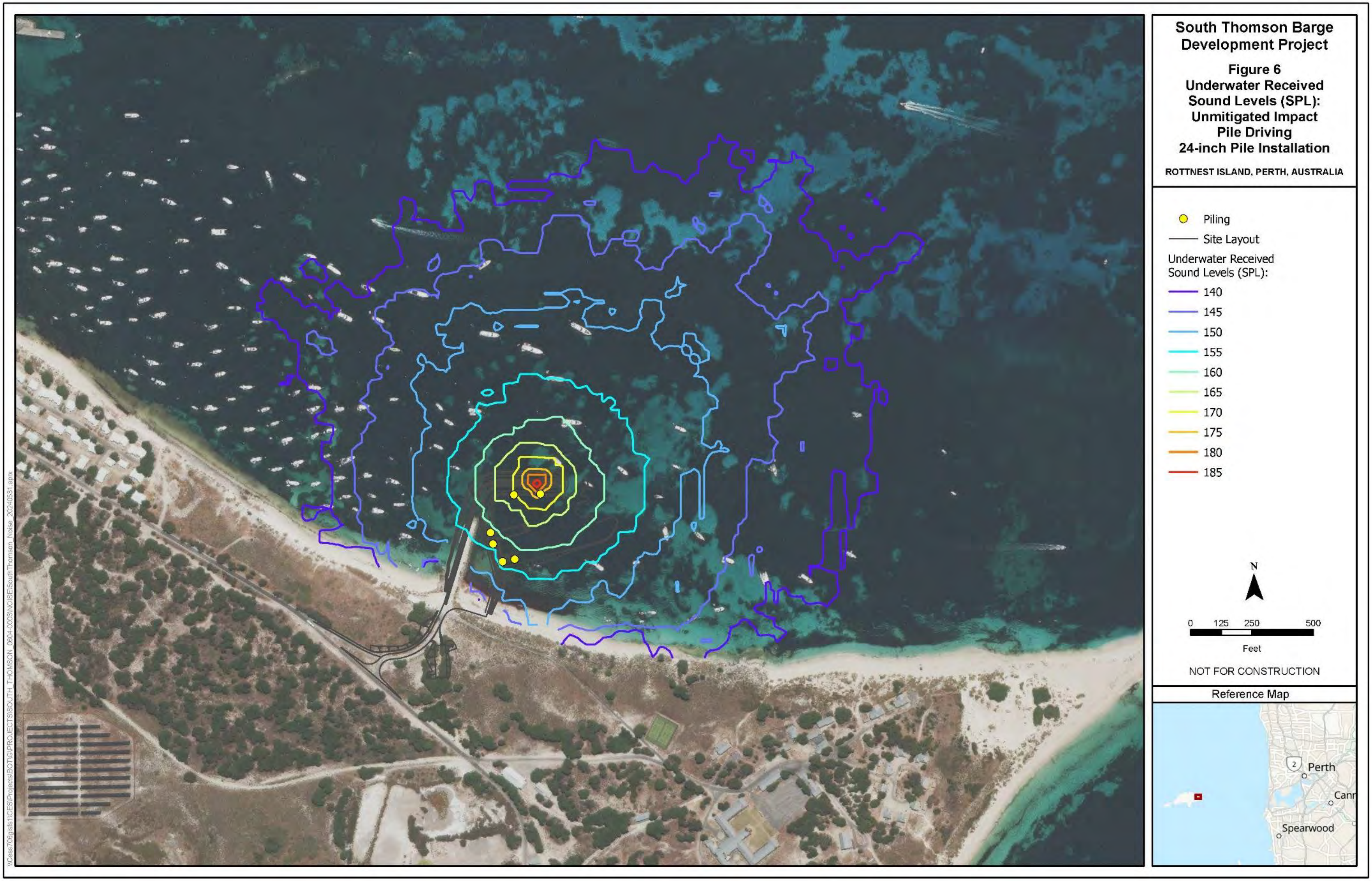

Figure 6. Underwater Received Sound Levels (SPL): Unmitigated Impact Pile Driving 24-inch Pile Installation

Figure 7. Underwater Received Sound Levels (SPL): Unmitigated Vibratory 24-inch Pile Installation

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APPENDIX A. SUMMARY OF ACOUSTICAL DISTANCES

IMPACT PILE DRIVING SUMMARY TABLES

Peak Sound Pressure Thresholds

Table A-1. Summary of R95% Ranges (in meters) to Lpk due to Impact Pile Driving of 24-inch Pile

Attenuation (dB)	$L_{p,pk}$ dB re 1 µPa											
	232	230	226	220	219	218	213	210	207	206	202	200
0	0	0	0	0	0	0	0	0	0	2	8	14

SPL_{rms} Thresholds

Table A-2 Summary of $R_{95\%}$ Ranges (in meters) to SPL_{rms} due to Impact Pile Driving of 24-inch Pile

Attenuation (dB)	L_p dB re 1 µPa								
	210	200	190	180	175	170	160	150	140
0	0	0	0	14	20	37	84	348	537

SEL Thresholds (Unweighted)

Table A-3 Summary of $R_{95\%}$ Ranges (in meters) to Unweighted Cumulative SEL due to Impact Pile Driving of 24-inch Pile

Attenuation (dB)	$L_{E,24hr}$ dB re 1 µPa²·s							
	220	219	210	207	200	187	183	180
0	0	0	0	4	16	52	76	106

SEL Thresholds (Weighted)

Table A-4 Summary of $R_{95\%}$ Ranges (in meters) to Cumulative SEL for Marine Mammals and Turtles Functional Hearing Groups due to Impact Pile Driving of 24-inch Pile

Attenuation (dB)	$L_{E,24hr}$ dB re 1 µPa²·s						
	LF 183	MF 185	HF 155	PP 185	OW 203	TU 204	TU 189
0	73	0	68	36	0	3	30

VIBRATORY HAMMER SUMMARY TABLES

SPL_{rms} Thresholds

Table A-5 Summary of $R_{95\%}$ Ranges (in meters) to SPL_{rms} due to Vibratory Hammer Installation of 24-inch Pile

Attenuation (dB)	L_p dB re 1 µPa									
	210	200	190	180	175	170	160	150	140	120
	0	0	0	0	0	0	0	6	29	176

SEL Thresholds (Unweighted)

Table A-6 Summary of $R_{95\%}$ Ranges (in meters) to Unweighted Cumulative SEL due to Vibratory Hammer Installation of 24-inch Pile

Attenuation (dB)	$L_{E,24hr}$ dB re 1 μPa²·s						
	220	219	210	200	187	183	180
0	0	0	0	0	7	16	22

SEL Thresholds (Weighted)

Table A-7 Summary of $R_{95\%}$ Ranges (in meters) to Cumulative SEL for Marine Mammal Functional Hearing Groups due to Vibratory Hammer Installation of 24-inch Pile

Attenuation (dB)	$L_{E,24hr}$ dB re 1 μPa²·s						
	LF 199	MF 198	HF 173	PP 201	OW 219	TU 220	TU 200
0	0	0	0	0	0	0	0

APPENDIX B. UNDERWATER SOUND PROPAGATION MODELING INPUTS

Underwater Sound Propagation Modeling Methodology

Tetra Tech has developed a reliable and effective approach to evaluating underwater acoustic impacts from pile driving as well as other in-water activities. The underwater noise modeling methodology used to evaluate the Project pile driving activities is described below.

Underwater Sound Propagation Modeling

Tetra Tech uses dBSea for underwater sound propagation modeling. dBSea is a software program developed by Marshall Day Acoustics and Irwin Carr Consulting for the prediction of underwater noise. The three-dimensional model is built by importing bathymetry data and placing noise sources in the environment. Each source can consist of equipment chosen from either the standard or user-defined databases. Noise mitigation methods may also be included. The user has control over the seabed and water properties including sound speed profile ("SSP"), temperature, salinity, and current.

Noise levels are calculated throughout the entire Project Area and displayed in three dimensions. Levels are calculated in third octave bands. For the Project, two different solvers are used for the low- and high-frequency ranges:

- dBSeaModes (Normal Modes Method): The normal models are calculated for each water depth, based on sediment properties and water SSP. The sound field is calculated based on coupling between the calculated modes across the interfaces between different depths. The calculation is of the adiabatic, single forward scattering type. The overlying space is modelled as a vacuum. dBeaModes is suitable where the frequency is low and/or the water depth is shallow. The sediment layer is extended down well below the depth of the water column, with the attenuation rapidly increasing at the lowest depths. In this way, there are no modes where energy is reflected from the very bottom of the sediment layer (the space underneath the bottom of the sediment is also a vacuum).
- dBSeaRay (Ray Tracing Method): The dBSeaRay solver forms a solution by tracing rays from the source to the receiver. Many rays leave the source covering a range of angles, and the sound level at each point in the receiving field is calculated by coherently summing the components from each ray. This is currently the only computationally efficient method at high frequencies.

The specific parameters used in the modeling analysis are described below.

Calculation Grid and Source Solution Setup

The calculation grid and source solution setup are based on the resolution and extents of the bathymetry data. The calculations within dBSea are made along each radial for each range point and depth point. Radials are generated from the source location out to the extent of the bathymetry area. The range points are generated along each radial and are evenly spaced out (range step). However, this spacing does not change if the source is moved. The number of "Radial slices" and "Range points" are entered, which represents the number of radial solution slices for each source and the evaluation range points along those slices (Figure B-1). The range points are determined based on the width and length of the modeled area as well as the required range step resolution (Equation B-1).

$$Range\ Points = \frac{\sqrt{Width^2 + length^2}}{\text{Range Step}} \quad (6)$$

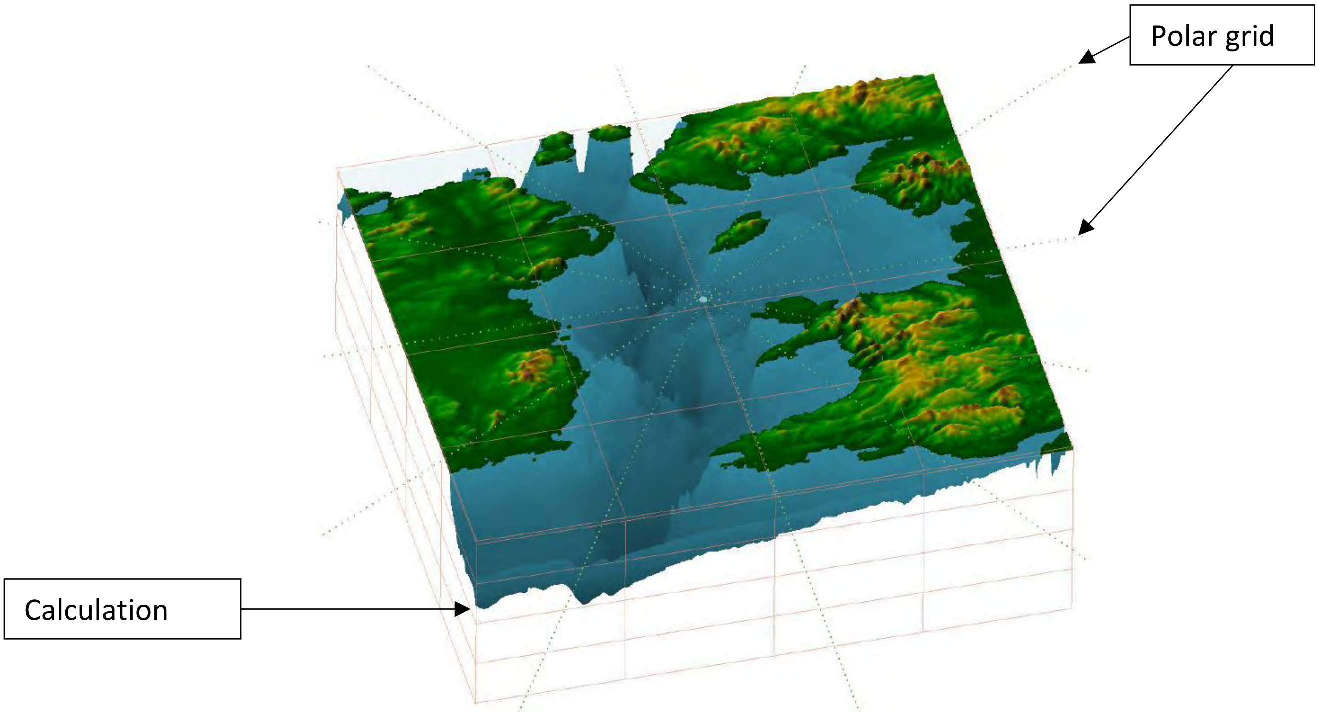

Figure B-1. Example Radial Solution Points

dBSea source solution calculations are completed along the radials (polar grid) based on the defined range and depth points. The calculation grid (cartesian) is filled from the polar grid using the nearest neighbor sampling, i.e., a point in the calculation results grid takes the value of the closest point in the polar grid. The calculation steps in dBSea are summarized below:

- Calculations are done in the polar grid (radials) at multiple depths, which are the same depths as the (cartesian) calculation grid.
- The calculation of the polar grid is smoothed with a triangular kernel, the width of which is selected by the user.
- The results of the cartesian grid is filled by the nearest neighbor sampling from the calculated polar grid using an inverse distance.

The more radials and range points used, the less interpolation needed for the cartesian grid. Because the calculation happens in the polar grid, while the results grid is cartesian, every point in the cartesian grid is “filled” depending on what point of the polar grid it is closest to (Figure B-2).

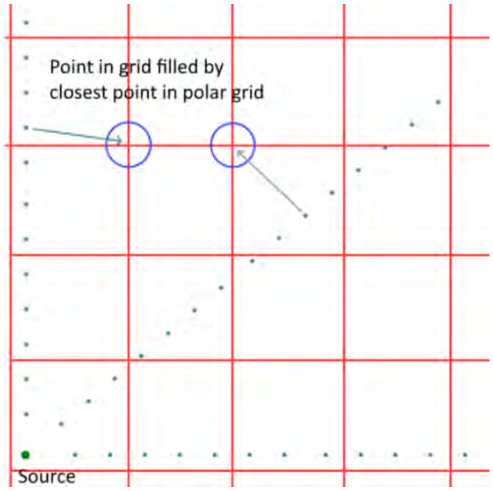

Figure B-2. Example Cartesian Grid Calculation

The underwater acoustic modeling analysis for the Project used a split-solver, with dBSeaModes evaluating the 12.5 Hz to 1 kHz range and dBSeaRay addressing the 1.2 kHz to 20 kHz range. The radial resolution was 10-degree intervals to the extent of the bathymetry. The specific parameters used in the modeling analysis are described below.

Bathymetry

Bathymetry data for Rottnest Island and shoreline surrounding the Army Groyne was provided by the Project. This data included bathymetric multibeam and LiDAR survey data and was obtained from the Government of Australia Department of Transport (DoT 2020). Bathymetric extents for the model were chosen to be 5 km x 5 km and the water depth within that extent ranges from 0 to 37 meters.

Sediment Characteristics

The geoacoustic properties of the surficial sediments by site-specific geophysical and geotechnical data provided by the Project. Based on a regional geological mapping at the site, it consists of sand, quartz, and shell debris (Department of Mines, Industry Regulation and Safety, 2020). The sediment profile is presented in Table B-1 and directly input into dBSea for each defined sediment layer. The parameters entered for each sediment layer is bulleted below:

- Sediment layer depth (provided by the client)
- Material name (provide by the client)
- Speed of sound (meters/second)
- Density (kilograms per cubic meter)
- Attenuation (dB/wavelength)

The acoustic parameters (speed of sound, density, and attenuation) are typically taken from Jensen et al. (2011), Hamilton (1976, 1982), and Hamilton and Bachman (1982).

Table B-1. Geoacoustic Properties of Sub-bottom Sediments as a Function of Depth

Depth	Speed of Sound	Geoacoustic Properties
0 to 2	Sand	Cp = 1650 m/s αs (dB/λ) = 0.8 dB/ λ ρ = 1900 kg/m³
2 to 10	Gravel	Cp = 1800 m/s αs (dB/λ) = 0.6 dB/ λ ρ = 2000 kg/m³

Sources: Shannon & Wilson (2018) and Jensen (2011)

Speed of Sound Profile

Sound speed profile information for the year was obtained per month for the construction period. The speed of sound profile was obtained using the NOAA Sound Speed Manager software incorporating the World Ocean Atlas 2018 extension algorithms (Garcia et al. 2019). Pile-driving will take place from February to June, and only taking place in the daytime. For the construction modeling scenarios, the average sound speed profile for the construction period was used in the model. The average sound speed profile was directly input into the dBSea model, and the input is shown in Figure B-3.

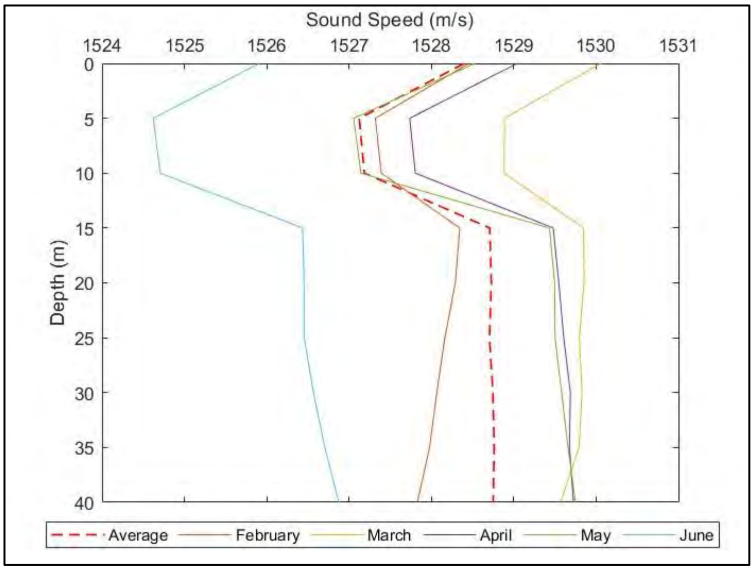

Figure B-3. Sound Speed Profile

Pile Driving Sound Source Characterization

The pile-driving sound source level was represented using three different metrics: peak sound level (L_{pk} [$L_{p,pk}$]), sound exposure level (SEL [$L_{E,24h}$]), and sound pressure level (SPL [$L_{p,rms}$]). The sound source spectrum is entered for each one-third octave band from 12.5 Hz to 20kHz.

For the L_{pk} underwater acoustic modeling scenario, the pile-driving sound source was represented as a point source at mid-water depth. The L_{pk} scenario evaluates a single pile-driving strike.

For the SEL underwater acoustic modeling scenario, the pile-driving sound source was represented by a moving source, which accounts for the speed of sound of steel for the pile itself. The pile-driving scenarios were modeled using a vertical array of point sources spaced at 0.5-meter intervals. Using the SEL level calculated by the empirical model, the SEL sound source is calculated using the following equation to distribute the sound emissions across the vertical array:

$$L_{E,N} = L_{E,\,1\,strike} + 10*\text{Log}(N) \qquad \text{(B-1)}$$

Where:

N is the number strikes

$L_{E,\,1\ strike}$ is the sound exposure level for a single strike

The SPL underwater acoustic modeling scenario is set up identical to the SEL underwater acoustic modeling scenario. The difference regarding the SPL underwater acoustic modeling scenario is that the total number of anticipated pile-driving blows in the 24-hour assessment period is not incorporated into the calculation. For the SPL underwater acoustic modeling scenario, only a single pile-driving strike is evaluated.

Vibratory Hammer Sound Source Characterization

The vibratory hammer source was modeled as a point source at mid-water depth. The source spectrums were entered for each one-third octave band from 12.5 Hz to 20 kHz. The sound source level was empirically obtained from published data as well as the Pile Driving Noise Measurements for Chevron Long Wharf Maintenance and Efficiency Project report (Illingworth & Rodkin 2020).

Time Domain Considerations

Tetra Tech also recognizes the effect time has on pile driving sound. As Bellman (2020) reports, the noise of a single strike is thus temporally stretched with increasing distance. Additionally, the amplitude decreases steadily with the distance to the source, so that the signal-to-noise-ratio continuously decreases. Figure B-4 from Bellman (2020) illustrates the change in signal over time.

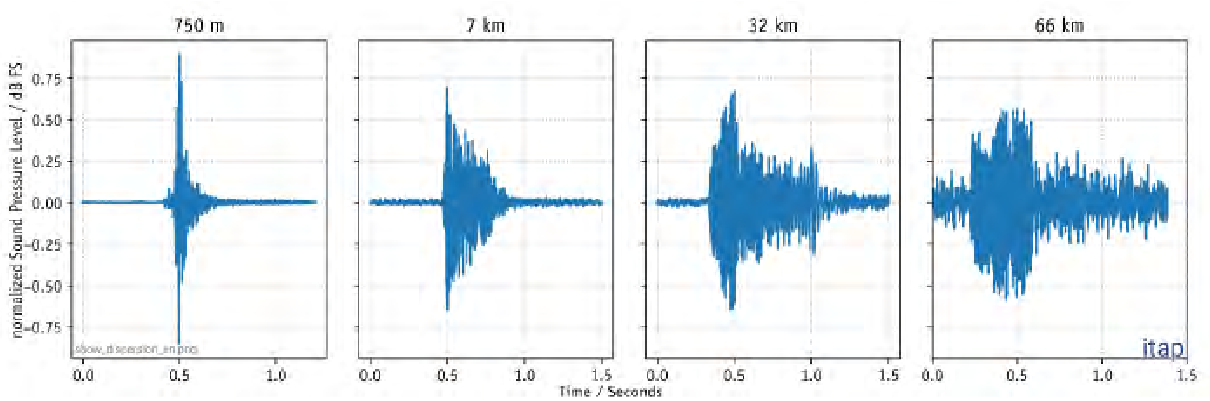

Figure B-4. Time Signal of a Single Strike, Measured in Different Distances to the Pile-Driving Activity (Bellman 2020)

The L_{pk} levels tend to decrease faster than the SEL sound levels as the propagation occurs. There are mixed views on whether the impulsivity of signals decrease over time, suggesting that non-impulsive limits should be applied to assess underwater acoustic impacts. While impulsivity may decrease, it is still observed that the rise times associated with impulsive signals are maintained (Martin et al. 2020). This is especially true when considering the narrow temporal windows (high temporal resolution) of many cetaceans and after application of weightings, excluding lower frequencies.

dBSea can account for the effects of the time domain using two different mechanisms. If time series information is available for use in the modelling analysis, it can be directly loaded into dBSea and used as sound source. The gaussian beam raytracer (dBSeaRay) will calculate the paths and arrival times from the source to all receiver points in the scenario for all the rays emitted from the source. At every receiver point, the transmission loss, phase inversion from the surface, loss to the sediment, and time of arrival is stored. This information is used to convolve all ray-arrivals into a single signal at that point. This means that each receptor point will receive a signal from many perceived origins and at various arrival times (depending on the length of the path travelled). This tends to “smooth” out and stretch the received signal at greater ranges or with more reflections.

Alternatively, if time series data are not known or available, dBSea can include a crest factor, which is a way to incorporate impulsiveness information into the source. The crest factor indicates the dB level above the rms level of the highest peak in the signal. It is applied when assessing peak levels and is applied to all frequency bands. Application of the crest factor is generally expected to yield more conservative results relative to using a time series for characterizing pile-driving sound source levels. Since time series data for the Project’s pile-driving activities were not available at the time of the modelling analysis, Tetra Tech used the conservative crest application methodology.

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