Scarborough Mermaid Sound Pile Driving Modelling Study

Acoustic Modelling for Assessing Marine Fauna Sound Exposures

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Contents

EXECUTIVE SUMMARY 1

1. INTRODUCTION 3

1.1. Modelling Scenario Details 4

2. NOISE EFFECT CRITERIA 5

2.1. Marine Mammals 5

2.1.1. Behavioural response 6

2.1.2. Injury and hearing sensitivity changes 6

2.2. Fish, Turtles, Fish Eggs, and Fish Larvae 6

3. METHODS 9

3.1. Modelling Overview 9

3.2. Modelling Approach 9

3.2.1. Per-strike Modelling 9

3.2.2. Accumulated SEL Modelling 10

4. RESULTS 11

4.1. Pile Driving 11

4.1.1. Per-strike sound fields 11

4.1.2. Multiple Strike Sound Fields 17

5. DISCUSSION AND SUMMARY 20

5.1. Pile Driving 20

5.1.1. Acoustic propagation 20

5.1.2. Marine mammals 21

5.1.3. Fish, turtles, fish eggs, and fish larvae 21

LITERATURE CITED 23

APPENDIX A. ACOUSTIC METRICS A-1

APPENDIX B. PILE DRIVING ACOUSTIC SOURCE MODEL B-1

APPENDIX C. SOUND PROPAGATION MODELS C-1

APPENDIX D. METHODS AND PARAMETERS D-1

Figures

Figure 1. Overview of the pile driving modelling site and features. 3
Figure 2. Force (in meganewtons) at the top of the pile corresponding to impact pile driving of 1.524 m diameter piles 9
Figure 3. One-third-octave-band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving after high-frequency extrapolation 11
Figure 4. Sound level contour map showing unweighted maximum-over-depth SPL results for a 4 m penetration depth. 14
Figure 5. Sound level contour map showing maximum-over-depth SEL results for a 4 m penetration depth. 15
Figure 6. Sound level contour map showing unweighted maximum-over-depth SPL results for a 10 m penetration depth. 15
Figure 7. Sound level contour map showing maximum-over-depth SEL results for a 10 m penetration depth. 16
Figure 8. Sound level contour map showing unweighted maximum-over-depth SPL marine mammal (160 dB re 1 µPa) behavioural criteria results for all modelled penetration depths. 16
Figure 9. Predicted SPL for 4 m penetration as a vertical slice, for (top) 0–0.1 km and (bottom) 0–8 km. 17
Figure 10. Predicted SPL for 10 m penetration as a vertical slice, for (top) 0–0.1 km and (bottom) 0–8 km. 17
Figure 11. Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for PTS in low-, mid-, and high-frequency cetaceans. 19
Figure 12. Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths relevant to fish injury and TTS. 19

Figure A-1. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2018). A-4
Figure B-1. Physical model geometry for impact driving of a cylindrical pile B-1
Figure D-1. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. D-1
Figure D-2. The modelling sound speed profile corresponding to June D-2

Tables

Table 1. Summary of permanent and temporary threshold shift (PTS and TTS) onset distances for marine mammals. 1
Table 2. Location details for the modelled site. 3
Table 3. Acoustic effects of impulsive noise on marine mammals: Unweighted SPL, SEL_{24h}, and PK thresholds 5
Table 4. Criteria for pile driving noise exposure for fish 7
Table 5. Total number of strikes and driving time. 10
Table 6. *Modelled maximum-over-depth per-strike SEL isopleths:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile. 12
Table 7. *Modelled maximum-over-depth SPL isopleths:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile. 12
Table 8. *SPL marine mammal and turtle behavioural response thresholds*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the piles to modelled maximum-over-depth isopleths per penetration depth. 12
Table 9. *Marine mammal PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (in m) from the pile to maximum-over-depth isopleths. 13

Table 10. *Mortality and potential mortal recoverable injury thresholds (peak pressure level metric) for fish, fish eggs, and fish larvae*: Maximum (R_{max}) horizontal distances (in m) from the pile. 13
Table 11. *Turtle peak pressure injury thresholds*: Maximum (R_{max}) horizontal distances (in m) from the pile to thresholds (PTS and TTS) for turtles. 13
Table 12. Maximum-over-depth distances (in km) to SEL_{24h} based marine mammal PTS and TTS thresholds NMFS (2018). 18
Table 13. Maximum-over-depth distances (in km) to SEL_{24h} based fish criteria. 18
Table 14. Summary of marine mammal PTS and TTS onset distances. 21

Table A-1. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2018). A-3
Table D-1. Geoacoustic profile used in the acoustic propagation models. D-3

Executive Summary

Acoustic models were used to predict underwater noise levels during the proposed installation of piles in Mermaid Sound to assist with potential pipelay operations for Scarborough. The effects of range-dependent environmental properties on sound propagation in the study area were accounted for by the numerical models.

These results are required for assessing the potential effects of noise exposure on marine mammals, fish, and turtles in and around the proposed operations. Sound levels due to pressure are presented as sound pressure levels (SPL), zero-to-peak pressure levels (PK), and either single-impulse (i.e., per-strike) or accumulated sound exposure levels (SEL) for noise effect criteria for impulsive (piling) noise sources.

The distances to all per-strike isopleths (contours of equal sound level) are farthest from the piles at the start of piling, when most of the pile remains in the water column, and shortest at the end of piling, when most of the pile is buried in the sediment. This is despite the increased frictional resistance of sediments and stronger stress-wave reflections at the pile toe at later stages of insertion.

When considering criteria based on SEL_{24h} metrics, the ranges must be considered in context of the duration of operations. One pile will be driven per day; therefore, the corresponding sound level is denoted as SEL_{24h}; however, the estimated time for driving a pile is 18.4 minutes. SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels within the driving period. It is based on the assumption that an animal is consistently exposed to such noise levels at a fixed position. The radii that correspond to SEL_{24h} typically represent an unlikely worst-case scenario for SEL-based exposure since, more realistically, marine fauna (mammals or fish) would not stay in the same location or at the same distance for an extended period. Therefore, a reported radius for SEL_{24h} criteria does not mean that any animal travelling within this radius of the source *will* be injured, but rather that it *could* be injured if it remained in that range for the entire duration of the pile driving.

The analysis considered multiple effects criteria commonly used in pile driving noise assessments. Key results of the modelling are summarised below.

Mammals

- United States National Marine Fisheries Service (NMFS 2014) acoustic threshold for behavioural effects in cetaceans: Pile driving impulse sounds are predicted to exceed the SPL threshold of 160 dB re 1 µPa for behavioural effects of marine mammals within 3.75 km of the pile at 4 m penetration and 1.77 km at 10 m penetration.
- NMFS (2018) marine mammal injury criteria: Permanent Threshold Shift (PTS), representing onset of auditory injury, were determined from PK and SEL_{24h} criteria. The greater of the two criteria exceedance distances is chosen as per the criteria. SEL is assessed here for the driving of a single pile within a 24 h period, which is estimated to take only 18.4 minutes, as stated above, this is still referred to as SEL_{24h}. These maximum predicted distances are summarised in Table 1, along with the distances to Temporary Threshold Shift (TTS).

Table 1. Summary of permanent and temporary threshold shift (PTS and TTS) onset distances for marine mammals.

Hearing group†	PTS		TTS	
	Threshold for SEL_{24h} (dB re 1 µPa²·s)	R_{max} (km)	Threshold for SEL_{24h} (dB re 1 µPa²·s)	R_{max} (km)
Low-frequency cetaceans	183	1.28	168	4.73
Mid-frequency cetaceans	185	0.03	170	0.23
High-frequency cetaceans	155	0.97	140	3.75

† The model does not account for shutdowns.

Turtles

- The U.S. NMFS criterion for behavioural effects of turtles is 166 dB re 1 µPa (SPL). This threshold was predicted to be exceeded within 2.46 km of the pile (R_{max} distances).
- The sound level associated with an agitated state in turtles is 175 dB re 1 µPa, (McCauley et al. 2000a, McCauley et al. 2000d, NSF 2011). This threshold was predicted to be exceeded within 0.98 km of the pile (R_{max} distances).
- Considering the per-strike PK criteria from Finneran et al. (2017a), turtles could experience temporary threshold shift (TTS; 226 dB re 1 µPa PK) and PTS (232 dB re 1 µPa PK) within less than 20 m from the impact hammer.

Fish, Fish Eggs, and Fish Larvae

- The distance from pile driving at which sound levels exceeded mortality and potential mortal injury for the most sensitive fish groups was 112 m (PK metric), based on Popper et al. (2014).
- Considering the defined 24 h period of exposure, fish (including sharks) could experience TTS from the proposed pile driving project. It is predicted that this will occur within 1.13 km of the impact hammer, based on Popper et al. (2014).

1. Introduction

JASCO Applied Sciences (JASCO) performed a modelling study of underwater sound levels associated with the proposed development of Scarborough to assist in understanding the potential acoustic impact on key regional receptors including marine mammals, fish, and turtles. The Scarborough gas field is in Permit Area WA-1-R, at this location a Floating Processing Unit (FPU) will be installed. The Development also involves a pipeline to the Pluto LNG facilities on the Burrup Peninsula. This study considers the driving of subsea piles which may be required to assist with pipelay operations close to the Pluto LNG facility, inside Mermaid Sound.

The modelling methodology considered source directivity and range-dependent environmental properties. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), zero-to-peak pressure levels (PK, L_{pk}), and either single-impulse (i.e., per-strike) or accumulated sound exposure levels (SEL, L_E) for noise effect criteria for impulsive (piling) noise sources. The geographic coordinates for the modelling site are provided in Table 2 and an overview of the modelling area is shown in Figure 1.

Table 2. Location details for the modelled site.

Site	Noise source	Latitude (S)	Longitude (E)	UTM (WGS84) Zone 50 S		Water depth (m)
				X (m)	*Y* (m)	
1	Pile 11	20° 35' 29.2558"	116° 44' 37.5483"	473297.8	7723044.5	15.4

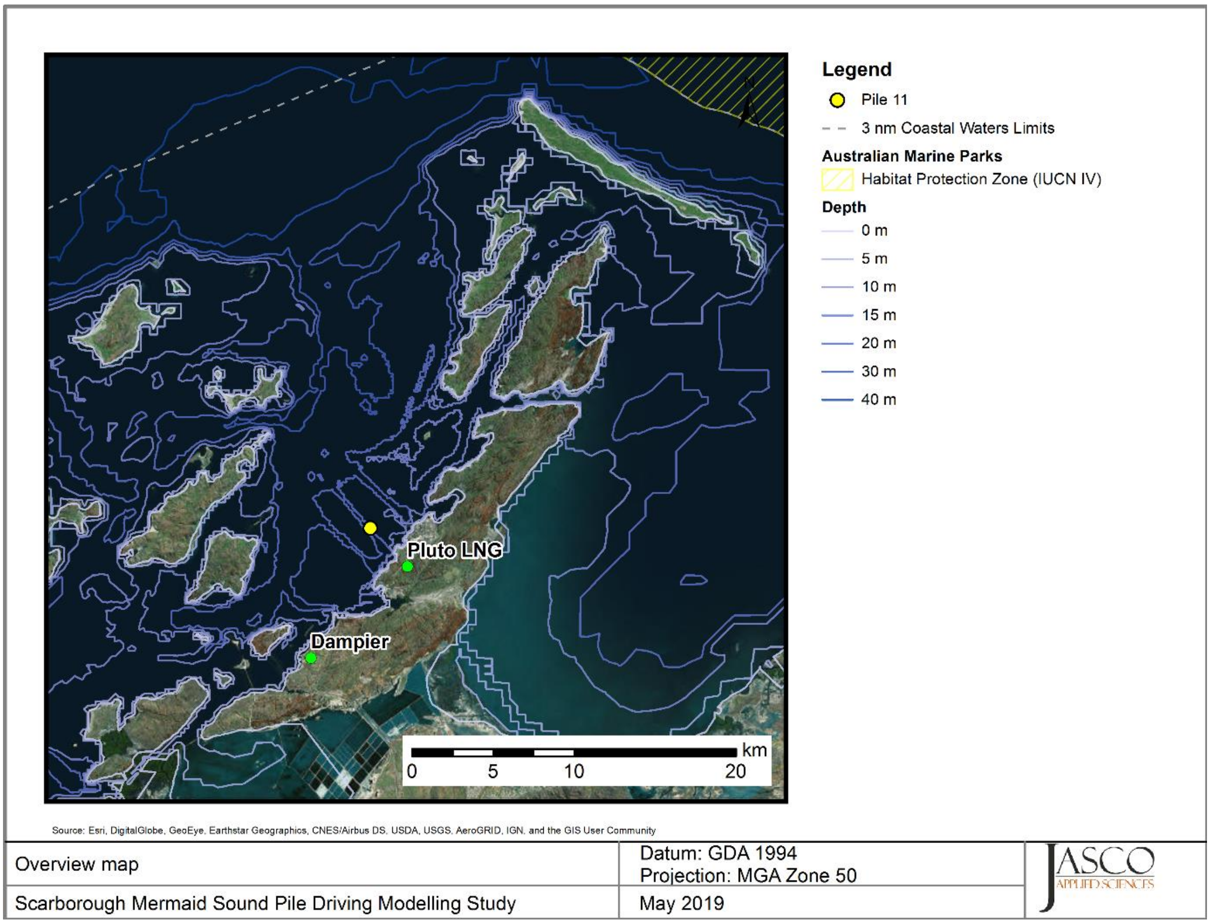


Figure 1. Overview of the pile driving modelling site and features.

1.1. Modelling Scenario Details

The modelling scenario for pile driving considers piles 12 m long, 1.524 m in diameter with wall thickness 50.8 mm, and driven a total of 10 m into the seabed by a Menck MHU 500T hammer. Eleven piles are planned to be driven, with one pile, Pile 11 (located about 1.3 km offshore) selected for modelling. Impact piling sounds depend on the length of pile within the water column and soil resistance/penetration rate. At the start of piling, most of the pile is in the water column, so sound levels can be high because of the relatively large source in water. Near the end of piling, most of the pile is buried in the sediment, so the in-water source is small; however, the pile penetration per-strike is usually less than at the start of piling, which can cause higher sound levels due to stronger stress-wave reflections at the pile toe. The soil at the piling location is expected to be 4 m of carbonate sediment, followed by increasingly consolidated calcarenite. To account for differences in the expected penetration rates through sediment and calcarenite, per-strike sound fields were modelled for two penetrations: 4 and 10 m. The drivability assessment provided by Woodside was used to derive the penetration rate (Table 5).

2. Noise Effect Criteria

To assess the potential impacts of a sound-producing activity, it is necessary to first establish exposure criteria (thresholds) for which sound levels may be expected to have a negative impact on animals. Whether acoustic exposure levels might injure or disturb marine fauna is an active research topic. Since 2007, several expert groups have developed SEL-based assessment approaches for evaluating auditory injury, with key works including Southall et al. (2007), Finneran and Jenkins (2012), Popper et al. (2014), and NMFS (2018). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially.

The perceived loudness of pile driving noise depends on the strike rise-time and duration, and its frequency content. Several sound level metrics, such as PK, SPL, and SEL, are commonly used to evaluate noise and its effects on marine life (Appendix A). The time period of accumulation of SEL is defined with this report as either a "per-strike" value (i.e., integrated over the time of a single strike), or over all strikes that occur in a 24 h time period. Appropriate subscripts indicate any applied frequency weighting applied (Appendix A.3). The acoustic metrics in this report reflect the updated ANSI and ISO standards for acoustic terminology, ANSI-ASA S1.1 (R2013) and ISO/DIS 18405.2:2017 (2017).

This study applies the following noise criteria, chosen for their acceptance by regulatory agencies and because they represent current best available science (Sections 2.1–2.2 and Appendix A.2):

1. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from the U.S. National Oceanic and Atmospheric Administration (NOAA) Technical Guidance (NMFS 2018) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals.
2. Marine mammal behavioural threshold based on the current interim U.S. National Marine Fisheries Service (NMFS) criterion NMFS (2014) for marine mammals of 160 dB re 1 µPa and 120 dB re 1 µPa SPL (L_p) for impulsive and non-impulsive sound sources respectively.
3. Sound exposure guidelines for fish, fish eggs and larvae (Popper et al. 2014).
4. For impulsive noise, a threshold for turtle per-strike PTS of 232 dB re 1 µPa (PK) (Finneran et al. 2017a), and a behavioural response of 166 dB re 1 µPa SPL (L_p) (NSF 2011), as applied by the US NMFS, along with a sound level associated with an increased level of response 175 dB re 1 µPa (SPL) (McCauley et al. 2000a, McCauley et al. 2000d, NSF 2011).

2.1. Marine Mammals

The criteria applied in this study to assess possible effects of pile driving noise on marine mammals are summarised in Table 3, and detailed in Sections 2.1.1 and 2.1.2, with frequency weighting explained in Appendix A.3.

Table 3. Acoustic effects of impulsive noise on marine mammals: Unweighted SPL, SEL_{24h}, and PK thresholds

Hearing group	NMFS (2014)	NMFS (2018)			
	Behaviour	PTS onset thresholds* (received level)		TTS onset thresholds* (received level)	
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)
Low-frequency cetaceans	160	183	219	168	213
Mid-frequency cetaceans		185	230	170	224
High-frequency cetaceans		155	202	140	196

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.
L_p-denotes sound pressure level period and has a reference value of 1 µPa
L_{pk}, flat–peak sound pressure is flat weighted or unweighted and has a reference value of 1 µPa
L_E - denotes cumulative sound exposure over a 24-hour period and has a reference value of 1 µPa²s

2.1.1. Behavioural response

Numerous studies on marine mammal behavioural responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioural reactions. However, it is recognised 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, Southall et al. 2016). Because of the complexity and variability of marine mammal behavioural responses to acoustic exposure, NMFS has not yet released updated technical guidance on behaviour thresholds for use in calculating animal exposures (NMFS 2018). The NMFS currently uses a step function to assess behavioural impact. A 50% probability of inducing behavioural responses at a SPL of 160 dB re 1 µPa was derived from the HESS (1999) report which, in turn, was based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1983, Malme et al. 1984). The HESS team recognised that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above a SPL of 140 dB re 1 µPa. An extensive review of behavioural 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 a 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.

Absence of controls, precise measurements, appropriate metrics, and context dependency of responses (including the activity state of the animal) all contribute to variability. Therefore, unless otherwise specified, the relatively simple sound level criterion for potentially disturbing a marine mammal applied by NMFS has been used. For impulsive sounds, this threshold is 160 dB re 1 µPa SPL for cetaceans (NMFS 2014).

2.1.2. Injury and hearing sensitivity changes

There are two categories of auditory threshold shifts or hearing loss: permanent threshold shift (PTS), a physical injury to an animal's hearing organs; and Temporary Threshold Shift (TTS), a temporary reduction in an animal's hearing sensitivity as the result of receptor hair cells in the cochlea becoming fatigued.

To assist in assessing the potential for injuries to marine mammals this report applies the criteria recommended by NMFS (2018), considering both PTS and TTS, to help assess the potential for injuries to marine mammals (Table 3). Appendix A.2 provides more information about the NMFS (2018) criteria.

2.2. Fish, Turtles, Fish Eggs, and Fish Larvae

In 2006, the Working Group on the Effects of Sound on Fish and Turtles was formed to continue developing noise exposure criteria for fish and turtles, work begun by a NOAA panel two years earlier. The Working Group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014). The guidelines define quantitative thresholds for three types of immediate effects:

- Mortality, including injury leading to death,
- Recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and
- TTS.

Masking and behavioural effects can be assessed qualitatively, by assessing relative risk rather than by specific sound level thresholds. However, as these depend upon activity-based subjective ranges, these effects are not addressed in this report and are included in Table 4 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish's susceptibility to injury from noise exposure depends on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for fish without a swim bladder (also appropriate for sharks in the absence of other information), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. Fish eggs, and fish larvae are considered separately.

Table 4 lists relevant effects thresholds from Popper et al. (2014) for pile driving. In general, any adverse effects of impulsive sound on fish behaviour depends on the species, the state of the individual exposed, and other factors. For turtle injury, a PTS of 232 dB re 1 µPa (PK), Finneran et al. (2017a) has been applied as it represents updated information compared to the information presented in Popper et al. (2014).

The SEL metric integrates noise intensity over some period of exposure. Because the period of integration for regulatory assessments is not well defined for sounds that do not have a clear start or end time, or for very long-lasting exposures, it is required to define an exposure evaluation time. Southall et al. (2007) defines the exposure evaluation time as the greater of 24 h or the duration of the activity. Popper et al. (2014) recommend a standard period of the duration of the activity; however, the publication also includes caveats about considering the actual exposure times if fish move. Integration times in this study have been applied over the time a single pile was driven since only one pile is expected to be driven per day.

Table 4. Criteria for pile driving noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	> 219 dB SEL_{24h} or > 213 dB PK	> 216 dB SEL_{24h} or > 213 dB PK	>> 186 dB SEL_{24h}	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	210 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	>> 186 dB SEL_{24h}	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	186 dB SEL_{24h}	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Fish eggs and fish larvae	> 210 dB SEL_{24h} or > 207 dB PK	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Peak sound pressure level dB re 1 µPa; SEL_{24h} dB re 1µPa^2·s.
All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

2.2.1.1. Turtles

There is a paucity of data regarding responses of turtles to acoustic exposure, and no studies of hearing loss due to exposure to loud sounds. To inform this report, a review of available literature on how turtles respond to acoustic exposure was undertaken. Most information is available from behavioural response to seismic sources, in lieu of specific information about pile driving.

For turtle injury, a PTS of 232 dB re 1 µPa (PK), and TTS of 226 dB re 1 µPa (PK) from Finneran et al. (2017b) has been applied as it represents updated information compared to the information in Popper et al. (2014), which suggested injury to turtles could occur for sound exposures above 207 dB re 1 µPa (PK) or above 210 dB re 1 µPa^2·s (SEL_{24h}).

McCauley et al. (2000c) observed the behavioural response of caged turtles—green (*Chelonia mydas*) and loggerhead (*Caretta caretta*)—to an approaching seismic airgun. For received levels above 166 dB re 1 µPa (SPL), the turtles increased their swimming activity and above 175 dB re 1 µPa they began to behave erratically, which was interpreted as an agitated state. The 166 dB re 1 µPa level has been used as the threshold level for a behavioural disturbance response by NMFS and applied in the Arctic Programmatic Environment Impact Statement (PEIS) (NSF 2011). At that time, and in the absence of any data from which to determine the sound levels that could injure an animal, TTS or PTS onset were considered possible at an SPL of 180 dB re 1 µPa (NSF 2011).

Some additional data suggest that behavioural responses occur closer to an SPL of 175 dB re 1 µPa, and TTS or PTS at even higher levels (Moein et al. 1995, McCauley et al. 2000c, McCauley et al. 2000b), but the received levels were unknown and the NSF (2011) PEIS maintained the earlier NMFS criteria levels of 166 and 180 dB re 1 µPa (SPL) for behavioural response and injury, respectively. Sound levels defined by Popper et al. (2014) show that animals are very likely to exhibit a behavioural response when they are near an airgun (tens of metres), a moderate response if they encounter the source at intermediate ranges (hundreds of metres), and a low response if they are far (thousands of meters) from the airgun. The NMFS criterion for behavioural disturbance (SPL of 166 dB re 1 µPa), the Moein et al. (1995) or McCauley et al. (2000c) criterion for behavioural disturbance (SPL of 175 dB re 1 µPa) were included in this analysis. The analysis did not, however, consider the ranges where an animal could suffer impairment, as defined by Popper et al. (2014).

3. Methods

3.1. Modelling Overview

To predict the acoustic field around the pile driving at frequencies of 10 Hz to 25 kHz, JASCO's Pile Driving Source Model (PDSM; Appendix B) was used in conjunction with JASCO's Full Waveform Range-dependent Acoustic Model (FWRAM, Appendix C.2). The environmental parameters used in the propagation models are summarised in Appendix D.

3.2. Modelling Approach

3.2.1. Per-strike Modelling

For impulsive impact pile driving sounds, time-domain representations of the pressure waves generated in the water are required for calculating sound pressure level (SPL), sound exposure level (SEL), and peak sound pressure level (PK). Appendix A.1 describes these sound level metrics. The following steps comprise the general approach applied in this study to model sounds from impact pile driving activities:

1. Piles driven into the sediment by impact driving are characterised as sound-radiating sources. This characterisation strongly depends on the rate and extent of pile penetration, pile dimensions, and pile driving equipment.
2. The theory of underwater sound propagation is applied to predict how sound propagates from the pile into the water column as a function of range, depth, and azimuthal direction. Propagation depends on several conditions including the frequency content of the sound, the bathymetry, the sound speed in the water column, and sediment geoacoustics (Appendix D.2 describes environmental properties such as bathymetry, sound speed profile, and geoacoustics).
3. The propagated sound field is used to compute received levels over a grid of simulated receivers, which distances to criteria thresholds and maps of ensonified areas are generated from.

To model sounds resulting from impact pile driving of cylindrical pipes, PDSM (Appendix B), a physical model of pile vibration and near-field sound radiation (MacGillivray 2014), is used in conjunction with the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010). JASCO modelled a MHU 500T impact hammer. Figure 2 shows the force at the top of the pile that is produced by GRLWEAP.

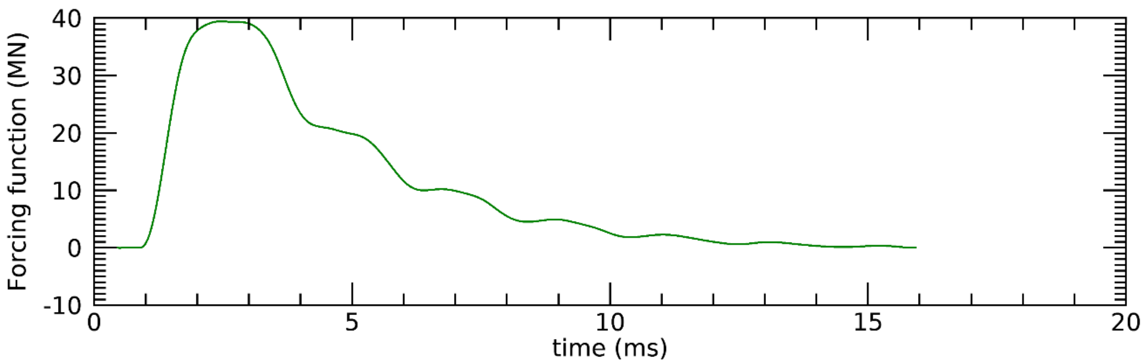


Figure 2. Force (in meganewtons) at the top of the pile corresponding to impact pile driving of 1.524 m diameter piles, computed using the GRLWEAP 2010 wave equation model for the MHU 500T impact hammer.

The forcing function (Figure 2) is used by the PDSM to obtain equivalent pile driving signatures for a vertical array of discrete point sources (Appendix B). These represent the pile as an acoustic source and account for parameters (pile type, material, size, and length), the pile driving equipment, and approximate pile penetration rate. The amplitude and phase of the point sources along the pile are computed so they collectively mimic the time-frequency characteristics of the acoustic wave at the pile wall that results from a hammer strike at the top of the pile. This approach accurately estimates spectral levels within the band 10–1000 Hz where most of the energy from impact pile driving is concentrated.

Time-domain Full Waveform Range-dependent model (FWRAM; Appendix C.2) calculates sound propagation from physically distributed impulsive sources and is valid at all distances. In the present study, received sound levels were calculated using FWRAM along 91 azimuths out to 150 km from the source in the offshore direction, generating a total modelling area of 22,163 km^2. Modelling was conducted in 5° azimuth increments, except along narrow land passages, for which increments between 2° and 3° degrees were used. Source band levels at 1000 Hz were extrapolated up to 25 kHz using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly-sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009).

Receiver depths are chosen to span the entire water column over the modelled areas, from 1 to 300 m, with step size that increase with depth. To produce maps of received sound level distributions and to calculate distances to specified sound level thresholds, the maximum-over-depth level is calculated at each modelled easting and northing position within the considered region. The radial grids of maximum-over-depth levels are then resampled (by linear triangulation) to produce a regular Cartesian grid. The contours and threshold ranges are calculated from these flat Cartesian projections of the modelled acoustic fields (Appendix D.1).

3.2.2. Accumulated SEL Modelling

The modelling approach outlined in Sections 3.2.1 provides per-strike SEL for two stages of pile driving (i.e., two penetration depths). Several noise effect criteria, however, depend on accumulated SEL over many strikes (Section 2). The accumulated SEL, therefore, depends on the total number of strikes. Total driving time was estimated assuming continuous piling at a rate of approximately 0.63 strikes/second (38 strikes/minute). The number of strikes required for the driving of the pile were determined based upon a drivability assessment provided by Woodside for a MHU 500T hammer operating at 80% efficiency. A summary of the total number of strikes per penetration depth and over the entire pile is provided in Table 5.

Table 5. Total number of strikes and driving time. Strikes were broken down into stages corresponding to the two modelled penetrations.

Modelled penetration (m)	Penetration range for accumulated SEL (m)	Number of strikes	Penetration rate (mm/strike)	Total number of strikes	Time for full penetration (min)
4	0–4	53	75.8	698	18.4
10	4–10	645	9.3		

4. Results

4.1. Pile Driving

Since piles are distributed and directional sources, they cannot be accurately approximated by a point source with corresponding source levels. It is possible to compare the maximum modelled levels at short distances from the piles. Figure 3 shows the one-third-octave-band levels for the receiver with highest SEL at the closest horizontal range (10 m), for the two modelled penetrations. The levels above 1000 Hz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly-sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009). The modelled results at a distance of 10 m are included to provide results comparable to other pile driving reports, such as Illingworth & Rodkin (2007), and Denes et al. (2016).

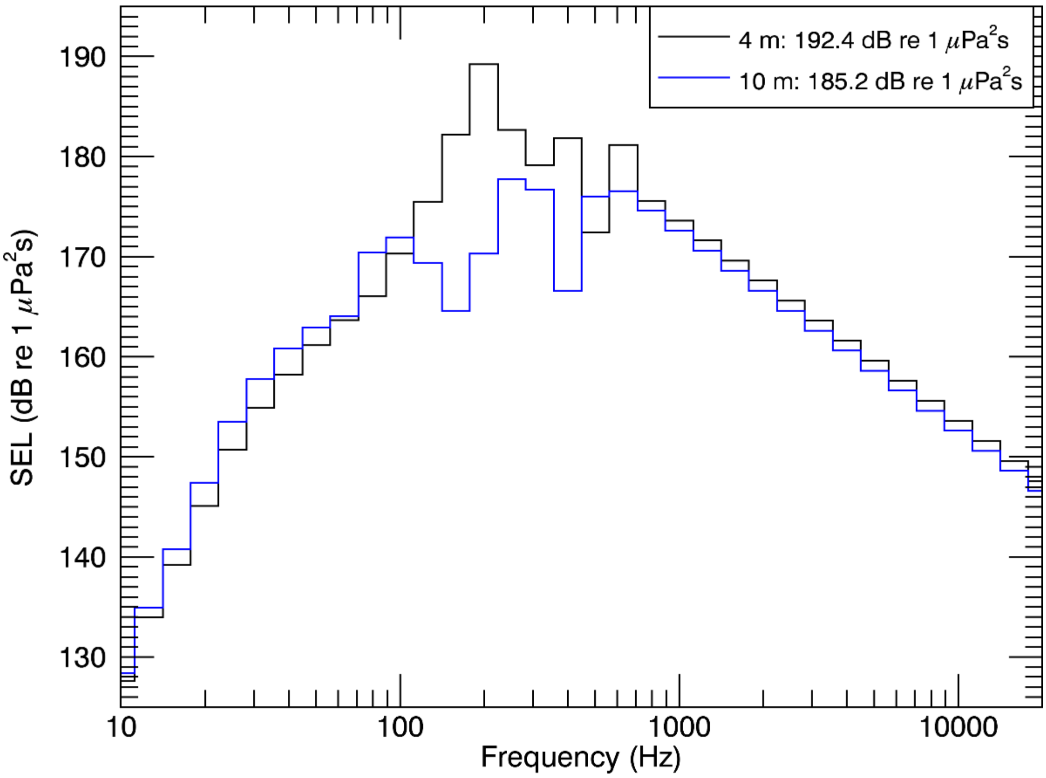


Figure 3. One-third-octave-band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving after high-frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration (Table 5) and the broadband SEL in dB re 1 μPa^2·s.

4.1.1. Per-strike sound fields

Per-strike results for the proposed pile driving are presented in this section for maximum-over-depth SPL, SEL, and PK, with tables in Section 4.1.1.1, maps and sound field vertical slices in Section 4.1.1.2.

4.1.1.1. Tabulated results

Tables 6–11 show the estimated distances for the various applicable per-strike effects criteria and isopleths of interest as maximum-over-depth.

Table 6. *Modelled maximum-over-depth per-strike SEL isopleths:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile.

Per-strike SEL (dB re 1 µPa²·s)	4 m penetration		10 m penetration	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.02	0.02	<0.01	<0.01
180	0.13	0.12	0.05	0.05
170	0.58	0.53	0.18	0.16
160	1.84	1.58	0.71	0.63
150	4.09	3.43	2.12	1.67
140	8.61	6.87	4.40	3.69
130	15.79	12.98	10.27	8.28
120	36.75	31.21	19.82	17.01
110	117.82	108.01	62.58	54.58

Table 7. *Modelled maximum-over-depth SPL isopleths:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile.

SPL (dB re 1 µPa)	4 m penetration		10 m penetration	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.01	0.01	<0.01	<0.01
190	0.11	0.10	0.03	0.03
180	0.50	0.46	0.15	0.13
170	1.70	1.44	0.60	0.54
160	3.75	3.18	1.77	1.48
150	7.43	6.31	3.82	3.21
140	13.79	11.37	10.12	7.67
130	31.78	25.55	17.99	15.68
120	139.60	124.11	62.53	54.11

Table 8. *SPL marine mammal and turtle behavioural response thresholds*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the piles to modelled maximum-over-depth isopleths per penetration depth.

Threshold	4 m penetration depth		10 m penetration depth	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Marine mammal behaviour, SPL: 160 dB re 1 µPa (NMFS 2014)	3.75	3.18	1.77	1.48
Turtle behaviour, SPL: 166 dB re 1 µPa (NSF 2011)	2.46	2.07	0.98	0.85
Turtle behaviour, SPL: 175 dB re 1 µPa (McCauley et al. 2000a, McCauley et al. 2000d)	0.98	0.86	0.30	0.28

Table 9. *Marine mammal PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (in m) from the pile to maximum-over-depth isopleths.

Hearing group	**PTS**			**TTS**		
	PK threshold (dB re 1 µPa)	Penetration depth (m)		PK threshold (dB re 1 µPa)	Penetration depth (m)	
		4	10		4	10
Low-frequency cetaceans	219	<20	<20	213	49	<20
Mid-frequency cetaceans	230	<20	<20	224	<20	<20
High-frequency cetaceans	202	205	106	196	477	203

Table 10. *Mortality and potential mortal recoverable injury thresholds (peak pressure level metric) for fish, fish eggs, and fish larvae*: Maximum (R_{max}) horizontal distances (in m) from the pile.

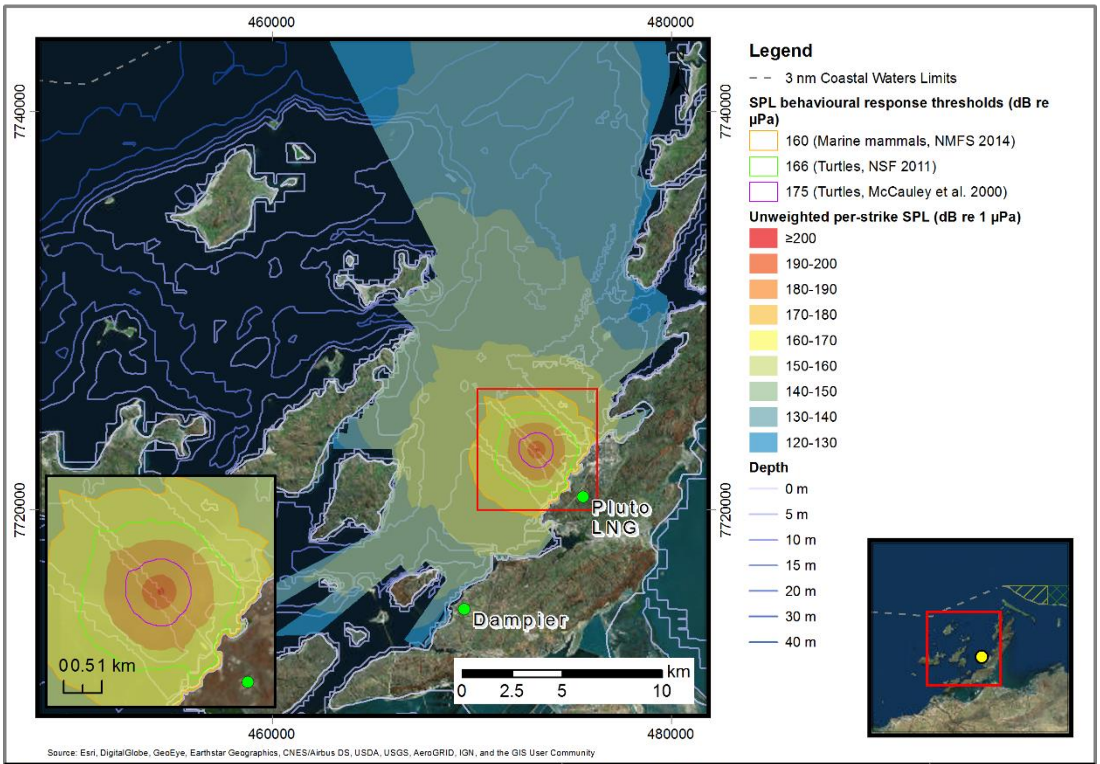
Marine animal group	**PK Threshold (dB re 1 µPa)**	**Penetration depth**	
		4 m	10 m
Fish: No swim bladder	213	49	<20
Fish: Swim bladder not involved in hearing, Swim bladder involved in hearing Fish eggs, and larvae	207	112	55

Table 11. *Turtle peak pressure injury thresholds*: Maximum (R_{max}) horizontal distances (in m) from the pile to thresholds (PTS and TTS) for turtles.

Hearing group	**PTS**			**TTS**		
	PK threshold (dB re 1 µPa)	Penetration depth (m)		PK threshold (dB re 1 µPa)	Penetration depth (m)	
		4	10		4	10
Turtle	232	<20	<20	226	<20	<20

4.1.1.2. Sound field maps and vertical slices

Maps of the per-strike SPL results associated with the two modelled penetration depths are shown in Figures 4 and 6, with per-strike SEL maps shown in Figures 5 and 7. The shallowest modelled penetration has the farthest distances to all per-strike isopleths. Additionally, a map showing the isopleths for marine mammal behavioural criteria (160 dB re 1 µPa) for each of the two considered penetration depths is provided in Figure 8 to demonstrate visually the reduction in extent with increased penetration depth. Vertical slice plots for both penetrations are shown in Figures 9 and 12.



SPL - 4 m penetration: Modelled maximum-over-depth sound field	Datum: GDA 1994 Projection: MGA Zone 50
Scarborough Mermaid Sound Pile Driving Modelling Study	May 2019

Figure 4. Sound level contour map showing unweighted maximum-over-depth SPL results for a 4 m penetration depth. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

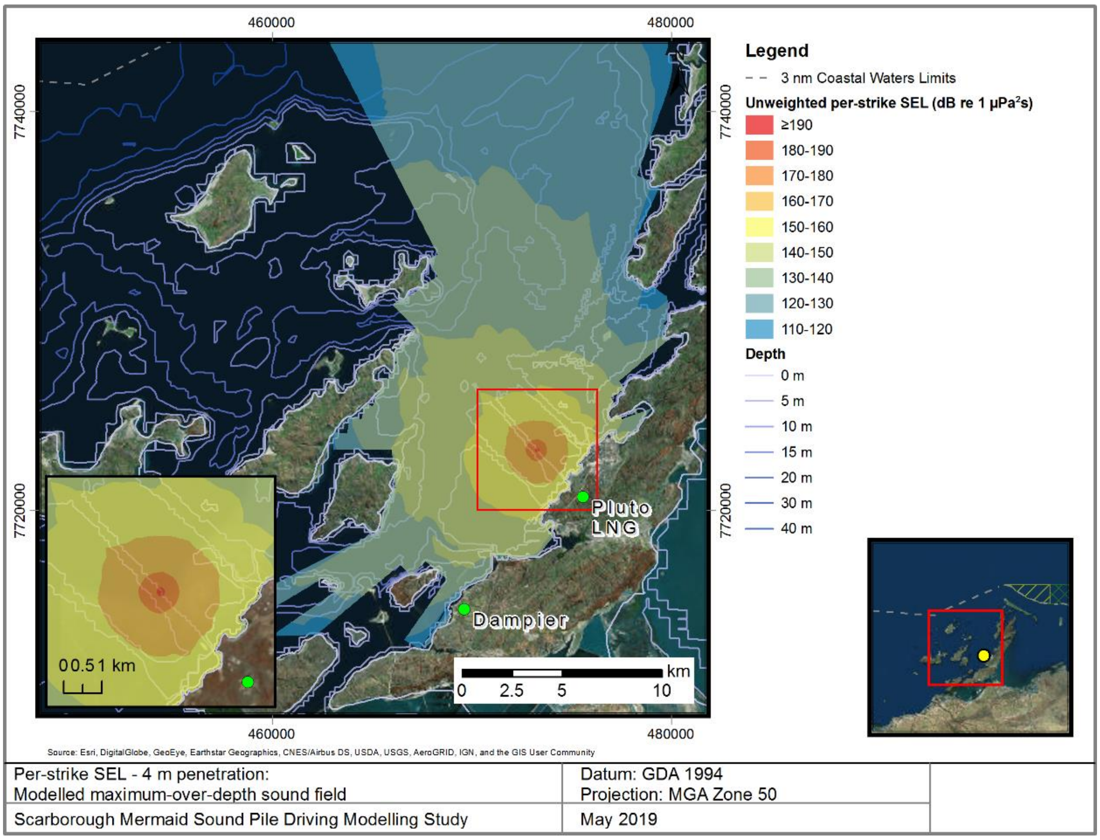


Figure 5. Sound level contour map showing maximum-over-depth SEL results for a 4 m penetration depth.

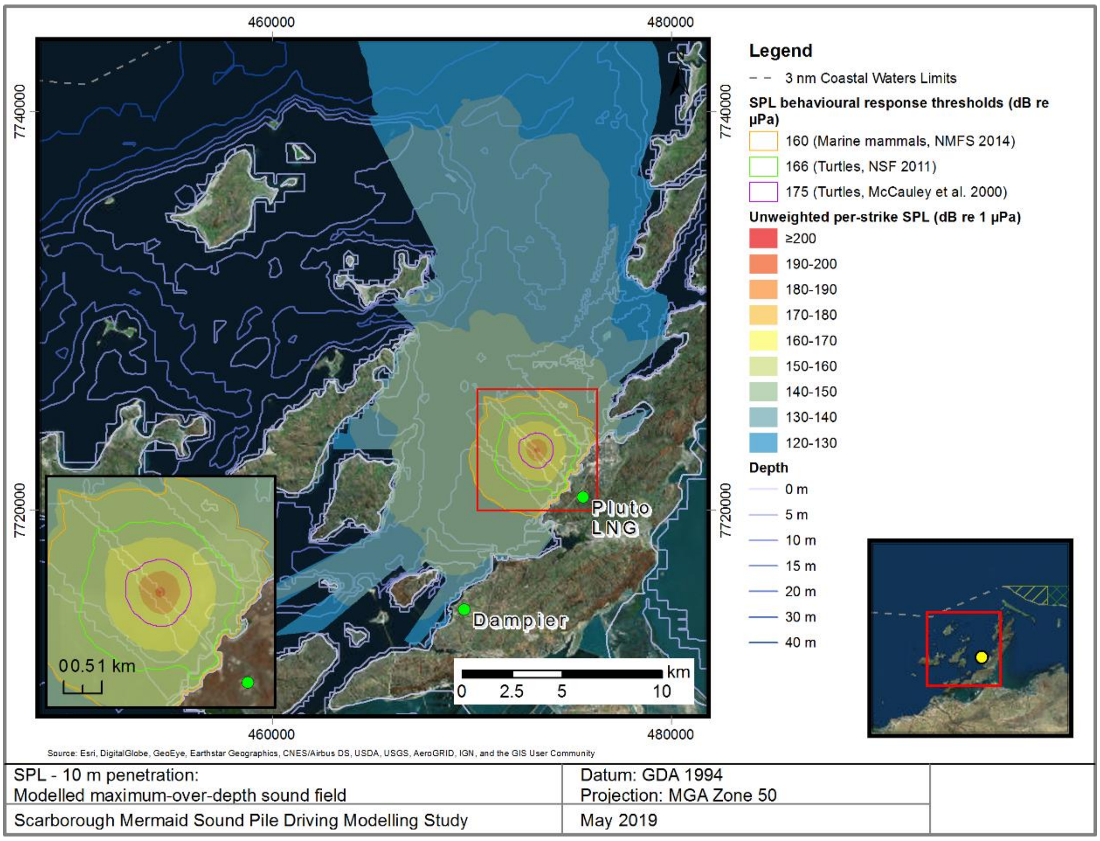


Figure 6. Sound level contour map showing unweighted maximum-over-depth SPL results for a 10 m penetration depth. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

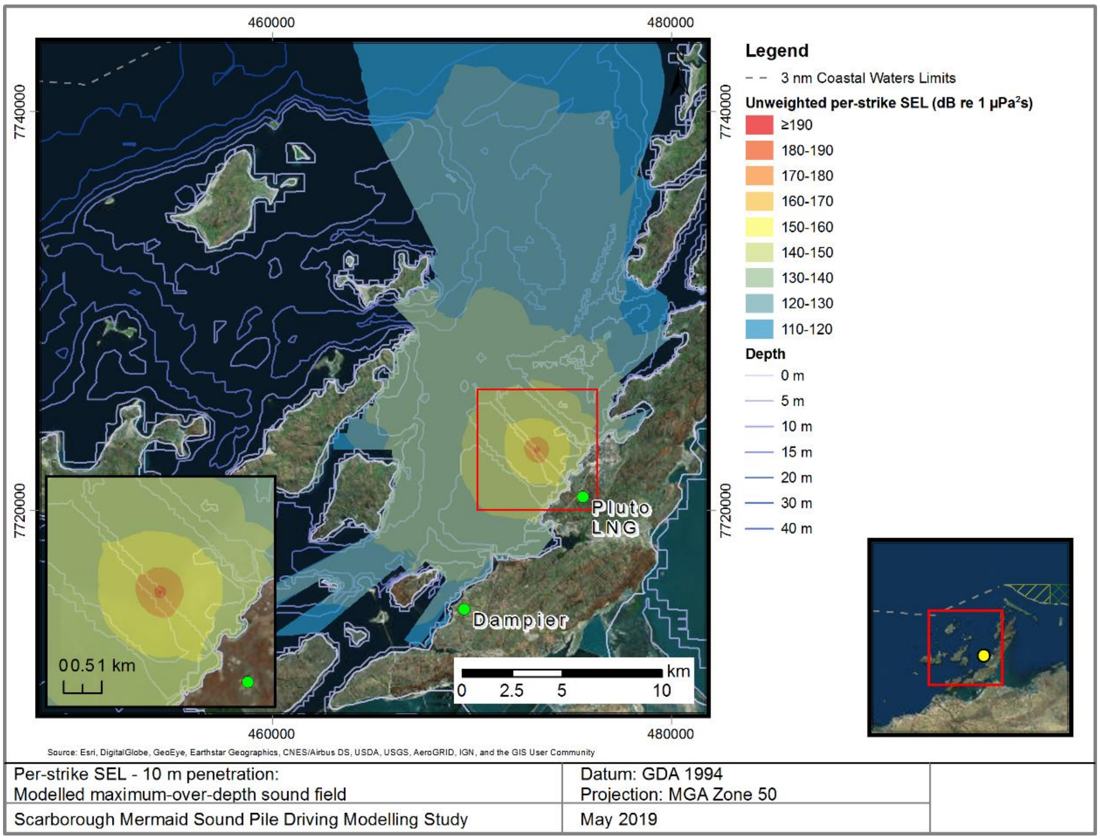


Figure 7. Sound level contour map showing maximum-over-depth SEL results for a 10 m penetration depth.

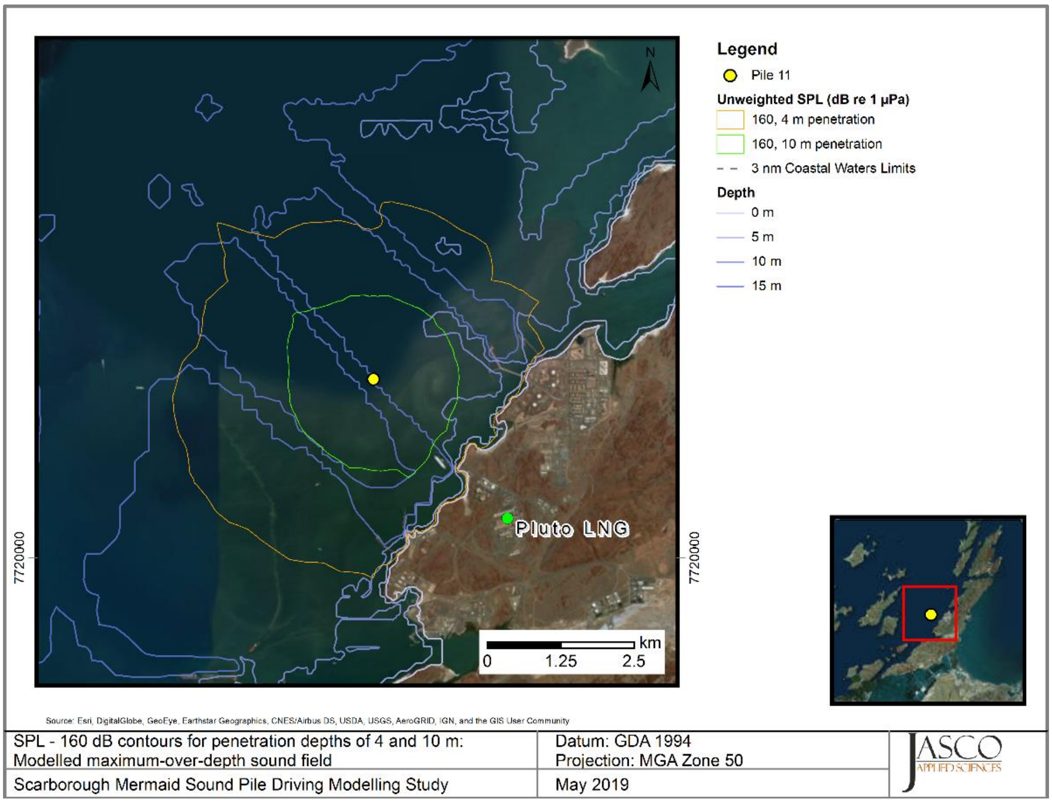


Figure 8. Sound level contour map showing unweighted maximum-over-depth SPL marine mammal (160 dB re 1 µPa) behavioural criteria results for all modelled penetration depths.

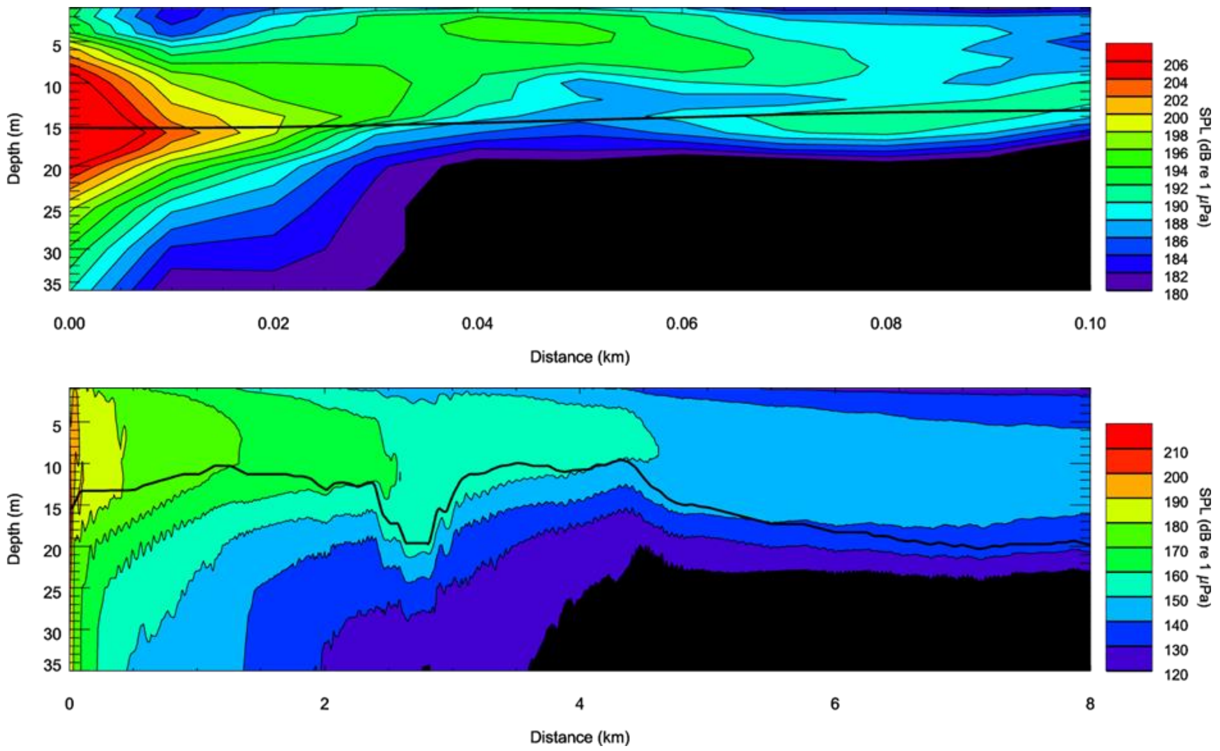


Figure 9. Predicted SPL for 4 m penetration as a vertical slice, for (top) 0–0.1 km and (bottom) 0–8 km. Levels are shown along a single transect of azimuth 0°. The seabed outline is shown as a thick black line.

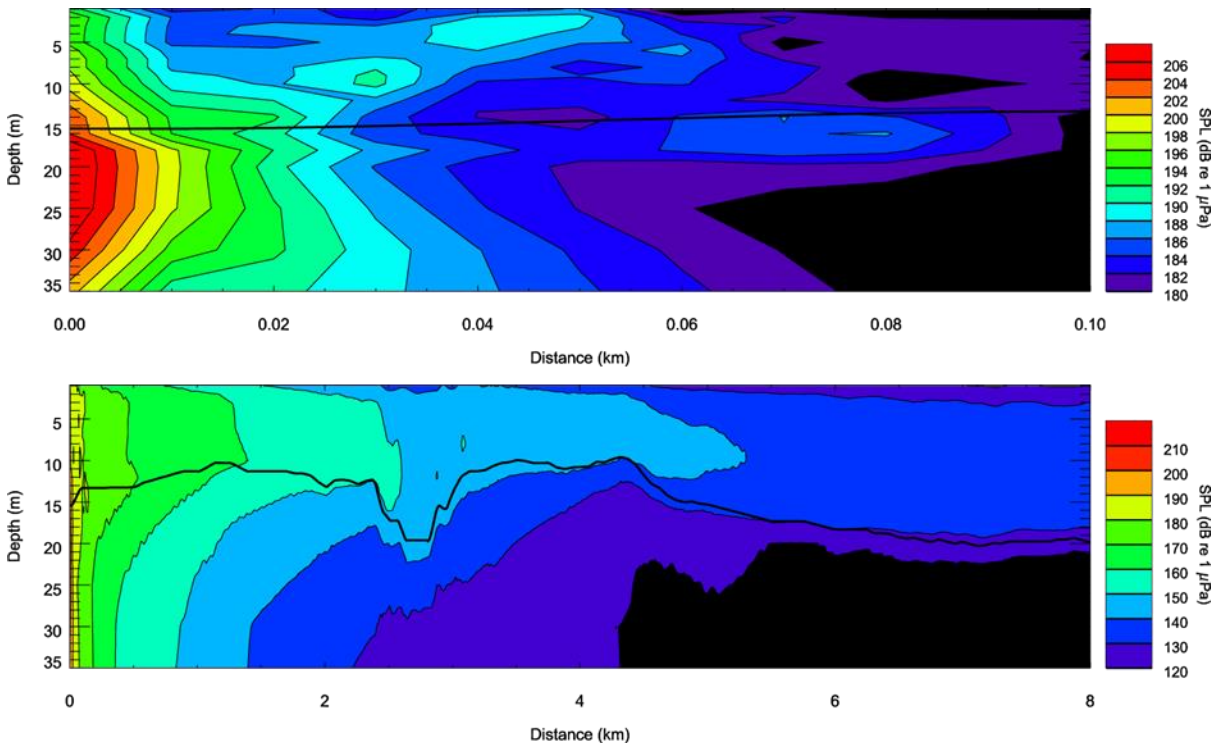


Figure 10. Predicted SPL for 10 m penetration as a vertical slice, for (top) 0–0.1 km and (bottom) 0–8 km. Levels are shown along a single transect of azimuth 0°. The seabed outline is shown as a thick black line

4.1.2. Multiple Strike Sound Fields

Table 12 presents the SEL_{24h} results relevant to marine mammals for the proposed pile driving operations, while Table 13 shows modelled distances to the cumulative exposure criteria contours for fish, fish eggs and larvae. The sound level contour maps are presented in Figure 11 (cetaceans) and Figure 12 (fish).

Table 12. Maximum-over-depth distances (in km) to SEL_{24h} based marine mammal PTS and TTS thresholds NMFS (2018).

Hearing group	PTS			TTS		
	Threshold for SEL_{24h} (dB re 1 µPa²·s)	R_{max} (km)	$R_{95\%}$ (km)	Threshold for SEL_{24h} (dB re 1 µPa²·s)	R_{max} (km)	$R_{95\%}$ (km)
Low-frequency cetaceans	183	1.28	1.10	168	4.73	3.99
Mid-frequency cetaceans	185	0.03	0.03	170	0.23	0.21
High-frequency cetaceans	155	0.97	0.85	140	3.75	3.27

Table 13. Maximum-over-depth distances (in km) to SEL_{24h} based fish criteria. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Marine animal group	Threshold for SEL_{24h} (dB re 1 µPa²·s)	Maximum-over-depth	
		R_{max} (km)	$R_{95\%}$ (km)
Fish mortality and potential mortal injury			
I	219	<0.02	<0.02
II Fish eggs and larvae	210	0.03	0.03
III	207	0.06	0.06
Fish recoverable injury			
I	216	<0.02	<0.02
II, III	203	0.10	0.10
Fish TTS			
I, II, III	186	1.13	0.99

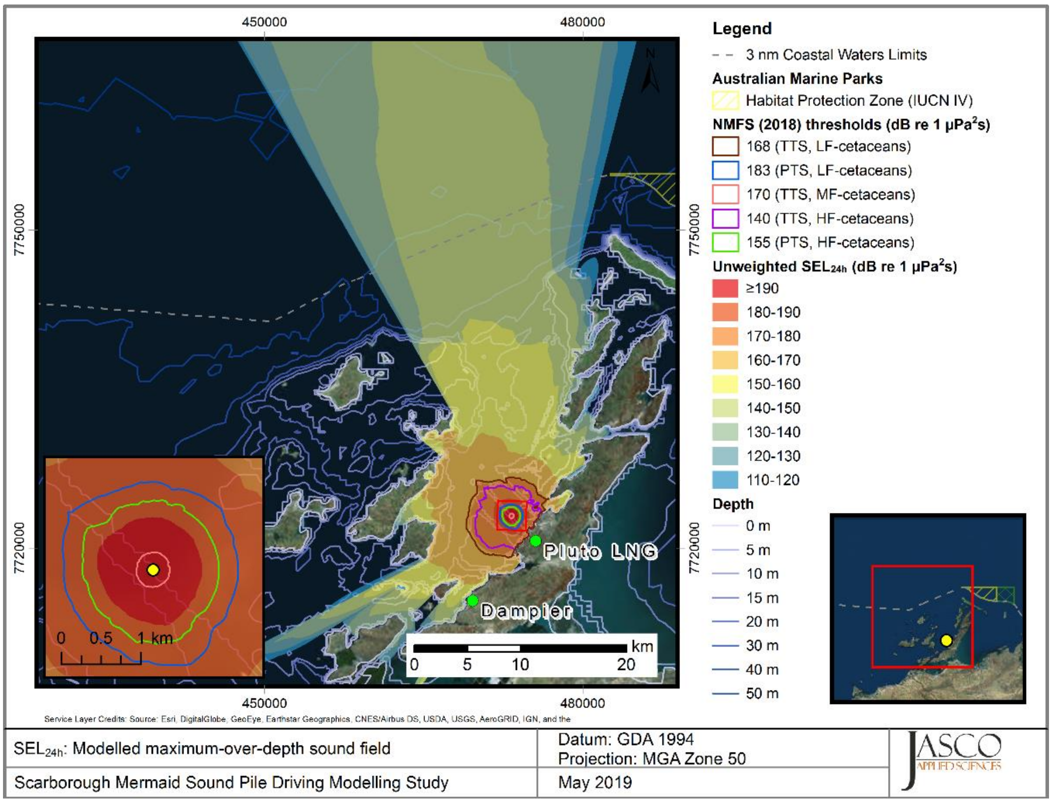


Figure 11. Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for PTS and TTS in low and high-frequency cetaceans, and TTS in mid-frequency cetaceans.

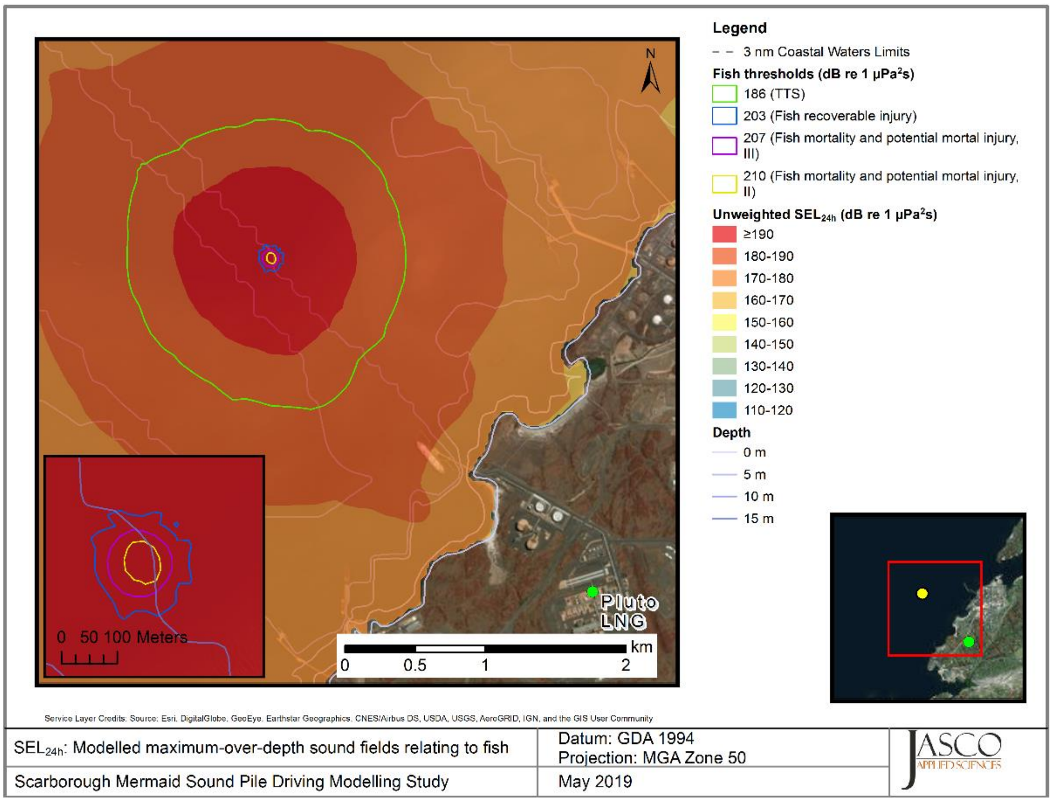


Figure 12. Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths relevant to fish injury and TTS. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

5. Discussion and Summary

5.1. Pile Driving

5.1.1. Acoustic propagation

This study predicted underwater sound levels associated with impact driving of subsea piles to assist with pipelay operations near Pluto LNG. The underwater sound field was modelled for 12 m long piles with a 1.524 m diameter with 50.8 mm wall thickness; The piles will be driven completely into the seabed. The modelling applied a sound speed profile derived from a public database (Appendix D.2.2), also accounted for bathymetric variations (Appendix D.2.1) and local geoacoustic properties (Appendix D.2.3). The broadband sound energy at 10 m for each penetration depth ranged from 192.4–185.2 dB re 1 µPa^2·s with the peak sound energy concentrated in the frequency range 100 to 300 Hz (Figure 3), with levels from the pile at the 4 m penetration depth having the highest energy.

Noise emissions from pile driving were considered here to be cylindrically isotropic (i.e., omnidirectional in the horizontal plane). As such, variations in noise that propagates across azimuths are attributed to the bathymetry alone, with this accounted for in the modelling methodology. When the hammer strikes the pile, noise propagates into the water as a downward Mach cone (see Appendix B). A portion of the energy from the strike is also reflected at the pile bottom, generating an upward Mach cone. This cycle of downward propagation, reflection, and upward propagation takes place multiple times per strike. At close range from the pile, noise levels are determined by the summation of Mach cones, which might add constructively (i.e., their summation results in a total wave with higher amplitude than the original ones), or destructively (i.e., wavefronts can cancel each other, resulting in low amplitudes). The way in which Mach cones combine with each other is strongly dependent on their frequency content, which is determined by the hammer forcing function and the pile dimensions.

Due to the relation between the speed of sound in steel (~5000 m/s) relative to the speed of sound in the water (~1529 m/s), the Mach cone propagates away from the pile and impinges the seabed at an angle of ~17°. The first bottom bounce occurs within 30 m from the pile, and the first surface bounce occurs within 60 m from the pile. As shown in Figure 9, the Mach cone corresponding to the shallowest pile penetration introduces significant energy that propagates through the water column, compared to the 10 m pile penetration scenario in Figure 10, for which underground sound propagation tends to dominate at close range from the pile.

The modelling of the two penetration depths for each pile provides a detailed quantification of the associated sound levels for each penetration. The distances to all per-strike isopleths are farthest at the start of piling when most of the pile is in the water column, and shortest at the end of piling when most of the pile is buried in the sediment. This is despite the per-strike pile penetration being less during the final stages of driving, and the increased resistance generating stronger stress-wave reflections at the pile toe. Therefore, the amount of pile in the water has greatest influence on the in-water sound levels. The isopleths for unweighted marine mammal behavioural thresholds for each penetration are presented on the same map for each site to assist with comparison (Figure 8). The highest peak pressure levels are predicted to occur at the shallowest penetration (4 m).

Sound propagation is strongly reduced by the proximity of the pile to land in most directions. The maximum distances to thresholds occur to the north, where sound propagates without interference from land towards deeper waters. The R_{max} radius is more representative of the effective extent of the footprint because the source is stationary and is more conservative. However, when determining potential impacts, the azimuthal distribution of sound should be considered. The model assumed no acoustic mitigation around the pile driving operation. Therefore, the modelling scenarios represent the maximum noise footprint from pile driving activities as a conservative estimate given likely soil resistance.

When considering criteria based on SEL_{24h} metrics, the ranges must be considered in context of the length of operations. One pile will be driven per day; therefore, the corresponding sound level is denoted SEL_{24h}; however, the estimated time for driving the pile is 18.4 minutes (Table 5). The SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels within the driving period and is based on the assumption that an animal is consistently exposed to such noise levels at a fixed position. The radii that correspond to SEL_{24h} typically represent an unlikely worst-case scenario for SEL-based exposure since, more realistically, marine fauna (mammals or fish) would not stay in the same location or at the same range for an extended period. Even over the duration of driving for 18.4 minutes, the animals are likely to move. Therefore, a reported radius of SEL_{24h} criteria does not mean that any animal travelling within this radius of the source *will* be injured, but rather that it *could* be injured if it remained in that range for the entire period of driving.

5.1.2. Marine mammals

5.1.2.1. Marine mammal injury

The results for the NMFS (2018) criteria applied for marine mammal PTS consider both metrics within the criteria (PK and SEL), with SEL assessed here for a single pile within a 24 h period, i.e.. a single pile per day. Although the driving of this single pile is estimated to take only 18.4 minutes within the 24 h period, this is still referred to as SEL_{24h}. The metric with the longest distance must be applied which in this case is SEL for all hearing groups, the maximum distances along with the relevant metric are summarised in Table 14.

Table 14. Summary of marine mammal PTS and TTS onset distances. PK results are in Table 9, while those for SEL_{24h} are in Table 12.

Hearing group†	**PTS**			**TTS**		
	Threshold for SEL_{24h} (dB re 1 µPa²·s)	R_{max} (km)	$R_{95\%}$ (km)	Threshold for SEL_{24h} (dB re 1 µPa²·s)	R_{max} (km)	$R_{95\%}$ (km)
Low-frequency cetaceans	183	1.28	1.10	168	4.73	3.99
Mid-frequency cetaceans	185	0.03	0.03	170	0.23	0.21
High-frequency cetaceans	155	0.97	0.85	140	3.75	3.27

† The model does not account for shutdowns.

5.1.2.2. Marine mammal behaviour

The maximum distance at which the NMFS (2014) marine mammal behavioural response criterion of 160 dB re 1 µPa (SPL) could be exceeded was within 3.75 km of the piling location at a penetration depth of 4 m (R_{max}; Table 8). This distance decreased during the driving of the pile, to 1.77 km at the 10 m penetration depth.

5.1.3. Turtles

Behavioural effects and PTS and TTS in turtles were also considered. The maximum distance to the isopleth associated with the U.S. NMFS criterion for behavioural effects in turtles (166 dB re 1 µPa) was within 2.46 km of the piling location (R_{max}; Table 8). The sound level associated with an agitated state in turtles, 175 dB re 1 µPa, (McCauley et al. 2000a, McCauley et al. 2000d, NSF 2011) was exceeded within 0.98 km of the pile (R_{max}). Considering the per-strike PK criteria from Finneran et al. (2017a), turtles could experience TTS (226 dB re 1 µPa PK) and PTS (232 dB re 1 µPa PK) within less than 20 m of the impact hammer (Table 11).

5.1.4. Fish, fish eggs, and fish larvae

The modelling study assessed the ranges for quantitative criteria from Popper et al. (2014) associated with mortality and potential mortal injury and impairment in the following:

- Fish without a swim bladder (also appropriate for sharks in the absence of other information)
- Fish with a swim bladder not used for hearing

- Fish that use their swim bladders for hearing
- Fish eggs, and fish larvae

Considering both per-strike modelling sites and associated SEL_{24h} scenarios, along with both PK and SEL_{24h} metrics, in line with the conditions of the criteria, the longest distance to the applicable criteria was always associated with the PK metric.

Therefore, applying the Popper et al. (2014) criteria:

- The farthest distance to sound levels associated with mortality and potential mortal injury to the most sensitive fish groups was 112 m (PK metric). The SEL_{24h} metric has an associated distance of 60 m.
- The distance to sound levels associated with recoverable injury to fish was 100 m (SEL_{24h} metric).

Considering the defined 24 h period of exposure, fish (including sharks) could experience temporary threshold shift (TTS) from the proposed pile driving project. It is predicted that this will occur within 1.13 km of the piling location.

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Appendix A. Acoustic Metrics

A.1. Pressure Related Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially impulsive noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. 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 level (PK; L_{pk}; $L_{p,pk}$; dB re 1 µPa), is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

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

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

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

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

The sound pressure level (SPL; L_p; dB re 1 µPa) is the rms pressure level in a stated frequency band over a specified time window (T, s) containing the acoustic event of interest. It is important to note that SPL always refers to a rms pressure level and therefore not instantaneous pressure:

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

The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or over a fixed duration. Because the window length, T, is the divisor, events with similar sound exposure level (SEL) but more spread out in time have a lower SPL. A fixed window length of 0.125 s (critical duration defined by Tougaard et al. (2015)) is used in this study for impulsive sounds.

The sound exposure level (SEL; L_E; $L_{E,p}$; dB re 1 µPa^2·s) is a measure related to the acoustic energy contained in one or more acoustic events (N). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T):

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

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

SEL can be calculated over periods with multiple acoustic events or over a fixed duration. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, SEL can be computed by summing (in linear units) SEL of the *N* individual events:

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

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LFC,24h}$; Appendix A.3). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should else be specified.

A.2. Marine Mammal Impact Criteria

It has been long recognised that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggested that communication distances of fin whales are reduced by shipping sounds. Subsequently, similar concerns arose regarding effects of other underwater noise sources and the possibility that impulsive sources—primarily airguns used in seismic surveys—could cause auditory injury. This led to a series of workshops held in the late 1990s, conducted to address acoustic mitigation requirements for seismic surveys and other underwater noise sources (NMFS 1998, ONR 1998, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed for both injury and disturbance. The following sections summarize the recent development of thresholds; however, this field remains an active research topic.

A.2.1. Injury

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

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

As of 2017, an optimal approach is not apparent. There is consensus in the research community that an SEL-based method is preferable either separately or in addition to an SPL-based approach to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalised technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing (NMFS 2016). The guidance describes injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). The latest revision to this work was published in 2018; only the PK criteria defined in NMFS (2018) are applied in this report.

A.3. Marine Mammal Frequency Weighting

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

A.3.1. Marine mammal frequency weighting functions

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

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right] \quad \text{(A-6)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2016, NMFS 2018). Table A-1 lists the frequency-weighting parameters for each hearing group; Figure A-1 shows the resulting frequency-weighting curves.

Table A-1. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2018).

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (kHz)	K (dB)
Low-frequency cetaceans (baleen whales)	1.0	2	200	19,000	0.13
Mid-frequency cetaceans (dolphins, plus toothed, beaked, and bottlenose whales)	1.6	2	8,800	110,000	1.20
High-frequency cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* and *L. australis*)	1.8	2	12,000	140,000	1.36

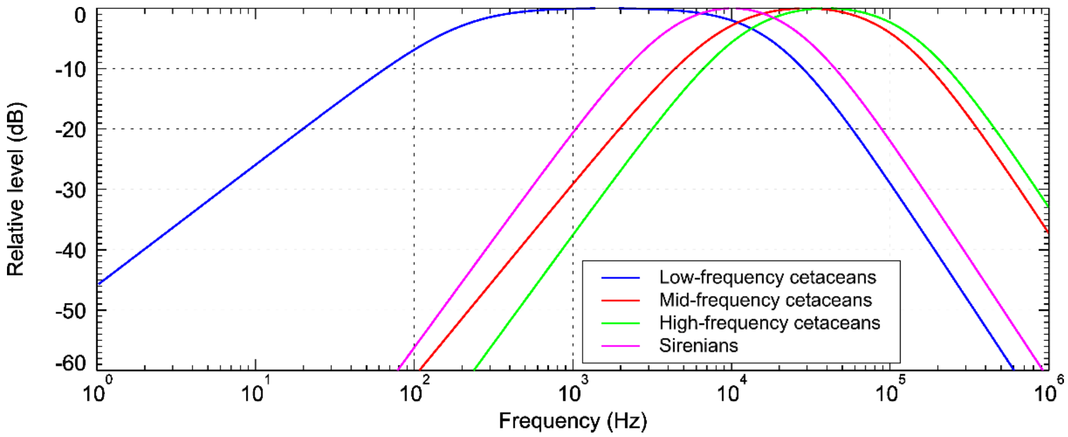

Figure A-1. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2018).

Appendix B. Pile Driving Acoustic 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 B-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 discretised 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 pile driving hammers also had to be modelled. 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 centred 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 (FWRAM, Appendix C.2). MacGillivray (2014) describes the theory behind the physical model in more detail. The accuracy of JASCO's pile driving model has been verified by comparing its output against benchmark scenarios (Lippert et al. 2016) and detailed measurement programs (Austin et al. 2016, Denes et al. 2016, MacGillivray 2018).

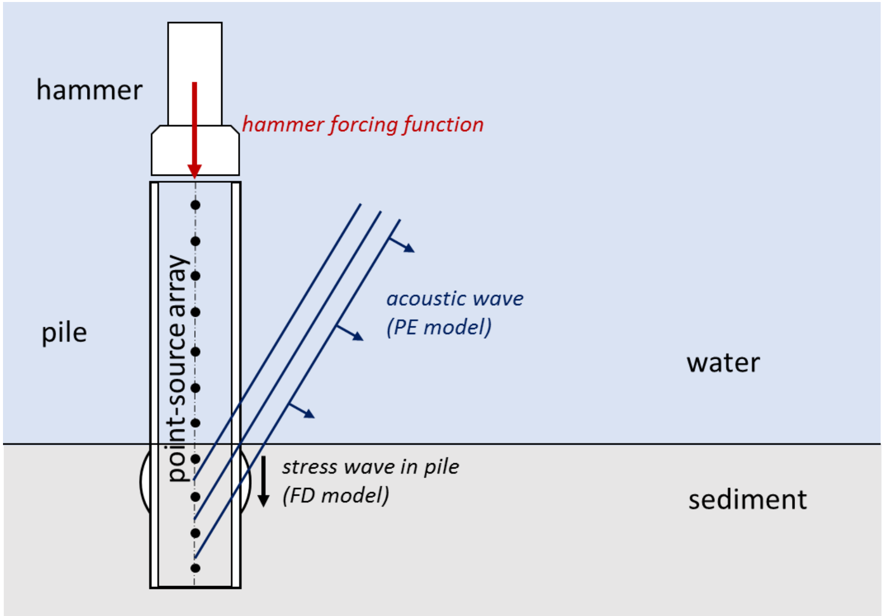

Figure B-1. Physical model geometry for impact driving of a cylindrical pile (vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE)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

Appendix C. Sound Propagation Models

C.1. Transmission Loss

The propagation of sound through the environment was modelled by predicting the acoustic transmission 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 transmission loss occurs. Transmission 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. Transmission loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic source level (SL), expressed in dB re 1 µPa^{2}m^2, and transmission loss (TL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 µPa by:

$$RL = SL - TL \tag{C-1}$$

C.2. Noise Propagation with FWRAM

For impulsive sounds from impact pile driving, time-domain representations of the pressure waves generated in the water are required to calculate SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterise vertical directivity effects in the near-field zone. For this study, synthetic pressure waveforms were computed using JASCO's Full Waveform Range-dependent Acoustic Model (FWRAM). FWRAM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for an elastic seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). FWRAM accounts for the additional reflection loss at the seabed due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. FWRAM incorporates the following site-specific environmental properties: a modelled area bathymetric grid, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

FWRAM computes pressure waveforms via Fourier synthesis of the modelled 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 from pile driving strikes were modelled and post-processed, after applying a travel time correction, to calculate standard SPL, SEL and PK metrics versus range and depth from the source.

Appendix D. Methods and Parameters

This section describes the specifications of the seismic source that was used at all sites and the environmental parameters used in the propagation models.

D.1. Estimating Range to Thresholds Levels

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled by taking the maximum value over all modelled depths above the sea floor for each location in the modelled region. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level: 1) R_{max}, the maximum range to the given sound level over all azimuths, and 2) $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure D-1).

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure D-1(a). In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In strongly asymmetric cases such as shown in Figure D-1(b), on the other hand, $R_{95\%}$ neglects to account for significant protrusions in the footprint. In such cases R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features affecting propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

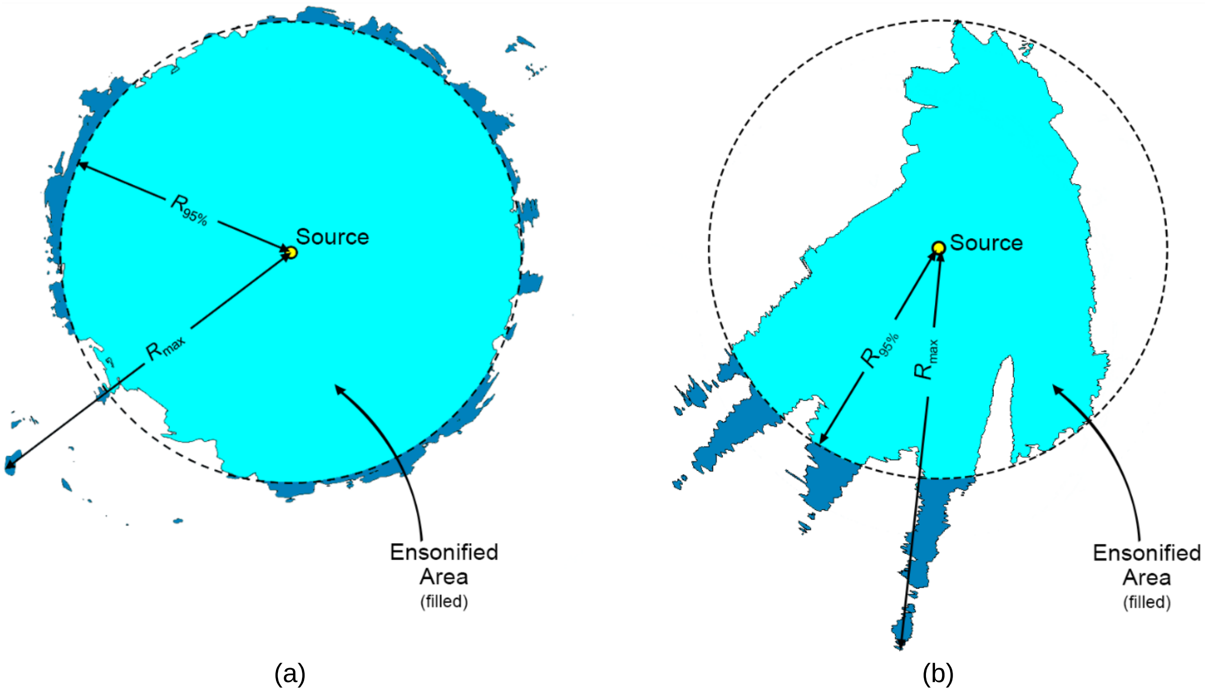

Figure D-1. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

D.2. Environmental Parameters

D.2.1. Bathymetry

Water depths (Mean Sea Level) throughout the modelled area as far as 150 km north from the pile were provided by Woodside. Within 1 km from the pile, the data has a grid resolution varying from 5 m × 5 m to 125 m× 125 m, while lower resolution data was available at longer distances. The data were adjusted for an increase of 1.7 m in depth (https://www.pilbaraports.com.au/PilbaraPortsAuthority/media/Documents/DAMPIER/Port%20Operations/Permits%20Procedures%20and%20Handbook/Port-of-Dampier-Dampier-Cargo-Wharf-Handbook.pdf), so the modelling results correspond to the most conservative propagation conditions at Mean High Water Springs. Bathymetry data were re-gridded onto a Map Grid of Australia (MGA) coordinate projection (Zone 50) with a regular grid spacing of 20 × 20 m.

D.2.2. Sound speed profile

The sound speed profile around Pile 11 was derived from temperature and salinity profiles from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep). The GDEM temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981).

Mean monthly sound speed profiles were derived from the GDEM profiles at distances less than 150 km around the modelling site. The June sound speed profile is expected to be most favourable to longer-range sound propagation across the entire year. As such, June was selected for sound propagation modelling to ensure precautionary estimates of distances to received sound level thresholds. Figure D-2 shows the resulting profile used as input to the sound propagation modelling.

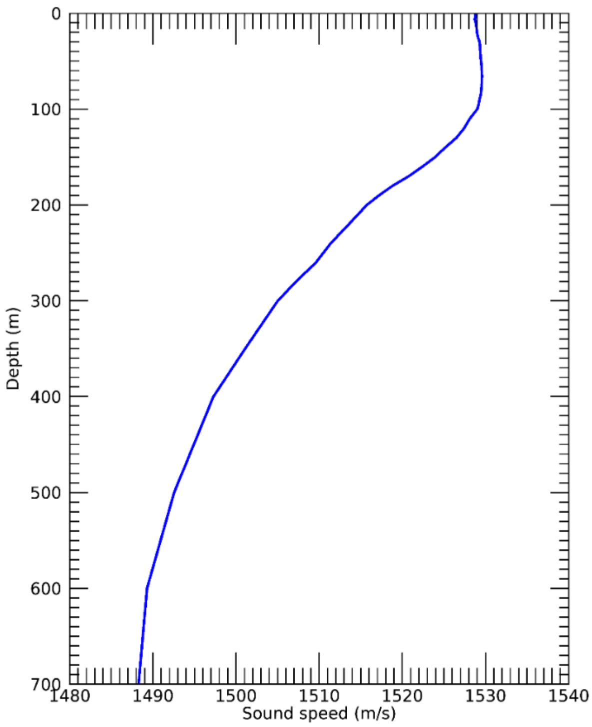

Figure D-2. The modelling sound speed profile corresponding to June Profiles are calculated from temperature and salinity profiles from *Generalized Digital Environmental Model* V 3.0 (GDEM; Teague et al. 1990, Carnes 2009).

D.2.3. Geoacoustics

Acoustic transmission loss modelling requires the geoacoustic properties of the seabed and sub-bottom to be as representative of the modelling area as possible. A qualitative description of the soil based on a pile drivability study conducted by the client shows that the seabed near the pile consists of 4 m of carbonate silts and sands, followed by increasingly consolidated calcarenite. Additionally, deeper core samples (Gallagher et al. 2017) indicate the presence of increasingly cemented packstone layers with depth below this surface sediment layer. Based on this layer information and generic properties for carbonate sediments and calcarenite from Hamilton (1980) and Duncan et al. (2013), the geoacoustic profile in Table D-1 was derived.

Table D-1. Geoacoustic profile used in the acoustic propagation models. Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave and the shear wave is the secondary wave.

Depth below seafloor (m)	**Material**	**Density (g/cm^3)**	**Compressional wave**		**Shear wave**	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–2	Silt	2.00–2.00	1656–1695	0.27–0.42	300	3.65
2–4	Very fine sand	2.04–2.04	1747–1783	0.51–0.64		
4–250	Slightly to semi-cemented sand/calcarenite	1.90	2100	0.12		
250–600	Semi-cemented sand/calcarenite	1.90	2200	0.12		
600–850	Well-cemented sand/calcarenite	2.20	2600	0.2		

D.3. Model Validation Information

Predictions from JASCO's propagation models (MONM, FWRAM and VSTACK) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including the United States and Canadian Artic, 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 modelling (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).