Potential Impact of Pile-Driving Noise at Cape Lambert

A Review of the Literature and International Regulations, 2018 Addendum

30 October 2018

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Acronyms and Abbreviations

Name	Description
%	percent
@	at
>	greater-than
>>	an approximation of >
≥	greater-than or equal-to
µPa	micro Pascal
μPa^2 s	micro Pascal squared per second
1/3	one third
24h	24 hours
AEP	auditory evoked potential
BIA	biologically important area
BMU	Bundesministerium für Umwelt (Germany)
BNatschG	German Federal Nature Conservation Act (Bundesnaturschutzgestzt)
CALTRANS	California Department of Transportation
CLA	Cape Lambert Port A
CLB	Cape Lambert Port B
cum	cumulative
dB	decibel
DEWHA	Department of Water, Heritage and the Arts (Australia), now the Department of the Environment and Energy
DoC	Department of Conservation (New Zealand)
DPTI	Department of Planning, Transport and Infrastructure (South Australia)
EPBC	Environment Protection and Biodiversity Conservation Act
ERMP	Ecosystem Research and Monitoring Program
et al.	and others
EU	European Union
ft	feet
GES	Good Environmental Status (EU)
h	hour

Name	Description
HESS	High Energy Seismic Survey Team
Hz	Hertz
ISO	International Standards Organisation
kHz	kilo Hertz
kips-ft	one thousand foot-pounds
kJ	kilojoule
km	kilometre
kN m	kilo-Newton metres
$L_{E,24h}$	Sound Exposure Level (SEL)
L_p	Sound Pressure Level (SPL)
L_{pk}	Peak Pressure
m	metres
m/s^2	metres per second squared
mm	millimetres
MNES	Matters of National Environmental Significance
MSFD	Marine Strategy Framework Directive (EU)
M-weighted	frequency weighted
NMFS	National Marine Fisheries Service (U.S.)
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NPWS	National Parks and Wildlife Service (Ireland)
NSF	National Science Foundation (U.S.)
PEIS	Programmatic Environment Impact Statement
PEPANZ	Petroleum Exploration and Production Association of New Zealand
PK	peak
PK-PK	peak-to-peak
PTS	permanent threshold shift
rms / RMS	root-mean-square
SEL	Sound Exposure level
SKM	Sinclair Knight Merz
SPL	Sound Pressure Level
spp.	species
ss	single strike (single pulse)
TSG	Technical Working Sub-Group (EU)
TTS	temporary threshold shift
U.S.	United States
U.K.	United Kingdom
WFD	Water Framework Directive (EU)

EXECUTIVE SUMMARY

Robe River Mining Co. Pty Limited (a member of the Rio Tinto Group of companies, Rio Tinto) is planning to carry out refurbishment of the Cape Lambert Port A wharf/jetty facilities, as part of the proposed Cape Lambert Port A Marine Structures Refurbishment Project. Refurbishment of marine structures as part of the project will require installation of 20 dolphins and associated piles (approximately 108 piles), and installation of an additional 36 piles in groups of four at nine locations along the wharf. Piles will be installed using a hydraulic pile hammer supported by a crane and jack-up barge. During implementation, there may be up to two simultaneously operating piling barges.

In 2011, JASCO Applied Sciences conducted a detailed literature review for pile driving noise for the Cape Lambert Port B development. The management of underwater noise is a rapidly advancing field of research and the purpose of this 2018 Addendum is to provide an update to the JASCO (2011) review. The focus of this 2018 Addendum is on relevant journal articles and research papers published since 2011, and changes in Australian and international regulations and guidelines on impact assessment for pile driving noise.

A review of marine fauna that may be present in the Cape Lambert region was conducted and this report covers the following key marine fauna groups that have the potential to be impacted by underwater noise from pile driving activities: marine mammals (whales, dolphins and dugong); marine reptiles (turtles and sea snakes); and fishes (bony fish and elasmobranchs).

The structure of this 2018 Addendum follows the structure of the JASCO (2011) review and provides cross-references to content that remains relevant. It is noted that fishes and sea snakes were not included in the JASCO (2011) review, and consequently additional information on the potential impacts of underwater noise to these faunal groups is included in this report. The JASCO (2011) review outlined international regulations relating to underwater noise impacts to marine life from pile driving. This 2018 Addendum provides a summary of new or updated regulations and guidance relating to pile driving and other relevant noise sources since 2011, including material from the following jurisdictions: Australia; New Zealand; USA; Germany; Denmark; Ireland; Sweden and the European Union.

Taking into account the information outlined in the JASCO (2011) review and the updated information provided in this 2018 Addendum, the following sound exposure criteria are recommended to be used for assessment of underwater noise impacts from the project:

- Marine mammals:
  - Single-impulse threshold for cetaceans (unweighted per-pulse SEL of 160 dB re 1 $\mu Pa^2 \cdot s$) outlined in the EPBC Act Policy Statement 2.1.
  - Peak pressure levels (PK) and frequency-weighted accumulated sound exposure levels (SEL) from the U.S. NOAA Technical Guidance for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals. Peak pressure levels (PK) unweighted sound exposure levels (SEL) from Finneran (2016) for the onset of TTS in marine mammals.
  - Marine mammal behavioural threshold based on the current interim U.S. NMFS criterion (NMFS 2013) for marine mammals of 160 dB re 1 µPa SPL for impulsive sound sources.
- Fishes, fish eggs and turtles
  - Sound exposure guidelines for fishes, fish eggs and larvae, and turtles from Popper et al. (2014).
  - Threshold for turtle behavioural response, 166 dB re 1 µPa (SPL), as applied by the U.S. NMFS (NSF 2011).

1. INTRODUCTION

1.1 Project Background and Objectives

Robe River Mining Co. Pty Limited is planning to carry out refurbishment of the Cape Lambert Port A (CLA) wharf/jetty facilities, as part of the proposed CLA Marine Structures Refurbishment Project (the project). Robe River Mining Co. Pty Limited is a member of the Rio Tinto Group of companies (Rio Tinto), and Rio Tinto is managing the environmental impact assessment and approvals process for the project on behalf of the proponent (Robe River Mining Co. Pty Limited).

Refurbishment of marine structures will require replacement of 20 dolphins and associated piles (approximately 108 piles), and installation of an additional 36 piles in groups of four at nine locations along the CLA jetty. Piles will be installed using a hydraulic pile hammer supported by a crane and jack-up barge. Open-ended steel piles of 1.2 m diameter are planned for use. There may be up to two simultaneously operating piling barges.

In 2011, JASCO Applied Sciences conducted a detailed literature review for pile driving noise for the Cape Lambert Port B (CLB) development (JASCO 2011).

The management of underwater noise is a rapidly advancing field of research and the purpose of this report is to provide an update to the JASCO (2011) review, with a focus on relevant journal articles and research papers published since 2011, and changes in Australian and international regulations and guidelines on impact assessment and mitigation for pile driving noise.

A review of marine fauna that may be present in the area of CLA facilities was conducted (refer to Section 1.2) and this report covers the following key marine fauna groups that have the potential to be impacted by underwater noise from pile driving activities:

- Marine mammals (whales, dolphins and dugong);
- Marine reptiles (turtles and sea snakes); and
- Fishes (bony fish and elasmobranchs).

The structure of this report follows the structure of the JASCO (2011) review and provides cross-references to content that remains relevant. It is noted that fishes and sea snakes were not included in the JASCO (2011) review. Additional information on the potential impacts of underwater noise to these faunal groups is therefore included in this report.

1.2 Use of the Project Area by Marine Life

A search of the Protected Matters Database for species listed under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) identified 12 listed threatened species, including two whale species, five marine turtle species, one sea snake and five fish (elasmobranch) species that may occur within 30 km of Cape Lambert (Table 1.1). Five additional migratory marine mammal species were identified including one whale, two dolphin species and dugong. A further five migratory elasmobranch species were also identified.

There is a ‘biologically important area’ (BIA) defined for pygmy blue whale (*Balaenoptera musculus brevicauda*) distribution off the coast of Cape Lambert. However, the BIA for blue whale migration is located more than 150 km to the west in deeper waters off the continental shelf. Blue whales are considered unlikely to occur in the coastal waters off Cape Lambert. There is also a BIA for humpback whale migration defined off the coast of Cape Lambert and humpback whales may be present during the northern and southern migration periods. The northern migration period in the area peaks in late July to early August, while the southern migration peaks late August to early September for bulls and in late September to early October for cow-calf pairs (Jenner et al. 2001). The migration corridor tends to be in deeper offshore waters on the northern migration, but the southern migration is closer to shore, and individuals have been sighted from the shore around Cape Lambert (SKM 2009).

As part of the CLB development Ecosystem Research and Monitoring Program (ERMP) Rio Tinto commissioned a series of aerial surveys of the Cape Lambert areas to monitor humpback whales during the peak southward migration period. The primary purpose of the surveys was to determine the whale use patterns around Nickol Bay and Cape Lambert; however, the presence of other significant marine fauna (whale sharks and dugongs) was also recorded (BMT Oceanica 2017). Aerial surveys were conducted in the months of August (2013, 2015), September (2014, 2016) and October (2012), and there was a total of 2,273 humpback whale pods (defined as more than 1 adult) and 3,571 individual humpback whales recorded between 2012 and 2016. From these surveys, it was concluded that breeding stock D humpback whale population transitions through Nickol Bay during their southern migration and that whale densities near to shore and Cape Lambert are similar to known resting areas (such as Exmouth Gulf). However, the density of pods with calves within Nickol Bay and adjacent waters was consistently lower than in these known resting areas. Despite lower densities, many of the pods with calves appear to use Nickol Bay for resting and milling close to shore, indicating the area is potentially significant for this purpose (BMT Oceanica 2017). The Cape Lambert area was primarily used as a broad transit pathway.

Table 1.1 Listed threatened marine species that may occur within the Cape Lambert Port area and surrounding waters

Common Name	Species Name	EPBC Act Conservation Status	Type of Presence
Marine Mammals			
Pygmy Blue Whale	*Balaenoptera musculus brevicauda*	Endangered	Species or species habitat likely to occur within area
Humpback Whale	*Megaptera novaeangliae*	Vulnerable	Species or species habitat known to occur within area
Marine Reptiles			
Loggerhead Turtle	*Caretta caretta*	Endangered	Foraging, feeding or related behaviour known to occur within area
Green Turtle	*Chelonia mydas*	Vulnerable	Breeding known to occur within area
Leatherback Turtle	*Dermochelys coriacea*	Endangered	Breeding likely to occur within area
Hawksbill Turtle	*Eretmochelys imbricata*	Vulnerable	Breeding known to occur within area
Flatback Turtle	*Natator depressus*	Vulnerable	Breeding known to occur within area
Short-nosed Sea snake	*Aipysurus apraefrontalis*	Critically Endangered	Species or species habitat likely to occur within area
Fishes			
Whale Shark	*Rhincodon typus*	Vulnerable	Species or species habitat may occur within area
Great White Shark	*Carcharodon carcharias*	Vulnerable	Species or species habitat may occur within area
Dwarf Sawfish	*Pristis clavata*	Vulnerable	Species or species habitat known to occur within area

Common Name	Species Name	EPBC Act Conservation Status	Type of Presence
Green Sawfish	*Pristis zijsron*	Vulnerable	Species or species habitat known to occur within area

There are beaches for turtle species in the vicinity of Cape Lambert, including Cooling Water Beach and Bells Beach (Figure 1.1). Turtle nesting occurs between November and March and occurs in relatively low numbers at these beaches compared to beaches (especially Cooling Water Beach) in the nearby Dampier Archipelago (SKM 2009). Cooling Water Beach has approximately 10 nests per year (3-4 individuals) (Jason Rossendell, Rio Tinto, pers. comm., October 2018). Modelling of turtle tagging data collected from 2008 – 2017 indicates a nesting population at Bells Beach in the order of 112-127 female flatbacks per season, compared with 2,700-3,900 flatbacks per season at Delambre Island, approximately 20 km north-west of Cape Lambert (Rossendell et al. in prep). Nesting around Cape Lambert is primarily by flatbacks, with occasional records of hawksbill and green turtle nesting. The waters off Cape Lambert are designated 'habitat critical for the survival of a species' for flatback, green and hawksbill turtle nesting. The area is also designated as a BIA for flatback, green and hawksbill turtle internesting.

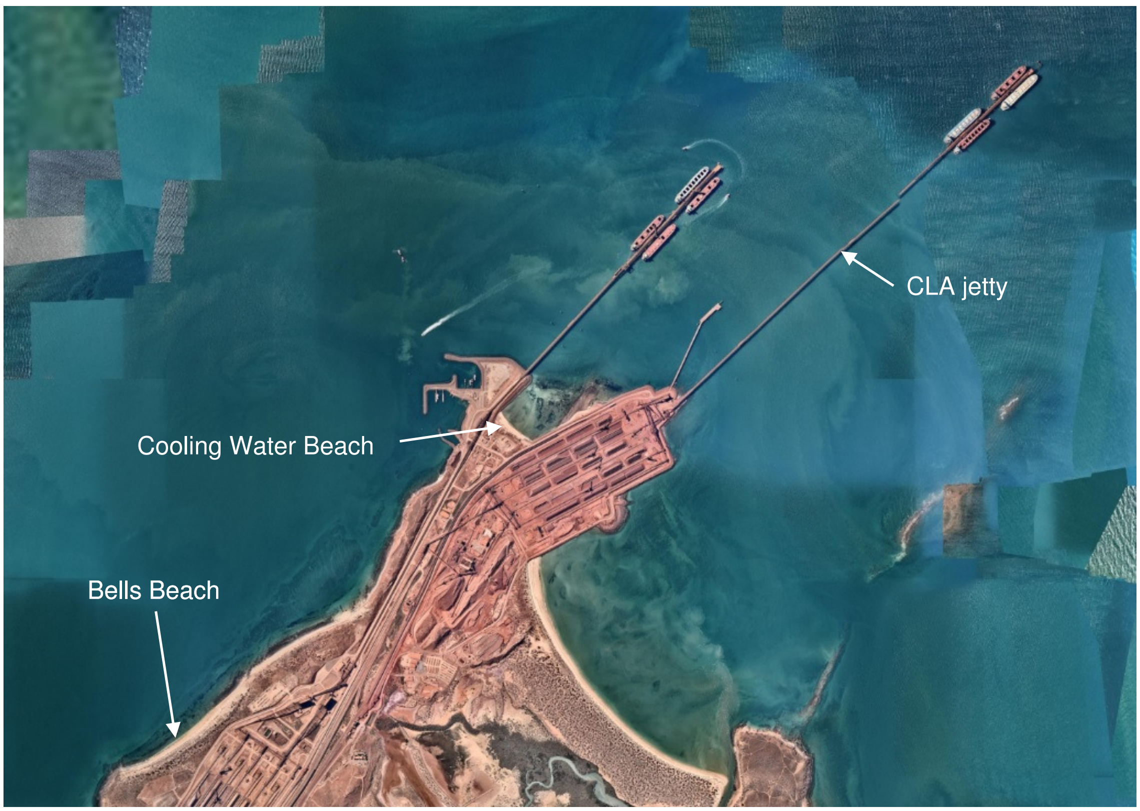


Figure 1.1 Location of turtle nesting beaches at Cape Lambert

Thums et al. (2018) provide the findings of a satellite tracking study of flatback turtles tagged on Bells Beach, which was undertaken to address two projects (Projects 4.3 and 4.4) of the ERMP. The study analysed data from 35 satellite transmitters deployed on adult female flatback turtles nesting in the vicinity of Cape Lambert to understand the spatial and temporal components of the main phases of their breeding cycle and assessed overlap with this industrial activity. The results of this research provided an objective and quantitative assessment of the spatial and temporal extent of the biologically important areas for flatback turtles, and the study found that flatback turtles from the Cape Lambert region did not use a discrete migratory corridor and dispersed widely to foraging grounds that had low spatial overlap. Furthermore, the data collected by this study suggest that industrial activities in the Cape Lambert area are likely to be of low risk to flatback turtles that use the area for nesting (Thums et al. 2018).

There are no BIAs for elasmobranch species in the Cape Lambert area.

1.3 Noise Generated by Pile Driving

JASCO Applied Sciences has been commissioned by ERM on behalf of Rio Tinto to conduct underwater acoustic modelling to assess sound levels from pile driving for the CLA marine structures refurbishment works. Both single strike and cumulative received sound levels will be considered and will be presented in a stand-alone modelling report to support the environmental impact assessment of underwater noise from piling activities.

This section provides an update to the general information on underwater noise generated by pile driving presented in the JASCO (2011) review.

Percussive pile driving involves a weight that hammers a pile into the ground. A hydraulic hammer will be used for piling associated with the CLA marine structures refurbishment activities. The weight falls onto the pile by gravity. Upon impact, sound is created in air at the top of the pile, and the acoustic energy spreads as a spherical wave. The impact also causes a stress wave travelling down the length of the pile. This wave couples with the surrounding medium (first air, then water farther down), radiating acoustic energy into the air and water. The stress wave in the pile also couples with the substrate below the water, creating an acoustic wave travelling through the seafloor. Sound can travel very fast and with low attenuation through various types of seafloor. Away from the pile, acoustic energy radiates back into the water from the seabed. The sound from impact pile driving is transient and discontinuous, i.e., pulsed. Within the water column, the arrival of acoustic pulses from different media and directions and with different phases and time delays results in a complex pattern of louder and quieter regions, in particular close to the source. Sound levels received in the water column at some distance from the pile depend on many operational and environmental factors, including:

- Pile size (diameter, wall thickness), shape (closed end, open end), and material,
- Hammer type and energy,
- Sediment type and thickness,
- Bedrock type and depth,
- Bathymetry, and
- Water salinity and temperature.

A review of the literature of acoustic source levels of impact hammer pile driving was undertaken by JASCO for hydroacoustic modelling of pile-driving noise (MacGillivray et al. 2011). The pile-driving measurements identified from this review are presented in Table 1.2 and provide an indication of noise levels for a variety of pile sizes, hammer types and hammer energy. Rough estimates of the source SELs are also given, which were back-propagated from the measured SEL assuming spherical spreading within 10 m of the source and cylindrical spreading thereafter (from 10 m to the measurement range). It is noted that none of the measurements cited in Table 1.2 are from peer-reviewed literature. Predicted spectra for pile-driving strikes are shown in Figure 1.2.

Table 1.2 Pile driver specifications and measured sound exposure levels (SELs) and frequency ranges from grey literature (from MacGillivray et al. 2011)

Pile diameter		Hammer type	Rated hammer energy		Measurement range		SEL (dB re 1 µPa²·s)		Frequency range (Hz)	Source
(ft)	(mm)		(kips-ft)	(kN·m)	(ft)	(m)	Measured	@ 1 m†		
3.0	900	Diesel	138	187	33	10	179	199	10–16,000	MacGillivray and Racca 2005
3.0	900	Drop	236	320	33	10	192	212	10–16,000	Racca et al. 2007
3.3	1015	Diesel	221	300	33	10	180	200	10–5000	Illingworth and Rodkin Inc. 2006
7.2	2200	Hydraulic	145	197	98	30	174	199	12.5–20,000	Schultz-von Glahn et al. 2006
7.9	2400	Hydraulic	738	1001	328	100	178	208	50–20,000	CALTRANS 2001
5.5	1675	Diesel	266	361	98	30	173	198	10–5000	Reyff 2003b
11.5	3500	Unknown	406	550	2789	850	174	213	30–20,000	Nehls et al. 2007
10.8	3300	Hydraulic	221	300	1739	530	173	210	16–20,000	Nehls et al. 2007
9.8	3000	Hydraulic	299	405	1050	320	173	208	16–12,000	McKenzie-Maxon 2000

Note: † Rough estimate of source SEL (for relative comparison only), back-propagated to 1 m range assuming spherical spreading within 10 m of the source and cylindrical spreading beyond.

Robinson et al. (2012) measured and analysed the pile driving of 5 m diameter piles installed in 15-20 m and driven by hydraulic hammers at a strike energy of 1000 kJ. Sound recordings were made using two mounted and a mobile system. Figure 1.2 shows the third octave spectra for pile driving pulses recorded from a single pile.

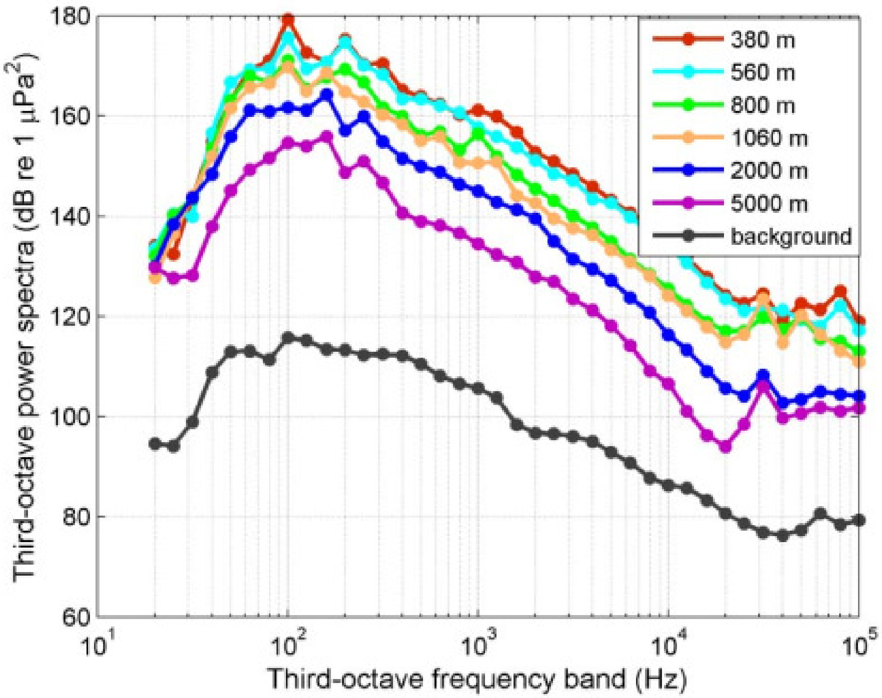
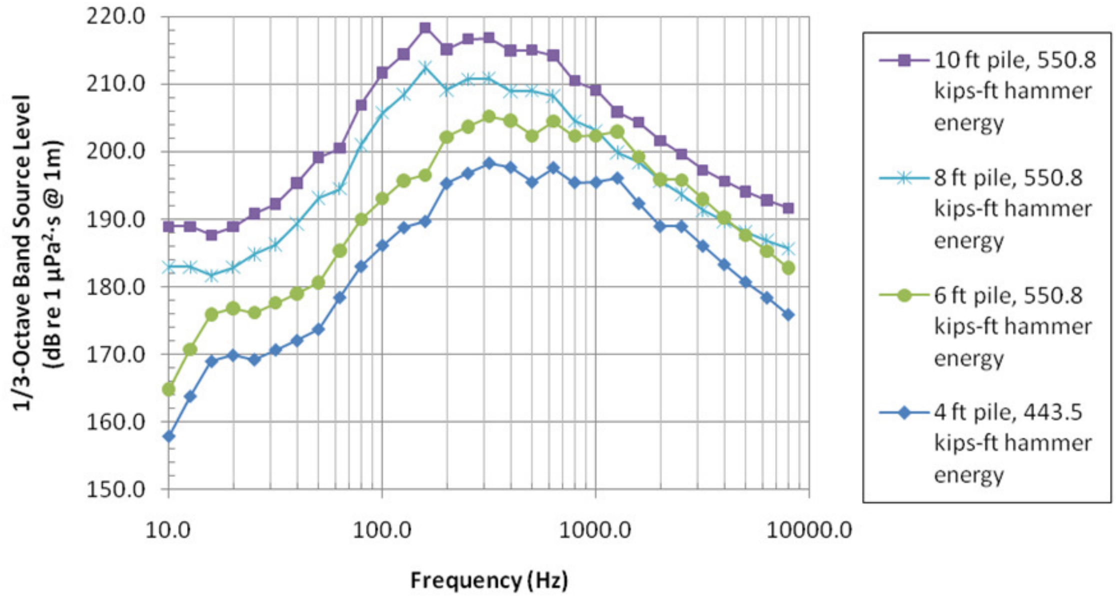


Figure 1.2 The third-octave band spectra for pulses recorded at ranges from 380 m to 5 km from a driven pile. Also shown are the levels for the background noise (from Robinson et al. 2012)

McGillivray et al. (2011) modelled the construction noise from the proposed Tappan Zee Bridge/I-287 Corridor Project. They analysed for 24 construction scenarios, encompassing seven unique pile driving locations, four different piles sizes, and five different acoustic metrics including acoustic particle velocity. Their modelling took the environment (bathymetry, geoacoustics and sound speed profile) into account and considered two distinct time scales: noise exposure over the brief duration of a single pile driving hammer strike and the cumulative exposure over a full day of construction activity. To provide the highest degree of accuracy they were using three different sound propagation modelling codes. Figure 1.3 depicts the 1/3-octave band source levels for the four pile-hammer configurations used in their modelling study.



Note: 1 kips-ft = 1.36 kN·m

Figure 1.3 Predicted 1/3-octave band source levels for impact driven steel piles with specified diameter and pile energy (from MacGillivray et al. 2011)

Analyses of noise measurements made during the installation of offshore wind turbine foundations in the North Sea (U.K.) indicate that pile diameter itself is not likely to substantially influence the sound radiation, but the hammer energy positively correlates with sound energy in the water with all other influencing factors remaining constant. The back-calculated source levels indicate that levels are likely to vary from site to site due to factors such as variation in the seabed and so comparisons are not straightforward. However, assuming that smaller pin piles require lower hammer energies and experience lower penetration resistance makes it more likely that the use of a jacket foundation would result in a lower SPL (PK) and SEL compared to a large diameter monopile foundation, which is likely to be subject to a higher penetration resistance and require a higher hammer blow energy. These assumptions are substantiated by the consideration of data from U.K. windfarms summarised in Table 1.3 (Scottish Power Renewables & Vattenfall 2012).

Table 1.3 Source level estimates from measured underwater noise data from U.K. windfarms (Scottish Power Renewables & Vattenfall 2012)

Source Level Estimates from Measured Underwater Noise Data from UK Windfarms							
Windfarm	**Pile Diameter (m)**	**Foundation Type**	**Peak Strike Hammer Energy (kJ)**	**Peak SPL Effective Source Level (dB re 1μPa·m)**	**SEL Effective Source Level (dB re 1μPa²·s·m²)**	**Water Depth (m)**	**Source**
Ormonde	1.8	Jacket	380	228-232	-	16-20	Data made available by Vattenfall
A UK windfarm (Commerical in Confidence)	5.2	Monopile	1157	226	205	20-23	Full data set not yet available
	5.2	Monopile	1130	231	212	17-20	
	5.2	Monopile	1335	243	216	15-17	
	5.2	Monopile	1367	241	221	14-20	
Greater Gabbard	1.37	Jacket (Quad)	604	217	188	28-48	Robinson et al. (2009)
	6.0	Monopile	822	242	218	28-48	Theobald et al. (2010)
	6.1	Monopile	1073	238	211	28-48	
	6.2	Monopile	780	240	223	28-48	
	6.3	Monopile	1051	240	219	28-48	
	6.3	Monopile	1082	237	211	28-30	

Measured Underwater Noise Data from UK Windfarms							
Barrow	4.7	Monopile	-	246	-	10-20	Nedwell et al. (2007)
North Hoyle	4.0	Monopile	450 Average	243	-	10-15	
Scroby Sands	4.2	Monopile	-	251	-	10-15	
Kentish Flats	4.3	Monopile	344 Average	237	-	5-8	
Burbo Bank	4.7	Monopile	-	243	-	7-24	
Thanet	4.11	Monopile	370	242	-	0*-20	Nedwell et al. (2009)
Thanet	4.9	Monopile	1297	241	-	0*-20	Nedwell et al. (2010)
Beatrice Demonstrator	1.8	Jacket (Quad)	185	220- 246	-	>40	Bailey et al. (2010)
Asingle test pile (Commerical in confidence)	2.0	Monopile	800	230	209	3-7	Full data set not yet available
Oil & Gas seafloor installation	0.75	Anchoring Pin Pile	-	210	-	95	McHugh et al. (2005)

1.4 Potential Effects of Underwater Noise on Marine Life

Underwater noise has the potential to impact marine fauna in a number of ways. Marine fauna use sound for a range of functions, including foraging, social interaction, and orientation and navigation. Therefore, exposure to anthropogenic noise sources may result in a variety of responses depending on the noise source levels and characteristics, distance from the noise source and the received noise levels, the type and duration of exposure, and the context and activity of animals at the time of exposure.

The potential effects of noise can be broadly categorised as follows:

- Behavioural response – Disturbance leading to behavioural changes, displacement, attraction or avoidance. The occurrence and intensity of behavioural responses is highly variable and depends on a range of factors relating to the animal and situation;
- Masking or interfering with other biologically important sounds (including vocal communication, echolocation, signals and sounds produced by predators or prey);
- Stress – Stress is an integral, necessary part of the body's homeostasis, and certain stress levels are tolerable. At higher levels, if repeated too often, or continued over long durations stress can become deleterious and may reduce the individual's fitness.
- Hearing impairment – Subject to the nature and duration of the exposure, hearing impairment may be temporary (TTS) or permanent (PTS);
- Injury – Sound received at very close range to some high-intensity sound sources can potentially cause tissue damage resulting in recoverable or mortal injury.

Further details on these potential effects of underwater noise on marine life are outlined in Section 1.4 of the JASCO (2011) review.

1.5 Metrics

The publication of ISO 18405 Underwater Acoustics – Terminology (ISO 2017) provided a dictionary of underwater bioacoustics. For future reference, the terminology defined in this standard should be used to avoid ambiguity in reported sound levels. However, most of the relevant studies on noise effects in marine fauna are not compliant as they were published before the new standards were released (Table 1.4).

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 hours 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 fishes move.

Table 1.4 Metrics used to describe underwater sound

Metric	Commonly used (before 2017)	ISO (2017) / NMFS (2018)	
		Main text	Tables/equations
Sound Pressure Level	SPL_{rms}, SPL_{RMS}	SPL	SPL (L_p)
Peak Pressure	SPL_{pk}	PK	PK (L_{pk})
Sound Exposure Level	SEL_{cum}	SEL_{24h}	SEL_{24h} ($L_{E,24h}$)

2. HEARING CAPABILITY OF SPECIES OF CONCERN AND IMPACTS OF PILE DRIVING

The degree of impact of underwater noise on marine life not only depends on the nature and context of the exposure, but on the hearing sensitivity of different marine fauna. The hearing capability and potential for impact to marine mammals and turtles from pile driving noise is detailed in Section 2 of the JASCO (2011) review. This section of the current report therefore provides a summary of relevant research in relation to the impacts of pile driving noise on marine mammals and turtles published since 2011.

Given fish species were not included in the JASCO (2011) review, a more detailed summary of hearing capability and potential underwater noise impacts to fishes is provided in Section 2.3. In addition, a search of the EPBC Protected Matters Database identified that the short-nosed sea snake (*Aipysurus apraefrontalis*), which is listed as critically endangered under the EPBC Act, may occur in the Cape Lambert area (refer to Section 1.2). Little information is available about the effects of underwater noise on sea snakes. However, given the threatened status of the short-nosed sea snake, some discussion is provided on the potential for impact to sea snakes from pile driving noise (Section 2.2.2).

2.1 Marine Mammals

The JASCO (2011) review summarised available information on the hearing capability and potential impacts to dolphins (focusing on Indo-Pacific humpback dolphins), whales (focusing on humpback whales) and dugong. The review includes details of the Southall et al. (2007) literature on marine mammal hearing and physiological and behavioural responses to anthropogenic sound. Appendix C.1 of the JASCO (2011) review outlines the noise exposure criteria proposed by Southall et al. (2007). This is notable as the Southall et al. (2007) criteria are referred to in some of the updates to Regulations and guidance outlined in Section 3 of this report.

Since 2011 a number of peer-reviewed publications and reports have been published on the impacts of pile driving noise on marine mammals, with a particular focus on renewable energy developments (primarily offshore wind farms – e.g. Bailey et al. 2010). Gedamke & Scholik-Schlomer (2011) provided an overview and summary of recent research into the potential effects of pile driving on cetaceans, with this review covering much of the material already incorporated into the JASCO (2011) report. A number of papers have reported on the findings of studies examining behavioural responses of harbour porpoises (*Phocoena phocoena*) to pile driving noise associated with wind farm construction in the North Sea (Dähne et al. 2013; Kastelein et al. 2015; Tougaard et al. 2015). Dähne et al. (2013) documented avoidance responses by harbour porpoises over long distances (up to 20 km) during pile driving activity associated with construction of an offshore wind farm. Kastelein et al. (2016) tested the effect of exposure duration on TTS in harbour porpoises by exposing two individuals to playbacks of pile driving sounds under controlled conditions. Based on their results, they calculated an onset of TTS for this type of sound at a SEL_{24h} of approximately 175 dB re 1 $\mu Pa^2 \cdot s$.

As pointed out by Ellison et al. (2012) and Dahl et al. (2015) it is apparent that the most significant population consequences from anthropogenic underwater noise (such as pile driving) to marine mammal populations are likely to occur as a result of a behavioural response rather than direct physical injury or mortality due to the sound.

A study in 2010 measured the noise energy created by impact and vibratory pile driving associated with wharf construction activities in the Fremantle Inner Harbour, and examined whether the reduced detection of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) within the vicinity of the wharf was associated with pile driving activities (Salgado Kent et al. 2012; Paiva et al. 2015). The key finding of this study was that the number of dolphin transit events detected was significantly greater when no pile driving activity occurred than when there was pile driving activity. While bottlenose dolphins using the Inner Harbour are regularly exposed to a relatively noisy environment, noise from pile driving elevated the level within the range in which behavioural responses have been observed in other studies (Paiva et al. 2015).

A technical report entitled *Auditory Weighting Functions and TTS/PTS Exposure Functions for Marine Mammals Exposed to Underwater Noise* was published by the U.S. Navy in 2016 (Finneran 2016), which underpins the technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing from the U.S. National Marine Fisheries Service (NMFS) and was included as an appendix to the technical guidance report (NMFS 2018). The NMFS guidance is outlined in Section 3.3.1 of this report. Finneran (2016) outlines frequency-dependent weighting functions and numeric thresholds for the onset of TTS and PTS for different groups of marine mammals based on hearing capability. Exposures just sufficient to cause TTS or PTS are denoted as “TTS onset” or “PTS onset” exposures. TTS and PTS onset thresholds derived by Finneran (2016) are summarised in Table 2.1.

Table 2.1 Summary of TTS/PTS thresholds for impulsive noise sources from Finneran (2016)

Marine Mammal Group	TTS Threshold		PTS Threshold	
	SEL (Unweighted)	Peak SPL (Unweighted)	SEL (Weighted)	Peak SPL (Unweighted)
Low frequency cetacean	168	213	183	219
Mid frequency cetacean	170	224	185	230
High frequency cetacean	140	196	155	202
Sirenian (dugong)	175	220	190	226

Note: SEL thresholds are in dB re 1 μPa^2 s and peak SPL thresholds are in dB re 1 µPa.

The intensity of behavioural responses of marine mammals to sound exposure ranges from subtle responses, which may be difficult to observe and have little implications for the affected animal, to obvious responses, such as avoidance or panic reactions. The context in which the sound is received by an animal affects the nature and extent of responses to a stimulus. The threshold for elicitation of behavioural responses depends on received sound level, as well as multiple contextual factors such as the activity state of animals exposed to different sounds, the nature and novelty of a sound, spatial relations between a sound source and receiving animals, and the gender, age, and reproductive status of the receiving animal.

The complexity of factors which are relevant for the elicitation of a behavioural response implies that animals are likely to exhibit a gradually increasing probability of response. Accordingly, and in the absence of detailed information on most of the relevant parameters, NMFS currently uses a step function with a 50% probability of inducing behavioural responses at an SPL of 160 dB re 1 µPa to assess behavioural impact. This threshold value was derived from the HESS (1999) report, which, in turn, was based on the responses of migrating mysticete whales to an airgun sounds (Malme et al. 1983, Malme et al. 1984). The HESS team recognized that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above an 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; to be updated soon). Appendix B of Southall et al. (2007), which is expected to be updated in the near future, provided a compilation of studies involving marine mammal behavioural responses to multiple pulses. They found varying responses for most marine mammals between an SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but a 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.

In 2012, Wood et al. (2012) proposed a graded probability of response for impulsive sounds using a frequency weighted SPL metric. They also designated behavioural response categories for sensitive species (such as harbour porpoises [*Phocoena* spp.] and beaked whales) and for migrating mysticetes (Table 2.2).

Table 2.2 Predicted probability of behavioural response in marine mammals as a function of frequency-weighted sound pressure level (Wood et al. 2012)

Marine Mammal Group	Probabilistic Disturbance SPL thresholds M-weighted dB re 1 µPa (rms)			
	120	140	160	180
Porpoises/beaked whales	50%	90%		
Migrating mysticete whales	10%	50%	90%	
All other species/behaviours		10%	50%	90%

Note: Probabilities are not additive.

2.2 Marine Reptiles

2.2.1 Turtles

In 2014, the Working Group on the Effects of Sound on Fish and Turtles published guidelines with specific thresholds for different levels of effects for several groups of species including marine turtles (Popper et al. 2014). The guidelines define quantitative thresholds for three types of 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.

Popper et al. (2014) recommend that potential for hearing effects, masking and behavioural disturbance to turtles be assessed qualitatively rather than strictly based on a specific threshold. For hearing effects including PTS and TTS, Popper et al. (2014) rated the likelihood as high in the near-field (in proximity to the source) and low in the intermediate to far-field. The likelihood was similarly rated as high in the near-field for behavioural disturbance, moderate in the intermediate-field and low in the far-field. Although specific distances were not ascribed to the near, intermediate and far-field by Popper et al. (2014), indicative distances of tens of metres from the source for the near-field, hundreds of metres for the intermediate-field, and thousands of metres for the far-field were provided.

Table 2.3 lists relevant effects thresholds for marine turtles from Popper et al. (2014) for pile driving.

Audiometry and behavioural studies on sea turtles found their hearing frequency range is approximately 50–2000 Hz, with highest sensitivity to sounds between 200 and 400 Hz (Bartol et al. 1999; Ketten and Bartol 2005; Bartol and Ketten 2006; Yudhana et al. 2010; Lavender et al. 2012; Lavender et al. 2014; Piniak et al. 2016).

McCauley et al. (2000) 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 the 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. 1994), 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.

A level of 175 dB re 1 μPa SPL (rms) is expected to be the received sound level at which marine turtles would actively avoid exposure to either impact or vibratory pile driving noise during Navy training activities, as reported in *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis* (U.S. Navy 2017). This report makes the comment that this criterion was selected following discussions with the NMFS.

Table 2.3 Criteria for pile driving noise exposure for turtles, adapted from Popper et al. (2014)

Mortality and potential mortal injury	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
210 dB SEL_{24h} or >207 dB PK	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low

Note: Peak sound pressure level dB re 1 μPa; SEL_{24h} dB re 1μPa^2·s. All criteria are presented as sound pressure 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).

2.2.2 Sea Snakes

There is little information available about the effects of underwater noise on sea snakes. It is possible that they will respond in a similar way to turtles, such as exhibiting behavioural avoidance of the sound source.

Three characteristics suggest that sea snakes could be vulnerable to impacts from impulsive pile driving noise:

- Sealed nostrils and an air-filled lung extending the length of the body, plus slower swimming speeds than other marine vertebrates, might mean they are unable to avoid tissue damage at close range.
- Scale sensillae that allow sea snakes to detect the vibrations of their prey show peak sensitivity to low frequencies that overlap those produced by pile driving, this may disrupt feeding (via acoustic masking) and provoke avoidance behaviour.
- Translocation (a common response to impulsive sound sources such as seismic and pile driving) is associated with high mortality in sea snakes; habitat displacement might have long term consequences for highly isolated populations.

The outcomes of a research project – “Investigating the impact of seismic surveys on threatened sea snakes in Australia's North West Shelf” (undertaken at the School of Earth and Environmental Sciences, University of Adelaide) has been made available (Sanders 2013). While not directly relevant to pile driving noise, seismic sources have similar sound characteristics and sea snake responses may therefore be expected to be comparable.

2.2.2.1 Morphology

Scanning electron microscopy and comparative phylogenetic analyses were used to provide evidence that the scale sensilla (touch receptors) of terrestrial elapid snakes may function as hydrodynamic receptors in sea snakes. Scale sensilla were more protruding (dome-shaped) in sea snakes than in their terrestrial counterparts, and exceptionally high overall coverage of sensilla was found only in the sea snakes. High sensilla coverage appears to have evolved multiple times within sea snakes, so that the impacts of anthropogenic noise on sea snakes will likely vary among species. These findings are now published (Crowe-Riddell et al. 2016) and were used to inform taxon selection in the audiometry study (below).

2.2.2.2 Audiometry

Terrestrial snakes are able to detect both airborne and ground-borne vibrations using their body surface (termed somatic hearing) as well as from their inner ears (Young 2003). The central auditory pathways for these two modes of "hearing" remain unknown. Experimental evidence has shown that snakes can respond behaviourally to both airborne and ground-borne vibrations; between 100-600 Hz using the auditory pathway and up to 1.5 kHz (highest frequency tested) via somatic perception (Wever 1978).

Auditory evoked potentials (AEP) of wild caught sea snakes were measured in 2015 and 2016, providing the first experimental data on the hearing abilities of sea snakes underwater (Sanders 2013). The audiogram of *Hydrophis stokesii* (based on two individuals) shows a limited frequency range of about 40 Hz to about 1,000 Hz, peaking at low frequencies (60 Hz). This sensitivity is similar to species of fish only receptive to particle motion (e.g. fishes without a swim bladder, elasmobranchs), which could suggest that sea snakes are not sensitive to sound pressure. By overlapping the signature of a typical airgun on the audiogram of *H. stokesii*, the research team predict that these snakes are able to detect an airgun sound up to 100 m from the source.

Sea snakes are not sedentary and, like turtles, can swim away from an approaching sound source. Potential mortality or mortal injury effects to sea snakes are therefore unlikely, with impacts more likely to be behavioural including avoiding or moving away from the area for the period of pile driving activities.

2.3 Fishes

2.3.1 Bony Fish

Fishes have developed two sensory mechanisms for detecting, localising, and interpreting underwater sounds and vibrations: the inner ear which is tuned to sound detection and the lateral line system which allows a fish to detect vibration and water flow. As sound passes through the body of the fish (which has a similar density compared to the surrounding water) the entire body of the fish moves back and forth with the particle motion of the sound. However, the otoliths in the ears lag behind that movement due to their higher density and mass thereby creating a shearing force on the motion-sensitive hair cells.

Fishes vary widely in their vocalisations and hearing abilities, but for most species, sensitivity to sound occurs from approximately 100 Hz to several hundred Hz or several kHz, with greatest sensitivity at low frequencies below 1 kHz (Ladich, 2000; Mann et al. 2001; Nedwell et al. 2004; Landrø and Amundsen, 2011; Popper et al. 2014). The predominant frequency range of pile driving sound emissions is less than 1 kHz (Figure 1.3), which is therefore within the detectable hearing range of most fishes.

Fish species with swim bladders connected to their inner-ear are considered to be most sensitive to sound pressure, while fish species without a swim bladder connection are less sensitive to sound pressure and may only be sensitive to the particle motion components of sound at very close ranges (Popper and Fay 2011; Popper et al. 2014; Carroll et al. 2017; Hawkins and Popper 2017).

Behavioural effects of noise on fishes will vary depending on the particular circumstances of the individual, its hearing sensitivity, the activities in which it is engaged, its motivation, and the context in which it is exposed to sounds (Hawkins and Popper 2017). Responses may include avoidance behaviours, startle reactions, increased swimming speed, change in orientation, change in position in the water column, changes to schooling behaviour (e.g. tightening of school structure), seeking refuge in reefs, and temporary avoidance of an area leading to temporary and localised changes in distribution (Simmonds and MacLennan 2005; McCauley et al. 2003; Engås et al. 1996; Engås and Løkkeborg 2002; Slotte et al. 2004; Fewtrell and McCauley 2012; Popper et al. 2014; Carroll et al. 2017).

In 2014, the Working Group on the Effects of Sound on Fish and Turtles published guidelines with specific thresholds for different levels of effects for various groups of fishes based on auditory capabilities as distinguished by anatomy (Popper et al. 2014). Based on a detailed review of available data, Popper et al. (2014) has recommended criteria for potential injury, TTS, masking and behavioural impacts in response to impulsive noise from pile driving, seismic surveys and explosions, as well as non-impulsive sound sources. The criteria for impulsive noise from pile driving are summarised in Table 2.4. As described for turtles in Section 2.2.1, where quantitative thresholds are not available, relative risk (high, moderate, low) is given for three general distances from a sound source, defined in relative terms as near (tens of metres), intermediate (hundreds of metres), and far (thousands of metres).

The published information on behavioural responses of fishes to pile driving sound is relatively scarce. Ruggerone (2008) conducted a behavioural response study in juvenile coho salmon (*Oncorhynchus kisutch*) that were held in cages next a pile driving operation in a harbour. The authors report that there was no apparent change in behaviour during the pile driving as only less than 10% of the fish exhibited a startle response during the first or subsequent hammer strikes of each pile.

In controlled exposure experiment, Mueller-Blenkle et al. (2010) exposed Atlantic cod and sole (*Solea solea*) held in two large (40 m) net pens located in a quiet bay to playbacks of pile-driving noise. They tracked their movements visually and quantified both the received sound pressure level and particle motion. Sole showed an increase in swimming speed at received peak sound pressure levels (PK) of 144-156 dB re 1µPa and cod exhibited significant freezing response at onset and cessation of playback at received peak sound pressure levels of 140-161 dB re 1 µPa (particle motion was determined to be between 6.51 x 10-3 m/s^2 peak and 8.62 x 10-4 m/s^2 peak). The authors report a high variability in behavioural reactions across individuals and a decrease of response with multiple exposures. The results further imply a relatively large zone of behavioural response to pile-driving sounds in marine fish (Mueller-Blenkle et al. 2010).

In a sound playback experiment in an enclosed, quiet, coastal sea lough, Hawkins et al. (2014) exposed free-living pelagic fish to sound playback of synthetic, low frequency, impulsive sounds, mimicking some of the features of sounds produced by pile drivers and seismic airguns. Behavioural responses of fishes were observed with a sonar/echo sounder. The fishes they encountered were predominantly sprat and Atlantic mackerel (*Scomber scombrus*) and were not accustomed to heavy disturbance from shipping and other intense sound sources. Sprat schools reacted to sound exposure, following a short latency, with lateral dispersal, taking them outside the sonar beam. The fish often then reappeared at a greater depth recombined into a school. Mackerels responded by dispersing and/or a rapid depth change. The lowest received sound pressure level (PK-PK) eliciting a response in free-living sprat was 140 dB re 1 µPa, while mackerel responded to a received sound pressure level of 143 dB re 1 µPa. There was an increase in the proportion of sprat and mackerel schools responding to sound playback with increasing sound levels. The 50% response level for sprat was at a received sound pressure level (PK-PK) of 163.2 dB re 1 µPa, for mackerel schools the 50% level was reached at a peak-to-peak sound pressure level (PK-PK) of 163.3 dB re 1 µPa.

Everley et al. (2016) used playbacks of pile driving sounds to study behavioural responses in fish held in net pens and experimental tanks.

The behaviour of fish in these studies cannot be confidently extrapolated to the normal behaviour of wild fish exposed to pile driving noise.

By comparison, Iafrate et al. (2016) reported the findings of a study that examined the effects of 35 days of pile driving at a wharf complex in Florida on the residency and movement of tagged reef fishes. Received sound pressure levels from pile strikes on the interior of the wharf, where reef fish primarily occur, were on average 152-157 dB re 1 µPa (PK). No significant decrease in sheepshead (*Archosargus probatocephalus*) daytime residency was observed during pile driving within the area of highest sound exposure, and there were no major indicators of displacement from the exposed wharf area with the onset of pile driving. There was evidence of potential displacement from the exposed wharf area that coincided with the start of pile driving observed for two out of four grey snappers (*Lutjanus griseus*), along with a decrease in daytime residency for a subset of this species. Results indicate that snapper may be more likely to depart an area of pile driving disturbance more readily than sheepshead but were less at risk for behavioural impact given the lower site fidelity of this species.

Table 2.4 Criteria for pile driving noise exposure for fishes (Popper et al. 2014)

Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fishes: No swim bladder (particle motion detection)	> 219 dB 24 h SEL or > 213 dB peak	> 216 dB 24 h SEL or > 213 dB peak	>> 186 dB 24 h SEL	N) Low (I) Low (F) Low	N) High (I) Moderate (F) Low
Fishes: Swim bladder not involved in hearing (particle motion detection)	210 dB 24 h SEL or > 207 dB peak	203 dB 24 h SEL or > 207 dB peak	>186 dB 24 h SEL	N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fishes: Swim bladder involved in hearing (primarily pressure detection)	207 dB 24 h SEL or > 207 dB peak	203 dB 24 h SEL or > 207 dB peak	186 dB 24 h SEL	(N) Low (I) Low (F) Moderate	(N) High (I) High (F) Moderate

Note: Peak sound pressure level dB re 1 µPa; SEL_{24h} dB re 1µPa²·s. All criteria are presented as sound pressure 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).

2.3.2 Sharks and Rays

Elasmobranchs (sharks) lack a swim bladder and it is thought that they are less sensitive than many bony fish species to sound pressure (McCauley 1994) and are mainly capable of detecting the particle motion component of sound at close range (Myberg 2001). Studies show that elasmobranchs may detect sound from 50 Hz to 500 Hz (Normandeau Associates 2012). The hearing capabilities of key listed species such as whale sharks and sawfish have not been studied specifically, but it has been suggested that, similar to other cartilaginous species, they are likely to be most responsive to low frequency sounds (Myberg 2001).

Popper et al. (2014) proposed that the sound exposure criteria for fishes without a swim bladder are appropriate for sharks in the absence of other information (refer to Table 2.4).

3. REGULATIONS

The JASCO (2011) review outlined international regulations relating to underwater noise impacts to marine life from pile driving. This section provides a summary of new or updated Australian and international regulations and guidance relating to pile driving and other relevant noise sources since 2011, including the following:

- Australia: Government of South Australia - *Underwater Piling Noise Guidelines* (DPTI 2012).
- New Zealand: *Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations* (DoC 2013).
- United States of America: *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing - Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts* (NMFS 2016).
- United States of America: *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish* (CALTRANS 2015).
- Germany: *Concept for the Protection of Harbour Porpoises from Sound Exposures during the Construction of Offshore Wind Farms in the German North Sea* (BMU 2014).
- Denmark: *Guideline for underwater noise – Installation of impact-driven piles* (Energistyrelsen 2016).
- Ireland: *Guidance to Manage the Risk to Marine Mammals from Man-made Sound Sources in Irish Waters* (NPWS 2014).
- Sweden: *Framework for Regulating Underwater Noise During Pile Driving* (Andersson et al. 2016).
- International: *European Marine Strategy Framework Directive* – Good Environmental Status (Van der Graaf et al. 2012).

3.1 Australia

There is no published Federal guidance on underwater noise from pile driving; however, the Government of South Australia (SA) published the *Underwater Piling Noise Guidelines* in 2012, which are adapted from EPBC Policy Statement 2.1 (DEWHA 2008). The Guidelines provide practical management and mitigation measures for the purpose of minimising the risk of injury to occur in marine mammals within the vicinity of piling activities, consistent with international good practice (DPTI 2012).

The DPTI (2012) Guidelines use noise exposure criteria based on interim criteria adopted by the US National Oceanic and Atmospheric Administration (NSF, USGS & NOAA 2011) for behavioural and physiological (PTS and TTS) impacts. These criteria have since been superseded by recent Guidance published by the U.S. NMFS in 2016 and updated in 2018 (refer to Section 3.3 below for details).

Standard management and mitigation procedures outlined in the DPTI (2012) Guidelines include:

- Safety zones, including observation and shut-down zones (sized by comparing expected received noise levels with defined noise exposure thresholds);
- 30-minute pre-start-up visual observations;
- 10-minute soft-start procedures;
- Standby and shut-down procedures, and
- Compliance and sighting reports.

Additional management and mitigation measures are recommended if the piling work will have, or is likely to have, a significant impact on any Matters of National Environmental Significance (MNES) under the Commonwealth EPBC Act. Example additional measures include:

- Increased safety zones;
- Use of qualified marine mammal observers;
- Operational procedures during night time or poor visibility;
- Use of a spotter vessel or aircraft if clear observations cannot be made from land or the piling rig, and
- Passive acoustic monitoring.

3.2 New Zealand

There is no specific guidance in relation to underwater noise from pile driving in New Zealand; however, in 2013 the New Zealand Department of Conservation released a *Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations* (DoC 2013), which is currently under review. While not directly relevant to pile driving noise, seismic sources have similar sound characteristics. The Code of Conduct is given effect under the *Marine Mammals Protection Act 1978* and *Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act 2012*. It has been endorsed as industry best practice by the Petroleum Exploration and Production Association of New Zealand (PEPANZ).

The Code of Conduct provides requirements for different levels of seismic surveys (defined by source size), including the requirement for marine mammal impact assessments and management and mitigation measures. The supporting reference document for the Code of Conduct (DoC 2012) references sound exposure criteria defined by Southall et al. (2007) and the U.S. NMFS (NMFS 2018) in determining mitigation zones.

3.3 United States of America

3.3.1 Marine Mammals

The NMFS, in consultation with the National Ocean Service, published *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts* in 2016 (NMFS 2016). The guidance was subject to extensive peer review and several public comment periods. It has recently been updated in 2018 for the purpose of providing improvements and clarification on implementation of the document (NMFS 2018). Specifically, the guidance identifies the received levels, or acoustic thresholds, above which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for all underwater anthropogenic sound sources. NMFS compiled, interpreted, and synthesized scientific literature to produce acoustic thresholds for the onset of both TTS and PTS.

The hearing of marine mammals differs between species in terms of sensitivity and frequencies. To reflect this variable hearing ability, the NMFS guidance uses recommendations from Southall et al. (2007) and divides marine mammals into functional groups based on their hearing frequency range. Since there are no studies on PTS in marine mammals, it is calculated based on the thresholds for TTS.

The main body of the document contains acoustic thresholds for onset of PTS for marine mammals exposed to underwater sound, which are derived from TTS values. Other information such as details on the development of marine mammal auditory weighting functions and acoustic thresholds, research recommendations, alternative methodology, the peer review and public comment process, and a glossary of acoustic terms can be found in the appendices. Table 3.1 summarises the PTS onset thresholds for marine mammals in response to impulsive noise sources such as pile driving outlined in the guidance document.

Table 3.1 Summary of PTS onset thresholds for impulsive noise sources as outlined in NMFS (2018)

Hearing Group	PTS Onset Thresholds (received level)[1]
Low frequency cetaceans	219 dB re 1 μPa (pk)[2]
	183 dB re 1 μPa^2 (SEL_{24h})[3]
Mid frequency cetaceans	230 dB re 1 μPa (pk)[2]
	185 dB re 1 μPa^2 (SEL_{24h})[3]
High frequency cetaceans	202 dB re 1 μPa (pk)[2]
	155 dB re 1 μPa^2 (SEL_{24h})[3]

[1] Dual metric thresholds for impulsive sounds: use whichever results in the largest isopleth for calculating PTS onset.
[2] Peak sound pressure levels (pk) are not unweighted within the generalized frequency hearing range of marine mammals.
[3] Cumulative SEL thresholds are frequency-weighted according to the low, mid and high frequency functional hearing categories for cetaceans. The recommended accumulation period is 24 hours.

3.3.2 Fishes

The California Department of Transportation have produced *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish* (CALTRANS 2015). The stated purpose of the technical guidance to provide guidance on the following topics (among others):

- Assessment of potential impacts on fishes and their habitat from sound generated from pile driving.
- Measures to avoid or minimize pile driving impacts.
- Methods to assess impacts, mitigation, and compensation for pile driving impacts on fishes.

The technical guidance outlines interim injury thresholds for fishes developed through a dedicated Fisheries Hydroacoustic Working Group (Popper et al. 2014). The working group agreed upon the following impact criteria:

- Sound pressure levels of 206 dB-peak and an accumulated SEL of 187 dB for fishes larger than 2 grams.
- An accumulated SEL of 183 dB, for fishes less than 2 grams.

The technical guidance recognises that because of the ongoing research efforts related to these criteria, they may evolve as new information is determined. In particular, recent research summarized in Popper et al. 2014 suggests that cumulative SEL thresholds for injury may be well above 200 dB re 1 $\mu Pa^2 \cdot s$.

The guidance states that little is known regarding the thresholds of behavioural effects of pile driving sound on fishes or the types of behavioural modification that may be considered ‘harm’ or ‘harassment’. It is clear that fishes can react to a sudden loud sound with a startle or avoidance response, but they also may quickly habituate to the sound. The guidance does not explicitly propose a noise level threshold for behavioural effects.

3.4 Germany

Germany has developed substantial regulation focused on pile driving, primarily due to the construction of windfarms in German waters. The Federal Nature Conservation Act (Bundesnaturschutzgestzt [BNatschG]) forms the legal basis for protection of individual marine mammals in Germany. As defined under the BNatschG, and differently from most other policies, injury is considered to include temporary impairment such as TTS. The BNatshG also includes protections for disturbance, which in turn encompasses behavioural responses, stress and masking.

Unlike other legislation, the German regulation prescribes fixed levels at a given distance that operators are required not to exceed, namely 160 dB re 1 μPa^2.s single impulse SEL and 190 dB re 1 μPa PK-PK at a range of 750 m ([BMU] Bundesministerium für Umwelt 2014), which would limit an SEL of 140 dB re 1 μPa^2.s (a level associated with disturbance in the German regulations) to within 8 km of a pile driving site. While these requirements were aimed at preventing injury or death, they also provided a means to account for cumulative impacts of other nearby activities.

This legislation was introduced initially as a reference value, due to the lack of technology to make it achievable; however, the legislation became mandatory in 2014, as reliable adherence to the thresholds became possible due to the availability and application of advanced noise reduction systems.

3.5 Denmark

In Denmark, a working group was formed in June 2014 with the mandate to examine how underwater noise from pile driving can be regulated in order to take due consideration of marine mammals. The group's findings and recommendations are presented in a 2015 technical report taking into account the most current research (Skjellerup et al. 2015). Recommended thresholds for TTS and PTS for harbour porpoise from Skjellerup et al. (2015) and Energinet (2015) are outlined in Table 3.2.

A detailed *Guideline for underwater noise – Installation of impact-driven piles* was published in Denmark in 2016 (Energistyrelsen 2016). The guideline is specifically developed for piling in relation to installation of offshore windfarms. It requires estimates of environmental impact using given source levels and sound propagation losses and calculation of the cumulative SEL experienced by a receptor (marine mammal) while it is fleeing away from the noise source. If necessary, noise mitigation methods must be proposed, which ensure that the threshold for cumulative SEL is not exceeded at any time during the piling activities. The threshold for cumulative SEL is defined as 190 dB re 1 μPa^2. The guideline requires sound verification measurements to be undertaken and 'soft-start' procedures using a seal scrammer device to scare away marine mammals and avoid causing trauma.

Table 3.2 Thresholds for TTS and PTS for harbour porpoises, from Skjellerup et al. (2015) and Energinet (2015)

	TTS	PTS
Single pulse	164 dB re 1 μPa^{2}s (SEL)	175 dB re 1 μPa^{2}s (SEL)
Series of pulses (>1 hour)	179 dB re 1 μPa^{2}s (SEL)	190 dB re 1 μPa^{2}s (SEL)

3.6 Ireland

Ireland published updated *Guidance to Manage the Risk to Marine Mammals from Man-made Sound Sources in Irish Waters* in 2014 (NPWS 2014). The stated aims of the guidance are as follows:

- To give an understanding of selected sound sources introduced into the environment by specific human activities, which may impact detrimentally on protected marine mammal populations or individuals of those species.
- To describe a structured, staged process for the informed assessment of risk and decision-making with regard to such sources.
- To outline practical risk avoidance and/or risk reduction measures which should be considered in order to minimise the potential effects of sound sources on the natural ecology of marine mammal species.

No actual thresholds are established for permissible noise levels during pile driving in the guidance. The noise levels addressed during the discussion on thresholds for TTS and PTS come from Southall et al. (2007), but caution is urged when using these in light of recent research:

"*While the current scientific literature provides some guidance for management and conservation purposes, ongoing flexibility will be necessary in (a) the evaluation of specific cases of anthropogenic sound introduction into the marine environment and (b) the continued development of guidance measures to mitigate the potential impacts of such events*" (NPWS 2014).

3.7 Sweden

The Swedish Environmental Protection Agency published a *Framework for Regulating Underwater Noise During Pile Driving* in 2016 (Andersson et al. 2016). The framework outlines sound exposure criteria (thresholds) for harbour porpoise (*Phocoena phocoena*) and the fish species herring (*Clupea clupea*) and cod (*Gadus morhua*). Recommended noise levels for underwater pile driving that risk resulting in serious environmental impacts on fishes, fish eggs and larvae are presented in Table 3.3 and for harbour porpoises in Table 3.4. Note that the noise levels are not frequency weighted; however, the guidance acknowledges that a weighting methodology should be included in future threshold studies when relevant research results become available in this field.

Table 3.3 Recommended thresholds for pile driving noise for fishes, fish eggs and larvae

	Fishes	Eggs and larvae
Mortality and injury to internal organs	$SPL_{(peak)}$ 207 db re 1 µPa	$SPL_{(peak)}$ 217 dB re 1 µPa
	$SEL_{(ss)}$ 174 dB re 1 µPa^{2}s*	$SEL_{(ss)}$ 187 dB re 1 µPa^{2}s*
	$SEL_{(cum)}$ 204 dB re 1 µPa^{2}s**	$SEL_{(cum)}$ 207 dB re 1 µPa^{2}s**

** Sound exposure level for a single sound pulse*
*** sum of the sound exposure levels for a number of pulses in a given period of time*

Table 3.4 Recommended thresholds for pile driving noise for harbour porpoise

	TTS	PTS
Harbour Porpoise	$SPL_{(peak)}$ 194 dB re 1 µPa	$SPL_{(peak)}$ 200 dB re 1 µPa
	$SEL_{(ss)}$ 164 dB re 1 µPa^{2}s*	$SEL_{(ss)}$ 179 dB re 1 µPa^{2}s*
	$SEL_{(cum)}$ 175 dB re 1 µPa^{2}s (≥1 h)**	$SEL_{(cum)}$ 190 dB re 1 µPa^{2}s (≥1 h)**

** Sound exposure level for a single sound pulse*
*** sum of the sound exposure levels for a number of pulses in a given period of time*

3.8 International

3.8.1 European Marine Strategy Framework Directive

The change in paradigm of the European Union water policy started with the Water Framework Directive (2000/60/EC, WFD) and was followed by the Marine Strategy Framework Directive (MSFD; EC MSFD 2008/56/EC). One of the main objectives of the MSFD is to achieve a Good Environmental Status (GES) for European marine waters by 2020 (Van der Graaf et al. 2012). The MSFD obliges every member state to achieve or maintain good environmental status, under which the introduction of energy including underwater noise is considered a main concern (Tasker et al. 2010). While developing a framework for underwater noise for the implementation of the MSFD, noise mapping on a regional basis should be used to analyse noise budgets of the oceans and regional sea areas. These directives changed Europe from a sectorial to a holistic approach, which accounts for the synergistic and cumulative effects of different anthropogenic pressures on the marine environment. For achieving GES, eleven descriptors were provided, including Descriptor 11, which states that "introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment." Two indicators for Descriptor 11 are identified. Proposed Indicator 1 deals with the registration of the distribution in time and place of loud, low- and mid-frequency impulsive sounds; Indicator 2 demands measurements on continuous low-frequency sound.

As recognized and suggested in the process of developing the framework for underwater noise for the implementation of the MSFD, regional noise mapping should be used to analyse noise budgets of the oceans and regional sea areas. This can be done by acoustic measurements and modelling based on data and information gained through the application of the suggested indicators for Descriptor 11:

> ***Indicator 1****: Distribution in time and place of loud, low and mid frequency impulsive sounds*
>
> *Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1μPa^{2}s) or as peak sound pressure level (in dB re 1μPa peak) at one metre, measured over the frequency band 10 Hz to 10 kHz.*
>
> ***Indicator 2****: Continuous low frequency sound*
>
> *Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate.*

In 2010, the European Commission decided that guidance was needed to help Member States implement the indicators under descriptor 11. A technical working sub-group (TSG Noise) focussed on clarifying the purpose, use and limitation of the indicators and described methodology that would be unambiguous, effective and practicable. For both the impulsive and ambient noise indicators it has been possible to make significant progress towards practical implementation of the indicators, and most ambiguities have been solved (Van der Graaf et al. 2012).

4. RECOMMENDATIONS FOR UNDERWATER NOISE CRITERIA TO BE USED IN IMPACT ASSESSMENT

Taking into account the information outlined in the JASCO (2011) review of pile driving noise at Cape Lambert and the update provided in this report, the following noise criteria are recommended to be used for assessment of underwater noise impacts from the CLA Marine Structures Refurbishment Project. The criteria are selected because of their acceptance by regulatory agencies and because they represent current best available science:

- Marine mammals:
  - Peak pressure levels (PK) and frequency-weighted accumulated sound exposure levels (SEL) from the U.S. NOAA Technical Guidance (NMFS 2018) for the onset of PTS and TTS in marine mammals (refer to Section 3.3.1 of this report).
  - Peak pressure levels (PK) unweighted sound exposure levels (SEL) from Finneran (2016) for the onset of TTS in marine mammals (refer to Section 2.1 of this report).
  - Marine mammal behavioural threshold based on the current interim U.S. NMFS criterion (NMFS 2013) for marine mammals of 160 dB re 1 µPa SPL for impulsive sound sources. Taking into consideration that behavioural reactions are individually different and strongly

context dependent, animals are likely to exhibit a gradually increasing probability of response for impulsive sounds as represented by Wood et al. (2012)

- Behavioural thresholds will soon be updated by a working group of subject matter experts in the United States (Southall et al.) based on the best knowledge available. The existing threshold of 160 dB re 1 µPa SPL is based on general conclusion from Malme et al. (1983, 1984) and Richardson et al. (1985, 1986) showing short-term/mild avoidance at received levels greater than 160 dB re 1 µPa SPL.
- Single shot threshold for cetaceans (unweighted per-pulse SEL of 160 dB re 1 $\mu Pa^2 \cdot s$) (from marine seismic surveys). This process is outlined in the EPBC Act Policy Statement 2.1 (DEWHA 2008) (refer to Appendix C.5.1 of the JASCO (2011) review for details). This is provided for reference for single strikes from piling operations.

- Fishes, fish eggs and turtles
  - Sound exposure guidelines for fishes, fish eggs and larvae, and turtles from Popper et al. (2014) (refer to Section 2.2.1 and 2.3.1 for details).
  - Threshold for turtle behavioural response, 166 dB re 1 µPa (SPL), as applied by the U.S. NMFS (NSF 2011) (refer to Section 2.2.1 for details).

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