Appendix 10-6:
NAS Modelling Report

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ORIEL WIND FARM PROJECT

Environmental Impact Assessment Report – Addendum
Appendix 10-6: NAS Modelling Report

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rpsgroup.com

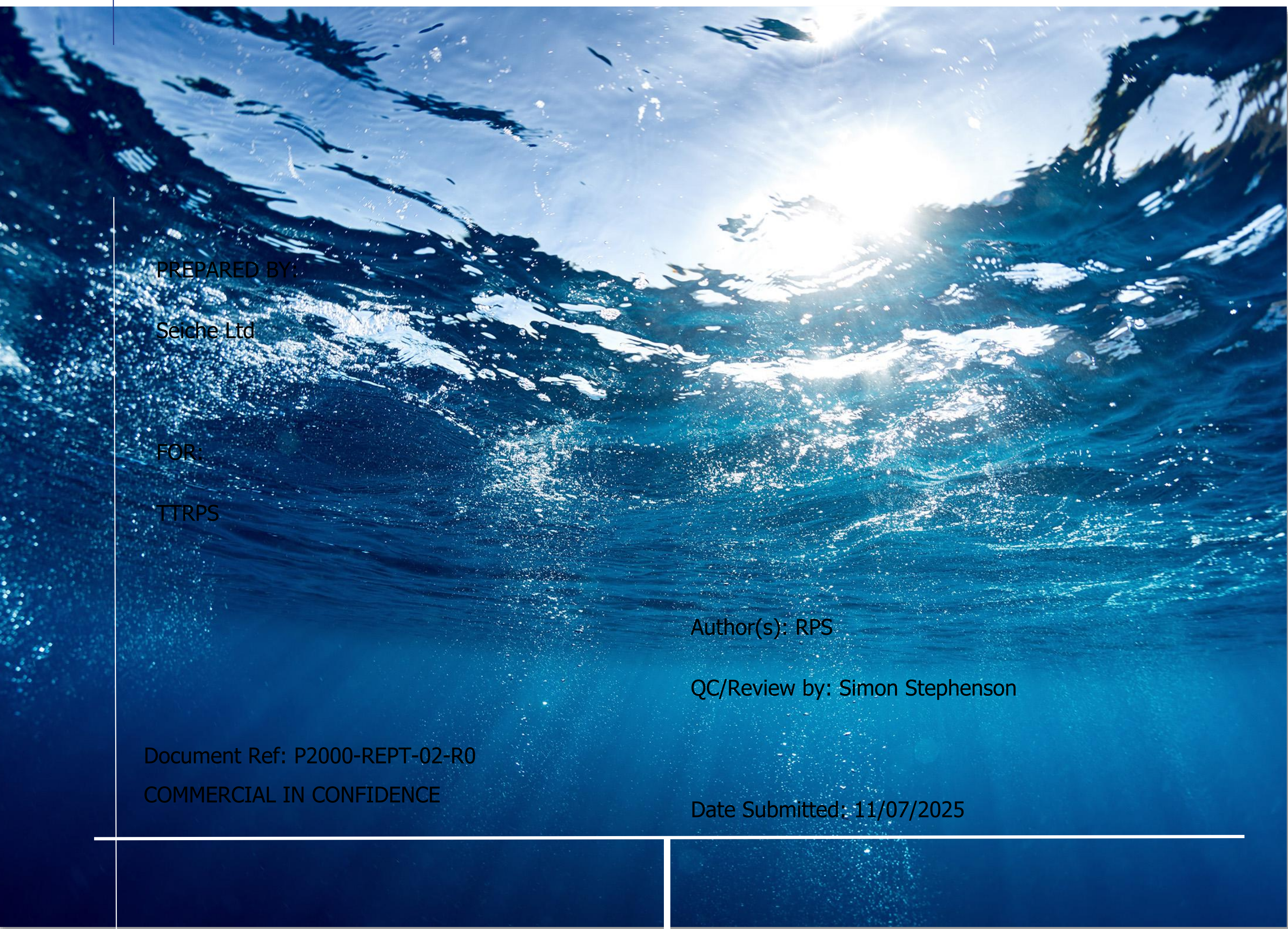
Seiche Ltd
Bradworthy Industrial Estate,
Langdon Road, Bradworthy,
Holsworthy, Devon, EX22 7SF,
United Kingdom

T +44(0)1409 404050

www.seiche.com

10-6 - NAS Modelling Report

NAS Modelling Report



PREPARED BY:

Seiche Ltd

FOR:

TTRPS

Author(s): RPS

QC/Review by: Simon Stephenson

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SEICHE GROUP

Seiche Ltd

Bradworthy Industrial Estate,
Langdon Road, Bradworthy,
Holsworthy, Devon, EX22 7SF,
United Kingdom

T +44(0)1409 404050

E https://www.seiche.com

E [Company Fax]

www.seiche.com

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Contents

List of Figures

List of Tables

1 Introduction

This document has been prepared in response to a Request for Further Information (RFI) from An Coimisiún Pleanála (formally An Bord Pleanála) regarding the planning application (case reference ABP-319799-24) for the Oriel Wind Farm Project (hereafter referred to as "the Project").

The following work has been undertaken to respond the RFI:

- Consideration of noise abatement systems (NAS) available for use, and acoustic modelling for these scenarios in both single NAS and double NAS configurations (RFI 9.Aiii)
- Updated modelling and injury ranges for ultra-short baseline (USBL) source (RFI 9.J)
- Empirical underwater noise modelling of operational wind turbines (RFI 9.M)

The updated assessments provided in chapter 9 Addendum: Fish and Shellfish and chapter 10 Addendum: Marine Mammals and Megafauna (EIAR volume 2B Addendum) have been informed by the above.

2 Acoustic Modelling Methodology

2.1 Impact Piling

The steps taken in modelling the offshore pile installations using an impact hammer are the same as those used in the updated modelling in response to Irish Whale and Dolphin Group comments (see appendix 10-4: Updated Subsea Noise Modelling Report, EIAR volume 2B Addendum. However, separate source level calculations and spectrum shapes were considered for the mitigated source levels. For the estimation of acoustic energy propagation loss at different distances from the noise source location (in different directions), the following steps were considered:

- The bathymetry of the domain around the source locations was extracted from the GEBCO database in 72 different transects.
- A geoacoustic model of the different seafloor layers in the survey region was calculated based on the British Geological Survey (BGS) borehole database and EMODnet sediment database.
- A calibrated line-source propagation model was employed to estimate the transmission loss matrices for different frequencies of interest (from 10 Hz to 80 kHz) along the 72 different transects.
- The line-source array is calibrated to match the received sound level and spectrum shape at 750 m from the pile, based on the scaling laws described by von Pein *et al.* (2022) (and in section 2.1.1 of this report).
- The line-source array model is used to produce frequency and range dependent received levels (RL) of acoustic energy around the chosen source position.
- The TTS and PTS potential impact distances for different marine mammal groups were calculated using relevant metrics and weighting functions (from Southall *et al.*, 2019 and NMFS, 2024) and by employing a simplistic animal movement model (movement directly away from the noise source at a pre-determined velocity) where appropriate.
- The recoverable injury, TTS and mortality impact distances for fish were calculated using relevant metrics (from Popper *et al.*, 2014) and by employing a simplistic animal movement model (movement directly away from the noise source at a pre-determined velocity) where appropriate.

For the sound exposure calculations to produce the potential marine mammal weighted SEL_{cum} impact ranges, the method is the same as implemented in appendix 10-2: Subsea Noise Technical Report (volume 2B) of the EIAR and in the updated modelling in response to Irish Whale and Dolphin Group comments (see appendix 10-4: Updated Subsea Noise Modelling Report), with the assumption made that a mammal will swim directly away from the sound source at the onset of activities. As an animal swims away from the sound source, the sound it is exposed to will become progressively lower (more attenuated); the cumulative SEL is derived by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation was used to estimate the approximate minimum start distance for an animal in order for it not to be exposed to sufficient acoustic energy to result in the onset of potential auditory injury or TTS.

It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a constant speed. In reality the situation is more complex, and the animal is likely to move in a more complex manner: at varying speed and direction. The swim speeds used in the estimation of cumulative sound exposure for the species likely to be present in the vicinity of the project are set out in Table 2-1.

Table 2-1: Assessment Swim Speeds of Marine Mammals and Fish that are Likely to Occur in the Vicinity of the Project, for the Purpose of Exposure Modelling

Species	Hearing group	Swim speed (m/s)	Source reference
Harbour seal	Phocid Carnivores in Water (PCW)	1.8	Thompson *et al.* (2015)
Grey seal	Phocid Carnivores in Water (PCW)	1.8	Thompson *et al.* (2015)
Harbour porpoise	Very High Frequency (VHF)	1.5	Otani *et al.* (2000)
Minke whale	Low Frequency (LF)	2.3	Boisseau *et al.* (2021)
Bottlenose dolphin	High Frequency (HF)	1.52	Bailey *et al.* (2010)
White-beaked dolphin	High Frequency (HF)	1.52	Bailey *et al.* (2010)
Short beaked common dolphin *Delphinus delphis*	High Frequency (HF)	1.52	Bailey *et al.* (2010)
Risso's dolphin *Grampus griseus*	High Frequency (HF)	1.52	Bailey *et al.* (2010)

2.1.1 Sound Levels from Piling at 750 m (No mitigation)

Piling sound levels were determined by scaling data measured during pile driving for similar operations to the Project in order to determine the sound level at 750 m. The subject of noise generation due to impact piling is an active area of research and the evidence base is constantly being updated by new measurements, research and published papers. A recent peer-reviewed paper (von Pein *et al.*, 2022) presents a methodology for the dependencies of the SEL on strike energy, diameter, ram weight, and water depth that can be used for scaling measured or computed SELs from one project to another. The method has been shown to be usable within practical ranges of accuracy, especially if the measurement uncertainties are taken into account. The paper suggests that scaling should be performed over either a small number of very similar piling situations or over a larger data set with according averaging.

Using the equation below (von Pein *et al.*, 2022), a broadband source level value is calculated for the noise emitted during impact pile driving operation in each operation window.

$$SEL_1 = SEL_0 + 10log_{10}\left(\frac{E_1}{E_0}\right) + 16.7log_{10}\left(\frac{d_1}{d_0}\right) - 10log_{10}\left(\frac{m_{r,1}}{m_{r,0}}\right) + 750\left[\frac{10log_{10}(|R_0|^2)}{2\,cot(\varphi)}\left(\frac{1}{h_1} - \frac{1}{h_0}\right)\right]$$

In this equation, *E* is the hammer energy employed in Joules, *d* is the pile diameter, m_r is the ram mass in kg, *h* is the water depth in m, $|R_0|$ is the reflection coefficient and φ is the propagation angle (approximately 17° for a Mach wave[1] generated by impact piling). The equation allows measured pile noise data from one site (denoted by subscript 0) to be scaled to another site (denoted by subscript 1).

The resulting single strike unweighted SEL at 750 for impact piling was estimated to be 179.3 dB re 1 μPa^{2}s. The spectral distribution of the source SELs for impact piling was derived from the reference spectrum provided in the ORJIP ReCon report (2023), reproduced in Figure 2-1.

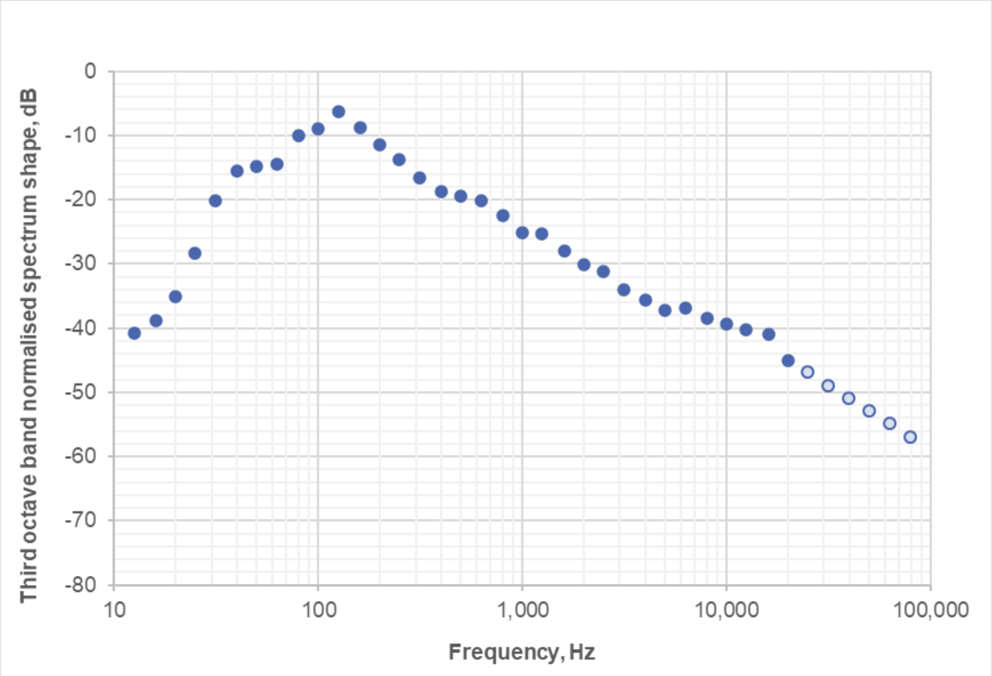

Figure 2-1: Normalised median 1/3 octave spectra for monopile installations used in the source level modelling.

2.1.2 Sound Levels from Piling at 750 m (With mitigation)

For mitigated sound modelling, three mitigation methods were considered, the PULSE mitigation system, a big bubble curtain (BBC) and a double big bubble curtain (DBBC), along with combined double mitigation systems. For each mitigation method, a reduction was applied to each frequency using a combination of publicly available data and previous Seiche measurements. The broadband reductions applied for each mitigation method and the resulting level at 750 m are outlined below in Table 2-2, and third octave spectrum in Figure 2-2.

[1] *a Mach wave, also known as a weak discontinuity, is a pressure wave traveling with the speed of sound caused by a slight change of pressure added to a compressible flow*

Table 2-2: Reductions used for modelling of mitigated scenarios, and the resulting unweighted broadband levels at 750 m.

Scenario / NAS	Reduction, dB	Overall SEL, dB re 1 μPa²s
Unmitigated	-	179.3
In line hammer noise reduction unit (Pulse)	6	173.3
Big bubble curtain (BBC)	7	172.3
Double big bubble curtain (DBBC)	12	167.3
Pulse + BBC	13	166.3
Pulse + DBBC	18	161.3

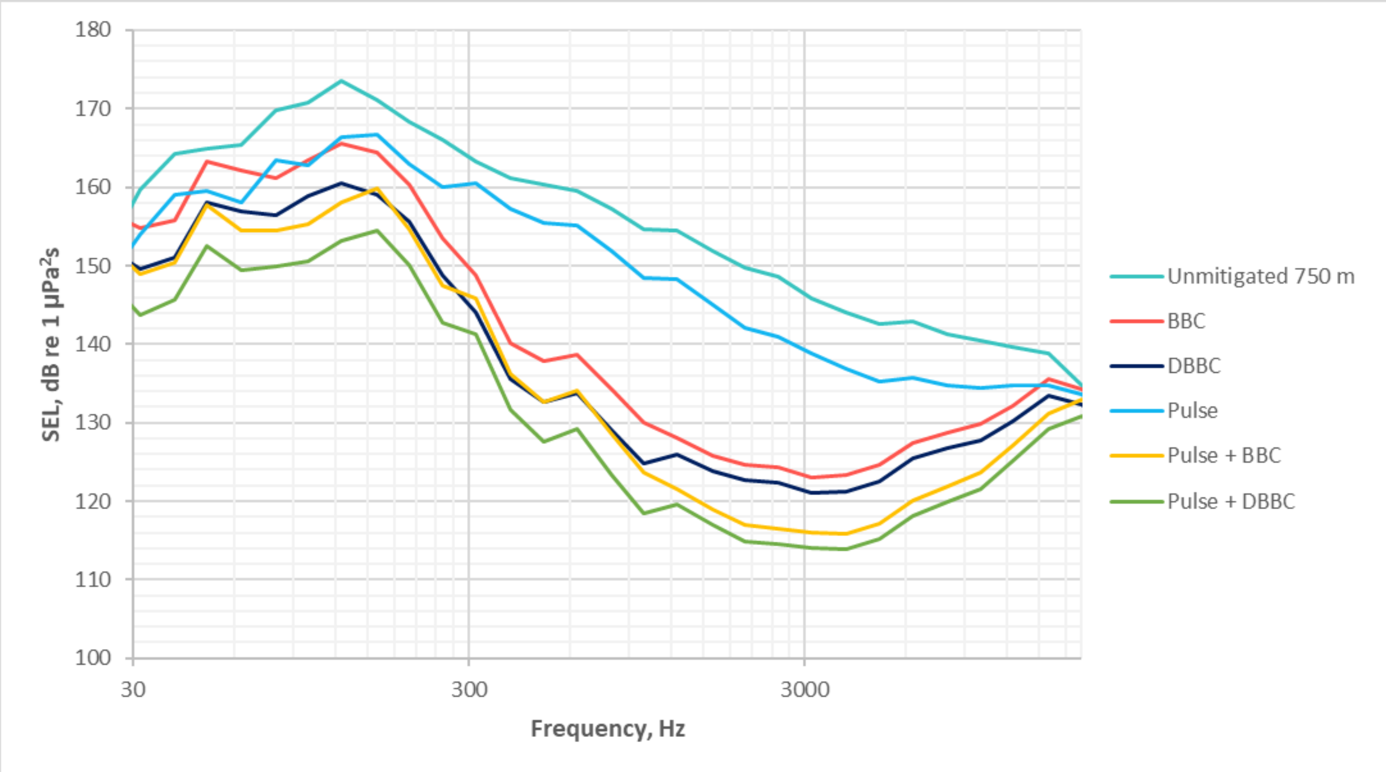

Figure 2-2: Third octave spectra for the unmitigated and mitigated levels at 750 m.

2.1.3 Project NAS

As outlined in chapter 5 Addendum: Project Description, the Applicant proposes to use a system (known as the MODIGA), which will be fitted with an internal air bubble ring to provide underwater noise reduction during piling. Although there are currently no empirical data available to confirm this on a quantitative basis, the principle of introducing an air barrier between the pile and the surrounding structure would theoretically lead to reduced sound transmission. The theoretical reduction in sound transmission arises because air has a much lower acoustic impedance than water or steel, resulting in a reflection of sound energy at the air-water or air-steel interface and reducing the proportion of vibrational energy from the pile transmitted through the air layer into the surrounding water. Therefore, taking both the theoretical considerations and manufacturer's claims into account, it is reasonable to expect that the use of this system will result in lower underwater noise levels compared to piling without the air bubble system in place. Whilst the amount of noise reduction (in decibel terms or impact ranges) cannot currently be quantified the Applicant is committed to undertake noise monitoring to provide useful data that will inform the use of this system in future developments."

2.2 Operational Noise Modelling Method

The wind farm, with monopile foundations, is comprised of 25 turbines, each with a 15 MW capacity, resulting in a cumulative capacity of 375 MW. Underwater sound from the operational wind turbine generators has been estimated based on the methodology presented in Tougaard *et al.* (2020). However, no detailed data from the manufacturer on underwater sound emissions from the specific turbines was available, so modelling was conducted using an empirical approach. The paper provides an empirical relationship between wind turbine power, wind speed and distance from the wind turbine in order to estimate the received sound level. The received sound level is estimated using the formula:

$$L_{eq} = C + \alpha\, log_{10}\left(\frac{distance}{100\ m}\right) + \beta\, log_{10}\left(\frac{wind\ speed}{10\ m/s}\right) + \gamma\, log_{10}\left(\frac{turbine\ size}{1\ MW}\right)$$

where α = -23.7 dB/decade, β = 18.5 dB/decade, γ = 13.6 dB/decade and C = 109 dB re 1 µPa (rms).

Calculations were performed for the maximum potential wind turbine size using a 10 m/s wind speed. It should be noted that during periods of higher wind speeds the sound level produced by the wind turbines will increase, although it is likely that the ambient sound levels will also increase due to higher wind speeds and wave conditions during these periods, which may result in additional masking of wind turbine sounds.

2.3 Pre-Construction Phase/Geophysical Survey Modelling

Several sonar-like survey types will potentially be used for the pre-construction geophysical surveys. During the survey, a transmitter emits an acoustic signal directly toward the seabed (or alongside, at an angle to the seabed, in the case of side scan techniques). The equipment likely to be used can typically work at a range of signal frequencies, depending on the distance to the bottom and the required resolution. The signal is highly directional and acts as a beam, with the energy narrowly concentrated within a few degrees of the direction in which it is aimed. The signal is emitted in pulses, the length of which can be varied as per the survey requirements. The assumed pulse rate, pulse width and beam width used in the assessment are based on a review of typical units used in other similar surveys. It should be noted that sonar like survey sources (e.g. MBES, SSS, SBP, USBL) are classed as non-impulsive noise because they generally comprise a single (or multiple discrete) frequency (e.g. a sine wave or swept sine wave) as opposed to a broadband signal with high kurtosis, high peak pressures and rapid rise times.

The characteristics assumed for each device modelled in this Technical Report are summarised in Table 23, these sources are considered to be continuous (non-impulsive).

Table 23: Typical survey equipment parameters used in the Underwater Noise Technical Report.

Survey Equipment Type	Frequency(s), kHz	Source Level, dB re 1 µPa re 1 m	Pulse Rate, s^{-1}	Pulse Width, ms	Beam Width, degrees
USBL	14	200	3	100	80

The assumed pulse rate has been used to calculate the SEL, which is normalised to 1 s, from the rms sound pressure level. Directivity corrections were calculated based on the transducer dimensions and ping frequency and taken from manufacturer's datasheets.

3 Sound modelling results

3.1 Impact piling

3.1.1 Injury ranges

The impact piling scenarios are modelled as a single impact pile unmitigated and with NAS. NAS modelling includes the use of Pulse, BBC, DBBC, Pulse and DBC, and Pulse and DBBC. All impact piling ranges are based on a comparison to the relevant impulsive sound thresholds from Southall (2019).

The injury ranges for sound exposure level (SEL) and peak sound pressure level (Lp,0-pk) are both modelled. Impact ranges for mammals for SELcum without ADD and with 15 minutes of ADD are presented in Table 3-1 and Table 3-2 respectively. Impact ranges for mammals for peak LP,0-pk for the first hammer strike and maximum hammer energy are presented in Table 3-3 and Table 3-4 respectively. Table 3-5 and Table 3-6 present impact ranges for fleeing and static fish SELcum respectively, and Tables 3-7 and 3-8 for Lp,0-pk for the first hammer strike and the maximum hammer strike respectively.

Table 3-1: Potential injury ranges for marine mammals from installation of a single pile based on the SEL_{cum} metric, without ADD.

Species / Group	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)					
		Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
LF	PTS – 183 dB re 1 µPa^{2}s	1,135	635	232	98	84	<curtain
	TTS – 168 dB re 1 µPa^{2}s	21,500	16,500	2,440	1,145	1,065	479
HF	PTS – 185 dB re 1 µPa^{2}s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 170 dB re 1 µPa^{2}s	21	19	<curtain	<curtain	<curtain	<curtain
VHF	PTS – 155 dB re 1 µPa^{2}s	815	454	370	280	272	218
	TTS – 140 dB re 1 µPa^{2}s	14,500	7,720	2,680	2,050	1,490	1,180
PCW	PTS – 185 dB re 1 µPa^{2}s	11	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 170 dB re 1 µPa^{2}s	5,520	2,470	137	<curtain	<curtain	<curtain
OCW	PTS – 203 dB re 1 µPa^{2}s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 188 dB re 1 µPa^{2}s	N/E	N/E	<curtain	<curtain	<curtain	<curtain

Table 3-2: Potential injury ranges for marine mammals from installation of a single pile based on the SEL_{cum} metric, with 15 minutes ADD.

Species / Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)					
		Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
LF	PTS – 183 dB re 1 µPa²s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 168 dB re 1 µPa²s	19,500	15,000	393	<curtain	<curtain	<curtain
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 170 dB re 1 µPa²s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
VHF	PTS – 155 dB re 1 µPa²s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 140 dB re 1 µPa²s	13,000	6,280	1,330	725	146	<curtain
PCW	PTS – 185 dB re 1 µPa²s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 170 dB re 1 µPa²s	3,890	910	<curtain	<curtain	<curtain	<curtain
OCW	PTS – 203 dB re 1 µPa²s	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS – 188 dB re 1 µPa²s	N/E	N/E	<curtain	<curtain	<curtain	<curtain

Table 3-3: Potential injury ranges for marine mammals from pile installation based on the peak metric, for the first hammer strike.

Species / Group	Threshold, $L_{p,0-pk}$, dB re 1 µPa	Range (m)					
		Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
LF	PTS – 219 dB re 1 µPa (pk)	169	144	113	< curtain	66	<curtain
	TTS – 213 dB re 1 µPa (pk)	273	241	160	106	94	< curtain
HF	PTS – 230 dB re 1 µPa (pk)	71	56	< curtain	< curtain	< curtain	< curtain
	TTS – 224 dB re 1 µPa (pk)	114	93	85	< curtain	< curtain	< curtain
VHF	PTS – 202 dB re 1 µPa (pk)	653	624	303	201	180	119
	TTS – 196 dB re 1 µPa (pk)	1,051	1,048	429	285	257	169
PCW	PTS – 218 dB re 1 µPa (pk)	183	157	120	< curtain	70	<curtain
	TTS – 212 dB re 1 µPa (pk)	295	263	170	112	100	<curtain
OCW	PTS – 232 dB re 1 µPa (pk)	60	47	<curtain	< curtain	<curtain	<curtain
	TTS – 262 dB re 1 µPa (pk)	97	79	75	< curtain	<curtain	<curtain

Table 3-4: Potential injury ranges for marine mammals from pile installation based on the peak metric, for the highest energy hammer strike.

Species / Group	Threshold, $L_{p,0\text{-}pk}$, dB re 1 µPa	Range (m)					
		Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
LF	PTS – 219 dB re 1 µPa (pk)	425	285	221	147	131	86
	TTS – 213 dB re 1 µPa (pk)	684	424	314	208	187	123
HF	PTS – 230 dB re 1 µPa (pk)	177	120	117	77	68	<curtain
	TTS – 224 dB re 1 µPa (pk)	286	180	166	110	97	<curtain
VHF	PTS – 202 dB re 1 µPa (pk)	1,638	804	594	395	357	235
	TTS – 196 dB re 1 µPa (pk)	2,638	1,178	841	559	509	335
PCW	PTS – 218 dB re 1 µPa (pk)	460	307	235	156	139	91
	TTS – 212 dB re 1 µPa (pk)	741	454	332	221	198	130
OCW	PTS – 232 dB re 1 µPa (pk)	151	109	104	<curtain	<curtain	<curtain
	TTS – 262 dB re 1 µPa (pk)	244	150	147	98	87	<curtain

Table 3-5: Potential injury ranges for moving fish from installation of a single pile based on the SEL_{cum} metric.

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)					
			Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
Group 1 Fish: No swim bladder	Mortality	219	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	Recoverable injury	216	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS	186	5,520	4,020	1,728	700	625	305
Basking shark	Mortality	219	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	Recoverable injury	216	N/E	N/E	<curtain	<curtain	<curtain	<curtain
	TTS	186	3,200	2,110	878	382	337	167
Group 2 Fish: Swim bladder not involved in hearing	Mortality	210	21	18	<curtain	<curtain	<curtain	<curtain
	Recoverable injury	203	147	107	119	<curtain	<curtain	<curtain
	TTS	186	5,520	4,020	1,728	700	625	305
Group 3 and 4 Fish: Swim bladder involved in hearing	Mortality	207	51	39	<curtain	<curtain	N/E	<curtain
	Recoverable injury	203	147	107	119	<curtain	<curtain	<curtain
	TTS	186	5,520	4,020	1,728	700	625	305
Sea Turtles	Mortality	210	21	18	<curtain	<curtain	<curtain	<curtain
Fish eggs and larvae	Mortality	210	935	810	760	506	469	321
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	19,580	15,820	6,720	4,800	4,660	3,260

Table 3-6: Potential injury ranges for static fish from installation of a single pile based on the SEL_{cum} metric.

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^2s)	Range (m)					
			Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
Group 1 Fish: No swim bladder	Mortality	219	385	340	331	265	242	166
	Recoverable injury	216	516	457	474	329	301	207
	TTS	186	9,620	7,920	3,980	2,820	2,700	1,880
Basking shark	Mortality	219	385	340	331	265	242	166
	Recoverable injury	216	516	457	474	329	301	207
	TTS	186	9,620	7,920	3,980	2,820	2,700	1,880
Group 2 Fish: Swim bladder not involved in hearing	Mortality	210	935	810	725	506	469	321
	Recoverable injury	203	1,860	1,580	1,190	835	780	540
	TTS	186	9,620	7,920	3,980	2,820	2,700	1,880
Group 3 and 4 Fish: Swim bladder involved in hearing	Mortality	207	1,250	1,075	900	630	580	402
	Recoverable injury	203	1,860	1,580	1,190	835	780	540
	TTS	186	9,620	7,920	3,980	2,820	2,700	1,880
Sea Turtles	Mortality	210	935	810	725	506	469	321
Fish eggs and larvae	Mortality	210	935	810	725	506	469	321
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	19,580	15,820	6,720	4,800	4,660	3,260

Table 3-7: Potential injury ranges for fish from pile installation based on the peak metric, from the first hammer strike.

Hearing Group	Response	Threshold, $L_{P,0-pk}$ (dB re 1 µPa)	Range (m)					
			Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
Group 1 Fish: No swim bladder	Mortality	213	273	168	160	106	94	<curtain
	Recoverable injury	213	273	168	160	106	94	<curtain
Basking shark	Mortality	213	273	168	160	106	94	<curtain
	Recoverable injury	213	273	168	160	106	94	<curtain
Group 2 Fish: Swim bladder not involved in hearing	Mortality	207	439	288	227	150	134	88
	Recoverable injury	207	439	288	227	150	134	88
Group 3 and 4 Fish: Swim bladder involved in hearing	Mortality	207	439	288	227	150	134	88
	Recoverable injury	207	439	288	227	150	134	88
Sea Turtles	Mortality	207	439	288	227	150	134	88
Fish eggs and larvae	Mortality	207	439	288	227	150	134	88

Table 3-8: Potential injury ranges for fish from pile installation based on the peak metric for the maximum hammer energy strike.

Hearing Group	Response	Threshold, $L_{P,0\text{-}pk}$ (dB re 1 µPa)	Range (m)					
			Unmitigated	Pulse	BBC	DBBC	Pulse + BBC	Pulse + DBBC
Group 1 Fish: No swim bladder	Mortality	213	684	424	314	208	187	<curtain
	Recoverable injury	213	684	424	314	208	187	<curtain
Basking shark	Mortality	213	684	424	314	208	187	<curtain
	Recoverable injury	213	684	424	314	208	187	<curtain
Group 2 Fish: Swim bladder not involved in hearing	Mortality	207	1,101	592	444	295	266	175
	Recoverable injury	207	1,101	592	444	295	266	175
Group 3 and 4 Fish: Swim bladder involved in hearing	Mortality	207	1,101	592	444	295	266	175
	Recoverable injury	207	1,101	592	444	295	266	175
Sea Turtles	Mortality	207	1,101	592	444	295	266	175
Fish eggs and larvae	Mortality	207	1,101	592	444	295	266	175

3.1.2 Comparison to German standards

The German Federal Nature Conservation Act (2010) states that sound levels for impulsive sound must not exceed single-strike sound exposure level (SEL_{ss}) 160 dB re 1 µPa^{2}s or zero-to-peak sound pressure level ($L_{p,0\text{-}pk}$) of 190 dB re 1 µPa at 750 m distance from the piling location (Andersson *et al.*, 2017). Measurements are taken using hydrophones during construction at a 750 m distance from the piling location (now widely adopted as a measurement standard).

In German waters, the primary concerns regarding underwater sound are in line with the EU's MSFD, aiming not to adversely affect the marine environment as well as to specifically prevent impacts to harbour porpoise (Müller et al., 2019). The regulations were developed in consideration of the acoustic threshold for TTS (as injury) in harbour porpoise as determined by Lucke *et al.* (2009) (164 dB re 1 µPa^{2}s SEL). The decibel limit was developed by the Federal Maritime and Hydrographic Agency and has been applicable throughout the German EEZ since 2008.

Modelled SEL_{SS} and $L_{P,0\text{-}pk}$ values from the mitigated and unmitigated sources at 750 m are presented below in Table 3-9. These show the only mitigation method that achieves or comes close to achieving both limits is the double mitigation combination of the Pulse and double big bubble curtain, although even that could still exceed the SEL limit slightly. It should be noted that the received levels are based on scaling and more accurate appraisal of whether the German limits could be met could require use of a detailed finite element full acoustic model, although even then a number of idealised assumptions need to be made introducing uncertainty into the prediction.

Table 3-9: SEL_{SS} and $L_{P,0\text{-}pk}$ values at 750 m for the unmitigated and mitigated source levels.

Source	Value at 750 m	
	SEL_{SS} dB re 1 µPa^2s	$L_{P,0\text{-}pk}$ dB re 1 µPa
Unmitigated	179.3	212
Pulse	173.3	204
BBC	172.3	202
DBBC	167.3	195
Pulse + BBC	166.3	194
Pulse + DBBC	161.3	187

3.2 Operational noise

Unweighted rms sound contours for operational sound from wind turbines is shown in Figure 3-1, based on an indicative layout for the largest (i.e. highest power rating) wind turbines.

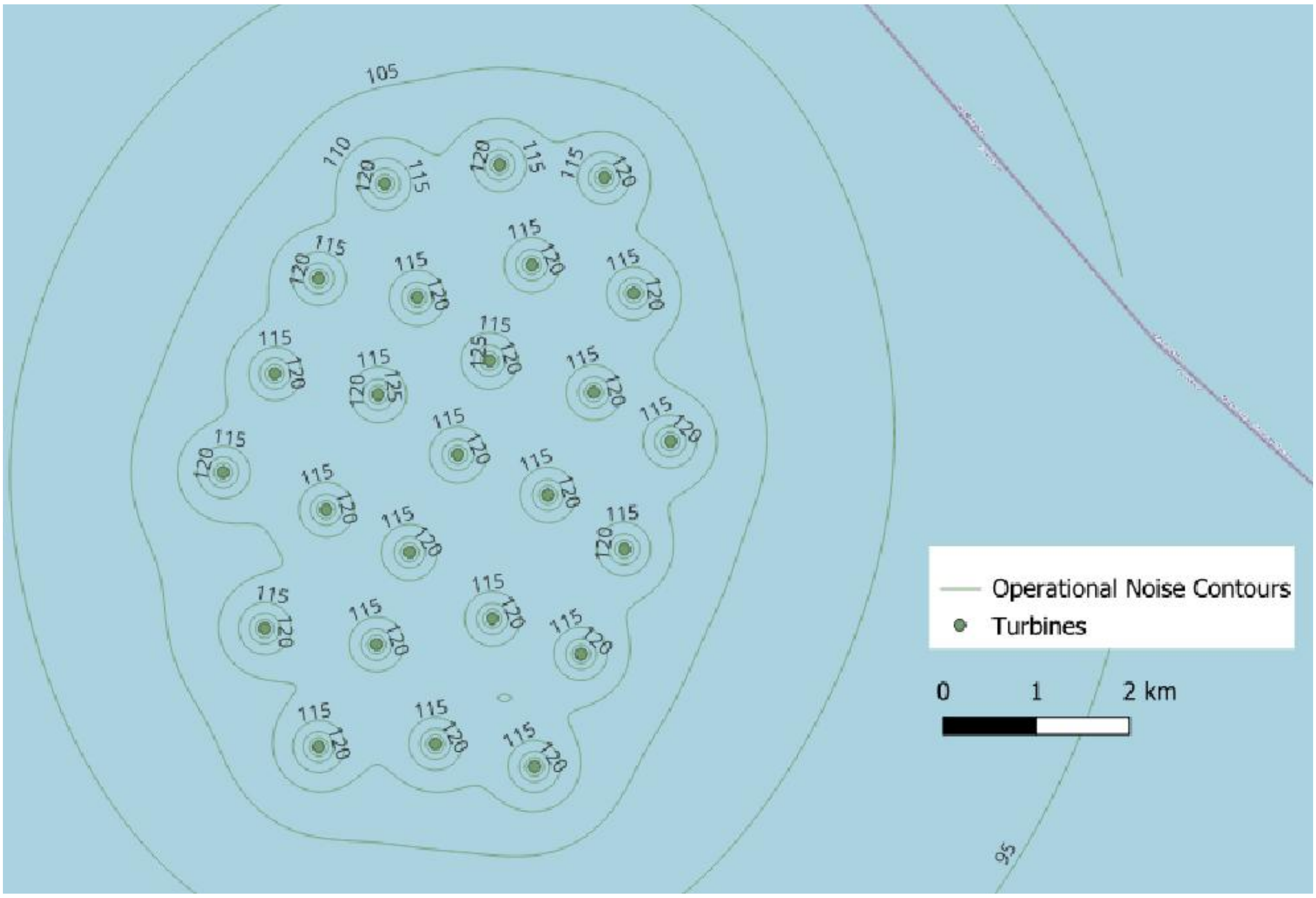

Figure 3-1: Unweighted RMS sound contours for operational noise.

Potential disturbance to marine mammals could occur within approximately 170 m of each wind turbine, based on the sound contour plot 120 dB re 1 μPa (rms) contours.

The calculated injury ranges for marine mammals, based on 24 hours exposure for a static animal, are below in Table 3-10 and the recoverable injury and TTS ranges for fish in Table 3-11. It should be noted that it is highly unlikely that a marine mammal or fish would stay static for 24 hours or even a few hours and this is therefore a highly precautionary assessment.

Table 3-10: Potential injury ranges for marine mammals due to operational wind turbines, based on static animal 24 hour exposure.

Species/Group	PTS threshold (dB re 1 µPa²s)	PTS range (m)	TTS threshold (dB re 1 µPa²s)	TTS range (m)
LF	199	35	179	5
HF	198	N/E	178	N/E
VHF	173	N/E	153	N/E
PCW	201	10	181	N/E
OCW	219	6	199	N/E

Table 3-11: Potential impact ranges (m) for group 3 and 4 fish due to operational wind turbines.

Source	Injury Zone Radius (m)	
	Recoverable Injury	TTS
	170 dB rms for 48 hours	158 dB rms for 12 hours
Operational wind turbines	N/E	4

3.3 Geophysical Sources

Geophysical surveying includes many sonar like noise sources and the resulting injury and disturbance ranges for marine mammals are presented in Table 3-12, based on the non-impulsive thresholds set out in Southall *et al.* (2019).

The potential impact distances from these operations vary based on their frequencies of operation and source levels and are rounded to the nearest 5 m. It should be noted that sonar like systems have very strong directivity which effectively means that there is only potential for injury when a marine mammal is directly underneath or within the swathe of the noise source. Once the animal moves outside of the main beam, there is significantly reduced potential for injury. The same is true in many cases for TTS where an animal is only exposed to enough energy to cause TTS when inside the direct beam of the sonar like source.

Table 3-12: Potential impact ranges (m) for marine mammals during the various geophysical investigation activities based on the non-impulsive SEL thresholds from Southall et al. (2019). (N/E refers to a threshold not exceeded).

Survey type	Effect	Hearing group impact range, m				
		LF	HF	VHF	PCW	OCW
USBL	PTS	N/E	N/E	53	N/E	N/E
	TTS	18	31	1,284	20	N/E

4 Conclusions

Acoustic modelling has been undertaken to determine distances at which potential effects on marine mammals and fish may occur due to sound from piling with and without NAS, operational noise and the use of a USBL survey.

For the operational noise marine mammal disturbance ranges are 170 m. PTS thresholds for the USBL survey are N/E except for VHF with an injury range of 53 m, and TTS ranges below 35 m for all hearing groups except VHF with a range of 1,284 m.

Acoustic modelling for impact piling with NAS shows reduced ranges for all NAS systems when compared to unmitigated piling, with the combined pulse and double bubble curtain providing the largest reduction. The combined pulse and double bubble curtain along with 15 minutes ADD reducing the SEL_{cum} TTS threshold for any marine mammal hearing group to within the radius of the bubble curtain. However, it is also clear that adding additional mitigation systems results in diminishing returns, and additional consideration of the increased vessel traffic and potential increases to programme duration.

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ORJIP, (2023) Reducing uncertainty in underwater noise assessments (ReCon)

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