Hornsea Project Four: Additional Application Information

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F2.5: Outline Marine Mammal Mitigation Protocol

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Glossary

Term	Definition
Commitment	A term used interchangeably with mitigation and enhancement measures. The purpose of Commitments is to reduce and/or eliminate Likely Significant Effects (LSEs), in EIA terms. Primary (Design) or Tertiary (Inherent) are both embedded within the assessment at the relevant point in the EIA (e.g. at Scoping, Preliminary Environmental Information Report (PEIR) or ES). Secondary commitments are incorporated to reduce LSE to environmentally acceptable levels following initial assessment i.e. so that residual effects are acceptable.
Development Consent Order (DCO)	An order made under the Planning Act 2008 granting development consent for one or more Nationally Significant Infrastructure Projects (NSIPs).
Environmental Impact Assessment (EIA)	A statutory process by which certain planned projects must be assessed before a formal decision to proceed can be made. It involves the collection and consideration of environmental information, which fulfils the assessment requirements of the EIA Directive and EIA Regulations, including the publication of an Environmental Statement (ES).
High Voltage Alternating Current (HVAC)	High voltage alternating current is the bulk transmission of electricity by alternating current, whereby the flow of electric charge periodically reverses direction.
Hornsea Project Four Offshore Wind Farm	The term covers all elements of the project (i.e. both the offshore and onshore). Hornsea Four infrastructure will include offshore generating stations (wind turbines), electrical export cables to landfall, and connection to the electricity transmission network. Hereafter referred to as Hornsea Four.
Maximum Design Scenario (MDS)	The maximum design parameters of each Hornsea Four asset (both on and offshore) considered to be a worst case for any given assessment.
Mitigation	A term used interchangeably with Commitment(s) by Hornsea Four. Mitigation measures (Commitments) are embedded within the assessment at the relevant point in the EIA (e.g. at Scoping, PEIR or ES).
Orsted Hornsea Project Four Ltd.	The Applicant for the proposed Hornsea Project Four Offshore Wind Farm Development Consent Order (DCO).
Permanent Threshold Shift (PTS)	Following a marine mammal's exposure to high noise levels, if a Threshold shift occurs and does not return to normal after several weeks then a Permanent Threshold Shift (PTS) has occurred. This results in a permanent auditory injury to the marine mammal.
Soft-start	The term 'soft-start' is applied to the gradual, or incremental, increase in hammer blow energy from the initiation of piling activity until required blow energy is reached for installation of each pile. Maximum hammer blow energy may not be required to complete pile installation.

Acronyms

Acronym	Definition
AC	Alternating Current
ADD	Acoustic Deterrent Device

Acronym	Definition
AfL	Agreement for Lease
BBC	Big Bubble Curtain
BND	Bottlenose dolphin
BSH	Bundesamt für Seeschifffahrt und Hydrographie
CD	Chart Datum
DBBC	Double Big Bubble Curtain
DCO	Development Consent Order
DML	Deemed Marine Licence
ECC	Export Cable Corridor
EIA	Environmental Impact Assessment
ES	Environmental Statement
HF	High Frequency (HF) cetacean
HP	Harbour porpoise
HSD	Hydro-Sound Damper
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
INSPIRE	Impulse Noise Sound Propagation and Impact Range Estimator
JNCC	Joint Nature Conservation Committee
LF	Low Frequency (LF) cetacean
MDS	Maximum Design Scenario
MMMP	Marine Mammal Mitigation Protocol
MMO	Marine Management Organisation
MW	Minke whale
NAS	Noise Abatement System
NMFS	National Marine Fisheries Service
NMS	Noise Mitigation System
NSIP	Nationally Significant Infrastructure Project
ORJIP	Offshore Renewables Joint Industry Programme
OSS	Offshore Substation
OWF	Offshore Wind Farm
PCW	Phocid Carnivores In Water
PEIR	Preliminary Environmental Information Report
PTS	Permanent Threshold Shift
RL	Received Level
SAC	Special Area of Conservation
SEL	Sound Exposure Level
SL	Source Level
SNCBs	Statutory Nature Conservation Bodies
SPL	Sound Pressure Level
TL	Transmission Loss
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High Frequency (VHF) cetacean
VMP	Vessel Management Plan
WBD	White-beaked dolphin
WTG	Wind Turbine Generators

Units

Unit	Definition
dB	Decibel
m	Metre
ms	Millisecond
ms^{-1}	Metres per second
km	Kilometre
kJ	Kilojoule
μPa	Micropascal

1 Introduction

1.1 Project background

1.1.1.1 Orsted Hornsea Project Four Limited (hereafter the 'Applicant') is proposing to develop Hornsea Project Four Offshore Wind Farm (hereafter 'Hornsea Four') which will be located approximately 69 km offshore from the East Riding of Yorkshire in the Southern North Sea and will be the fourth project to be developed in the former Hornsea Zone.

1.1.1.2 Hornsea Four will include both offshore and onshore infrastructure including an offshore generating station (wind farm) including up to 180 wind turbine generators (WTGs), export cables to landfall, and connection to the National Grid Electricity Transmission (NGET) network at Creyke Beck.

1.1.1.3 The Hornsea Four Agreement for Lease (AfL) area was 846 km^2 at the Scoping phase of project development. In the spirit of keeping with Hornsea Four's approach to Proportionate Environmental Impact Assessment (EIA), the project has due consideration to the size and location (within the existing AfL area) of the final project that is being taken forward to Development Consent Order (DCO) application. This consideration is captured internally as the "Developable Area Process", which includes Physical, Biological and Human constraints in refining the developable area, balancing consenting and commercial considerations with technical feasibility for construction.

1.1.1.4 The combination of Hornsea Four's Proportionality in EIA and Developable Area process has resulted in a marked reduction in the array area taken forward at the point of DCO application. Hornsea Four adopted a major site reduction from the array area presented at Scoping (846 km^2) to the Preliminary Environmental Information Report (PEIR) boundary (600 km^2), with a further reduction adopted for the Environmental Statement (ES) and DCO application (468 km^2) due to the results of the PEIR, technical considerations and stakeholder feedback. The evolution of the Hornsea Four Order Limits is detailed in **Volume A1, Chapter 3: Site Selection and Consideration of Alternatives** and **Volume A4, Annex 3.2: Selection and Refinement of the Offshore Infrastructure**.

1.2 Purpose of the Outline Marine Mammal Mitigation Protocol (MMMP)

1.2.1.1 The primary aim of this Outline MMMP is to reduce to negligible the risk of Permanent Threshold Shift (PTS) auditory injury to any marine mammal species in close proximity of the pile driving for the installation of Hornsea Four foundation structures. This Outline MMMP draws on the guidance provided by the Joint Nature Conservation Committee (JNCC) (2010) and recent Statutory Nature Conservation Bodies (SNCB) recommendations with regards to Acoustic Deterrent Device (ADD) use (JNCC et al. 2016).

1.2.1.2 Hornsea Four have developed a range of Commitments though the EIA process to eliminate or reduce impacts as far as possible. All Commitments are detailed with **Volume A4, Annex 5.2: Commitments Register**. Of primary relevance to this Outline MMMP, the Commitments Register includes a Commitment (Co110) to develop and implement a piling MMMP (**Table 1**).

Table 1: Marine Mammal Commitments.

Commitment ID	Measure proposed	How the measure will be secured
Co85	Primary: No more than a maximum of two foundations are to be installed simultaneously.	DCO Schedule 11, Part 2 - Condition 13(1)(g) and; DCO Schedule 12, Part 2 - Condition 13(1)(g) (Marine Mammal Mitigation Protocol) DCO Schedule 11, Part 2 - Condition 13(1)(c) and; DCO Schedule 12, Part 2 - Condition 13(1)(c) (Construction Method Statement)
Co108	Tertiary: A Vessel Management Plan (VMP) will be developed pre-construction which will determine vessel routing to and from construction areas and ports to minimise, as far as reasonably practicable, encounters with marine mammals.	DCO Schedule 11, Part 2 - Condition 13(1)(d)(v)and; DCO Schedule 12, Part 2 - Condition 13(1)(d)(v) (Vessel Management Plan)
Co110	Tertiary: A piling Marine Mammal Mitigation Protocol (MMMP), will be developed in accordance with the Outline MMMP and will be implemented during construction. The piling MMMP will include measures to ensure the risk of instantaneous permanent threshold shift (PTS) to marine mammals is negligible and will be in line with the latest relevant available guidance. The piling MMMP will include details of soft starts to be used during piling operations with lower hammer energies used at the beginning of the piling sequence before increasing energies to the higher levels.	DCO Schedule 11, Part 2 - Condition 13(1)(g) and; DCO Schedule 12, Part 2 - Condition 13(1)(g) (Marine Mammal Mitigation Protocol)
Co113	A Decommissioning Marine Mammal Mitigation Protocol (MMMP) will be implemented during decommissioning. The Decommissioning MMMP will be approved by the Marine Management Organisation (MMO) in consultation with Natural England. The Decommissioning MMMP will include measures to ensure the risk of instantaneous permanent threshold shift (PTS) to marine mammals is negligible and will be in line with the latest relevant available guidance.	A separate Marine Licence will be applied for at the point of decommissioning which will include Conditions relevant to minimising impacts on marine mammals where appropriate.

1.2.1.3 In addition to the Outline MMMP, Hornsea Four have produced a Southern North Sea Special Area of Conservation (SAC) (designated for harbour porpoise) Outline South North Sea Special Area of Conservation Site Integrity Plan as part of the DCO Application (**F2.11: Outline Southern North Sea Special Area of Conservation Site Integrity Plan**). This plan sets out the approach for Hornsea Four to deliver any project mitigation or management measures in relation to the Southern North Sea SAC, in the event that driven or part-driven pile foundations are to be used for Hornsea Four.

1.3 Implementation of the Outline MMMP

1.3.1.1 This Outline MMMP establishes the principles which will be implemented during construction. Following the granting of the DCO for Hornsea Four, and once the final project design has been confirmed, a final MMMP will be prepared following the principles established in the Outline MMMP. This is supported by the inclusion of Condition 13(1)(g) of the draft DCO Schedule 11 and 12 which states:

> *"13. — (1) The licensed activities for each stage of construction of the project must not commence until the following (insofar as relevant to that activity or stage of activity) has been submitted to and approved in writing by the MMO, in consultation with, where relevant, Trinity House and the MCA*
>
> *(g) in the event that driven or part-driven pile foundations are proposed to be used for the relevant stage, a piling marine mammal mitigation protocol for that stage, in accordance with the outline marine mammal mitigation protocol, the intention of which is to prevent injury to marine mammals, including details of soft start procedures with specified duration periods following current best practice as advised by the relevant statutory nature conservation bodies."*

1.3.1.2 In line with the wording in Condition 13(1), Hornsea Four will adopt a staged approach to the approval of DML conditions enabling conditions to be approved in part or in whole prior to the commencement of the relevant stage of works according to whether a staged approach is to be taken to construction of the works in question. This approach will be governed by the inclusion of Conditions 23 and 25 within the draft DMLs (Schedules 11 & 12 of the draft DCO, respectively) which require a written scheme setting out the stages of construction to be approved by the MMO prior to the commencement of the licensed activities. As such, it is likely that a final MMMP will be prepared in relation to WTGs and another final MMMP prepared for the offshore substations (OSS).

2 Pile Driving Scenarios

2.1 Scenarios considered

2.1.1.1 Hornsea Four will require the installation of up to 180 WTG foundations and the following other piled infrastructure:

- Up to six offshore transformer substations (small OSS) and three offshore High Voltage Direct Current (HVDC) convertor substations (large OSS) in the array area;
- Up to one accommodation platform; and
- Up to three High Voltage Alternating Current (HVAC) Booster Stations (small OSS) in the offshore Export Cable Corridor (ECC).

2.1.1.2 It is important to note that the offshore HVDC converter substation(s) are mutually exclusive with HVAC booster station(s) in a single transmission system. Therefore, these two figures should not be combined in the total number. The maximum number of structures within the Hornsea Four array area is 190 (i.e. 180 turbines, one accommodation platform, six offshore transformer substations and three offshore HVDC converter substations).

2.1.1.3 There will be a maximum of four piling vessels on site at the same time (two vessels for WTG foundation installation and two vessels for OSS and HVAC booster station foundation installation) with a maximum of two piling operations at any one time. There will, however, be no concurrent piling operations between the Hornsea Four array area and the HVAC booster stations located in offshore ECC.

2.1.1.4 The maximum foundation installation duration is expected to be 12 months in total for the WTGs and other piled infrastructure. Both monopiles and pin piles could be installed at Hornsea Four and so both foundation types have been assessed in the ES (see **Volume A2, Chapter 4: Marine Mammals**). A summary of the parameters assessed are presented in the sections below, with the outcome of the marine mammal assessment summarised in **Section 3**.

2.1.1.5 In **Volume A2, Chapter 4: Marine Mammals** of the ES, the assessment provides predicted impacts from the maximum design scenario (MDS). The MDS is intended to cover the maximum piling parameters that would ever be required to install a foundation (in terms of maximum hammer energies and longest piling durations). The MDS, based on engineering predictions, is a maximum 5,000 kJ hammer energy for monopiles and 3,000 kJ for pin piles.

2.1.1.6 Following the formal pre-application consultation on the PEIR, a refinement was made to increase the maximum hammer energy for pin piles (MDS) based on analyses undertaken by foundation installation engineers. Following these analyses, foundation installation engineers also confirmed that the ramp-up profile for the MDS could be modified to incorporate a lower strike rate upon commencement of piling.

2.2 Monopile MDS

2.2.1.1 **Table 2** details the piling parameters that represent the MDS for monopiles (spatial MDS for Hornsea Four).

Table 2: Monopile MDS parameters.

Parameter	WTG Foundations (180 monopile foundations)	Other Piled Infrastructure (13 monopile foundations)
Maximum hammer driving energy	5,000 kJ	5,000 kJ
Maximum pile diameter	15 m	15 m
Soft start duration	30 minutes	30 minutes
Ramp up duration	22.5 minutes	22.5 minutes
Maximum piling time per foundation	262.5 minutes	262.5 minutes
Maximum piling time[a]	787.5 hours	56.88 hours
Total number of piling days[b]	216 piling days over 12 month construction period	16 piling days over 12 month construction period
	232 days over 12 month construction period	

[a] = number of foundations multiplied by time per foundation

[b] = assuming 1.2 days per monopile

2.3 Pin Pile MDS

2.3.1.1 Table 3 details the piling parameters that represent the MDS for pin piles (temporal MDS for Hornsea Four).

Table 3: Pin pile MDS parameters.

Parameter	WTG Foundations (180 pin pile foundations – three piles per jacket = 540 piles)	Other Piled Infrastructure (16 pin pile foundations per OSS = 208 piles)
Maximum hammer driving energy	3,000 kJ	3,000 kJ
Maximum pile diameter	4 m	4 m
Soft start duration	30 minutes	30 minutes
Ramp up duration	22.5 minutes	22.5 minutes
Maximum piling time per pile	262.5 minutes	262.5 minutes
Maximum piling time[a]	2,362.5 hours	910 hours
Total number of piling days[b]	270 piling days over 12 month construction period	69 piling days over 12 month construction period
	339 days over 12 month construction period	

[a] = number of foundations multiplied by time per foundation

[b] = assuming 1.5 days per jacket foundation (WTG) and 5.3 days per OSS.

3 Summary of Potential Impacts

3.1 Maximum Design Scenario

3.1.1.1 For both the monopile and pin pile MDS, the maximum instantaneous PTS-onset impact ranges predicted at the commencement of the soft start (20% hammer energy) are shown in Table 4.

Table 4: Estimated instantaneous PTS-onset impact ranges at soft-start hammer energy (maximum design scenario).

Species	Threshold	Monopile (1,000 kJ)	Pin pile (600 kJ)
		Maximum range (m)	Maximum range (m)
Harbour porpoise (HP)	unweighted SPL_{peak} 202 dB re 1µPa	740	380
Minke whale (MW)	unweighted SPL_{peak} 219 dB re 1µPa	<50	<50
White-beaked and bottlenose dolphin (WBD and BND)	unweighted SPL_{peak} 230 dB re 1µPa	<50	<50
Seal species	unweighted SPL_{peak} 218 dB re 1µPa	<50	<50

3.1.1.2 For both the monopile and pin pile MDS, the maximum instantaneous (peak Sound Pressure Level - SPL_{peak}) and cumulative (cumulative Sound Exposure Level - SEL_{cum}, the potential for PTS-onset as a result of exposure to piling noise over a 24-hour period) PTS-onset impact ranges predicted at full hammer energy are shown in Table 5.

Table 5: Estimated instantaneous and cumulative PTS-onset impact ranges at full hammer energy (maximum design scenario).

Species	Threshold	Monopile (5,000 kJ)	Pin pile (3,000 kJ)
		Maximum range (m)	Maximum range (m)
Harbour porpoise Very high frequency (VHF) cetacean	unweighted SPL_{peak} 202 dB re 1μPa	2,900	2,100
	VHF weighted SEL_{cum} 155 dB re 1 μPa^2 s	450	12,000
Minke whale Low frequency (LF) cetacean	unweighted SPL_{peak} 219 dB re 1μPa	140	100
	LF weighted SEL_{cum} 183 dB re 1 μPa^2 s	11,000	9,200
White-beaked and bottlenose dolphin High frequency (HF) cetacean	unweighted SPL_{peak} 230 dB re 1μPa	<50	<50
	HF weighted SEL_{cum} 185 dB re 1 μPa^2 s	<100	<100
Seal species Phocid carnivores in water (PCW)	unweighted SPL_{peak} 218 dB re 1μPa	170	120
	PCW weighted SEL_{cum} 185 dB re 1 μPa^2 s	<100	<100

3.2 Summary of impact assessment for marine mammal in relation to PTS for piling noise

3.2.1.1 **Volume A2, Chapter 4: Marine Mammals** presents the full assessment of the impacts of PTS-onset for piling noise of marine mammals. In summary, the assessment concluded that, with the use of embedded mitigation methods (Commitment Co110 of **Volume 4, Annex 5.2 Commitment Register** and outlined within this Outline Marine Mammal Mitigation Protocol), it is expected that the risk of PTS will be negligible under the MDS for both monopiles and pin piles, and is not therefore not considered to have a significant effect on any marine mammal species considered in the assessment.

4 Mitigation Methodology

4.1 Introduction

4.1.1.1 In order to minimise the risk of any auditory injury to marine mammals from underwater noise during pile driving, there are a suite of mitigation measures that the Applicant could implement for Hornsea Four piling. These mitigation measures may include (but are not limited to) the following measures:

- Pre-piling deployment of ADDs;
- Concurrent Marine Mammal Observation; and
- Piling soft-start procedure[1].

[1] It is important to note that the Applicant is committed to implementing a soft-start procedure, as detailed in Co110 and within the wording of the MMMP DML condition (Condition 13(1)(g) of the draft DCO Schedule 11 and 12).

4.1.1.2 The specific mitigation measure (or suite of measures) that will be implemented during the construction of Hornsea Four will be determined, in consultation with the relevant SNCBs, following confirmation of final hammer energies and foundation types, collection of additional survey data (noise or geophysical data) and/or acquisition of noise monitoring data, and/or information on maturation of emerging technologies. This additional data and information will allow the noise modelling to be updated to feed into the final MMMP and discussions on the appropriate mitigation measure(s).

4.1.1.3 The following sections provide a high-level methodology for each of these elements. A final MMMP will be produced prior to the relevant stage of construction for approval by the MMO (**Section 1.3**).

4.2 Mitigation zone

4.2.1.1 The mitigation zone is defined as the maximum potential instantaneous PTS-onset impact ranges. At the commencement of the soft-start (20% hammer energy) this is a maximum mitigation zone for all species of 740 m for the monopile MDS and 380 m for the pin pile MDS. Mitigation measures would aim to ensure that no marine mammals remained within the mitigation zone at the start of the piling soft-start to reduce the risk of injury to negligible levels.

4.2.1.2 The maximum cumulative PTS zone is 11 km for monopiles and 12 km for pin piles (**Table 5**). However, the Applicant considers that the calculated SEL_{cum} PTS-onset impact ranges are highly over-precautionary and unrealistic. Full details on the limitations of SEL_{cum} modelling are provided in **Appendix A: Mitigation for PTS-Onset SPLpeak and SELcum Thresholds**. In summary, the key limitations are:

- Growing empirical evidence that the equal energy hypothesis assumption behind the SEL_{cum} threshold is not valid;
- Impulsive noise thresholds overestimate the risk of PTS-onset as impulsiveness reduces over distance;
- Fleeing swim speed modelled is precautionary; and
- SEL_{ss} levels are lower at surface -model can overpredict exposure at the surface.

4.2.1.3 It is important to note that this Outline MMMP focuses on mitigating only the "instantaneous" SPL_{peak} PTS-onset impact ranges. As discussed in **paragraph 4.1.1.2**, the Applicant will update the noise modelling prior to construction once the final project details are known. This updated modelling will, in turn, feed into the consideration of mitigation requirements. One of the potential mitigation measures that will be considered at this point, will be the use of at-source noise reduction measures in order to reduce the potential for cumulative PTS-onset risk to negligible levels. For example, bubble curtains and double bubble curtains can be used to significantly reduce predicted impact ranges (see **Appendix B: Additional Modelling of Underwater Noise from Impact Piling Using Bubble Curtains** for examples).

4.2.1.4 The actual mitigation zone for Hornsea Four piling will be confirmed in the final MMMP and will be determined based on the final confirmed foundation options and hammer energies etc.

4.3 ADD choice and specification

4.3.1.1 If an ADD device is chosen as part of the suite of mitigation measures set out in the final MMMP, the ADD device that is likely to be used is the Lofitech AS seal scarer[2] although this will be confirmed within the final MMMP. This ADD has been shown to have the most consistent effective deterrent ranges for harbour seals (*Phoca vitulina*), grey seals (*Halichoerus grypus*), minke whales (*Balaenoptera acutorostrata*) and harbour porpoise (*Phocoena phocoena*) (the primary species of relevance at Hornsea Four) in environments similar to the offshore wind farm (OWF) construction site (Sparling et al. 2015; McGarry et al. 2017). The Lofitech AS seal scarer has been successfully used for marine mammal mitigation purposes at a number of OWF construction projects in Europe, including the C-Power Thornton Bank OWF in Belgium (Haelters et al. 2012), the Horns Rev II, Nysted and Dan Tysk OWFs in Denmark (Carstensen et al. 2006; Brandt et al. 2009; Brandt et al. 2011; Brandt et al. 2013; Brandt et al. 2016) and on various German sites (Georg Nehls, pers comm). An Offshore Renewables Joint Industry Programme (ORJIP) study undertook trials of ADD efficacy on minke whale (McGarry et al. 2017). The results presented in the ORJIP study demonstrate that the Lofitech ADD modifies the behaviour of free-ranging minke whales at both 500 m and 1000 m. Minke whales demonstrated a significant increase in swim speed, and an increase in the directness of their movement away from the site of the ADD playback. This indicates clear avoidance behaviour, which indicates utility as a mitigation tool for the deterrence of minke whales from a standard mitigation zone. The Lofitech device has recently been successfully used for marine mammal mitigation purposes for harbour porpoises, harbour and grey seals, and minke whales during piling construction activities at the several OWFs.

4.3.1.2 There is currently no published evidence of the effectiveness of ADDs on white-beaked dolphins (*Lagenorhynchus albirostris*) or bottlenose dolphins (*Tursiops truncatus*) but deterrents only have to be effective over a small range for white-beaked and bottlenose dolphins in order to ensure these species are not at risk of instantaneous auditory injury. Further to this, it is also noted that these species are also much less likely to be encountered at the site compared to harbour porpoise due to the lower densities of these species recorded in the area. As such, the likelihood of a white-beaked or bottlenose dolphins being exposed to the risk of auditory injury is considered to be extremely low.

4.3.1.3 It is important to note that there may be additional ADD models identified in the pre-construction phase for Hornsea Four that are available and suitable for use. As such, if an ADD device is chosen as part of the suite of mitigation measures set out in the final MMMP, the final ADD choice and specification will be confirmed within the final MMMP.

4.4 Duration of deployment

4.4.1.1 The duration of ADD deployment will be calculated using swimming speed assumptions to ensure that marine mammals are beyond the mitigation zone when piling commences.

4.4.1.2 A swim speed of 1.5 ms^{-1} (Otani et al. 2000; Lepper et al. 2012) is assumed for all marine mammals with the exception of minke whales. A swim speed of 3.25 ms^{-1} is assumed for minke whales (Blix and Folkow, 1995). There is evidence to suggest that these selected swim speeds are precautionary and that animals are likely to flee at much higher speeds, at least initially. Minke whales have been shown to flee from ADDs at a mean swimming speed of 4.2 ms^{-1} (McGarry et al. 2017). A recent study by Kastelein et al. (2018) showed

[2] http://www.lofitech.no/en/seal-scarer.html

that a captive harbour porpoise responded to playbacks of pile driving sounds by swimming at speeds significantly higher than baseline mean swimming speeds, with greatest speeds of up to 1.97 ms^{-1} which were sustained for the 30 minute test period. In another study, van Beest et al. (2018) showed that a harbour porpoise responded to an airgun noise exposure with a fleeing speed of 2 ms^{-1}.

4.4.1.3 Marine mammals are expected to continue moving away during the soft-start and throughout the ramp-up. In addition, the presence of novel vessel activity on-site is also predicted to result in animals moving away from the piling location and out of the mitigation zone prior to the commencement of piling (Brandt et al. 2018; Graham et al. 2019).

4.4.2 Instantaneous PTS

4.4.2.1 Under the monopile MDS, the mitigation zone at the commencement of the soft-start (20% hammer energy) is 740 m. Given a conservative swim speed of 1.5 ms^{-1}, animals starting at the pile location would take a total of 8.2 minutes to exit the 740 m mitigation zone (quicker for minke whales as they are assumed to swim at a faster speed of 3.25 ms^{-1}). It is assumed that marine mammals continue to flee during the soft-start and ramp-up, therefore, given an initial ADD activation period, followed by a 30 minute soft-start and then a 22.5 minute ramp-up, there is sufficient time for marine mammals to be outside of the 2.9 km impact range before the full hammer energy is reached (**Table 6**).

4.4.2.2 Under the pin pile MDS, the mitigation zone at the commencement of the soft-start (20% hammer energy) is 380 m. Given a conservative swim speed of 1.5 ms^{-1}, animals starting at the pile location would take a total of 4.2 minutes to exit the 380 m mitigation zone (quicker for minke whales as they are assumed to swim at a faster speed of 3.25 ms^{-1}). It is assumed that marine mammals continue to flee during the soft-start and ramp-up, therefore, given an initial ADD activation period, followed by a 30 minute soft-start and then a 22.5 minute ramp-up, there is sufficient time for marine mammals to be outside of the 2.1 km impact range before the full hammer energy is reached (**Table 6**).

Table 6: Estimated time for marine mammals to flee the mitigation zone at the commencement of the soft-start and time for marine mammals to flee the maximum PTS-onset impact range at full hammer energy.

	Monopile MDS		Pin pile MDS	
	Commencement of soft-start (1,000 kJ)	Maximum hammer energy (5,000 kJ)	Commencement of soft-start (600 kJ)	Maximum hammer energy (3,000 kJ)
Maximum instantaneous PTS-onset range (m)	740	2,900	380	2,100
Time to flee mitigation zone (assuming 1.5 ms^{-1})	8.2 min	32.2 min	4.2 min	23.3 min

4.4.2.3 Therefore, ADD use for 15 minutes before the soft-start commences would ensure that animals are displaced from the soft-start mitigation zone before the piling commences, and the continued fleeing of animals throughout the 30 minute soft-start and 22.5 minute ramp-up will ensure that animals are beyond the maximum PTS-onset impact range before the full hammer energy is reached.

4.4.3 Cumulative PTS

4.4.3.1 Under the monopile maximum design scenario, the maximum SEL_{cum} PTS range is 11 km for minke whales. Given a swim speed of 3.2 ms^{-1} for minke whales, animals starting at the pile location would take 57.3 minutes to exit the 11 km SEL_{cum} PTS impact range. It would take less time for each of the other species to exit their maximum SELcum PTS ranges for monopiles (**Table 7**).

4.4.3.2 Under the pin pile maximum design scenario, the maximum SEL_{cum} PTS range is 12 km for harbour porpoise. Given a swim speed of 1.5 ms^{-1} for harbour porpoise, animals starting at the pile location would take 133.3 minutes to exit the 12 km SEL_{cum} PTS impact range. It would take less time for each of the other species to exit their maximum SEL_{cum} PTS ranges for pin piles (**Table 7**).

4.4.3.3 In order to ensure that the SEL_{cum} PTS range is free of animals, it requires ADD activation for 57.3 minutes for monopiles and 133.3 minutes for pin piles. This extended duration of ADD activation is likely to cause significant levels of disturbance and is therefore not considered to be a feasible mitigation option. Therefore, Hornsea Four will commit to providing at-source noise reduction measures in order to reduce the potential for cumulative PTS risk to negligible levels. For example, bubble curtains and double bubble curtains can be used to significantly reduce predicted impact ranges (see **Appendix B: Additional Modelling of Underwater Noise from Impact Piling Using Bubble Curtains** for examples). The choice of at-source noise reduction method will be confirmed in the final MMMP and the need for any ADD activation periods will be confirmed.

Table 7: Estimated time for marine mammals to flee the SEL_{cum} PTS impact zone.

	Monopile MDS (5,000 kJ)				Pin pile MDS (3,000 kJ)			
Species	**HP**	**MW**	**WBD & BND**	**Seal species**	**HP**	**MW**	**WBD & BND**	**Seal species**
Maximum SEL_{cum} PTS range (m)	2,900	11,000	<100	<100	12,000	9,200	<100	<100
Swim speed (ms^{-1})	1.5	3.2	1.5	1.5	1.5	3.2	1.5	1.5
Time to flee SEL_{cum} range (mins)	32.2	57.3	<1	<1	133.3	47.9	<1	<1

4.5 ADD deployment procedure

4.5.1.1 It is expected that during monopile or pin pile installation, one ADD will be deployed from the deck of the piling platform/vessel, with the control unit and power supply on board the platform/vessel in suitable, safe positions on deck. The ADD will be verified for operation prior to pre-piling activation. The exact deployment procedure will be agreed once the piling contractor is in place and will follow safe, standard working practices using experienced/trained staff to ensure the ADD equipment is used and deployed correctly within the confines of different vessel layouts.

4.6 ADD operator training and responsibilities

4.6.1.1 A trained and dedicated ADD operator will be responsible for ADD maintenance, operation and reporting. The ADD duties involved would be to deploy the ADD from the installation platform or vessel, to verify the operation of the ADD before deployment, to operate the

ADD throughout the pre-piling period (and be available in the case of piling breaks to reactivate), ensure batteries are fully charged and that spare equipment is available in case of any problems, and record and report on all ADD and piling activity. Prior to the start of the marine mammal observer pre-piling watch period, the ADD operator will test the equipment to ensure the ADD is working and ensure they are deployed appropriately from the vessel or jacket to an agreed depth. Following the deployment and testing of the ADD equipment, before the commencement of the soft-start procedure (for monopiles/pin piles respectively), the ADD operator will activate the ADD and the marine mammal observer will commence the pre-piling watch. When the soft-start commences the ADD operator will deactivate the ADD.

4.7 Marine mammal observers

4.7.1.1 The pre-piling watch for marine mammals will be conducted for a set period of 30 minutes prior to the commencement of the soft-start procedure. The marine mammal observer will undertake visual marine mammal observations within the defined mitigation zone around the piling location from a suitable elevated platform. The marine mammal observer will record all periods of marine mammal observations, including start and end times. Details of environmental conditions (sea state, weather, visibility, etc.) and any sightings of marine mammals around the piling vessel will also be recorded as per JNCC marine mammal recording forms and guidelines. In addition, any obvious responses of animals to the ADD activation will be recorded (e.g. a change in behaviour from milling or bottling to directed travel away from the ADD at the onset of ADD activation).

4.7.1.2 If, during the marine mammal observer pre-piling watch, a marine mammal is detected within the mitigation zone, the ADD should be checked to ensure correct operation, and soft-start will be delayed until it is assessed by the MMO that the marine mammal has vacated the mitigation zone. The marine mammal observer will continue to note detections and observations on animal behaviour during the soft-start period.

4.8 Soft-start procedure

4.8.1.1 Following the pre-piling deployment of the ADDs and the marine mammal observer pre-piling watch, the installation of each foundation will commence with a soft-start of a maximum of 20% of the maximum hammer energy for a duration of 30 minutes. The hammer energy will then ramp-up in steps until the levels required to install the pile are reached or up to the maximum hammer energy. The hammer energy will not be increased above the hammer energy required to complete each installation – i.e. if ground conditions are such that a lower than maximum hammer energy is sufficient to complete installation, then hammer energy will not be unnecessarily ramped up to full hammer energy.

4.9 Breaks in piling procedure

4.9.1.1 Breaks in the piling process could provide the potential for marine mammals to re-enter the mitigation zone. The guidance provided in JNCC (2010) states that *"If there is a pause in the piling operations for a period of greater than 10 minutes, then the pre-piling search and soft-start procedure should be repeated before piling recommences"*. However, the ability to restart with a soft-start may depend on the stage of piling and the pile/soil behaviour. If it is not possible to re-start with a soft-start, the pre-piling ADD deployment and marine mammal observer pre-piling watch will be carried out before recommencing piling. The final procedure for breaks in piling will be agreed with input from the piling contractor (once contracted) and SNCBs and set out within the final MMMP.

4.10 Delays in the commencement of piling

4.10.1.1 Should there be a delay in the commencement of piling, there is a risk of animals moving back into the mitigation zone when ADDs are switched off. However, there is also a risk of habituation as a result of no aversive piling noise commencing after ADD activation. ADDs will therefore be turned off as soon as the delay in the commencement is realised. The ADD will not be switched on again until there is confirmation that piling is ready to commence. The ADD will then be reactivated, as above, for the minimum duration required for animals to move out of the mitigation zone.

4.11 Communications

4.11.1.1 The final MMMP will detail a communications protocol to ensure that all marine mammal mitigation measures, including any delays in commencing piling due to marine mammals being present in the area, are undertaken for all piling activities.

4.11.1.2 The final MMMP will also detail all key personnel and their responsibilities to ensure that all marine mammal mitigation measures are successfully undertaken for all piling activities. This will be developed based on the mitigation measures and personnel required with the titles and responsibilities being refined depending on the contractual agreement.

4.12 Reporting

4.12.1.1 Reports detailing the piling activity and mitigation measures will be prepared. Where appropriate these will include, but not necessarily be limited to:

- Outline of the marine mammal monitoring methodology and procedures employed;
- Record of piling operations detailing date, soft-start duration, piling duration, hammer energy during soft-start and piling and any operational issues for each pile;
- Record of ADD deployment, including start and end times of all periods of ADD activation, any problems with ADD deployment;
- Record of marine mammal observations including duration of marine mammal observer pre-piling watch;
- Environmental conditions during the pre-piling watch, description of any marine mammal sightings and any actions taken and a record of any incidental sightings made during out with the pre-piling watch;
- Details of any problems encountered during the piling process including instances of noncompliance with the agreed piling protocol; and
- Any recommendations for amendment of the protocol.

4.12.1.2 Reports will be collated and provided to the MMO on a weekly basis during the period during which piling operations are being conducted. In addition, a final report will be provided following the completion of the construction activity which will be submitted to the MMO. The final report will include any data collected during piling operations, details of ADD deployment, details of marine mammal observer watch periods and observations, a detailed description of any technical problems encountered and what, if any, actions were taken. The report will also discuss the protocols followed and put forward recommendations based on project experience and the use of ADDs as mitigation during the construction period that could benefit future construction projects.

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Appendix A: Mitigation for PTS-Onset SPL_{peak} and SEL_{cum} Thresholds

Drafted by SMRU Consulting, May 2020

Introduction

Exposure to loud sounds can lead to a reduction in hearing sensitivity (a shift in hearing threshold), which is generally restricted to particular frequencies (e.g. Kastelein et al. 2017). This threshold shift results from physical injury to the auditory system and may be temporary (Temporary Threshold Shift - TTS) or permanent (PTS).

The Hornsea Four impact assessment for marine mammals presents PTS impact ranges for piling events, using the Southall et al. (2019) thresholds for all species. The thresholds are based on a dual criteria approach whereby both should be evaluated and that predicting the largest range of impact, should be considered for the impact assessment. The first metric is pressure based, taken as zero-to-peak sound pressure level (SPL_{zp}) or as peak-to-peak sound pressure level (SPL_{pp}). Any single exposure at or above this pressure-based metric is considered to have the potential to cause PTS, regardless of the exposure duration. The second metric is energy based and is a measure for the accumulated sound energy an animal is exposed to over an exposure period, referred to as sound exposure level (SEL) when considering single pulses, or cumulative sound exposure levels (SEL_{cum}) when considering exposure periods with multiple pulses.

The SEL metric is based on the 'equal-energy assumption', having its origin in human research, and stating that sounds of equivalent energy will have generally similar effects on the auditory systems of exposed human subjects, even if they differ in SPL, duration, and /or temporal exposure pattern (Southall et al. 2007). While the sound pressure levels are analysed unweighted, National Marine Fisheries Service (NMFS) (2018) and Southall et al. (2019) describe species specific frequency filters to be applied before the SEL is calculated.

The SEL-thresholds for PTS take into account the received level and the duration of exposure, accounting for the accumulated exposure over the duration of an activity within a 24-hour period. NMFS (2018) recommends the application of SEL_{cum} for the individual activity within 24 hours (e.g. one piling event with multiple strikes) rather than for multiple activities occurring within the same area or over the same time (e.g. concurrent piling).

The methods used to calculate PTS impact ranges for 'instantaneous' PTS (SPL_{pk}), and PTS induced by cumulative sound exposure (SEL_{cum}, over 24 hours) are detailed in **Volume A4, Annex 4.5: Subsea Noise Technical Report**.

Precaution in cumulative PTS (SEL_{cum}) calculations

There is much more uncertainty associated with the prediction of levels of cumulative exposure due to the difficulty in predicting the true levels of sound exposure over long periods of time, as a result of uncertainties about responsive movement, the position of animals in the water column, extent of recovery between pulses or in breaks in piling and the extent to which pulsed sound loses its impulsive characteristics over time. As a result of this uncertainty, model parameters are generally highly conservative and when considered across multiple parameters this precaution is compounded therefore the resulting predictions are very precautionary and very unlikely to be realised.

It is important to note that the SEL_{cum} thresholds were determined with the assumption that a) the amount of sound energy an animal is exposed to within 24 hours will have the same effect on its auditory system, regardless of whether it is received all at once or in several smaller doses spread over a longer period (called the equal-energy hypothesis), and b) the sound keeps its impulsive character, regardless of the distance to the sound source. Both assumptions lead to a conservative determination of the impact ranges. Modelling the SEL_{cum} impact ranges of PTS with a 'fleeing animal' model, as is typical in noise impact assessments, is subject to both of these uncertainties and the result is a highly precautionary prediction of impact ranges.

Equal energy hypothesis

The equal energy hypothesis assumes that "exposures of equal energy are assumed to produce equal amounts of noise-induced threshold shift, regardless of how the energy is distributed over time". However, in a review on noise induced threshold shifts in marine mammals, Finneran (2015) showed that several marine mammal studies have demonstrated that the temporal pattern of the exposure does in fact affect the resulting threshold shift (e.g. Kastak et al. 2005, Mooney et al. 2009, Finneran et al. 2010, Kastelein et al. 2013). Intermittent noise allows for some recovery of the threshold shift in between exposures, and therefore recovery can occur in the gaps between individual pile strikes and in the breaks in piling activity, resulting in a lower overall threshold shift compared to continuous exposure at the same SEL. The study by Kastelein et al. (2013) showed that for seals, the threshold shifts observed did not follow the assumptions made in the guidance regarding the equal energy hypothesis, and that instead, the threshold shifts observed were more similar to the hypothesis presented in Henderson et al. (1991): hearing loss induced due to noise does not solely depend upon the total amount of energy, but on the interaction of several factors such as the level and duration of the exposure, the rate of repetition, and the susceptibility of the animal.

Therefore, the equal energy hypothesis assumption behind the SEL_{cum} threshold is not valid, and as such, models will overestimate the level of threshold shift experienced from intermittent noise exposures.

Impulsive characteristics

Southall et al. (2019) acknowledges that, as a result of propagation effects, the signal of certain sound sources (e.g., pile driving) loses its impulsive characteristics and could potentially be characterised as a non-impulsive beyond a certain distance. The changes in noise characteristics with distance generally result in exposures becoming less physiologically damaging with increasing distance as sharp transient peaks become less prominent (Southall et al. 2019). In the draft version of the NMFS (2018) guidance that was released in 2015 for public consultation, four criteria were proposed to determine whether a signal is impulsive or non-impulsive in nature. These criteria were based on signal duration, rise time, crest factor and peak pressure divided by signal duration. Hastie et al. (2019) used these criteria to estimate the transition from impulsive to non-impulsive characteristics of pile driving noise during the installation of offshore wind turbine foundations in The Wash and in the Moray Firth based on sound recorded at increasing distances from the piling site. Southall et al. (2019) state that mammalian hearing is most readily damaged by transient sounds with rapid rise-time, high peak pressures, and sustained duration relative to rise-time. Therefore, of the four criteria used by Hastie et al. (2019), the rise-time and peak pressure may be the most appropriate indicators to determine the impulsive/non-impulsive transition. Based on the rise-time criterion (rise time <25 ms defines a signal as impulsive), Hastie et al. (2019) showed that the noise signal experienced a high degree of change in its impulsive characteristics within three to nine km from the source. For pile driving at the Moray Firth (1.8 m diameter pin-piles in 42 m water depth), the probability of the piling noise being impulsive reduced from 70% at ~0.7 km down to 1% at ~3.1 km.

For pile driving at The Wash (5.2 m diameter monopiles in water depths of 8-20 m), this probability reduced from 70% at ~1.4 km down to 1% at ~8.6 km.

Therefore, predicted PTS-onset impact ranges based on the impulsive noise thresholds will overestimate the risk of PTS-onset in cases and at ranges where the likelihood increases that an animal is exposed to non-impulsive sound.

Swimming speed

To determine the number of animals experiencing energy-induced PTS, one has to calculate the accumulated energy over the course of the series of pile strikes. To do this, assumptions have to be made regarding swimming speed and direction of movement, which introduces a degree of uncertainty in the range within which animals are at risk of PTS-onset. All marine mammals were modelled to swim away at the onset of piling at a swimming speed of 1.5 ms^{-1} apart from minke whales which were modelled to flee at 3.25 ms^{-1}. There are data to suggest that these selected swim speeds are precautionary and that animals are likely to flee at much higher speeds, at least initially. Minke whales have been shown to flee from ADDs at a mean swimming speed of 4.2 ms^{-1} (McGarry et al. 2017). A recent study by Kastelein et al. (2018) showed that a captive harbour porpoise responded to playbacks of pile driving sounds by swimming at speeds significantly higher than baseline mean swimming speeds, with greatest speeds of up to 1.97 ms^{-1} which were sustained for the 30 minute test period. In another study, van Beest et al. (2018) showed that a harbour porpoise responded to an airgun noise exposure with a fleeing speed of 2 ms^{-1}.

These recent studies have demonstrated porpoise and minke whale fleeing swim speeds that are greater than that used in the Hornsea Four fleeing model, which makes the modelled speeds used in the Hornsea Four marine mammal assessment precautionary.

Animal depth

Empirical data on SEL_{ss} levels recorded during piling construction at the Lincs OWF have been compared to estimates obtained using the Aquarius pile driving model[3] (Whyte et al. 2020). This has demonstrated that measured recordings of SEL_{ss} levels made at 1 m depth were all lower than the model-predicted single-strike SELs for the shallowest depth bin (2.5 m). In contrast, measurements made at 9 m depth were much closer to the model-predicted single-strike SELs. This highlights the limitations of modelling exposure using depth averaged sound levels, as the acoustic model can overpredict exposure at the surface. This is important to note since animals may conduct shorter and shallower dives when fleeing (e.g. van Beest et al. 2018).

Piling MMMP approach

Given the above, the Applicant considers that the calculated SEL_{cum} PTS-onset impact ranges are highly over-precautionary and unrealistic. Therefore, the piling MMMP focuses on mitigating only the "instantaneous" SPL_{peak} PTS-onset impact ranges.

[3] From more information on the Aquarius model see: de Jong, C., Binnerts, B., Prior, M., Colin, M., Ainslie, M., Mulder, I., and Hartstra, I. (2019). "Wozep – WP2: update of the Aquarius models for marine pile driving sound predictions," TNO Rep. (2018), number R11671, The Hague, Netherlands, p. 94. Retrieved from https://www.noordzeeloket.nl/publish/pages/160801/update_aquarius_models_pile_driving_sound_predeictions_tno_2019.pdf

This follows the approach taken in Scotland, where Marine Scotland and Scottish Natural Heritage have agreed that mitigation should focus on the prevention of instantaneous PTS.

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Appendix B: Additional Modelling of Underwater Noise from Impact Piling Using Bubble Curtains

Drafted by Subacoustech Environmental Ltd. December 2019 and adapted by SMRU Consulting for inclusion in the MMMP.

Introduction

Underwater noise modelling was carried out for Hornsea Four as part of the ES to assess the effects of noise from the installation of monopile and pin pile foundations. Further modelling has now been carried out to show the potential reduction in noise levels and impact ranges when using a bubble curtain during foundation installation.

The northwest (NW) location has been modelled for the monopile and pin pile MDS parameters. This location represents the maximum water depth within the Hornsea Four boundary; the NW location is situated in approximately 55 m water at mean tide. Please refer to the **Volume A4, Annex 4.5: Subsea Noise Technical Report** for more details on the modelling undertaken and the impact criteria.

It is important to note that modelling undertaken in this appendix initially used a NW location of the Hornsea Four Order Limits presented at PEIR (PEIR NW location). A site reduction was subsequently adopted for the Environmental Statement (ES) and the PEIR NW location was no longer within the Hornsea Four Order Limits. A new NW location within the Hornsea Four Order Limits for DCO application (ES NW location) was selected and is approximately 4 km away from the PEIR NW location, in a water depth of approximately 50 m, compared to the previous water depth of 55 m for the PEIR NW location. As the water is slightly shallower, and bubble curtains are more effective in shallower water, it is therefore expected that the bubble curtain would be slightly more effective in the ES NW location. Therefore the previous prediction of the benefit of the bubble curtain represents a worst case for sound propagation.

Fundamentals of noise modelling

The basic requirements of noise modelling, or the calculation of the noise level magnitude at a particular location, is common for almost all noise-related situations that require an EIA. The general approach for airborne noise is described in ISO 9613-2 (Acoustics - Attenuation of sound during propagation outdoors - Part 2: General method of calculation) and the same principles apply underwater. In summary, a source or number of sources will generate a particular noise level which, over distance, will be attenuated by various physical processes (dependent on the environment), resulting in the received level at a particular location. The extent to which this will be perceived by a receptor animal will depend on the sensory capabilities of the receptor species. This can be seen in the simplified sonar equation below:

Received Level (RL) = Source Level (SL) – Transmission Loss (TL).

Transmission loss includes all factors which attenuate noise levels between the source location and the received location. This includes losses due to spreading and absorption, both of which vary with frequency, water depth and environmental conditions.

Noise propagation models attempt to characterise the likely transmission loss in a given environment in order to estimate the received level for a known source level. As both SL and TL are frequency dependent, RL will be dependent on the frequency characteristics of both SL and TL, and not just the overall level.

In the case of underwater noise from offshore impact piling, the noise from the hammer impacting the pile radiates into the water column and the seabed. Noise then travels through the water and seabed being attenuated by spreading and absorption with increasing distance.

The addition of a noise reduction device, such as a bubble curtain, adds an additional frequency-dependent element to the transmission loss calculation. The sonar equation may be modified with an additional term as follows:

Received Level = Source Level – Transmission Loss – Mitigation Loss

Where mitigation loss is the attenuation due to the noise reduction device.

The effect of frequency characteristics

As noted above, the frequency characteristics of the noise is an important factor in the modelling calculations. Too often, source levels or attenuation values are given as single dB values without any specific reference to frequency (usually for ease of presentation). Caution should be exercised when considering such values as they are likely to be valid in only some certain contexts.

For example, a report quoting an attenuation of 6 dB in received levels resulting from a noise reduction device is only valid in the original context. If the same mitigation were applied to a noise source with different frequency characteristics, there may be increased, decreased or no attenuation.

For this reason, the full frequency characteristics of the source, transmission loss and mitigation loss needs to be included in all modelling calculations.

It should also be noted that the hearing sensitivity of a receptor species adds a further frequency-dependent consideration not considered in this report.

Modelling of noise mitigating devices

The recent publication of SNH Research Report No. 1070 by Verfuss et al. (2019) provided up to date data on currently available mitigation devices – noise abatement systems (NAS) – that could be used in noise modelling. Some of these systems have been in wide use in northern European waters for some time in order to comply with regulations originally set by Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Germany.

The report includes the following table for a variety of underwater NAS. These are the Big Bubble Curtain (BBC), Double Big Bubble Curtain (DBBC), Noise Mitigation System (NMS), Hydro-Sound Damper (HSD) and combinations of them. All data on noise reduction were derived from measurements during OWF construction in German waters (Bellman et al. 2018).

Unconstrained NAS that rely on air released into the water column, such as bubble curtains, are the most commonly deployed in the offshore wind industry. These work in two ways. The first is at low frequencies, where the bubbles act as a barrier to sound passing by virtue of their significant difference in density to the water, and the second is at high frequencies by causing the bubbles to resonate as the sound passes, which leads to sound absorption.

As a rule, impediments to bubble curtain efficacy are high currents and deep waters, both of which lead to bubble dispersion and thus a reduction in the barrier effect. The effectiveness of the bubble curtain will not fundamentally change between two piling events that occur in largely the same environment (in this case the North Sea). Thus, results in German waters are expected to provide reasonable approximations for results at Hornsea, given similar depth and current. Different hammer energies or pile types will affect the sound level or frequency of the noise pulse, which should be considered in estimation of bubble curtain performance.

As noted above, water depth and current are the primary environmental factors influencing the efficacy of a bubble curtain. Within the Hornsea Four array area, water depths vary from around 30 m below Chart Datum (CD) in the south to more than 60 m below CD in the north (**Volume A1, Chapter 4: Project Description**). Therefore, the majority of the Hornsea Four array area is in water depths similar to the sites given in **Table B-1**, and thus the noise reduction levels provided in **Table B-1** are expected to be reasonable estimates of the expected noise reduction levels achievable at Hornsea Four. However, as parts of the Hornsea Four site, especially at the north, are deeper (>60 m) this may affect the performance of the NAS. Increases in performance can be achieved by increasing the air flow, which could mitigate the effect of greater depth. Bubble curtains have been commercially deployed on OWFs in water depths up to 45 m and have been applied as mitigation during Unexploded Ordnance (UXO) clearance in water depths up to 90 m (Verfuss et al. 2019).

Table B-1: Minimum and maximum noise reduction efficacy of single BBC or DBBC applied with different air volume flow (given in m³/(min*m), NMS, HSD and combined systems in German OWF-projects with pile sites at given water depths. From Verfuss et al. 2019 – based on Bellman et al. (2018).

Noise Attenuation System	Water depth	Noise reduction (SEL_{ss} dB)
BBC (>0.3m³/(min*m)	~ 40 m	7 – 11
DBBC (>0.3m³/(min*m)	~ 40 m	8 – 13
DBBC (>0.4m³/(min*m)	~ 40 m	12 – 18
DBBC (>0.5m³/(min*m)	> 40 m	~ 15-16 (based on 1 pile)
NMS	Up to 40 m	13 – 16
HSD	Up to 40 m	10 – 12
NMS + optimised BBC (>0.4m³/(min*m)	~ 40 m	17-18
NMS + optimised BBC (>0.5m³/(min*m)	~ 40 m	18-20
HSD + optimised BBC (>0.4m³/(min*m)	~ 30 m	15-20
HSD + optimised DBBC (0.48m³/(min*m)	20-40 m	15-28
HSD + optimised DBBC (> 0.5m³/(min*m)	< 45 m	18-19

As stated previously, taken without any supporting data for these systems' frequency performance, the noise reduction levels can be misleading. Verfuss et al. (2019) also provide information on the noise reduction in selected frequency bands (see **Figure B-1** and **Figure B-2** below). For example, the HSD is noted to offer 10-12 dB attenuation in **Table B-1**, but **Figure B-1** shows that it is, in the design currently applied, ineffective above 2 kHz. This would suggest that it would provide a negligible benefit for harbour porpoises, which are relatively insensitive below 2 kHz but increasingly sensitive above this frequency.

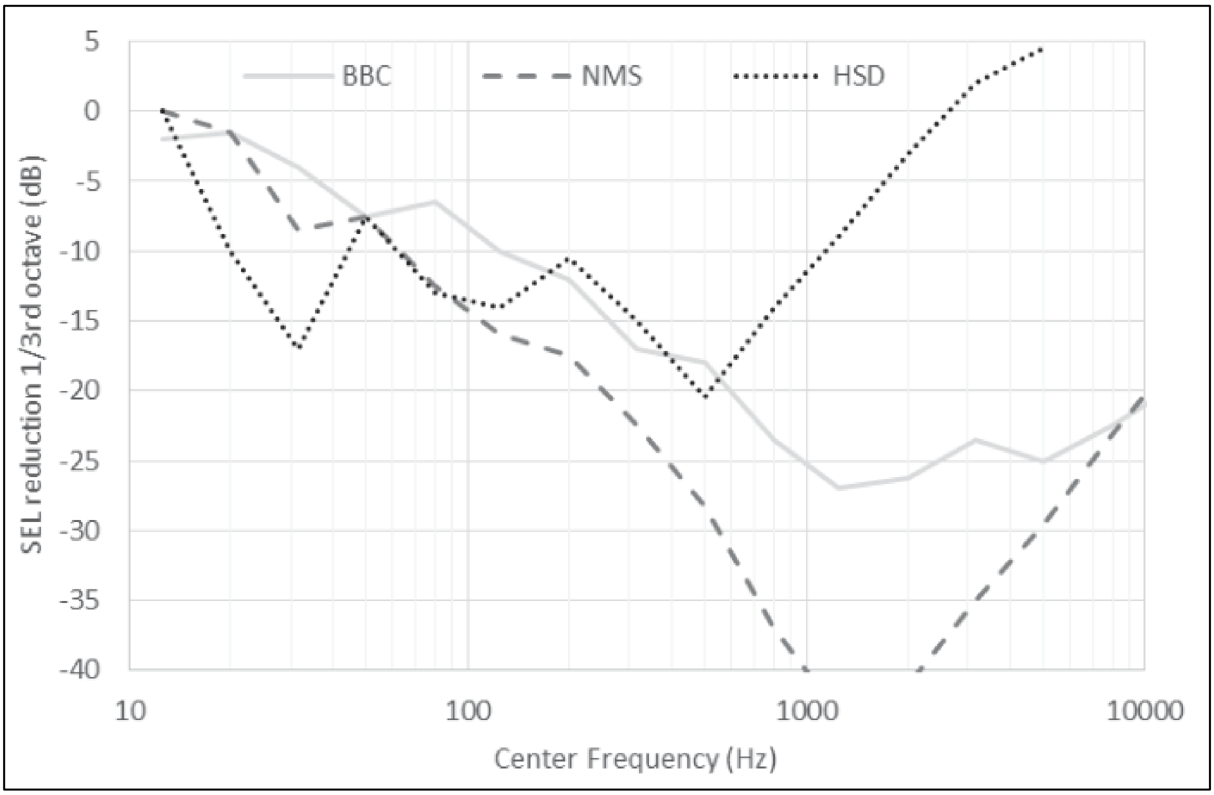

Figure B-1: Reduction of the 1/3rd octave band frequency spectrum of a pile strike when comparing mitigated versus unmitigated piling. The reduction achieved by a single BBC at OWF Borkum West II, NMS 6500 (several wind farms) and HSD at OWF Amrumbank West are shown. From Verfuss et al. (2019).

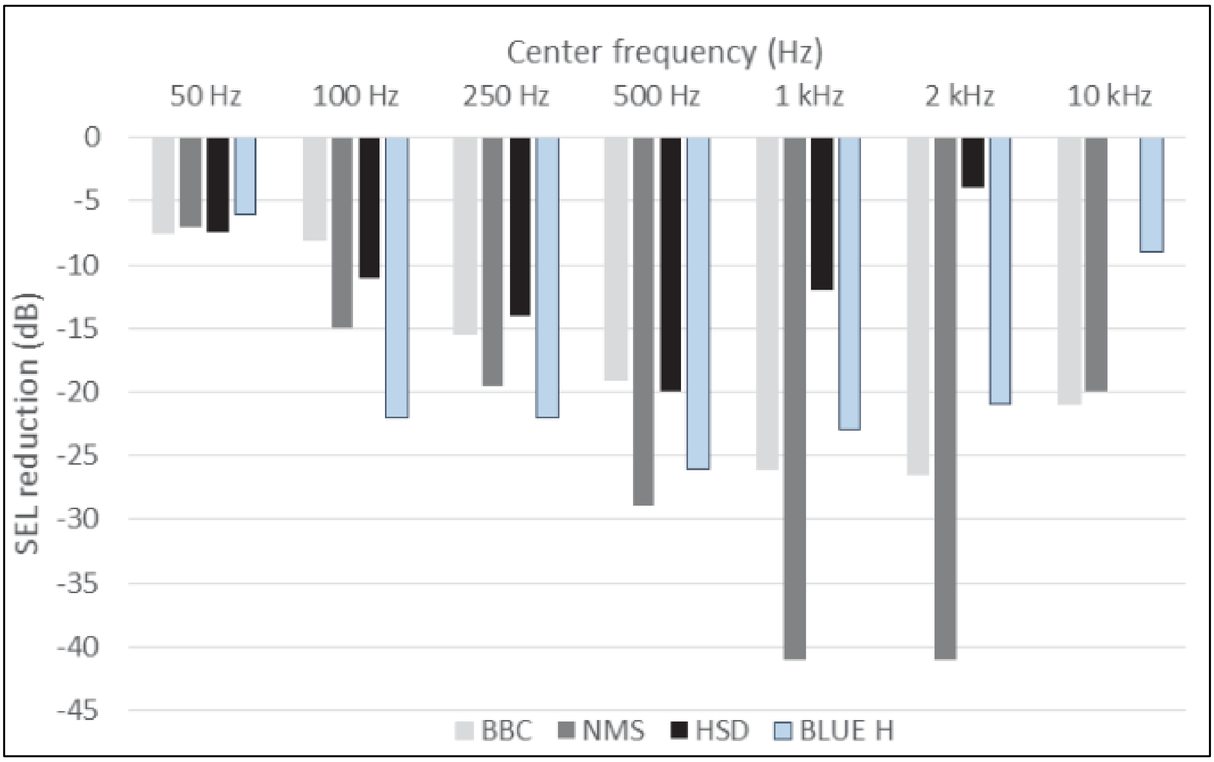

Figure B-2: Reduction in SEL at the frequencies 100 Hz, 250 Hz, 500 Hz, 1 kHz and 2 kHz in the 1/3rd octave band frequency spectrum of a pile strike when comparing mitigated versus unmitigated piling. From Verfuss et al. (2019).

The application of noise reduction in noise modelling discards the 'single figure' attenuations above and takes into account only the available frequency data for a NAS into a whole-system calculation. A particular device will effectively perform differently depending on which species is under consideration. Verfuss et al. (2019) only report frequency data up to 10 kHz but it can be seen in **Figure B-1** that (for example) the bubble curtain will perform above this frequency, which is important for harbour porpoise. Therefore, an extrapolation can be made in the modelling, and doing so gives an overall single-figure performance result in excess of the stated 7-11 dB reduction. However, as it is based on assumptions, it is recommended in modelling that this assumption is acknowledged, and a 'safe' value is also included in the modelling based only on the known values.

For all underwater noise modelling applications used by Subacoustech, including INSPIRE (Impulse Noise Sound Propagation and Impact Range Estimator), a NAS can be built into the model to estimate its effect on impact ranges, provided that sufficient frequency data is available for the performance of the system.

It must be noted that the NAS operate in a highly complex natural system, which modelling can only approximate. The environmental conditions, including water depth and current, will affect the performance of a device and so the modelling will always be based on best available data. The actual performance is likely to vary on site and will be less effective when operated out-with the devices' optimum operating conditions.

Noise reduction from bubble curtains

In order to assess the effect of using bubble curtains, dB reductions have been included with the predicted source levels from piling. Two types of bubble curtain mitigation have been considered: the BBC and DBBC.

Table B-2 and **Table B-3** summarise the decibel reductions for the use of bubble curtains as unweighted broadband noise and weighted noise from Southall et al. (2019). These attenuations are based on detailed 1/3rd octave band data as provided by itap from the Bay State prognosis report, and appropriate frequency spectra for pile strikes. This also takes water depth into account.

Estimates have had to be made for the reductions at high frequencies above 16 kHz and these have been done using conservative estimates, with attenuations progressively reducing above this frequency. As bubble curtains are in general considered more effective at high frequency, this means reductions in noise, especially for marine mammal-weighted values, may be greater in practice.

Table B-2: Summary of the dB reductions used for modelling assuming use of a BBC for MDS parameters.

BBC	Unweighted	LF	HF	VHF	PCW
NW (Monopile)	- 8.8 dB	- 9.6 dB	- 15.7 dB	- 13.3 dB	- 13.1 dB
NW (Pin Pile)	- 9.7 dB	- 10.9 dB	- 16.2 dB	- 15.5 dB	- 13.0 dB

Table B-3: Summary of the dB reductions used for modelling assuming use of a DBBC for MDS parameters.

DBBC	Unweighted	LF	HF	VHF	PCW
NW (Monopile)	- 10.8 dB	- 11.6 dB	- 17.7 dB	- 15.3 dB	- 15.1 dB
NW (Pin Pile)	- 11.7 dB	- 12.9 dB	- 18.2 dB	- 17.5 dB	- 15.0 dB

Summary of modelling results

Presented below are tables of modelled impact ranges for the NW model location, assuming the use of the two types of bubble curtain (BBC and DBBC). Results are given for marine mammals using Southall *et al*. (2019) thresholds (unweighted SPL_{peak} and weighted SEL_{cum} (fleeing)).

As with the modelling in the ES, for all the results given, impact ranges calculated to be less than 50 m for single strike criteria and 100 m for cumulative criteria have not been included due to the uncertainty in the accuracy of the results at such close range. In this case, the ranges are given as "<50 m" or "< 100 m," indicating that the impact range will be closer to the pile than this distance. Also shown are the equivalent non-mitigated noise levels for easy comparison.

The modelling with the two types of bubble curtains shows significant reductions in both SPL_{peak} and SEL_{cum} PTS-onset ranges[4]. In summary:

- MDS monopile maximum instantaneous PTS-onset impact range for harbour porpoise reduces from 2.9 km with no mitigation to 0.64 km with a BBC and 0.45 km with a DBBC (**Table B-4**);
- MDS pin pile maximum instantaneous PTS-onset impact range for harbour porpoise reduces from 2.1 km with no mitigation to 0.38 km with a BBC and 0.26 km with a DBBC (**Table B-5**);
- MDS monopile maximum cumulative PTS-onset impact range for minke whale reduces from 6.8 km with no mitigation to <100 m with a BBC or a DBBC (**Table B-6**);
- MDS pin pile maximum cumulative PTS-onset impact range for harbour porpoise reduces from 8.7 km with no mitigation to <100 m with a BBC or a DBBC (**Table B-7**); and
- MDS pin pile maximum cumulative PTS-onset impact range for minke whale reduces from 5.7 km with no mitigation to <100 m with a BBC or a DBBC (**Table B-7**).

Table B-4: Unweighted SPL_{peak} impact ranges for PTS-onset in marine mammals using the criteria from Southall et al. (2019), installing a monopile at the NW location with reduction comparisons for two types of bubble curtain mitigation.

NW Monopile MDS (5,000 kJ)					
Unweighted SPL_{peak}		LF	HF	VHF	PCW
		219 dB	230 dB	202 dB	218 dB
No Mit.	Area (km²)	0.06	< 0.01	25	0.09
	Max range (m)	140	< 50	2900	170
	Min range (m)	140	< 50	2800	170
	Mean range (m)	140	< 50	2800	170
BBC	Area (km²)	< 0.01	< 0.01	1.3	< 0.01
	Max range (m)	< 50	< 50	640	< 50
	Min range (m)	< 50	< 50	640	< 50
	Mean range (m)	< 50	< 50	640	< 50
DBBC	Area (km²)	< 0.01	< 0.01	0.62	< 0.01
	Max range (m)	< 50	< 50	450	< 50
	Min range (m)	< 50	< 50	440	< 50
	Mean range (m)	< 50	< 50	450	< 50

[4] Please note that the unmitigated distances relate to the PEIR NW location modelling (not the ES NW location modelling as presented in **Volume A4, Annex 4.5: Subsea Noise Technical Report**). Further details are presented in the Introduction section of this note.

Table B-5: Unweighted SPL_{peak} impact ranges for PTS-onset in marine mammals using the criteria from Southall et al. (2019), installing pin piles at the NW location with reduction comparisons using two types of bubble curtain mitigation.

NW Pin Pile MDS (3,000 kJ)					
Unweighted SPL_{peak}		LF	HF	VHF	PCW
		219 dB	230 dB	202 dB	218 dB
No Mit.	Area (km^2)	0.03	< 0.01	13	0.04
	Max range (m)	100	< 50	2100	120
	Min range (m)	100	< 50	2100	120
	Mean range (m)	100	< 50	2100	120
BBC	Area (km^2)	< 0.01	< 0.01	0.45	< 0.01
	Max range (m)	< 50	< 50	380	< 50
	Min range (m)	< 50	< 50	380	< 50
	Mean range (m)	< 50	< 50	380	< 50
DBBC	Area (km^2)	< 0.01	< 0.01	0.21	< 0.01
	Max range (m)	< 50	< 50	260	< 50
	Min range (m)	< 50	< 50	260	< 50
	Mean range (m)	< 50	< 50	260	< 50

Table B-6: Weighted SEL_{cum} impact ranges for PTS-onset in fleeing marine mammals using the impulsive criteria from Southall et al. (2019), installing a monopile at the NW location with reduction comparisons using two types of bubble curtain mitigation.

NW Monopile MDS (5,000 kJ)					
Weighted SEL_{cum} (Impulsive)		LF (3.25 ms^{-1})	HF (1.5 ms^{-1})	VHF (1.5 ms^{-1})	PCW (1.5 ms^{-1})
		183 dB	185 dB	155 dB	185 dB
No Mit.	Area (km^2)	67	< 0.01	< 0.01	< 0.01
	Max range (m)	6800	< 100	< 100	< 100
	Min range (m)	3700	< 100	< 100	< 100
	Mean range (m)	4600	< 100	< 100	< 100
BBC	Area (km^2)	< 0.01	< 0.01	< 0.01	< 0.01
	Max range (m)	< 100	< 100	< 100	< 100
	Min range (m)	< 100	< 100	< 100	< 100
	Mean range (m)	< 100	< 100	< 100	< 100
DBBC	Area (km^2)	< 0.01	< 0.01	< 0.01	< 0.01
	Max range (m)	< 100	< 100	< 100	< 100
	Min range (m)	< 100	< 100	< 100	< 100
	Mean range (m)	< 100	< 100	< 100	< 100

Table B-7: Weighted SEL_{cum} impact ranges for PTS-onset in fleeing marine mammals using the impulsive criteria from Southall et al. (2019), installing pin piles at the NW location with reduction comparisons using two types of bubble curtain mitigation.

		NW Pin Pile MDS (3,000 kJ)			
Weighted SEL_{cum} (Impulsive)		LF (3.25 ms^{-1})	HF (1.5 ms^{-1})	VHF (1.5 ms^{-1})	PCW (1.5 ms^{-1})
		183 dB	185 dB	155 dB	185 dB
No Mit.	Area (km^2)	43	< 0.01	160	< 0.01
	Max range (m)	5700	< 100	8700	< 100
	Min range (m)	2900	< 100	6500	< 100
	Mean range (m)	3600	< 100	7200	< 100
BBC	Area (km^2)	< 0.01	< 0.01	< 0.01	< 0.01
	Max range (m)	< 100	< 100	< 100	< 100
	Min range (m)	< 100	< 100	< 100	< 100
	Mean range (m)	< 100	< 100	< 100	< 100
DBBC	Area (km^2)	< 0.01	< 0.01	< 0.01	< 0.01
	Max range (m)	< 100	< 100	< 100	< 100
	Min range (m)	< 100	< 100	< 100	< 100
	Mean range (m)	< 100	< 100	< 100	< 100

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