Salamander Offshore Wind Farm

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SALAMANDER

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Salamander Floating Offshore Wind Farm: Underwater Noise Assessment

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Units

Unit	Definition
dB	Decibel (sound pressure)
GW	Gigawatt (power)
Hz	Hertz (frequency)
kg	Kilogram (mass)
kJ	Kilojoule (energy)
kHz	Kilohertz (frequency)
km	Kilometre (distance)
km^2	Square kilometres (area)
m	Metre (distance)
mm/s	Millimetres per second (particle velocity)
m/s	Metres per second (speed)
MW	Megawatt (power)
Pa	Pascal (pressure)
Pa^2s	Pascal squared seconds (acoustic energy)
µPa	Micropascal (pressure)

Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10\log_{10}(actual/reference)$ where $(actual/reference)$ is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}(actual\ pressure/reference\ pressure)$. The standard reference for underwater sound is 1 micro pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum})	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 µPa for water and 20 µPa for air.
Sound Pressure Level Peak (SPL_{peak})	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same level of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
Unweighted sound level	Sound levels which are "raw" or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a "weighting envelope" in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans in air, or the filters used by Southall *et al*. (2019) for marine mammals.

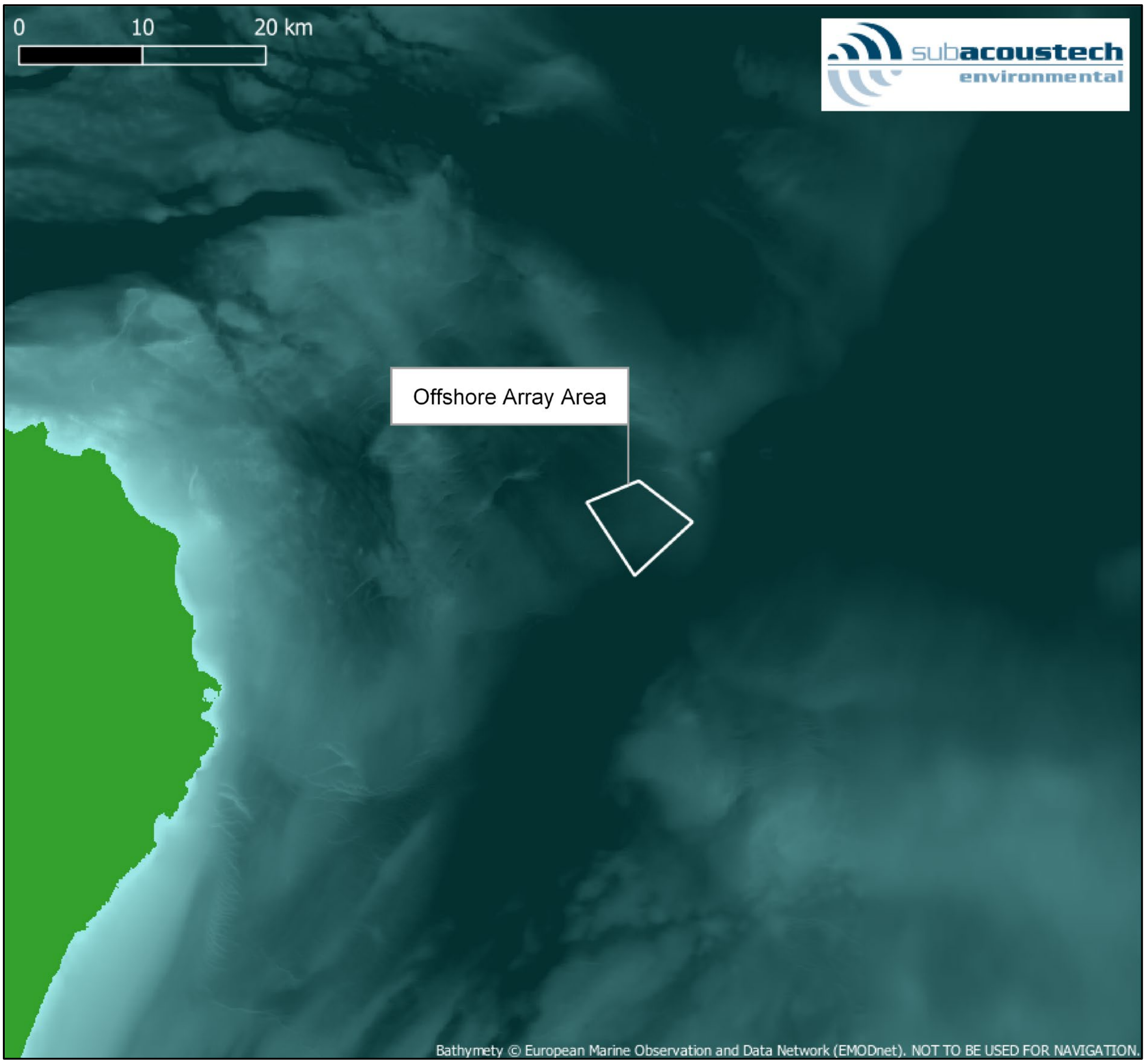
Acronyms

Acronym	Definition
ADD	Acoustic Deterrent Device
BGS	British Geological Survey
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
FPSO	Floating Production Storage and Offloading
GIS	Geographic Information System
HE	High Explosive
HF	High-Frequency Cetaceans (Marine mammal hearing group from Southall *et al.*, 2019)
INSPIRE	Impulse Noise Sound Propagation and Range Estimator (Subacoustech Environmental's noise model for estimating impact piling noise)
LF	Low-Frequency Cetaceans (Marine mammal hearing group from Southall *et al.*, 2019)
MTD	Marine Technology Directorate
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
PCW	Phocid Carnivores in Water (Marine mammal hearing group from Southall *et al.*, 2019)
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SNH	Scottish Natural Heritage (now NatureScot)
SPL	Sound Pressure Level
SPL_{peak}	Peak Sound Pressure Level
$SPL_{peak\text{-}to\text{-}peak}$	Peak-to-peak Sound Pressure Level
SPL_{RMS}	Root Mean Square Sound Pressure Level
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans (Marine mammal hearing group from Southall *et al.*, 2019)
WTG	Wind Turbine Generator

1 Introduction

The Salamander Offshore Wind Farm ("the Salamander Project") is a proposed floating wind farm development located approximately 35 km off the coast of Aberdeenshire, Scotland. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd. have undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish at the site.

The Salamander Offshore Array Area covers an area of approximately 33 km^2 and the project will deploy up to seven Wind Turbine Generators (WTGs). The location of the Offshore Array Area is shown in Figure 1-1.



Bathymety © European Marine Observation and Data Network (EMODnet). NOT TO BE USED FOR NAVIGATION.

Figure 1-1 Overview map showing the Salamander Offshore Array Area and the surrounding bathymetry and nearby Aberdeenshire coastline

This Annex presents a detailed assessment of the potential underwater noise during construction and operation of the Salamander Project, and includes the following:

- Background information covering the units for measuring and assessing underwater noise and a review of the underwater noise metrics and criteria used to assess the possible environmental effect in marine receptors (section 2);
- Discussion of the modelling approach, input parameters and assumptions of the detailed noise modelling undertaken (section 3);
- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to its effect on marine mammals and fish (section 4);
- Noise modelling of the other noise sources expected during the construction and operation of the Salamander Project including cable laying, dredging, rock placement, trenching, vessel movements, operational WTG noise and unexploded ordnance (UXO) clearance (section 5); and
- Summary and conclusions (section 6).

Additional modelling results are presented in Appendix A.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air.

It should be noted that stated underwater noise levels should not be confused with noise levels in air, which use a different scale.

2.1.1 Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because, rather than equal increments of sound having an equal increase in effect, typically each doubling of sound level will cause a roughly equal increase of "loudness."

Any quantity expressed in this scale is termed a "level." If the unit is sound pressure, expressed on the dB scale, it will be termed a "sound pressure level."

The fundamental definition of the dB scale is given by:

$$Level = 10 \times \log_{10}\left(\frac{Q}{Q_{ref}}\right)$$

where Q is the quantity being expressed on the scale, and Q_{ref} is the reference quantity.

The dB scale represents a ratio. It is therefore used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale so that any level quoted is positive. For example, a reference quantity of 20 μPa is used for sound in air since that is the lower threshold of human hearing.

When used with sound pressure, the pressure value is squared. So that variations in the units agree, the sound pressure must be specified as units of Root Mean Square (RMS) pressure squared. This is equivalent to expressing the sound as:

$$Sound\ pressure\ level = 20 \times \log_{10}\left(\frac{P_{RMS}}{P_{ref}}\right)$$

For underwater sound, a unit of 1 μPa is typically used as the reference unit (P_{ref}); a Pascal is equal to the pressure exerted by one Newton over one square metre, on micropascal equals one millionth of this.

2.1.2 Sound Pressure Level (SPL)

The Sound Pressure Level (SPL) is normally used to characterise noise and vibration of a continuous nature, such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific period to determine the RMS level of the time-varying sound. The SPL can therefore be considered a measure of the average unweighted level of sound over the measurement period.

Where SPL is used to characterise transient pressure waves, such as that from impact piling, seismic airgun or underwater blasting, it is critical that the period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean averaged over one second. Often, transient sounds such as these are quantified using "peak" SPLs or Sound Exposure Levels (SELs).

Unless otherwise defined, all SPL noise levels in this Annex are referenced to 1 µPa.

2.1.3 Peak Sound Pressure Level (SPL_{peak})

Peak SPLs are often used to characterise transient sound from impulsive sources, such as percussive impact piling. SPL_{peak} is calculated using the maximum variation of the pressure from positive to zero within the wave. This represents the maximum change in positive pressure (differential pressure from positive to zero) as the transient pressure wave propagates.

A further variation of this is the peak-to-peak SPL ($SPL_{peak\text{-}to\text{-}peak}$) where the maximum variation of the pressure from positive to negative is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the peak level, or 6 dB higher (see section 2).

2.1.4 Sound Exposure Level (SEL)

When considering the noise from transient sources, the issue of the duration of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b, 1955), and later by Rawlins (1987), to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing injury ranges for fish and marine mammals from various noise sources (Popper *et al.*, 2014; Southall *et al.*, 2019).

The SEL sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound and the duration it is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_{0}^{T} p^2(t)dt$$

where p is the acoustic pressure in Pascals, T is the total duration of sound in seconds, and t is time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa^2s).

To press the SE on a logarithmic scale by means of a dB, it must be compared with a reference acoustic energy (${p^2}_{ref}$) and a reference time (T_{ref}). The SEL is then defined by:

$$SEL = 10 \times \log_{10}\left(\frac{\int_0^T p^2(t)dt}{{p^2}_{ref}T_{ref}}\right)$$

By using a common reference pressure (p_{ref}) of 1µPa for assessments of underwater noise, the SEL and SPL can be compared using the expression:

$$SEL = SPL + 10 \times \log_{10} T$$

where the SPL is a measure of the average level of broadband noise and the SEL sums the cumulative broadband noise energy.

This means that, for continuous sounds of less than one second, the SEL will be lower than the SPL. For periods greater than one second, the SEL will be numerically greater than the SPL (i.e., for a continuous sound of 10 seconds duration, the SEL will be 10 dB higher than the SPL; for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL, and so on).

Where a single impulse noise such as the soundwave from a pile strike is considered in isolation, this can be represented by a “single strike” SEL or SEL_{ss}. A cumulative SEL, or SEL_{cum}, accounts for the exposure from multiple impulse or pile strikes over time, where the number of impulses replaces the T in the equation above, leading to:

$$SEL_{cum} = SEL + 10 \times \log_{10} X$$

Where SEL is the sound exposure level of one impulse and X is the total number of impulses or strikes.

Unless otherwise defined, all SEL noise levels in this Annex are referenced to 1 μPa^{2}s.

2.2 Analysis of environmental effects

Over the last 20 years it has become increasingly evident that noise from human activities in and around underwater environments can have an impact on the marine species in the area. The extent to which intense underwater sound might cause adverse impacts in species is dependent upon the incident sound level, source frequency, duration of exposure, and/or repetition rate of an impulsive sound (see, for example, Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic species has increased. Studies are primarily based on evidence from high level sources of underwater noise such as blasting or impact piling, as these sources are likely to have the greatest immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

The impacts of underwater sound on marine species can be broadly summarised as follows:

- Physical traumatic injury and fatality;
- Auditory injury (either permanent or temporary); and
- Disturbance.

The following sections discuss the underwater noise criteria used in this study with respect to species of marine mammals and fish that may be present around the Salamander Project.

The main metrics and criteria that have been used in this study to aid assessment of environmental effects come from two key papers covering underwater noise and its effects:

- Southall *et al*. (2019) marine mammal exposure criteria; and
- Popper *et al*. (2014) sound exposure guidelines for fishes and sea turtles.

At the time of writing these include the most up-to-date and authoritative criteria for assessing environmental effects for use in impact assessments.

2.2.1 Marine mammals

The Southall *et al*. (2019) paper is effectively an update of the previous Southall *et al*. (2007) paper and provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals (although it names marine mammal categories slightly differently).

The Southall *et al*. (2019) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor in question. The hearing groups given by Southall *et al*. (2019) are summarised in Table 2-1 and Figure 2-1. Further groups for sirenians and other marine carnivores in water are given, but these have not been included in this study as those species are not commonly found in the waters in the North Sea around Scotland.

Table 2-1 Marine mammal hearing groups (from Southall et al., 2019)

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoise)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seals)

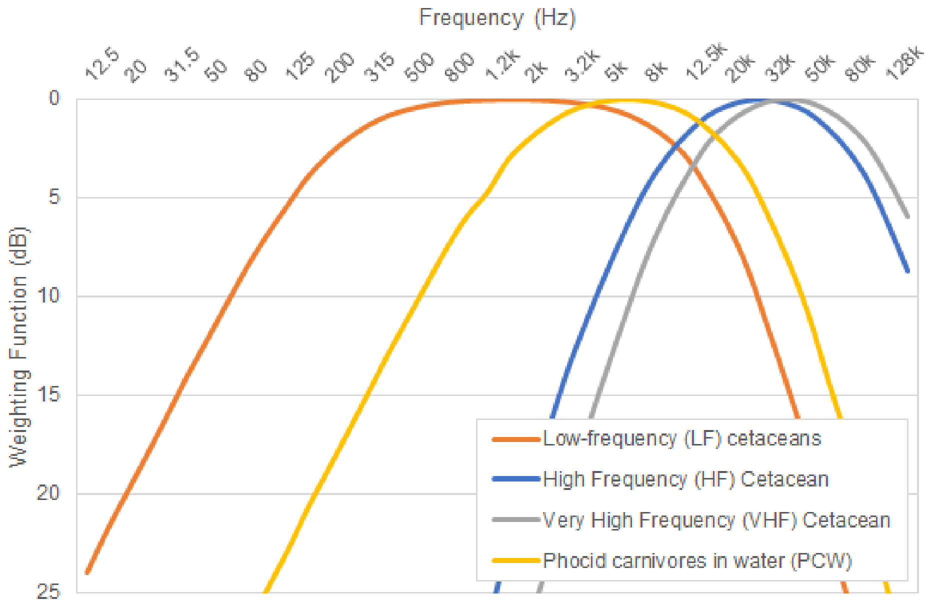


Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HD), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

Southall *et al*. (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall *et al*. (2019) categorises impulsive noises as having high peak sound pressure, short duration, fast rise-time and broad frequency content at source, and non-impulsive sources as steady-state noise. Explosives, impact piling and seismic airguns are considered impulsive noise sources and sonars, vibro-piling, drilling and other low-level continuous noises are considered non-impulsive. A non-impulsive noise does not necessarily have to have a long duration.

Southall *et al*. (2019) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative weighted sound exposure criteria (SEL_{cum}, i.e., can include the accumulated exposure of multiple pulses) for both permanent threshold shift (PTS), where unrecoverable (but incremental) hearing damage may occur, and temporary threshold shift (TTS), where a temporary reduction in hearing sensitivity may occur in individual receptors. These dual criteria (SPL_{peak} and SEL_{cum}) are only used for impulsive noise: the criteria set giving the greatest calculated range is typically used as the relevant impact range.

As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise time and high peak sound pressure) and become more like a “non-pulse” at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate it. Although the situation is complex, the paper reported that most of the signals crossed their threshold for rapid rise time and high peak sound pressure characteristics associated with impulsive noise at around 3.5 km from the source. Southall (2021) discusses this further and suggests that the impulsive characteristics can correspond with significant energy content of the pulse above 10 kHz. This will naturally change depending on the noise source and the environment over which it travels.

Research by Martin *et al*. (2020) casts doubt on these findings, showing that noise in this category should be considered impulsive as long as it is above effective quiet, or a noise sufficiently low enough that it does not contribute significantly to any auditory impairment or injury. To provide as much detail as possible, both impulsive and non-impulsive criteria from Southall *et al*. (2019) have been included in this study.

Although the use of impact ranges derived using the impulsive criteria are recommended for all but the clearly non-impulsive sources (such as drilling), it should be recognised that where calculated ranges are beyond 3.5 km, they would be expected to become increasingly less impulsive and harmful, and the impact range is therefore likely to be somewhere between the modelled impulsive and non-impulsive impact range. Where the impulsive impact range is significantly greater than 3.5 km, the non-impulsive range should be considered.

Table 2-2 and Table 2-3 present the unweighted SPL_{peak} and weighted SEL_{cum} criteria for marine mammals from Southall *et al*. (2019) covering both impulsive and non-impulsive noise.

Table 2-2 Single strike SPL_{peak} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

Southall *et al.* (2019)	**Unweighted SPL_{peak} (dB re 1 µPa)**	
	Impulsive	
	PTS	**TTS**
Low-frequency cetaceans (LF)	219	213
High-frequency cetaceans (HF)	230	224
Very high-frequency cetaceans (VHF)	202	196
Phocid carnivores in water (PCW)	218	212

Table 2-3 Impulsive and non-impulsive SEL_{cum} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

Southall *et al.* (2019)	**Weighted SEL_{cum} (dB re 1 µPa^{2}s)**			
	Impulsive		**Non-impulsive**	
	PTS	**TTS**	**PTS**	**TTS**
Low-frequency cetaceans (LF)	183	168	199	179
High-frequency cetaceans (HF)	185	170	198	178
Very high-frequency cetaceans (VHF)	155	140	173	153
Phocid carnivores in water (PCW)	185	170	201	181

Where SEL_{cum} thresholds are required for marine mammals, a fleeing animal model has been used. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. For this, the following flee speeds have been used for each marine mammal group:

- 2.1 m/s for low-frequency cetaceans (LF) (Scottish Natural Heritage (SNH), 2016);
- 1.52 m/s for high-frequency cetaceans (HF) (Bailey and Thompson, 2006);
- 1.4 m/s for very high-frequency cetaceans (VHF) (SNH, 2016); and
- 1.8 m/s for phocid carnivores in water (PCW) (SNH, 2016).

These are considered worst case assumptions as marine mammals are expected to swim much faster under stress conditions (Kastelein *et al*., 2018), especially at the start of any noisy process when the receptor will be closest to the noise source.

2.2.2 Fish and other megafauna

The large number of, and variation in, fish species leads to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas previous studies applied broad criteria based on limited studies of fish that are not present in UK waters (e.g., McCauley *et al*., 2000) or measurement data not intended to be used as criteria (Hawkins *et al*., 2014), the publication of Popper *et al*. (2014) provides an authoritative summary of the latest research and guidelines for fish exposure to sound and uses categories for fish that are representative of the species present in UK waters.

The Popper *et al*. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; groups for sea turtles and fish eggs and larvae are also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources. (It is recognised that these are related to sound pressure, whereas more recent documents (e.g., Popper and Hawkins, 2019) clearly state that many fish species are most sensitive to particle motion. This is discussed in section 2.2.2.1.)

For this study, criteria for impact piling, continuous noise sources, and explosions have been considered; these are summarised in Table 2-4 to Table 2-6.

Table 2-4 Criteria for mortality and potential mortal injury, recoverable injury, and TTS in species of fish from impact piling noise (Popper et al., 2014)

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	> 219 dB SEL_{cum} > 213 dB SPL_{peak}	> 216 dB SEL_{cum} > 213 dB SPL_{peak}	>> 186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	> 186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	186 dB SEL_{cum}
Sea turtles	> 210 dB SEL_{cum} > 207 dB SPL_{peak}	See Table 2-7	
Eggs and larvae	> 210 dB SEL_{cum} > 207 dB SPL_{peak}		

Table 2-5 Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper et al., 2014)

Type of animal	Impairment	
	Recoverable injury	TTS
Fish: swim bladder involved in hearing	170 dB SPL_{RMS} for 48 hrs	158 dB SPL_{RMS} for 12 hours

Table 2-6 Criteria for potential mortal injury in species of fish from explosions (Popper et al., 2014)

Type of animal	Mortality and potential mortal injury
Fish: no swim bladder	229 – 234 dB SPL_{peak}
Fish: swim bladder is not involved in hearing	229 – 234 dB SPL_{peak}
Fish: swim bladder involved in hearing	229 – 234 dB SPL_{peak}
Sea turtles	229 – 234 dB SPL_{peak}
Eggs and larvae	> 13 mm/s peak velocity

Where insufficient data are available, Popper *et al*. (2014) also gives qualitative criteria that summarise the effect of the noise as having either a high, moderate, or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 2-7 to Table 2-9.

Table 2-7 Summary of the qualitative effects on species of fish from impact piling noise (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 2-4		(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing			(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing			(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 2-8 Summary of the qualitative effects on fish from continuous noise from Popper et al. (2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	**Mortality and potential mortal injury**	**Impairment**			**Behaviour**
		Recoverable injury	**TTS**	**Masking**	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	See Table 2-5		(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Table 2-9 Summary of the qualitative effects on species of fish from explosions (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	**Impairment**			**Behaviour**
	Recoverable injury	**TTS**	**Masking**	
Fish: no swim bladder	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) High (F) Low
Fish: swim bladder involved in hearing	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Sea turtles	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Eggs and larvae	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

Both fleeing animal and stationary animal models have been used to cover the SEL_{cum} criteria for fish. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild, and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al.*, 2015; Popper *et al.*, 2014), some may seek protection in the sediment and others may dive deeper in the water column. For those species that flee, the speed chosen for this study of 1.5 m/s is relatively slow in relation to data from Hirata (1999) and thus is considered somewhat conservative.

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species or species without a swim bladder; these are the least sensitive species. Popper *et al*. (2014) states species without a swim bladder are less likely to experience physical injury from noise exposure "There is evidence (e.g., Goertner *et al*., 1994; Stephenson *et al*., 2010; Halvorsen *et al*., 2012) that little or no damage occurs to fish without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish."

Stationary animal modelling has been included in this study, acknowledging other modelling for similar EIA projects. Basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, assuming that an individual would remain in the high noise level region of the water column for the whole duration of piling. This additional conservatism is additional to the precautionary nature of the parameters already built into the cumulative exposure calculations.

2.2.2.1 Particle motion

The criteria defined in the above section define the noise impacts on fishes in terms of sound pressure or sound pressure-associated functions (i.e., SEL). It has been identified by researchers (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al.,* 2012) that many species of fish, as well as invertebrates, actually detect particle motion rather than acoustic pressure. Particle motion describes the back-and-forth movement of a tiny theoretical 'element' of water, substrate or other media as a sound wave passes, rather than the pressure caused by the action of the force created by this movement. Particle motion is usually defined in reference to the velocity of the particle (often a peak particle velocity, PPV), but sometimes the related acceleration or displacement of the particle is used. Note that species in the "Fish: swim bladder involved in hearing" category, the species most sensitive to noise, are sensitive to sound pressure.

Popper and Hawkins (2018) state that in derivation of the sound pressure-based criteria in Popper *et al.* (2014) it may be the unmeasured particle motion detected by the fish, to which the fish were responding: there is a relationship between particle motion and sound pressure in a medium. This relationship is very difficult to define where the sound field is complex, such as close to the noise source or where there are multiple reflections of the sound wave in shallow water. Even these terms "shallow" and "close" do not have simple definitions.

The primary reason for the continuing use of sound pressure as the criteria, despite particle motion appearing to be the physical measure to which so many fish react or sense, is a lack of data (Popper and Hawkins, 2018) both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fish, to a particle motion value. There continue to be calls for additional research on the levels of and effects with respect to levels of particle motion. Until sufficient data are available to enable revised thresholds based on the particle motion metric, Popper and Hawkins (2019) states that "since there is an immediate need for updated criteria and guidelines on potential effects of anthropogenic sound on fishes, we recommend, as do our colleagues in Sweden (Andersson *et al*., 2017), that the criteria proposed by Popper *et al*. (2014) should be used".

3 Modelling methodology

To estimate the underwater noise levels likely to arise during the construction and operation of the Salamander Project, predictive noise modelling has been undertaken. The methods described in this section, and used within this Annex, meet the requirements set by the National Physical Laboratory (NPL) Good Practice Guide 133 for underwater noise measurement (Robinson *et al*., 2014).

Of those considered, the noise source most important to consider is impact piling to install anchors for the floating WTG substructures due to the noise level and duration it will be present (Bailey *et al*., 2014). As such, the noise related to impact piling activities is the primary focus of this study.

The modelling of impact piling has been undertaken using the INSPIRE underwater noise model. The INSPIRE model (currently version 5.2) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, based around a combined geometric and energy flow/hysteresis loss method, and measured data. It is designed to calculate the propagation of noise in shallow (i.e., less than 100 m), mixed water; typical of the conditions around the UK. The model has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring around offshore piling activities.

The model provides estimates of unweighted SPL_{peak}, SEL_{ss} and SEL_{cum} noise levels, as well as various other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every two degrees). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised as necessary. INSPIRE also produces these contours as GIS shapefiles.

INSPIRE considers a wide array of input parameters, including variations in bathymetry and source frequency to ensure accurate results are produced specific to the location and nature of the piling operation. It should also be noted that the results should be considered conservative as maximum design parameters and worst-case assumptions have been selected for:

- Piling hammer blow energies;
- Soft start, hammer energy ramp up, and strike rate;
- Total duration of piling; and
- Receptor swim speeds.

Simpler modelling approaches have been used for noise sources other than piling that may be present during the construction and operation of the Salamander Project; these are discussed in section 5.

3.1 Modelling confidence

INSPIRE is semi-empirical, as such, a validation process is inherently built into the development process. Whenever a new set of good, reliable, impact piling measurement data is gathered through offshore surveys it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted. Currently over 80 separate impact piling noise datasets from all around the UK have been used as part of the development for the latest version of INSPIRE, and in each case, an average fit is used.

In addition, INSPIRE is also validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties, for example Thompson *et al*. (2013).

The current version of INSPIRE (version 5.2) is the product of reanalysing all the impact piling noise in Subacoustech Environmental's measurement database and any other data available and crossreferencing it with blow energy data from piling logs. This gives a database of single strike noise levels referenced to a specific blow energy at a specific range and conditions.

Previous iterations of the INSPIRE model have endeavoured to give a worst-case estimate of underwater noise levels produced by various permutations of impact piling parameters. There is always some natural variability with underwater noise measurements, even when considering measurements of pile strikes under the same conditions (i.e., at the same blow energy, taken at the same range). For example, there can be variations in noise level of up to five or even 10 dB, as seen in Bailey *et al*. (2010) and the data shown in Figure 3-1. When modelling using the upper bounds of this range, in combination with other worst-case parameter selections, conservatism can be compounded to create excessively overcautious predictions, especially when calculating $\mathrm{SEL}_{\mathrm{cum}}$. With this in mind, the current version of INSPIRE attempts to calculate closer to the average fit of the measured noise levels at all ranges.

Figure 3-1 presents a small selection of the measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE v5.2, matching the pile size, blow energy and position of the measured data. These show the fit to the data, with the INSPIRE data points sitting, more or less, in the middle of the measured noise levels at each range. When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary.

The greatest deviations from the model tend to be at the greatest distances, where the influence on the $\mathrm{SEL}_{\mathrm{cum}}$ will be minimal.

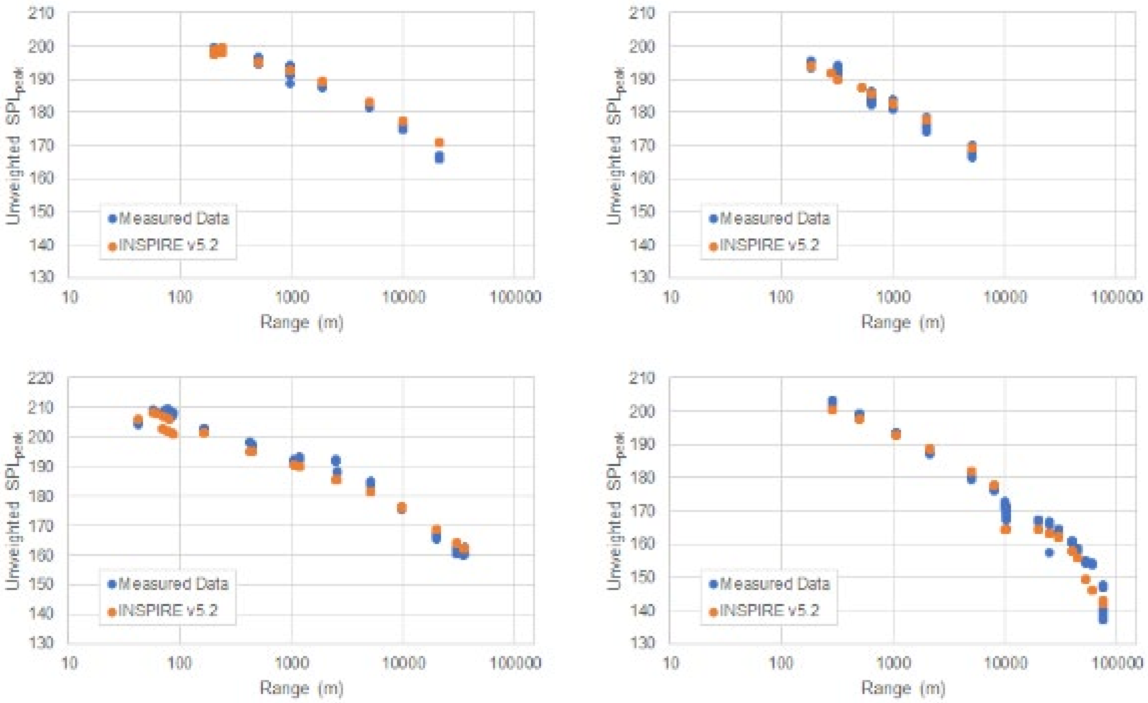


Figure 3-1 Comparison between example measured impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)[1]

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[1] Top Left: 6.0 m pile, off the Suffolk coast, North Sea, 2009; Top Right: 1.8 m pile, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3 m pile, off the North Welsh coast, 2012; Bottom Right: 6.0 m pile, off the coast of Cumbria, 2010.

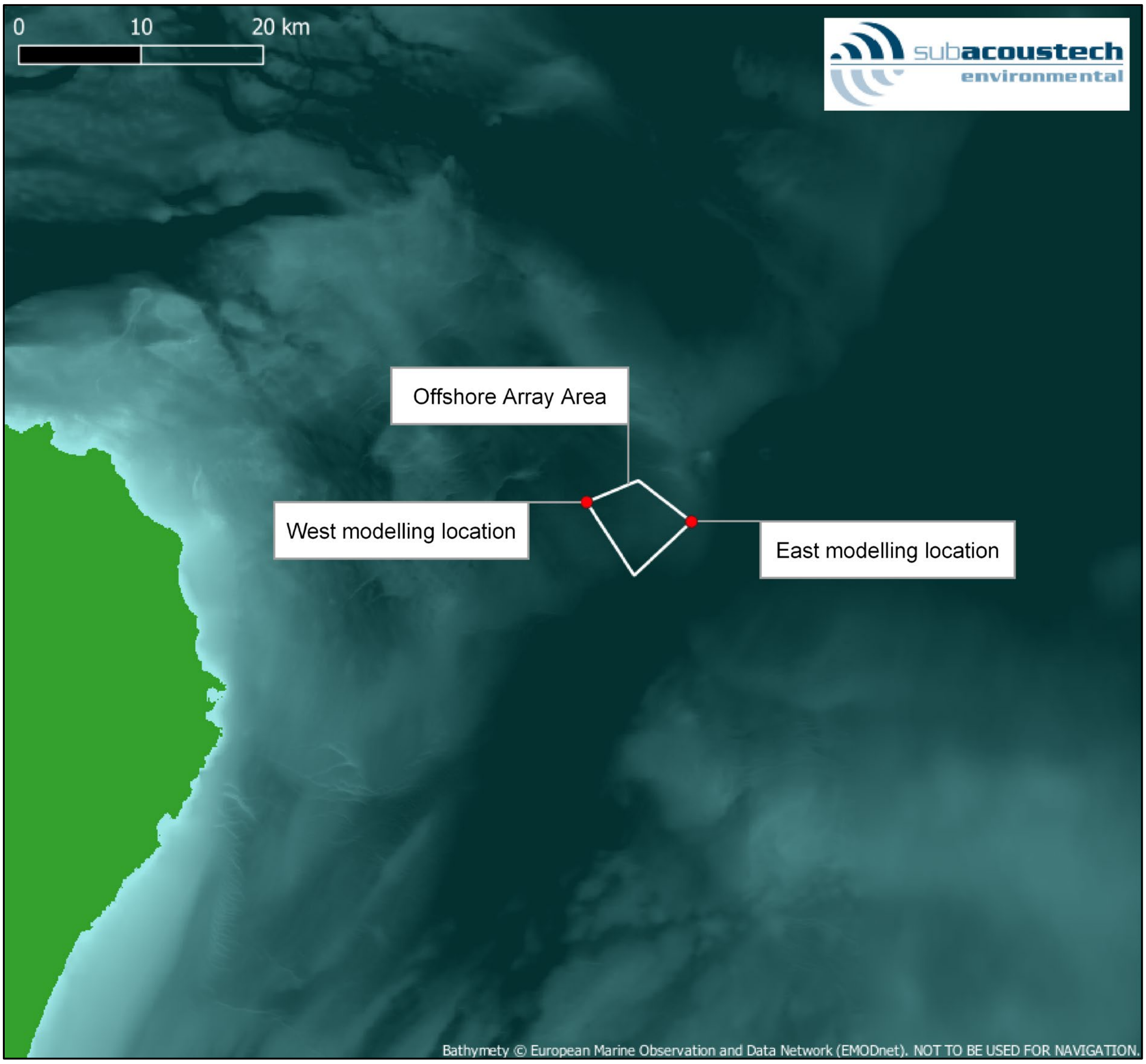
3.2 Modelling parameters

3.2.1 *Modelling locations*

Modelling for the anchor impact piling has been undertaken at two representative locations covering the east and west extents of the Salamander Offshore Array Area. These locations are summarised in Table 3-1 and illustrated in Figure 3-2.

Table 3-1 Summary of the underwater noise modelling locations used for this study

Modelling locations	East location	West location
Latitude	57.6156°N	57.6319°N
Longitude	01.1249°W	01.2678°W
Water depth	89.7 m	97.1 m



Bathymety © European Marine Observation and Data Network (EMODnet). NOT TO BE USED FOR NAVIGATION.

Figure 3-2 Approximate positions of the modelling locations at the Salamander Offshore Array Area

3.2.2 Impact piling parameters

Two anchor pile scenarios have been considered for this study, both considering a 3 m diameter pile: one installed with a maximum blow energy of 2,500 kJ, and one with a maximum blow energy of 1,500 kJ.

For $\mathrm{SEL_{cum}}$ criteria, the soft start and ramp up of blow energies, along with the total duration of piling and strike rate, must also be considered. These are summarised in Table 3-2 and Table 3-3. Both scenarios consider the same duration, strike rate and number of strikes, with Scenario 1 reaching maximum blow energy more quickly than Scenario 2.

In a 24-hour period it is expected that up to four anchor piles can be installed per vessel. Scenarios covering both a single anchor pile installation and multiple sequential anchor pile installations have been considered for this study.

Due to the length of the anchor piles and the deep water at the Array Area all impact piling will occur underwater with the hammer submerged. As the length of pile in the water gets shorter the radiating area of sound from the pile will reduce, which has been incorporated into the modelling calculations. At the end of each anchor pile installation the pile will stand 3 m proud of the seabed.

Table 3-2 Summary of the Scenario 1 soft start and ramp up scenario used for the anchor pile installation modelling

Anchor pile (Scenario 1)	**250 kJ**		**500 kJ**	**1,000 kJ**	**2,500 kJ**
No. of strikes	60	1,140	1,200	1,200	4,800
Duration	20 mins	38 mins	40 mins	40 mins	2 hours, 40 mins
Strike rate	3 blows/min	30 blows/min			
8,400 strikes over 4 hours 58 mins per pile / 33,600 strikes over 19 hours 52 mins for 4 piles					

Table 3-3 Summary of the Scenario 2 soft start and ramp up scenario used for the anchor pile installation modelling

Anchor pile (Scenario 2)	**150 kJ**		**300 kJ**	**600 kJ**	**1,500 kJ**
No. of strikes	60	2,040	2,100	2,100	2,100
Duration	20 mins	1 hour, 8 mins	1 hour, 10 mins	1 hour, 10 mins	1 hour, 10 mins
Strike rate	3 blows/min	30 blows/min			
8,400 strikes over 4 hours 58 mins per pile / 33,600 strikes over 19 hours 52 mins for 4 piles					

3.2.3 Apparent source levels

Noise modelling requires knowledge of a source level, which is the theoretical noise level at one metre from the noise source. It is worth noting that the ‘source level’ technically does not exist in the context of many shallow water (< 100 m) noise sources (Heaney *et al*., 2020). The noise level at one metre from the pile will be highly complex and vary up and down the water column by the pile, rather than being one simple noise level. In practice, for underwater noise modelling such as this, it is effectively an ‘apparent source level’ that is used, essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The INSPIRE model requires an apparent source level, which is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location to allow for the length of pile (and effective surface area) in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings.

The unweighted, single strike SPL_{peak} and SEL_{ss} apparent source levels estimated for this study are provided in Table 3-4. These figures are presented in accordance with typical requirements by regulatory authorities, although as indicated above they are not necessarily compatible or comparable with any other model or predicted apparent source level. In each case, the differences in apparent source level for each location within a scenario are minimal.

Table 3-4 Summary of the unweighted source levels used for modelling

Source levels	**Anchor pile** 3 m / 2,500 kJ	**Anchor pile** 3 m / 1,500 kJ
Unweighted SPL_{peak}	241.1 dB re 1 µPa @ 1 m	239.4 dB re 1 µPa @ 1 m
Unweighted SEL_{ss}	221.7 dB re 1 µPa^{2}s @ 1 m	219.7 dB re 1 µPa^{2}s @ 1 m

3.2.4 Environmental conditions

With the inclusion of measured noise propagation data for similar offshore piling operations in UK waters, the INSPIRE model intrinsically accounts for various environmental conditions. This includes the differences that can occur with the temperature and salinity of the water, as well as the sediment type surrounding the site. Data from the British Geological Survey (BGS) show that the seabed in and around the Salamander Project is generally made up of sand and muddy sand.

Digital bathymetry from the European Marine Observation and Data Network (EMODnet) has been used for this modelling. Mean tidal depth has been used throughout.

3.3 Cumulative SELs and fleeing receptors

Expanding on the information in section 2.2 regarding SEL_{cum} and the fleeing animal assumptions used for modelling, it is important to understand the meaning of the results presented in the following sections.

When an SEL_{cum} impact range is presented for a fleeing animal, this range can essentially be considered a starting position (at the commencement of piling) for the fleeing receptor. For example, if a receptor began to flee in a straight line from the noise source, starting at the position (distance from pile) denoted by a modelled PTS contour, the receptor would receive exactly the noise exposure as per the PTS criterion under consideration.

When considering a stationary receptor (i.e., one that stays at the same position throughout piling), calculating the SEL_{cum} is fairly straightforward: all the noise levels produced and received at a single point along a transect are aggregated to calculate the SEL_{cum}. If this calculated level is greater than the threshold being modelled, the model steps away from the noise source and the noise levels form that new location are aggregated to calculate a new SEL_{cum}. This continues outward until the threshold is met.

For a fleeing animal, the receptor's distance from the noise source while moving away also needs to be considered. To model this, a starting point close to the source is chosen and the received noise level for each noise event (e.g., pile strike) while the receptor is fleeing is noted. For example, if a noise event occurs every six seconds and an animal is fleeing at a rate of 1.5 ms^{-1}, it is 9 m further from the source after each noise pulse, resulting in a slightly reduced noise level each time. These values are then aggregated into an SEL_{cum} value over the entire operation. The faster an animal is fleeing the greater distance travelled between noise events. The impact range outputted by the model for this situation is the distance the receptor must be at the start of the operation to exactly meet the exposure threshold.

As an example, the graphs in Figure 3-3 and Figure 3-4 show the difference in the received SEL from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 ms^{-1}, using the anchor pile foundation Scenario 1 at the East location for a single pile installation.

The received SEL_{ss} from the stationary receptor, as illustrated in Figure 3-3, shows the noise level gradually increasing as the blow energy increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the noise source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. The reducing noise level as the pile is installed further into the ground can also been seen. As an example, for the first 50 minutes of piling, where the blow energy is 250 kJ, fleeing at a rate of 1.5 ms^{-1}, a receptor has the potential to move 5.2 km from the noise source. After the full 4 hours and 58 minutes, the receptor has the potential to be almost 27 km from the noise source.

Figure 3-4 shows the effect these different received levels have when calculating the SEL_{cum}. It clearly shows the difference in cumulative effect between the receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 210.8 dB re 1 μPa^2s. If the receptor were to remain stationary throughout the piling operation it would receive a cumulative level of 258.9 dB re 1 μPa^2s, whereas when fleeing at 1.5 ms^{-1} over the same scenario, a cumulative received level of just 211.2 dB re 1 μPa^2s is achieved.

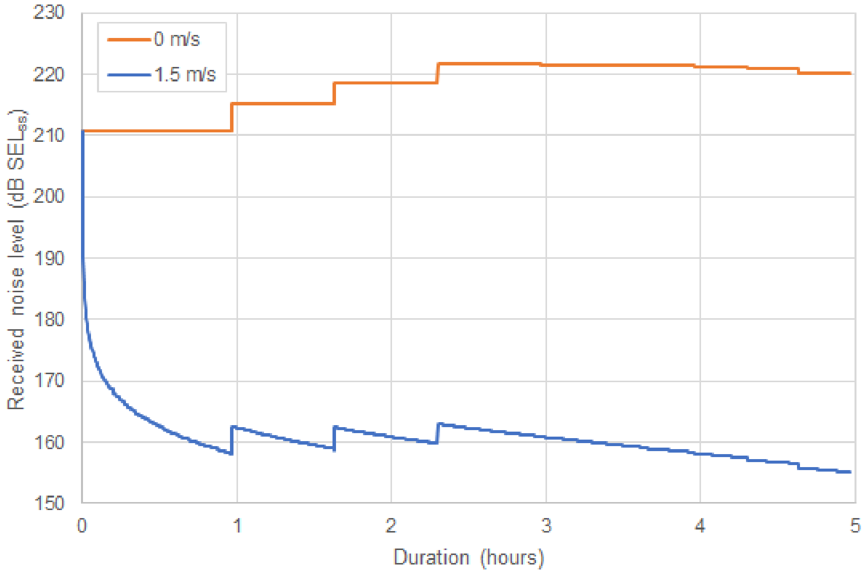


Figure 3-3 Received single-strike noise levels (SEL_{ss}) for receptors during the monopile foundation parameters, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

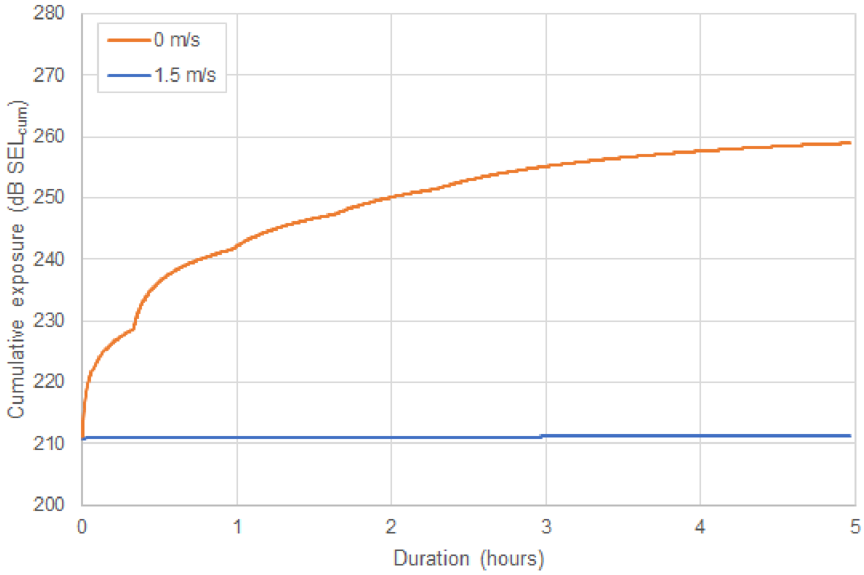


Figure 3-4 Cumulative received noise levels (SEL_{cum}) for receptors during monopile foundation parameters, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled value it would receive a noise exposure in excess of the criteria, and if the receptor were to start fleeing from a range further than the modelled value it would receive a noise exposure below the criteria. This is illustrated in Figure 3-5.

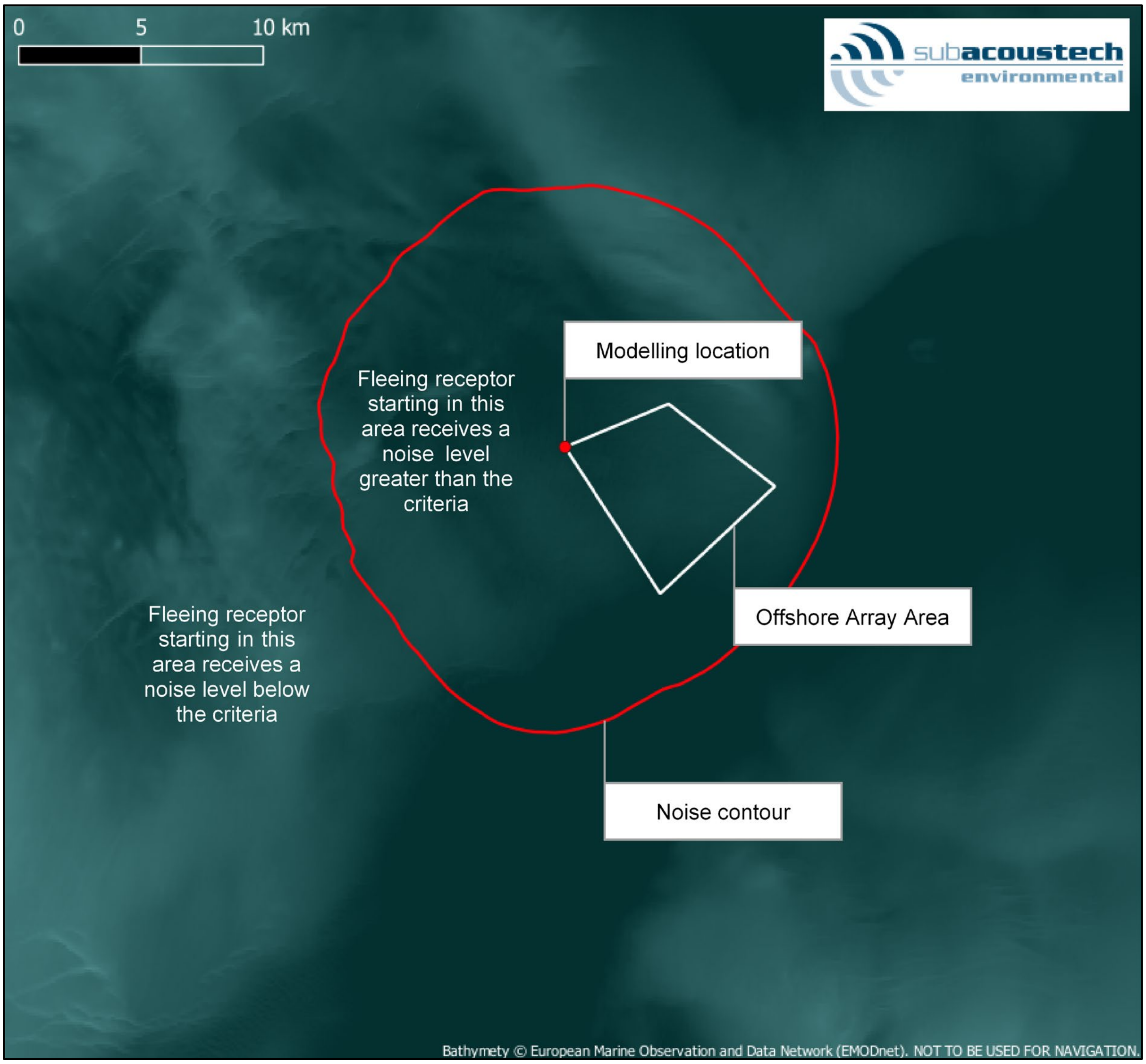


Figure 3-5 Plot showing a fleeing animal SEL_{cum} criteria contour and the areas where the cumulative noise exposure will exceed the impact criteria

3.3.1 *The effects of input parameters on SELs and fleeing receptors*

As discussed in section 3.2.2, parameters such as bathymetry, hammer blow energies, piling ramp up, strike rate and duration all have an effect on predicted noise levels. When considered SEL_{cum} and a fleeing animal model, some of these parameters can have a greater influence than others.

Parameters like hammer blow energy can have a clear effect on impact ranges, with higher energies resulting in higher source noise levels and therefore larger impact ranges. When considering cumulative noise levels, these higher levels are compounded sometimes thousands of times due to the number of pile strikes. With this in mind, the ramp up from low blow energies to higher ones requires careful consideration for fleeing animals, as the levels while the receptors are relatively close to the noise source will have a greater effect on the overall cumulative exposure level.

Linked to the effect of the ramp up is the strike rate, as the more pile strikes that occur while the receptor is close to the noise source, the greater the exposure and the greater effect it will have on the SEL_{cum}.

The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to greater exposure.

In general, the greatest impacts are found when a receptor is close to the noise source. For example, if high blow energies or a fast strike rate are used at the start of the piling activities, bigger increases in impact ranges will occur.

The other main element that can cause big differences in calculated impact ranges is the bathymetry, as deep-water results in a slower attenuation of noise. However, it is not always feasible to limit piling activity in or near to deep water.

4 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters detailed in section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2). To aid navigation, Table 4-1 contains a list of the impact range tables included in this section.

For the results presented throughout this Annex any predicted ranges smaller than 50 m and areas less than 0.01 km^2 for single strike criteria and ranges smaller than 100 m and areas less than 0.1 km^2 for cumulative criteria, have not been presented. At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to complex acoustic effects present near the pile. These ranges are given as "less than" this limit (e.g., "<100 m").

The modelling results for the Southall *et al*. (2019) non-impulsive criteria are presented in Appendix A.

Table 4-1 Summary of the impact piling modelling results tables presented in this section.

Table (page)	Parameters (section)		Criteria		
Table 4-2 (p22)	Anchor pile scenario 1 (4.1.1)	East location (4.1.1)	Southall *et al*. (2019)	Unweighted SPL$_{\text{peak}}$	
Table 4-3 (p23)				Weighted SEL$_{\text{cum}}$ (Impulsive)	Single pile
Table 4-4 (p23)					4 sequential piles
Table 4-5 (p23)			Popper *et al*. (2014)	Unweighted SPL$_{\text{peak}}$	
Table 4-6 (p24)				Unweighted SEL$_{\text{cum}}$ (Pile driving)	Single pile
Table 4-7 (p24)					4 sequential piles
Table 4-8 (p24)		West location (4.1.1.2)	Southall *et al*. (2019)	Unweighted SPL$_{\text{peak}}$	
Table 4-9 (p25)				Weighted SEL$_{\text{cum}}$ (Impulsive)	Single pile
Table 4-10 (p25)					4 sequential piles
Table 4-11 (p25)			Popper *et al*. (2014)	Unweighted SPL$_{\text{peak}}$	
Table 4-12 (p26)				Unweighted SEL$_{\text{cum}}$ (Pile driving)	Single pile
Table 4-13 (p26)					4 sequential piles
Table 4-14 (p27)	Anchor pile scenario 2 (4.1.2)	East location (4.1.2.1)	Southall *et al*. (2019)	Unweighted SPL$_{\text{peak}}$	
Table 4-15 (p27)				Weighted SEL$_{\text{cum}}$ (Impulsive)	Single pile
Table 4-16 (p27)					4 sequential piles
Table 4-17 (p28)			Popper *et al*. (2014)	Unweighted SPL$_{\text{peak}}$	
Table 4-18 (p28)				Unweighted SEL$_{\text{cum}}$ (Pile driving)	Single pile
Table 4-19 (p28)					4 sequential piles
Table 4-20 (p29)		West location (4.1.2.2)	Southall *et al*. (2019)	Unweighted SPL$_{\text{peak}}$	
Table 4-21 (p29)				Weighted SEL$_{\text{cum}}$ (Impulsive)	Single pile
Table 4-22 (p29)					4 sequential piles
Table 4-23 (p30)			Popper *et al*. (2014)	Unweighted SPL$_{\text{peak}}$	
Table 4-24 (p30)				Unweighted SEL$_{\text{cum}}$ (Pile driving)	Single pile
Table 4-25 (p30)					4 sequential piles

4.1 Modelling results

Table 4-2 to Table 4-25 present the modelling results for anchor pile installations at the Salamander Project using the parameters presented in section 3.2, in terms of the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2). Separate results have been considered for a single pile installation and four piles installed sequentially at the same location.

The largest marine mammal impact ranges are predicted for LF cetaceans for anchor pile scenario 1 using the SEL$_{\text{cum}}$ criteria, with PTS ranges up to 21 km for a single pile installation and 26 km for four sequentially installed piles. For VHF cetaceans, PTS ranges are predicted up to 6.9 km and 9.1 km for the same scenarios.

For fish, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) are predicted out to 5.8 km for a single pile installation and 13 km for four sequentially installed piles assuming a stationary receptor. If a fleeing animal is assumed, these ranges are expected to fall below 100 m.

Smaller ranges are predicted for anchor pile scenario 2 due to the lower blow energies and longer ramp up to the maximum hammer energy.

There are only small differences between the two modelling locations due to the deep water at both locations, slightly larger ranges are predicted at the East location due to the open water to the east of the site away from the Scottish coast.

4.1.1 Anchor pile scenario 1

4.1.1.1 East location

Table 4-2 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 1 modelling at the East location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Anchor pile scenario 1, East location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.2 km²	610 m	610 m	610 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.2 km²	1.6 km	1.6 km	1.6 km
	PCW (212 dB)	0.05 km²	120 m	120 m	120 m

Table 4-3 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 1 (single pile installation) modelling at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 1, East location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	1,000 km^2	21 km	13 km	18 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	120 km^2	6.9 km	5.6 km	6.3 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	24,000 km^2	120 km	31 km	85 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	9,800 km^2	68 km	29 km	55 km
	PCW (170 dB)	3,000 km^2	36 km	21 km	31 km

Table 4-4 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 1 (4 piles installed per 24 hours) modelling at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 1, East location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	1,400 km^2	26 km	14 km	21 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	190 km^2	9.1 km	6.3 km	7.9 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	29,000 km^2	137 km	31 km	91 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	13,000 km^2	85 km	29 km	63 km
	PCW (170 dB)	4,200 km^2	47 km	21 km	36 km

Table 4-5 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 1 modelling at the East location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Anchor pile scenario 1, East location foundation**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km^2	100 m	100 m	100 m
207 dB	0.23 km^2	270 m	270 m	270 m

Table 4-6 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 1 (single pile installation) modelling at the East location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Anchor pile scenario 1, East location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	2,600 km^2	33 km	22 km	28 km
Stationary	219 dB	0.7 km^2	480 m	450 m	460 m
	216 dB	1.8 km^2	780 m	750 m	760 m
	210 dB	12 km^2	2.0 km	1.9 km	1.9 km
	207 dB	30 km^2	3.1 km	3.1 km	3.1 km
	203 dB	100 km^2	5.8 km	5.6 km	5.7 km
	186 dB	6,300 km^2	49 km	40 km	45 km

Table 4-7 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 1 (4 piles installed per 24 hours) modelling at the East location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Anchor pile scenario 1, East location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	3,500 km^2	42 km	22 km	33 km
Stationary (0 m/s)	219 dB	4.9 km^2	1.3 km	1.2 km	1.3 km
	216 dB	12 km^2	2.0 km	1.9 km	2.0 km
	210 dB	73 km^2	4.9 km	4.8 km	4.9 km
	207 dB	180 km^2	7.6 km	7.4 km	7.5 km
	203 dB	540 km^2	13 km	13 km	13 km
	186 dB	15,000 km^2	81 km	40 km	68 km

4.1.1.2 West location

Table 4-8 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 1 modelling at the West location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Anchor pile scenario 1, West location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.2 km^2	610 m	610 m	610 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km^2	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.2 km^2	1.6 km	1.6 km	1.6 km
	PCW (212 dB)	0.05 km^2	120 m	120 m	120 m

Table 4-9 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 1 (single pile installation) modelling at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 1, West location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	960 km^2	21 km	10 km	17 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	120 km^2	6.8 km	5.8 km	6.2 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	23,000 km^2	115 km	25 km	82 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	9,400 km^2	65 km	24 km	53 km
	PCW (170 dB)	2,900 km^2	35 km	17 km	30 km

Table 4-10 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 1 (4 piles installed per 24 hours) modelling at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 1, West location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	1,300 km^2	25 km	10 km	20 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	190 km^2	8.8 km	6.0 km	7.7 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	27,000 km^2	133 km	25 km	89 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	12,000 km^2	81 km	24 km	61 km
	PCW (170 dB)	4,000 km^2	44 km	17 km	35 km

Table 4-11 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 1 modelling at the West location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Anchor pile scenario 1, West location foundation**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km^2	100 m	100 m	100 m
207 dB	0.23 km^2	270 m	270 m	270 m

Table 4-12 Summary of the unweighted SEL$_{cum}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 1 (single pile installation) modelling at the West location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL$_{cum}$		**Anchor pile scenario 1, West location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	2,400 km^2	32 km	17 km	27 km
Stationary	219 dB	0.7 km^2	480 m	450 m	460 m
	216 dB	1.8 km^2	780 m	750 m	760 m
	210 dB	12 km^2	2.0 km	1.9 km	1.9 km
	207 dB	30 km^2	3.1 km	3.1 km	3.1 km
	203 dB	100 km^2	5.7 km	5.7 km	5.7 km
	186 dB	6,000 km^2	48 km	33 km	44 km

Table 4-13 Summary of the unweighted SEL$_{cum}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 1 (4 piles installed per 24 hours) modelling at the West location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL$_{cum}$		**Anchor pile scenario 1, West location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	3,300 km^2	40 km	17 km	32 km
Stationary (0 m/s)	219 dB	4.9 km^2	1.3 km	1.2 km	1.3 km
	216 dB	12 km^2	2.0 km	1.9 km	2.0 km
	210 dB	73 km^2	4.9 km	4.8 km	4.9 km
	207 dB	180 km^2	7.6 km	7.5 km	7.6 km
	203 dB	540 km^2	13 km	13 km	13 km
	186 dB	14,000 km^2	78 km	33 km	66 km

4.1.2 Anchor pile scenario 2

4.1.2.1 East location

Table 4-14 Summary of the unweighted SPL$_{peak}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 2 modelling at the East location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		**Anchor pile scenario 2, East location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.67 km^2	460 m	460 m	460 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.7 km^2	1.2 km	1.2 km	1.2 km
	PCW (212 dB)	0.03 km^2	90 m	90 m	90 m

Table 4-15 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 2 (single pile installation) modelling at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Anchor pile scenario 2, East location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	21 km^2	3.6 km	1.8 km	2.6 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	12,000 km^2	81 km	25 km	60 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	4,200 km^2	43 km	23 km	36 km
	PCW (170 dB)	900 km^2	20 km	13 km	17 km

Table 4-16 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 2 (4 piles installed per 24 hours) modelling at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Anchor pile scenario 2, East location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	43 km^2	5.3 km	2.1 km	3.6 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	15,000 km^2	97 km	25 km	66 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,800 km^2	55 km	23 km	42 km
	PCW (170 dB)	1,400 km^2	26 km	13 km	21 km

Table 4-17 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 2 modelling at the East location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Anchor pile scenario 2, East location foundation**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km^2	80 m	80 m	80 m
207 dB	0.13 km^2	210 m	210 m	210 m

Table 4-18 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 2 (single pile installation) modelling at the East location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Anchor pile scenario 2, East location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	410 km^2	13 km	10 km	11 km
Stationary	219 dB	0.2 km^2	250 m	230 m	240 m
	216 dB	0.5 km^2	400 m	380 m	390 m
	210 dB	2.9 km^2	980 m	950 m	960 m
	207 dB	7.6 km^2	1.6 km	1.6 km	1.6 km
	203 dB	26 km^2	2.9 km	2.9 km	2.9 km
	186 dB	2,700 km^2	31 km	28 km	30 km

Table 4-19 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 2 (4 piles installed per 24 hours) modelling at the East location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Anchor pile scenario 2, East location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	660 km^2	18 km	11 km	14 km
Stationary (0 m/s)	219 dB	1.2 km^2	630 m	600 m	610 m
	216 dB	2.9 km^2	980 m	950 m	960 m
	210 dB	19 km^2	2.5 km	2.5 km	2.5 km
	207 dB	49 km^2	4.0 km	3.9 km	4.0 km
	203 dB	160 km^2	7.3 km	7.1 km	7.2 km
	186 dB	8,200 km^2	57 km	40 km	51 km

4.1.2.2 West location

Table 4-20 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 2 modelling at the West location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Anchor pile scenario 2, West location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.70 km^2	460 m	460 m	460 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.7 km^2	1.2 km	1.2 km	1.2 km
	PCW (212 dB)	0.03 km^2	90 m	90 m	90 m

Table 4-21 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 2 (single pile installation) modelling at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 2, West location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	18 km^2	3.3 km	700 m	2.3 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	11,000 km^2	76 km	20 km	58 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	4,000 km^2	42 km	18 km	35 km
	PCW (170 dB)	830 km^2	19 km	9.6 km	16 km

Table 4-22 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the anchor pile foundation scenario 2 (4 piles installed per 24 hours) modelling at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 2, West location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	38 km^2	4.7 km	700 m	3.3 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	14,000 km^2	92 km	20 km	63 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,500 km^2	52 km	18 km	41 km
	PCW (170 dB)	1,300 km^2	25 km	9.6 km	20 km

Table 4-23 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 2 modelling at the West location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Anchor pile scenario 2, West location foundation**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km²	80 m	80 m	80 m
207 dB	0.13 km²	210 m	210 m	210 m

Table 4-24 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 2 (single pile installation) modelling at the West location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Anchor pile scenario 2, West location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms⁻¹)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	390 km²	13 km	8.6 km	11 km
Stationary	219 dB	0.2 km²	250 m	230 m	240 m
	216 dB	0.5 km²	400 m	380 m	390 m
	210 dB	2.9 km²	980 m	950 m	960 m
	207 dB	7.6 km²	1.6 km	1.6 km	1.6 km
	203 dB	27 km²	2.9 km	2.9 km	2.9 km
	186 dB	2,700 km²	31 km	28 km	29 km

Table 4-25 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the anchor pile foundation scenario 2 (4 piles installed per 24 hours) modelling at the West location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Anchor pile scenario 2, West location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms⁻¹)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	620 km²	17 km	8.6 km	14 km
Stationary (0 m/s)	219 dB	1.2 km²	630 m	600 m	610 m
	216 dB	2.9 km²	980 m	950 m	960 m
	210 dB	20 km²	2.5 km	2.5 km	2.5 km
	207 dB	49 km²	4.0 km	4.0 km	4.0 km
	203 dB	160 km²	7.3 km	7.2 km	7.2 km
	186 dB	7,800 km²	56 km	33 km	49 km

5 Other noise sources

Although impact piling is expected to be the greatest overall noise source during offshore construction and development (Bailey *et al.*, 2014), several other anthropogenic noise sources may be present. Each of these has been considered, and relevant biological noise criteria presented, in this section.

Table 5-1 provides a summary of the various noise producing sources, aside from impact piling, that are expected to be present during the construction and operation of the Salamander Project.

Table 5-1 Summary of the possible noise making activities at the Salamander Project other than impact piling

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain foundation options, as well as for the export cable, array cables and interconnector cable installation.
Rock placement	Potentially required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Trenching	Plough trenching may be required during offshore cable installation.
Vessel noise	Jack-up barges for cable installation and repair. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational WTG. The project design envelope gives floating WTGs with max rotor diameter 250 m (see section 5.2).
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the Salamander Project Offshore Development Area, which would need to be cleared before construction can begin (see section 5.3).

Most of these activities are considered in section 5.1, with operational WTG noise and UXO clearance assessed in sections 5.2 and 5.3 respectively.

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al.*, 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with UXO detonation). The high-level overview of modelling that has been presented here is considered sufficient and there would be little benefit in using a more detailed model at this stage. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence.

5.1 Noise making activities

For the purposes of identifying the greatest noise levels, approximate subsea noise levels have been predicted using a simple modelling approach based on measurement data from Subacoustech Environmental's own underwater noise measurement database, scaled to relevant parameters for the site and to the specific noise sources to be used. The calculation of underwater noise transmission loss for the non-impulsive sources is based on an empirical analysis of the noise measurements taken along transects around these sources by Subacoustech Environmental. The predictions use the following principle fitted to the measured data, where R is the range from the source, N is the transmission loss, and α is the absorption loss:

$$Recieved\ level = Source\ level\ (SL) - N \log_{10} R - \alpha R$$

Predicted apparent source levels and propagation calculations for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all $\mathrm{SEL}_{\mathrm{cum}}$ criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be reiterated that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at, or surrounding, the Salamander Project.

Table 5-2 Summary of the estimated unweighted apparent source levels and transmission losses for the different considered noise sources related to construction

Source	Estimated unweighted apparent source level	Transmission loss parameters	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	N: 13, α: 0 (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations.
Dredging (Backhoe)	165 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on three datasets from backhoe dredgers.
Dredging (Suction)	186 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on five datasets from suction and cutter suction dredgers.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0005	Based on four datasets from rock placement vessel ‘*Rollingstone.’*
Trenching	172 dB re 1 µPa @ 1 m (RMS)	N: 13, α: 0.0004	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0021	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0021	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.

All values of N and α are empirically derived and will be linked to the size and shape of the machinery and the noise source on it, the transect on which the measurements are taken and the local environment at the time.

For $\mathrm{SEL}_{\mathrm{cum}}$ calculations in this section, the duration the noise is present also needs to be considered, with all sources assumed to operate constantly for 24 hours to give a worst-case assessment of the noise. Due to the low noise level of the sources considered both fleeing and stationary animals have been included for all $\mathrm{SEL}_{\mathrm{cum}}$ criteria.

To account for the weightings required for modelling using the Southall *et al.* (2019) criteria (see section 2.2.1), reductions in apparent source level have been applied to the various noise sources; Table 5-1 shows the representative noise measurements used for this, which have been adjusted for the apparent source levels given in Table 5-2. Details of the reductions in apparent sources levels for each of the weightings used for modelling are given in Table 5-3.

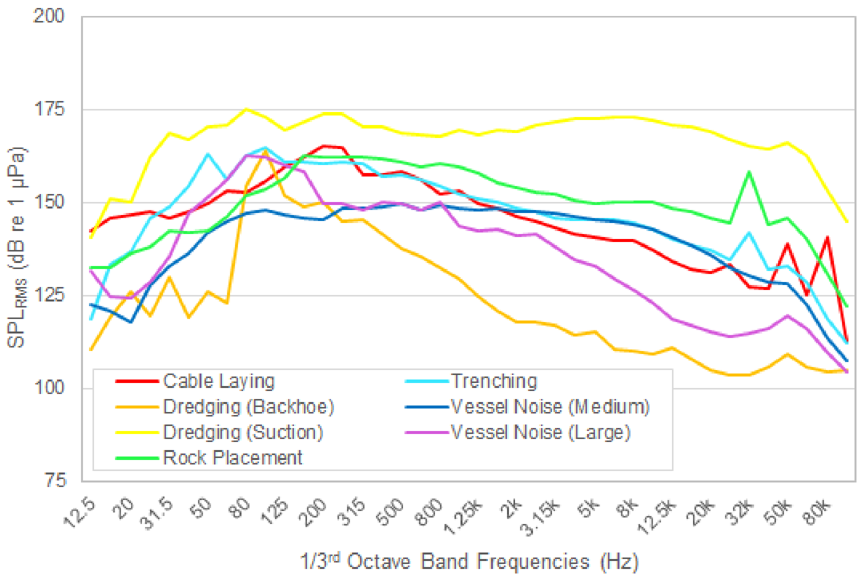


Figure 5-1 Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling

Table 5-3 Reductions in apparent source level for the different construction noise sources considered when the Southall et al. (2019) weightings are applied

Source	**Reduction in source level from the unweighted level (Southall *et al.*, 2019)**			
	LF	**HF**	**VHF**	**PCW**
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 dB
Dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

Table 5-4 to Table 5-6 summarise the predicted impact ranges for these noise sources. All the sources in this section are considered non-impulsive or continuous. As with the previous results, ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented.

Given the modelled impact ranges, almost any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumes the same receptor swim speeds as the impact piling modelling in section 4. As explained in section 3.3, this would only mean that the receptor reaches the ‘onset’ stage at these ranges, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups, the noise levels are low enough that there is a minimal risk.

For fish, there is a minimal risk of any injury or TTS with reference to the SPL$_{RMS}$ guidance for continuous noise sources in Popper *et al*. (2014).

All sources presented here result in much quieter levels than those presented for impact piling in section 4.

Table 5-4 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$	**PTS (non-impulsive)**				**TTS (non-impulsive)**			
	LF 199 dB	**HF** 198 dB	**VHF** 173 dB	**PCW** 201 dB	**LF** 179 dB	**HF** 178 dB	**VHF** 153 dB	**PCW** 181 dB
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	110 m	< 100 m
Dredging (Backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (Suction)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	230 m	< 100 m
Rock placement	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	990 m	< 100 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-5 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a stationary animal

Southall *et al.* (2019) Weighted SEL$_{cum}$	**PTS (non-impulsive)**				**TTS (non-impulsive)**			
	LF 199 dB	**HF** 198 dB	**VHF** 173 dB	**PCW** 201 dB	**LF** 179 dB	**HF** 178 dB	**VHF** 153 dB	**PCW** 181 dB
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	810 m	< 100 m	2.3 km	110 m
Dredging (Backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (Suction)	< 100 m	< 100 m	570 m	< 100 m	640 m	390 m	4.3 km	420 m
Rock placement	< 100 m	< 100 m	900 m	< 100 m	2.1 km	410 m	13 km	460 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	830 m	< 100 m	1.9 km	120 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	480 m	< 100 m	140 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	130 m	< 100 m	< 100 m	< 100 m

Ranges for a stationary animal are theoretical only and are expected to be over-conservative as the assumption is for the animal to remain stationary in respect to the noise source, when the source itself is moving in most cases.

Table 5-6 Summary of the impact ranges for the different noise sources related to construction using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Recoverable injury** 170 dB (48 hours)	**TTS** 158 dB (12 hours)
Cable laying	< 50 m	< 50 m
Dredging (Backhoe)	< 50 m	< 50 m
Dredging (Suction)	< 50 m	< 50 m
Rock placement	< 50 m	< 50 m
Trenching	< 50 m	< 50 m
Vessel noise (large)	< 50 m	< 50 m
Vessel noise (medium)	< 50 m	< 50 m

5.2 Operational WTG noise

The main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the WTGs, which is transmitted into the water column through the structure of the WTGs tower and foundations (Nedwell *et al*., 2003; Tougaard *et al*., 2020). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

Tougaard *et al.* (2020) published a study investigating underwater noise data from 17 operational WTGs in Europe and at the United States, from 0.2 MW to 6.15 MW nominal power output. The paper identified the nominal power output and wind speed as the two primary driving factors for the underwater noise generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational wind farms, allowing a broadband noise level to be estimated based on the application of wind speed, WTG size (by nominal power output) and distance from the WTG:

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

With C a fixed constant and the coefficients α, β and γ derived from the empirical data for the 17 datasets.

The WTG sizes proposed at the Salamander Project are much larger than those used by Tougaard *et al.* (2020). Although confirmed power outputs are not currently available, rotor diameter has been used as an approximate proxy. WTGs up to 250 m rotor diameter are being considered. The Salamander Array Area is also situated in greater water depths than the sites in the Tougaard *et al*. (2020) study, so in theory this would suggest that sound would attenuate more slowly in this location than the mainly continental North Sea and coastally located wind farms.

The noise source for most operational WTGs is the radiating area of the foundation in the water. For a fixed bottom monopile foundation, this is the surface area of the cylindrical pile in the water column. Other fixed foundations such as jacket or tripod foundations are more complex. The complexities of the acoustics in large structures such as any of these make it difficult to predict their effect on the noise output (Tougaard *et al*., 2020). The radiating area source for a floating WTG is limited to the weighted and buoyant section that rests beneath the sea surface, a significantly smaller area than a fixed WTG. With a much smaller submerged radiating area, the noise is expected to be lower, with a reasonable assumption of equivalent sound generation within the WTG and transmission through the tower.

Little empirical data exists for the operational noise data produced by floating WTGs. Tougaard *et al.* (2020) and a similar study by Stöber and Thomsen (2021) did not include any floating designs. Measurements taken by Jasco Applied Science (Martin *et al*., 2011) of the HYWIND demonstrator, west of Stavanger, Norway, showed broadband noise levels of the order of 120 dB SPL_{RMS} over an approximate 10-week period in June to August 2011, at 150 m from the WTG. However much of this was found to be influenced by ambient noise from existing shipping sources and none of the components of the noise relating to WTG operation appeared to exceed 110 dB at the monitoring location. It is worth noting that this is dominated by noise at low frequency (<100 Hz), which is below the auditory sensitivity of most marine mammals, and they differ minimally from background noise over the long term at all measured frequencies up to approximately 16 kHz (1/3rd octave band). It is therefore likely that even if the noise measurement at the position near the WTG position was influenced by WTG noise, ambient noise levels will typically reach this level naturally; the WTG was 2.3 MW (82.4 m rotor diameter). While some other monitoring data for floating wind farm projects do exist (Molinero, 2020), comparing potential noise levels to worst-case examples such as those from HYWIND are considered best practice for this study as they are the largest available.

Using the Tougaard *et al.* (2020) calculator, an uplift of approximately 13 dB would apply to increase the sound output from a 82.4 m WTG to a 250 m rotor diameter WTG. This would suggest an upper limit of 118 dB $\mathrm{SPL_{RMS}}$ at 150 m from the largest proposed WTG at the Salamander Project. At 10 m, this would be 145 dB $\mathrm{SPL_{RMS}}$, and 122 dB at 100 m.

Based on the criteria from Popper *et al.* (2014) for continuous noise, the TTS threshold of 158 dB $\mathrm{SPL_{RMS}}$ would require an individual to be much closer than 10 m for 12 hours continuously, which, for a source near the surface in depths of the order of 90 m would be very low risk. As studies have shown that fish populations have increased in the vicinity of offshore wind farms (Stenberg *et al.* 2015), there appears to be minimal risk to fish from operational WTGs.

To compare this to the relevant marine mammal impact thresholds in Southall *et al.* (2019) requires the values to be presented in SEL. For continuous-type noise sources, a sound as a 1-second $\mathrm{SPL_{RMS}}$ (as described above) is roughly equivalent to an SEL over 1-second. An $\mathrm{SPL_{RMS}}$ for a continuous noise will remain the same over an extended period of time, where, as an exposure metric, SEL will increase with and is thus dependent on the time the exposure to the sound continues.

As an example, at an arbitrary 100 m from the WTG for an hour, a receptor would receive an unweighted 158 dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$ SEL. With weighting considered, this is still well below potentially injurious or TTS thresholds for any Southall *et al*. (2019) species group, and somewhat quieter than vessels at this range (see section 5.1).

Therefore, for noise from operational WTGs, TTS risk is small. Importantly this assumes a stationary animal model with an individual remaining within 100 m from a WTG for much more than a 1-hour period. This is a highly unlikely scenario; when the animal is able to move, the risk of direct harm from the noise is minimal.

Multiple WTGs operating simultaneously will each contribute to the underwater noise within the wind farm boundary. It has been shown that a receptor would need to remain very close (much less than 100 m) to a WTG over an extended period to have any risk of impact. At this range the closest WTG, combined with natural ambient noise, will be much louder than any other WTG in the wind farm. To give a numeric example, if the noise level was 122 dB $\mathrm{SPL_{RMS}}$ at 100 m from a WTG, and the next nearest WTG was separated by 1,000 m (approximate minimum separation, actual separations vary between designs) then the predicted noise level contribution from the next WTG would be 23 dB lower, which combined would contribute less than 0.1 dB to the overall noise level from the closest WTG. At the centre-point between two WTGs separated by 1,000 m, the theoretical noise level would be under 110 dB, well below any impact threshold. The contribution to a receptor’s total noise exposure from any other WTG will therefore be minimal.

5.2.1 Cable noise

The availability of underwater noise-related data for operational noise from floating WTGs is limited due to the relatively small number of WTGs installed and generating offshore. Of those that have been installed, measurements taken by Jasco (2011) for Statoil presented underwater noise levels sampled at 150 m from the HYWIND 1 installation, off the coast of Norway. Measurements were taken in water depths of 200 m at 91 m off the seabed, approximately mid-depth.

As well as relatively low noise levels from the operational machinery in a variety of conditions (see Operational Noise in section 5.2), the measurements identified what appeared to be a “snapping” noise that were thought to be related to tension release in the mooring system, although this has not been verified. It is understood that the mooring cables are designed to be permanently in tension such that no line should ever go into slack, even in extreme conditions, partly to avoid the risk of entanglement of marine mammals (Statoil, 2015). If the cables are the source of the noise, this will be caused by the specific circumstances at the HYWIND 1 project: that is, the depth of water, length of cables in use, current and current fluctuations. The findings at HYWIND 1 were isolated, and it does not necessarily follow that this will occur at the Salamander Project but does not rule out the potential for it either. Unless there was further evidence that other floating WTG moorings, or some other noise source associated with the WTGs, is shown to create this snap then it may be an anomaly or potentially even an artifact of the monitoring system.

According to Jasco (2011), up to 23 of these snaps were identified per day. Over the two months of monitoring undertaken by Jasco, less than 10 snaps exceeding 160 dB SPL_{peak} at the measurement position, 150 m from the WTG were identified on most days.

As the source of noise is unclear, its distance from the monitor cannot be ascertained and thus a prediction of the noise closer to the source is not possible for estimation of PTS in terms of SPL_{peak}. Subsequent analysis of the HYWIND 1 data by Xodus (2015) for the HYWIND Scotland Pilot Park Project predicted a potential cumulative SEL of up to 157 dB re 1 μPa^{2}s over 24 hours caused by snapping chains from six WTGs; the equivalent for ten would be approximately 160 dB SEL re 1 μPa^{2}s. This prediction makes a series of worst-case assumptions (e.g., all WTGs producing the maximum number of snaps in a day, equivalent noise levels from multiple locations affecting a receptor to the same degree) and this level is below any PTS or injury criteria to marine mammals or fish.

There are no reliable noise thresholds that would be recommended to identify disturbance for rare/intermittent impulses of this type. As any snapping occurs at an average rate of less than one snap per hour, disturbance leading to avoidance behaviour is considered unlikely.

5.3 UXO clearance

It is possible that UXO devices with a range of charge weights (or quantity of contained explosive) are present within the Salamander Project Offshore Development Area. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burial over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed. A selection of explosive sizes has been considered based on what might be present, and in each case, it has been assumed that the maximum explosive charge in each device is present and either detonates with the clearance (high-order) or alternatively a clearance method such as deflagration (low-order) may be used.

5.3.1 Estimation of underwater noise levels

5.3.1.1 High-order clearance

The noise produced by the detonation of explosives is affected by several different elements, only one of which can easily be factored into a calculation: the charge weight. In this case the charge weight is based on the equivalent weight of TNT. Many other elements relating to its situation (e.g., its design, composition, age, position, orientation, whether it is covered by sediment) and exactly how they will affect the sound produced by detonation are usually unknown and cannot be directly considered in this type of assessment. This leads to a high degree of uncertainty in the estimation of the source noise level. A worst-case estimation has therefore been used for calculations, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its “as new” condition. It assumes that a “high-order” clearance technique is used, using an external ‘donor charge’ initiator to detonate the explosive material in the UXO, producing a blast wave equivalent to full detonation of the device.

The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of degradation would be expected.

The maximum equivalent charge weight for the potential UXO devices that could be present within the Salamander Project Offshore Development Area has been estimated as 698 kg. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525 and 698 kg. In each case, an additional donor weight of 0.5 kg has been included to initiate detonation.

Estimation of the source noise level for each charge weight has been carried out in accordance with the methodology of Soloway and Dahl (2014), which follows Arons (1954) and the Marine Technical Directorate Ltd (MTD) (1996).

5.3.1.2 Low-order clearance

Other techniques are being considered to reduce the impact of noise impacts from high order UXO clearance, caused by detonation of the main charge of the UXO. Deflagration is such an alternative technique, intended to result in a ‘low order’ burn of the explosive material in a UXO, which destroys, but does not detonate, the internal explosive.

Deflagration is a lower noise technique for UXO disposal as it is intended to avoid the high pressures associated with an explosion, which would lead to an increased risk of adverse effects to marine life. Where the UXO device cannot be moved, deflagration is preferred over high-order clearance, where it is evaluated as a suitable and safe clearance method in respect to environmental effects.

Where the technique proceeds as intended, it is still not without noise. The process requires an initial shaped explosive donor charge, typically less than 250 g, to breach the casing and ignite the internal high explosive (HE) material without full detonation. The shaped charge and burn will both produce noise, although it will be significantly less than the high order detonation of the much larger UXO. It may not destroy all of the HE, necessitating further deflagration events or collection of the remnants. The deflagration may produce an unintentional high order event.

For calculation of the scenario of destruction of the HE material using deflagration, it is anticipated that the initial shaped charge is the greatest source of noise (Cheong *et al.* 2020). The shaped charge is treated as a bulk charge with NEQ determined according to the size of UXO on which it is placed. A prediction of this impact is based on a charge weight of 250 g. The worst-case scenario would of course be a high order detonation with maximum pressures from complete detonation of the UXO, and this has also been used in the calculation of impact for comparison.

5.3.2 *Estimation of underwater noise propagation*

For this assessment, the attenuation of the noise from UXO detonation has been accounted for in calculations using geometric spreading and a sound absorption coefficient, primarily using the methodologies cited in Soloway and Dahl (2014), which establishes a trend based on measured data in open water. These are, for $\mathrm{SPL_{peak}}$:

$$SPL_{peak} = 52.4 \times 10^{6} \left(\frac{R}{W^{1/3}}\right)^{-1.13}$$

and for $\mathrm{SEL_{ss}}$

$$SEL = 6.14 \times \log_{10}\left(W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12}\right) + 219$$

where W is the equivalent charge weight for TNT in kilograms and R is the range from the source.

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless of where it is used. An attenuation correction can be added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North Sea and Irish Sea. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, $\mathrm{SPL_{peak}}$ noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results are similar to the measurements presented by von Benda-Beckmann *et al*. (2015). At longer ranges, greater confidence is expected with the SEL calculations.

A further limitation in the Soloway and Dahl (2014) equations that must be considered are that variations in noise levels at different depths are not considered. Where animals are swimming near the surface, the acoustics can cause the noise level, and hence the exposure, to be lower (MTD, 1996). The risk to animals near the surface may therefore be lower than indicated by the impact ranges and therefore the results presented can be considered conservative in respect of the impact at different depths.

Additionally, an impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning the injurious potential of a wave at greater range can be even lower than just a reduction in the absolute noise level. An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the degree of smoothing of the peak with increasing distance is less critical.

The selection of assessment criteria must also be considered in light of this. As discussed in section 2.2, the smoothing of the pulse at range means that a pulse may be considered non-impulsive with distance, suggesting that, at greater ranges, it may be more appropriate to use the non-impulsive criteria. This consideration may begin at 3.5 km (Hastie *et al.*, 2019).

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 5-7.

Table 5-7 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO clearance modelling

Charge weight	**SPL_{peak} source level**	**SEL_{ss} source level**
Low order (0.25 kg)	269.8 dB re 1 µPa @ 1 m	215.2 dB re 1 μPa^2s @ 1 m
25 kg + donor	284.9 dB re 1 µPa @ 1 m	228.0 dB re 1 μPa^2s @ 1 m
55 kg + donor	287.5 dB re 1 µPa @ 1 m	230.1 dB re 1 μPa^2s @ 1 m
120 kg + donor	290.0 dB re 1 µPa @ 1 m	232.3 dB re 1 μPa^2s @ 1 m
240 kg + donor	292.3 dB re 1 µPa @ 1 m	234.2 dB re 1 μPa^2s @ 1 m
525 kg + donor	294.8 dB re 1 µPa @ 1 m	236.4 dB re 1 μPa^2s @ 1 m
698 kg + donor	295.7 dB re 1 µPa @ 1 m	237.1 dB re 1 μPa^2s @ 1 m

5.3.3 *Impact ranges*

Table 5-8 to Table 5-11 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 2-6). A UXO detonation source is defined as a single pulse, and as such the SEL_{cum} criteria from Southall *et al*. (2019) have been given as SEL_{ss} in the tables below. Thus, fleeing animal assumptions do not apply. As with the previous sections, ranges smaller than 50 m have not been presented.

Although the impact ranges in Table 5-8 to Table 5-11 are large, the duration the noise is present must also be considered. For the detonation of a UXO, each explosion is a single noise event, compared to the multiple pulse nature and longer durations of impact piling.

Table 5-8 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL_{peak} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Unweighted SPL_{peak}	**PTS (impulsive)**				**TTS (impulsive)**			
	LF 219 dB	**HF** 230 dB	**VHF** 202 dB	**PCW** 218 dB	**LF** 213 dB	**HF** 224 dB	**VHF** 196 dB	**PCW** 212 dB
Low order (0.25 kg)	170 m	60 m	990 m	190 m	320 m	100 m	1.8 km	360 m
25 kg + donor	820 m	260 m	4.6 km	910 m	1.5 km	490 m	8.5 km	1.6 km
55 kg + donor	1.0 km	340 m	6.0 km	1.1 km	1.9 km	640 m	11 km	2.1 km
120 kg + donor	1.3 km	450 m	7.8 km	1.5 km	2.5 km	830 m	14 km	2.8 km
240 kg + donor	1.7 km	560 m	9.8 km	1.9 km	3.2 km	1.0 km	18 km	3.5 km
525 kg + donor	2.2 km	730 m	12 km	2.5 km	4.1 km	1.3 km	23 km	4.6 km
698 kg + donor	2.4 km	810 m	13 km	2.7 km	4.5 km	1.4 km	25 km	5.0 km

Table 5-9 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Weighted SEL_{ss}	**PTS (impulsive)**				**TTS (impulsive)**			
	LF 183 dB	**HF** 185 dB	**VHF** 155 dB	**PCW** 185 dB	**LF** 168 dB	**HF** 170 dB	**VHF** 140 dB	**PCW** 170 dB
Low order (0.25 kg)	230 m	< 50 m	80 m	40 m	3.2 km	< 50 m	750 m	570 m
25 kg + donor	2.2 km	< 50 m	570 m	390 m	29 km	150 m	2.4 km	5.2 km
55 kg + donor	3.2 km	< 50 m	740 m	570 m	41 km	210 m	2.8 km	7.5 km
120 kg + donor	4.7 km	< 50 m	950 m	830 m	57 km	300 m	3.2 km	10 km
240 kg + donor	6.5 km	< 50 m	1.1 km	1.1 km	76 km	390 m	3.5 km	14 km
525 kg + donor	9.5 km	50 m	1.4 km	1.6 km	100 km	530 m	4.0 km	19 km
698 kg + donor	10 km	60 m	1.5 km	1.9 km	110 km	590 m	4.1 km	22 km

Table 5-10 Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Weighted SEL_{ss}	**PTS (non-impulsive)**				**TTS (non-impulsive)**			
	LF 199 dB	**HF** 198 dB	**VHF** 173 dB	**PCW** 201 dB	**LF** 179 dB	**HF** 178 dB	**VHF** 153 dB	**PCW** 181 dB
Low order (0.25 kg)	< 50 m	< 50 m	< 50 m	< 50 m	460 m	< 50 m	110 m	80 m
25 kg + donor	130 m	< 50 m	< 50 m	< 50 m	4.4 km	< 50 m	730 m	790 m
55 kg + donor	190 m	< 50 m	< 50 m	< 50 m	6.4 km	60 m	940 m	1.1 km
120 kg + donor	280 m	< 50 m	70 m	< 50 m	9.4 km	80 m	1.1 km	1.6 km
240 kg + donor	390 m	< 50 m	100 m	70 m	13 km	110 m	1.4 km	2.3 km
525 kg + donor	570 m	< 50 m	130 m	100 m	18 km	160 m	1.7 km	3.3 km
698 kg + donor	660 m	< 50 m	140 m	110 m	21 km	180 m	1.8 km	3.8 km

Table 5-11 Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for species of fish

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Mortality and potential mortal injury**	
	234 dB	229 dB
Low order (0.25 kg)	40 m	70 m
25 kg + donor	170 m	290 m
55 kg + donor	230 m	380 m
120 kg + donor	300 m	490 m
240 kg + donor	370 m	620 m
525 kg + donor	490 m	810 m
698 kg + donor	530 m	890 m

5.3.4 Summary

The maximum PTS range calculated for UXO detonation is 13 km for the VHF cetacean category, when considering the unweighted SPL_{peak} criteria for the largest high-order clearance. For SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact of 10 km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al*., 2020) (the equivalent range based on LF cetacean non-pulse criteria is 660 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum ‘impulsive’ range for all species is very precautionary.

6 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of Salamander Wind Project Company Limited to assess the potential underwater noise and its effects during construction and operation of the Salamander Project, to be located off the coast of Aberdeenshire, Scotland.

The level of underwater noise from the installation of WTG foundations during construction has been estimated using the semi-empirical underwater noise model INSPIRE. The modelling considers a wide variety of input parameters including bathymetry, hammer blow energy, strike rate, and receptor fleeing speed.

Two representative modelling locations were chosen to give spatial variation across the Offshore Array Area. At each location a two anchor pile installation scenarios were considered: a 3 m diameter pile installed using a maximum hammer energy of 2,500 kJ and a 3 m diameter pile installed using a maximum hammer energy of 1,500 kJ, both installed so that 3 m of the pile stands proud of the seabed. Up to four anchor piles could be installed in a day.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of the impact piling on marine mammals (Southall *et al*., 2019) and fish (Popper *et al*., 2014), which have been used to aid biological assessments.

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges up to 21 km for a single pile installation and 26 km for four sequentially installed piles.. For fish, the largest recoverable injury ranges (203 dB SEL_{cum}) were predicted to be 13 km for four sequentially installed piles with a stationary receptor, falling to below 100 m for a fleeing receptor.

Noise sources other than piling were considered using a high-level, simple modelling approach, including cable laying, dredging, rock placement, and vessel movements. The predicted noise levels for the other construction noise sources and during WTG operation are well below those predicted for impact piling noise. The risk of any potentially injurious effects to fish or marine mammals from these sources are expected to be minimal as the noise emissions from these are close to, or below, the appropriate injury criteria even when very close to the source of the noise.

Additionally, noise from the operational WTGs has been considered based on recent review papers of WTGs currently in use in European waters. The noise level predicted for the largest prospective WTGs under consideration at the Salamander Project are not expected to be high enough to cause PTS or TTS to any species, even assuming that a marine mammal or fish were to remain in proximity to a WTG for over an hour. Due to the relatively low noise output and the spacing between the WTGs, noise from multiple WTGs operating simultaneously will not produce any significant cumulative effect.

UXO clearance has also been considered at the Salamander Project site, and for the expected UXO clearance noise, there is a risk of PTS up to 13 km from the largest, 698 kg, UXO device considered, using the unweighted SPL_{peak} criteria for VHF cetaceans. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

The outputs of this modelling have been used to inform analysis of the impacts of underwater noise on marine mammals and fish in their respective chapters.

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APPENDIX A Additional modelling results

In addition to the Southall *et al.* (2019) modelled impact ranges presented in section 4 of the main Annex, the modelling results for the non-impulsive criteria from impact piling noise at the Salamander Project (as discussed in section 2.2.1) are presented below. The predicted ranges here fall well below the impulsive criteria previously presented.

Table A 1 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 1 (single pile installation) modelling at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 1, East location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	3,500 km^2	40 km	20 km	33 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	360 km^2	12 km	9.7 km	11 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 2 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 1 (4 piles installed per 24 hours) modelling at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 1, East location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	4,400 km^2	49 km	20 km	37 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	530 km^2	15 km	10 km	13 km
	PCW (181 dB)	0.5 km^2	700 m	100 m	340 m

Table A 3 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 1 (single pile installation) modelling at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 1, West location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	3,300 km^2	39 km	15 km	32 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	350 km^2	12 km	9.5 km	11 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 4 Summary of the weighted SEL$_{cum}$ *impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 1 (4 piles installed per 24 hours) modelling at the West location assuming a fleeing animal*

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Anchor pile scenario 1, West location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	4,100 km^2	46 km	15 km	35 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	510 km^2	15 km	9.6 km	13 km
	PCW (181 dB)	0.4 km^2	600 m	100 m	330 m

Table A 5 Summary of the weighted SEL$_{cum}$ *impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 2 (single pile installation) modelling at the East location assuming a fleeing animal*

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Anchor pile scenario 2, East location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	610 km^2	17 km	9.1 km	14 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	3.6 km^2	1.3 km	700 m	1.1 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 6 Summary of the weighted SEL$_{cum}$ *impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 2 (4 piles installed per 24 hours) modelling at the East location assuming a fleeing animal*

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Anchor pile scenario 2, East location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	840 km^2	21 km	9.1 km	16 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	10 km^2	2.3 km	1.1 km	1.8 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 7 Summary of the weighted SEL_{cum} impact ranges kmfor marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 2 (single pile installation) modelling at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 2, West location, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	550 km^2	16 km	6.0 km	13 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	3.3 km^2	1.3 km	900 m	1.0 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 8 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the anchor pile foundation scenario 2 (4 piles installed per 24 hours) modelling at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Anchor pile scenario 2, West location, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	770 km^2	20 km	6.0 km	15 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	9.1 km^2	2.2 km	1.0 km	1.7 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

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