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Recommendations for assessing the risk of injury to marine mammals and fish posed by pile driving noise in UK waters

Virginia Iorio-Merlo, Tim Mason, James Robbins, William Brown, Leah Brown, Victoria Rutherford, Gillian Vallejo and Sónia Mendes

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For further information please contact:
JNCC, Quay House, 2 East Station Road, Fletton Quays, Peterborough PE2 8YY.
https://jncc.gov.uk/

Communications@jncc.gov.uk

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Author affiliations:
[1] Natural Power Consultants Ltd, Kirkcudbrightshire, United Kingdom, DG7 3XS.
[2] Subacoustech Environmental Ltd, Southampton, SO14 5QH.
[3] JNCC, Quay House, Peterborough, PE2 8YY.

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1. Introduction to the project

Pile driving activities in the marine environment have been critical for the development of man-made structures in coastal (e.g. harbour developments, bridges, wharfs, etc.) and offshore (e.g. offshore wind farms (OWFs), offshore oil and gas structures) areas. Noise arising from construction activities associated with pile driving has been a concern for marine fauna due to the potential for disturbance or injury (Dahl *et al.* 2015; Herbert-Read *et al.* 2017; JNCC 2010). In the UK, these activities have the potential to conflict with legislative provisions that protect marine fauna, such as The Conservation of Habitats and Species Regulations (UK Statutory Instruments 2017a) and The Conservation of Offshore Marine Habitats and Species Regulations (UK Statutory Instruments 2017b). Hence, risk assessment of potential impacts caused by piling activities is required.

Currently, noise impact assessment is carried out by first modelling the propagation of sound generated from proposed activities (referred to as noise) and then carrying out species-specific noise exposure assessments. New methods and evidence relating to the impacts of noise from anthropogenic activities on marine fauna, such as definition of noise exposure criteria for marine mammals (NMFS 2024; Southall *et al.* 2019) and fish (Popper *et al.* 2014), and changes in definitions and methods used to model noise propagation (Hastie *et al.* 2019; Matei *et al.* 2024) have led to significant changes to noise impact assessments over the last 10 years. However, there are still inconsistencies among projects relating to the way in which assessments are undertaken, and how results are reported and interpreted (Farcas *et al.* 2016; Verfuss *et al.* 2023).

This project aims to synthesise current knowledge and practices in underwater noise assessment, to provide a set of recommendations for undertaking assessment of the injurious impacts of underwater noise arising from impact-piling activities in UK waters, with a focus on impacts to marine mammals and fish. The report does not cover the risk of disturbance.

1.1. Report structure and intention

Based on the overall aim of the project, three objectives were outlined:

- A literature review of the current knowledge underpinning underwater impact assessments for pile driving activities (Section 2).
- Development of a recommendations and guidance note, written on behalf of JNCC (Section 3).
- Discussion of potential further improvements to the assessment based on ongoing research activities or knowledge gaps that need to be addressed (Section 4).

2. Literature review

Knowledge on how underwater noise exposure is measured and perceived by marine fauna is continuously evolving with new evidence frequently being published. The following report reviews and summarises recent publications to offer recommendations on how noise modelling assessments of auditory injury should be carried out in UK waters, with particular focus on marine mammals and fish.

The noise assessment process typically involves the modelling of sound propagation from a noise source, the identification of biological receptors at risk and the application of quantitative noise exposure thresholds to estimate resulting effect zones for each species. Thresholds vary depending on the species of interest and for different categories of effect (e.g. risk of injury, behavioural responses). These can be for single noise exposure or for cumulative exposure to successive events.

The following literature review aims to provide an up-to-date overview of the knowledge underpinning underwater noise injury risk impact assessments for impact-pile driving activities.

2.1. Scope

The scope of the literature review was defined in agreement with JNCC, who provided a list of recommended literature sources to which additional relevant publications were added. The scope of the literature review was:

- To review recent literature sources on **auditory injury or impairment** impacts from impact pile driving activities on **marine mammals and fish**. Sources reporting on disturbance or other behavioural effects were out of scope.

- To review recent literature sources on noise propagation caused by **impact-piling activities**.

- To review outcomes of recent projects aimed at reviewing current practices in underwater noise modelling, along with underwater noise assessment guidelines published by other statutory bodies or national agencies from other countries.

The literature sources reviewed concerned impact piling activities and did not consider other noise emission sources. Appendix 1 provides a list of the publications that were reviewed.

2.2. Methodology

The focus of this review centred on a selection of key literature identified by JNCC which were expected to be central to the literature landscape and highly relevant to informing this report. In addition to these central references, other recent and influential publications often used for piling assessments were reviewed. Finally, additional relevant publications were targeted from searches using literature review techniques often employed in systematic reviews to target both scientific publications and published ‘grey literature’ reports on the subject. This included using Google Scholar and Web of Science to determine relevant literature using key words relating to the scope of this project. It should be noted that due to the scope of this project, this search for additional literature was not fully systematic or comprehensive and was instead used to supplement the reference list provided. Therefore, a full methodology on the literature search is not reported here. Details on recommended and additional resources reviewed is provided in Appendix 1.

An evidence database was developed to collate information reviewed when developing this report. When constructing this, each publication was determined to be within or outside of the scope of the review, and those within scope were assigned a theme relating to noise, marine mammals, or fish. The species covered by the publication, and the geographic region it pertains to were also captured. The study objectives, methodology used by the authors, and key findings were summarised. As a result of this review, each publication was scored on the relevance to the UK, its likely contribution to the recommendations set out in this report, and the confidence the reviewers had in the methodology. These scores range from 1 (low), 2 (medium) and 3 (high) for confidence in the methodology and the relevance to the UK, and 1 (minimal), 2 (moderate) and 3 (considerable) for the contribution to the report. As these scoring metrics are qualitative and relatively subjective, examples of reasons for scores being assigned are provided here in Table 1.

Table 1. Examples of scoring used in the evidence database.

Example publication	Relevance to UK	Contribution to report	Confidence in Methodology
Herbert-Read *et al.* 2017	High (3) – The study species (European seabass) is present in UK waters. Methods and study objectives remain relevant to the UK.	Minimal (1) – The paper focuses on pile-driving effects on the social behaviour of fish, with no investigation into physical injury	Medium (2) – Methodology appears sound; however, experiments were undertaken in lab conditions with recorded piling sounds, rather than *in-situ*.
Faulkner *et al.* 2018	High (3) – the study aims to provide UK regulators with a framework for assessing the impacts from underwater noise	Considerable (3) – The resulting framework is highly relevant, and highlights different approaches taken during an EIA and common pitfalls	Not applicable – the study is a discussion piece and review
Popper *et al.* 2014	High (3) – the study is relevant globally, using generalised species groups	Considerable (3) – the paper presents sound exposure criteria guidelines which are highly relevant	High (3) – the study is well accepted in the field, and has a robust methodology

2.3. Outcomes of literature review

A total of 32 literature sources were reviewed across scientific peer-reviewed publications, reports commissioned by statutory bodies, national guidelines existing from other countries and publicly available underwater noise assessments (e.g. from existing developments) (Figure 1).

A list of the literature resources which underwent an in-depth review as part of the assessment is presented in Appendix 1.



Figure 1. Overview of the number of literature sources reviewed split by category.

Knowledge from the reviewed sources has been summarised according to the following four themes:

- **Estimating the impacts of underwater noise**: An overview of approaches and assumptions currently used within underwater noise pile-driving impact assessments, and across published guidelines from other countries.
- **Sensitivity of biological receptors to noise:** An overview of how marine mammal and fish species sense sound and the split of species into hearing groups.
- **Criteria for scoping species and species groups into assessments:** Considerations for scoping biological receptors into quantitative assessments.
- **Marine mammal and fish auditory injury from noise exposure**: An overview of noise exposure thresholds and flee speeds used in cumulative assessments.

2.3.1. Impact-pile driving noise characterisation

Our understanding of how noise propagates into the marine environment has significantly increased over the last decade, improving our knowledge on how environmental characteristics influence propagation (Farcas *et al.* 2016). In support of the recommendations made in this report, this section provides an overview of:

(i) the factors that have been highlighted to influence sound propagation estimates, related to both environmental conditions and characteristics of construction activities (Verfuss *et al.* 2023; Von Pein *et al.* 2022)

(ii) recent literature addressing some of the conservatisms of current underwater assessments, particularly in relation to the impulsiveness of sound (Hastie *et al.* 2019; Matei *et al.* 2024)

(iii) current recommendations in national guidelines from other countries

(iv) a comparison of the structure and content of publicly available underwater noise assessments.

2.3.1.1. Factors affecting sound propagation

In its most simplistic form, the estimated received sound levels at any given location are a function of the level of sound at its source and its attenuation with distance into the surrounding environment. Although conceptually simple, accurately estimating these two factors is not straightforward, often requiring sophisticated underwater sound modelling approaches. In this section, we review the factors that should be considered when modelling underwater noise propagation into the marine environment for pile driving activities, and some of the approaches that are currently used.

Source characterisation

Information on the sound source levels is often a critical component of any analytical propagation model, both for numerical and empirical approaches. Source levels are defined by convention as the theoretical level of sound at 1m from the source in decibels (dB), but it can also be expressed within a range of meters away from the piling location, provided this range is made clear.

Although environmental characteristics such as the water depth at the piling location can influence source level predictions, the main factors determining sound source level of piling events will be determined by the details of the construction activities. Von Pein *et al.* (2022) used Sound Exposure Levels (SEL) estimated in previous assessments to show that factors that should be considered when estimating source levels are hammer strike energy, pile diameter, ram weight, and whether noise mitigation measures were used (Table 2). Similar conclusions were drawn by Verfuss *et al.* (2023), where authors investigated the most significant factors affecting the impact piling noise measurements from several windfarms. Verfuss *et al.* (2023) showed that blow energy, pile diameter, water depth, penetration depth and phase of piling sequence were strong predictors of SEL. Given their importance, this report includes details on how these parameters (Table 2) should be reported within assessments (see Section 3.3.1).

The empirical models used to estimate source levels are often proprietary and based on real-world data measured from previous pile driving events. Von Pein *et al.* (2022) and Wood *et al.* (2023) tried to simplify and define a more generalised process by using existing datasets to derive more straightforward approaches to estimate source levels. (Both approaches reach source levels by estimating SEL at close range from the piling activity.)

Table 2. Summary of how characteristics of construction activities influence noise and noise propagation.

Variable	Impact on noise and/or noise propagation
Blow energy	Effectively how hard the pile is hit with the impact piling hammer, typically measured in kilojoules (kJ). The harder the pile is hit, the greater the noise produced. Blow energy varies during the piling sequence with lower energies during the soft-start, increasing during the ramp-up.
Pile diameter	The pile diameter affects the surface area, and thus the noise radiating area, of the pile. It can also affect the frequency of the noise, with lower frequency noise caused by larger piles.
Water depth	The depth of water also controls the pile surface area in the water, and thus its radiating area.

Variable	Impact on noise and/or noise propagation
Penetration depth	A pile driven deep into the seabed is 'gripped' more firmly than one with the base at the seabed (i.e. at the start of piling). Therefore, where a pile is driven with the hammer underwater, the surface radiating area progressively reduces.
Phase of piling sequence	The blow energy and speed of blows rarely remain constant throughout the pile installation, particularly for piling with large hammers offshore. A 'soft start' where the pile is struck with a low energy is generally required for engineering purposes at the start of the sequence and helps minimise noise levels.

The approach described by Von Pein *et al.* (2022) used data from previous underwater noise monitoring to determine how SEL varied over a range of values of key parameters affecting noise propagation. They then summarised all the resulting relationships in one generalised equation with the aim of scaling the sound levels from the source to a specified distance. This approach was validated by applying the scaling equation to publicly available data on impact-piling activities from a range of wind farms across the North Sea and comparing scaled SEL at 750m from the noise source with actual measured values. There was overall agreement between the scale measurements with only a 0.5 dB mean difference and 2.0 dB standard deviation (Von Pein *et al.* 2022). Although the scaling law approach does come with limitations and is based on a set of assumptions, the validation presented suggests that the approach does yield realistic SEL and may provide initial indications of SEL for future projects.

Wood *et al.* (2023) presents a review on the use of an Energy Conversion Factor (ECF) to estimate SEL. Specifically Wood *et al.* (2023) reviews the use of the point-source equivalent ECF which involves the calculation of a broadband sound level for a pile based only on the hammer strike energy and a value for the conversion factor. The ECF approach uses a conversion factor to represent the acoustic radiation efficiency and is intended to allow users to estimate the total energy radiated in the water column based on a specific hammer energy input. As this approach is based on published recorded data, the factors affecting transmission loss in the environment or characteristics of the pile are intrinsically included. By compiling published ECF values from previous underwater noise assessments, Wood *et al.* (2023) found a large variability in ECF ranging from 0.17% to 1.56% - a range that would translate to over 10 dB difference in SEL estimates. This high variability raises the issue of identifying the most suitable ECF value to be applied in future projects (Wood *et al.* 2023). An additional limitation identified with current estimates of ECF is that most reported values are currently for shallow water projects, raising a further concern relating to the transferability of ECF values to developments further offshore. In conclusion, Wood *et al.* (2023) recommended that the point-source equivalent ECF approach should not be used in Environmental Impact Assessments (EIA), unless further significant developments are undertaken to reduce the uncertainties.

Wood *et al.* (2023) does note the suitability of numerical and empirical models, provided they are coupled with an appropriate transmission loss model. It recommends reference to Reinhall and Dahl (2011) for numerical modelling using the Mach cone concept; empirical processes based on scaling laws such as those presented by von Pein *et al.* (2022) can be effective provided that the scaling is derived from a sufficiently focused, or large, dataset.

Transmission loss

All approaches require accurate information on sound source levels. However, the approaches taken to account for sound attenuation with range into the surrounding water (i.e. transmission loss) have taken various forms. Transmission loss has been estimated by using numerical theoretical modelling approaches or semi-empirical approaches in underwater noise assessments (Verfuss *et al.* 2023). In summary, from the overview presented by Verfuss *et al.* (2023), numerical models have the advantage of being able to model any radiating noise from the activity and being able to describe the sound propagation. However, they are strongly dependent on accurate input parameters which are rarely available, leading to simplification of the parameters and inclusion of uncertainty in the model. On the other hand, the empirical approaches rely on geometric dispersion functions based on empirical data. Although these models rely less on input parameters, their reliability highly depends on the quantity and quality of data that they are based on.

Both approaches are complex and often time consuming, and they strongly depend on the quality of the input data (Farcas *et al.* 2016). It is recognised that simple spreading laws in which sound attenuates as a function of distance to the source are often not sufficient to capture sound propagation in practice (Farcas *et al.* 2016). This can lead to under-estimation of the sound levels near the sound source and over-estimation at greater distances, as there are several factors affecting how sound transmits through the water column (Farcas *et al.* 2016). The selection of an appropriate model will depend on factors such as the sound frequency that is being assessed and the overall environment (e.g. acoustically shallow vs deep water). The environment plays a significant role in shaping sound propagation, with bathymetry, sediment, water column stratification, and the condition of the sea surface all influencing how sound transmits and loses energy as it travels away from the source (Table 3).

Furthermore, other than static environmental characteristics (e.g. sediment), consideration should also be given to temporally explicit variables, for example for impact piling activities that are expected to occur over an extended period. Environmental characteristics such as tidal levels and water temperature may vary through the activity period. Farcas *et al.* (2016), for example, reports that the variation in sea water levels and the change in temperature from cold to warm water may affect the final predicted SEL by 5–20 dB and 5–10 dB respectively.

Table 3. Summary of how environmental variables may influence sound transmission loss.

Variable	Factors affecting sound transmission loss
Bathymetry	The depth of the water and its variation affects, for example, the reflections, dispersion and attenuation of sound.
Sediment	The type, layers, density and granularity of sediment at the seabed and the layers affect sound absorption and reflection.
Water column stratification	Transmission of sound is affected by the variation in water conditions with depth, especially through changes in temperature and salinity. This changes with location and time.
Sea surface	Variability of the roughness of the sea surface, size of waves and bubbles affect sound absorption and dispersion.

Considerations for reporting

Given the strong influence that the variables may have on the final predictions, Farcas *et al.* (2016) urges authors of underwater noise impact assessments to carefully report the

characterisation of the noise source, the modelling of transmission loss, the sound source levels and the uncertainties in the input data that were used in the model. This should be included along with the underlying assumptions and scientific basis for the selected transmission loss model. Recommended points by Farcas *et al.* (2016) were included in the recommendations and guidance note (see Section 3).

2.3.1.2. Consideration on the impulsiveness of sound in noise assessments

The assessment of impacts from underwater noise typically makes a distinction between impulsive and non-impulsive (continuous) sounds. This is due to the implications for physiological and behavioural impacts to biological receptors. Currently, underwater noise assessments of nominally impulsive noise use exposure thresholds (i.e. a noise level above which injuries or behavioural responses may occur) which assume exposure to a noise that always retains its impulsive characteristics. However, the situation is more complex. Over the last decade, the flaw in this assumption has been highlighted in publications (i) questioning how and when impulsive sounds become non-impulsive, as sound tends to lose its impulsive characteristics over time and distance, and (ii) highlighting how further consideration should be given to the types of noisy activities to which animals are exposed (i.e. singular or repetitive, brief or extended) and how these affect the defined threshold criteria and responses of receptors. The implication of understanding when the transition from impulsive to non-impulsive sound occurs relates to the levels of noise to which receptors need to be exposed to cause any form of auditory injury or elicit a behavioural response. As such, the impulsiveness of sound is discussed in relation to Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS), namely defining the level of sound to which an individual needs to be exposed to lead to a shift in their hearing sensitivity (hearing threshold) and whether that will be a permanent or a recoverable shift (Popper *et al.* 2014; Southall *et al.* 2019). (More details on noise exposure thresholds are presented in Section 2.3.4.) These assumptions currently remain within the assessment since the limited evidence available regarding how changes in sound impulsiveness and cumulative exposure affect the elicitation of PTS and TTS onset is not yet sufficient to support changes in the criteria (Matei *et al.* 2024). The following provides an overview of the evidence available which supports some of the recommendations made in this report (see Section 3.5).

Although it is recognised that impulsive sound will lose its impulsive characteristics as a function of distance from the source and could become effectively non-impulsive (and less injurious), there are several challenges to identifying a distance at which the transition occurs. The first challenge is how impulsiveness is defined and measured. Several different metrics have been used to quantify impulsiveness of a signal. For example, Hastie *et al.* (2019) used metrics like rise time, pulse duration, quotient between peak pressure and duration, and crest factor, while Matei *et al.* (2024) also considered kurtosis and high frequency content (following Southall 2021). Definitions and recommended thresholds for impulsive sound for the factors considered by Hastie *et al.* (2019) and Matei *et al.* (2024) are provided below:

- Rise time is the time taken by a signal to reach its maximum pressure and 25 m/s has been used as threshold for impulsive sounds (Hastie *et al.* 2019).
- In terms of their duration, signals could be considered impulsive if they lasted less than 1 sec (Hastie *et al.* 2019).
- A quotient of the peak pressure and the signal duration of 5,000 Pa/s has been used as an approximate indication for the transition into non-impulsive sounds (Hastie *et al.* 2019).

- The crest factor is the measurement of the difference between peak sound pressure levels and average (root-mean-square) of a pulse (Starck & Pekkarinen 1987). Recommended thresholds suggest that sounds with a crest factor above 15 dB could be considered impulsive (Pekkarinen & Starck 1983).

- Kurtosis is a summary of the temporal structure of a signal and directly relates by how variable a sound is in pressure amplitudes, or the 'sharpness' of the signal. Sound kurtosis has been found to be a good indicator of impulsiveness with potential impulsiveness thresholds, suggesting that signals with a kurtosis < 3 should be considered non-impulsive and signals with a kurtosis > 40 should be considered fully impulsive (Hamernik *et al.* 2007; Qiu 2020).

- Finally, high frequency content (particularly > 10 kHz) is recommended by Southall *et al.* (2021) as a proxy for impulsiveness.

Analysis of underwater sounds recorded from piling at wind farms across the North Sea indicated that although all these metrics generally decrease over distance, the intensity of the relationship varies between metrics (Hastie *et al.* 2019; Matei *et al.* 2024). Hastie *et al.* (2019) found that, based on a definition relating to rise time and the quotient of peak pressure over duration, impulsive sounds transition to non-impulsive beyond 3.5 km, while using a definition based on the signal durations, sound remained impulsive up to 37 km, and the crest factor threshold was never exceeded. On the other hand, the more recent study by Matei *et al.* (2024) found that:

- Kurtosis significantly decreased within the first 1 km, after which the reduction slowed. This was unaffected by piling parameters such as pile diameter and hammer energy. The transition below fully impulsive, with kurtosis values below 40, happened between the first 0.6 to 3.3 km, while the noise became non-impulsive (i.e. kurtosis < 3) between 13.5 to over 55 km.

- Crest factor decreased rapidly in the first 4 km and then continued decreasing steadily up to 40km from the source. Crest factor values below the 15 dB threshold were reached between 0.4–55 km.

- Peak pressure decreased rapidly in the first 1 km and then continued to decrease until the maximum predicted distance (55 km). Matei *et al.* (2024) placed these results in the context of the PTS onset thresholds for the four marine mammal functional hearing groups (see Section 2.3.2.3). They reported that for piles of a diameter less than 5 m, animals in the high frequency hearing group may never experience impulsive sounds. However, for larger diameters, while animals of all species may still be at risk within the first kilometre, peak pressure dropped below PTS onset thresholds for all functional hearing groups beyond 2 km.

- High frequency content was also found to decrease with distance, but as no thresholds have been specified for this metric, it is not clear where the transition from impulsive to non-impulsive sound would occur.

The difference in the findings of the two studies and between the parameters selected raises uncertainty as to where the transition between impulsive to non-impulsive sounds realistically occurs, and this remains too uncertain for a threshold to be defined. This report, however, recommends that based on the rise time and quotient pressure over duration (Hastie *et al.* 2019), and kurtosis (Matei *et al.* 2024), additional contextual impacts can be presented which apply non-impulsive onset criteria beyond 3.5 km (see Section 3.5.1).

Another approach to account for changes in impulsiveness of sound has been to follow terrestrial studies which have shown that accounting for signal kurtosis by using kurtosis-based correction of SEL thresholds provides a better correlation with animal physiological responses to sound exposure (Hamernik & Qiu 2001) and improved prediction probability of PTS in animals and humans (Goley *et al.* 2011; Zhao *et al.* 2010). As such von Benda-Beckmann *et al.* (2022) investigated the application of kurtosis-correction factors on the auditory injury thresholds for harbour porpoise. The applicability of kurtosis-corrected thresholds was assessed by comparing the results with a generic TTS growth model (i.e. increase of levels of TTS) used for marine mammals (von Benda-Beckmann *et al.* 2022). The results showed that kurtosis-corrected frequency weighted SEL consistently followed the growth of TTS levels for intermittent sound exposure but was not consistent for continuous sound exposure.

Within their limited applicability and transferability to other species, these results indicate that the application of kurtosis corrected thresholds for marine mammals may be justifiable (Lucke *et al.* 2024). By applying the kurtosis thresholds reported in Qiu (2020), Lucke *et al.* (2024) proposes a simplified method to adjust the SEL thresholds using kurtosis. Figure 2 presents a schematic where marine mammal PTS thresholds as defined in NMFS (2018) are kurtosis-corrected and adjusted for sounds that fall within the non-impulsive to fully impulsive spectrum. Taking the methods presented by Lucke *et al.* (2024) into consideration, additional contextual analysis could apply kurtosis-adjusted onset criteria to adjust thresholds based on kurtosis levels. This can also be presented along a graphical representation of kurtosis ranges, by for example displaying on a map where kurtosis levels drop below 40 (no longer fully impulsive), and when they drop below 3 (non-impulsive sound threshold) (see Section 3.5.1).

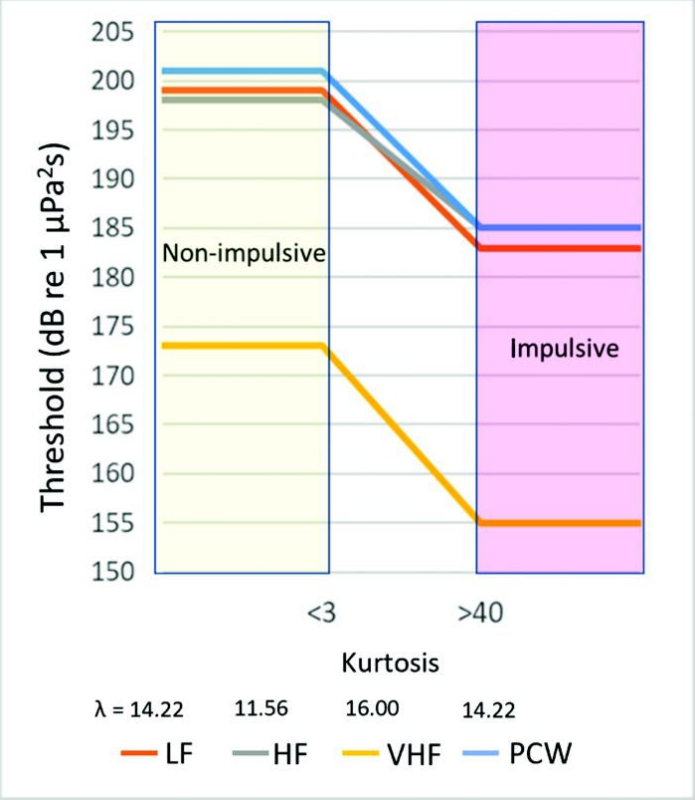


Figure 2. Schematic is adapted from Zeddies *et al.* (2023) and shows the SEL adjustment using kurtosis based on PTS thresholds for four functional marine mammal hearing groups (NMFS 2018). Nomenclature for functional hearing groups is based on Southall *et al.* (2019). (Figure from Lucke *et al.* 2024).

To better understand the implications of accounting for the transition from impulsive to non-impulsive sounds on PTS impact ranges, Matei *et al.* (2024) used an Agent-Based Model (ABM) where animals were simulated to flee from a sound source. In the model, the speed that animals were moving (i.e. the flee speed), the sound source and the ranges where PTS thresholds should be used for impulsive and non-impulsive sounds could be varied. The results showed that flee speed was the most significant factor affecting PTS onset range, and that the sound impulsiveness transition point only influenced PTS onset range at the slowest flee speeds. For example, the most significant difference reached was for the low frequency group where, at the lowest flee speed and with a non-impulsive transition at 1km from the source, only animals within 1 km would be exposed to sound exceeding the PTS onset threshold, while with a transition at 50 km animals within 3 km would exceed the threshold. However, when higher flee speeds were used (e.g. 4 m/s compared to 0.5 m/s or lower) impact ranges dropped to 500 m despite the transition distance at which non-impulsiveness sound occurs.

2.3.1.3. Cumulative exposure and hearing recovery

In a review of noise-induced hearing loss in marine mammals, Finneran (2015) summarises the results of four studies which investigated the role of intermittency and/or exposure duty cycle (i.e. sound being played over a fraction of the time, for example 30 sec of sound followed by 30 sec of silence is a 50% duty cycle, or 'on time') on TTS in marine mammals (Finneran *et al.* 2010; Kastelein *et al.* 2014, 2015; Mooney *et al.* 2010). The studies showed that although TTS accumulates through multiple exposures, the resulting degree of TTS is less than the TTS from a single continuous exposure (Finneran 2015) because of short-term recovery. The recovery could be observed even with very short intervals; for example, Kastelein *et al.* (2014) showed that 1 second of silence in between pulses resulted in a 3–5 dB lower TTS for a captive harbour porpoise, compared to continuous sounds, and that harbour porpoise experience a 5.5 to 8.3 dB lower TTS when exposed to sounds with a 25% duty cycle compared to continuous sounds.

Sinclair *et al*. (2023) and Sinclair and Verfuss (2021) used these findings to highlight the potential conservatism in the current PTS assessments for pile driving, which typically have a duty cycle < 25% during the soft start and initial ramp up. Southall *et al*. (2019) calculates the PTS-onset thresholds based on the assumption that a TTS of 40 dB will lead to PTS, and that an animal's hearing threshold will shift by 2.3 dB per dB SEL received from an impulsive sound. This means, if the same SEL elicits a ≥ 5.5 dB lower TTS at 25% duty cycle compared to 100% duty cycle, as noted above, to elicit the same TTS as a sound of 100% duty cycle, a ≥ 2.4 dB (≥ 5.5 dB / 2.3) higher SEL is needed with a 25% duty cycle than with a 100% duty cycle. Therefore, the threshold at which PTS-onset is likely is at least 2.4 dB higher than the PTS-onset threshold proposed by Southall *et al.* (2019) when considering a 25% duty cycle (see Box 1). The methods suggested by Sinclair *et al.* (2023) and Sinclair and Verfuss (2021) are recommended in this report to provide additional contextual analysis within the noise assessment (see Section 3.5.2).

Box 1. Worked example to achieve estimated increase by 2 dB to 3 dB supported by Sinclair *et al.* (2023).

Harbour porpoise cumulative PTS threshold = 155 dB SEL_{cum} at 100% duty cycle

If a 25% duty cycle leads to 5.5 dB lower TTS response:

155 dB SEL_{cum} PTS cumulative threshold: 40–5.5 = 34.5 dB TTS response

To reach the 40 dB TTS, the threshold shift needs to increase enough to elicit an additional 5.5 TTS response. Based on the assumption: 1 dB SEL = 2.3 dB hearing threshold shift.

2.3 dB hearing: x = 1: 5.5d B TTS

5.5 dB TTS response / 2.3 dB hearing threshold shift = 2.4 dB

New PTS threshold is 155 + 2.4 = 157.4 dB SEL_{cum}

2.3.1.4. Temporal patterns of pile strikes

Matei *et al.* (2024) were also able to use their ABM to assess the impacts of the temporal pattern of hammer strikes (i.e. the variation in hammer blow rates), on PTS onset ranges by accounting for different hammer logs (i.e. records of timings and blow energies in real piling events). The results showed that the selection of flee speeds was the most significant factor influencing PTS onset ranges. Accounting for the changing blow rates showed a significant reduction in PTS impact ranges compared to baseline in almost all cases, with a 57% median reduction in the area subjected to PTS onset noise exposures. Mean inter-blow interval in the first 45 minutes of piling was found to be the best predictor for a reduction in PTS impact ranges. This report includes the use of Matei *et al.* (2024) ABM method as an additional analysis that can be used to assess how piling intervals can be used to reduce PTS impact ranges (see Section 3.5.2).

2.3.1.5. International underwater noise assessment guidance for pile driving

The current lack of guidance on how to present underwater noise assessments in UK waters led to inconsistencies into presentation of results in previous assessments and hinders the comparability of future ones (Verfuss *et al.* 2023).

Several countries across Europe, and the United States, have released recommendations and guidance on how to assess and mitigate the impacts of underwater noise from impact-piling activities on key receptors. The level of detail in the guidance varies significantly between countries where guidance is available, with some providing broader reviews of impacts of anthropogenic noise, including pile driving (Andersson *et al.* 2016; Persohn *et al.* 2020), to others which provide direct guidance on how to carry out underwater noise assessments for pile-driving activities and reporting requirements (BOEM 2023; Danish Energy Agency 2022a; Müller & Zerbs 2013).

Current guidance from the Bureau of Ocean Energy (BOEM) in the United States, the Danish Energy Agency, and the Federal Maritime and Hydrographic Agency of Germany (BSH *in German*) provide detailed examples of how underwater noise assessment could be carried out as part of applications for construction permits for offshore wind farms (BOEM 2023; Danish Energy Agency 2022a; Müller & Zerbs 2013). The American and Danish approaches follow a similar structure, where the first section of the guidance focusses on the noise modelling, including key factors that should be considered, details that should be included in the reports (see Table 4), and details of the noise thresholds that should be used

for various species to assess auditory injury and disturbance. The second part of the reports focus on recommendations and guidelines on how to collect data in the field to verify modelled outputs. On the other hand, the German guidance mostly focusses on the information required in the final report.

Key additional points included in these examples of guidance notes are:

- Considerations around the use of Individual (i.e. Agent) Based Models (IBMs) as one of the most accurate methods to assess individual noise exposure (BOEM 2023).

- In Denmark, the use of Acoustic Deterrent Devices (ADD) is mandatory during construction, except for a few low-noise scenarios. Thus, the guidance reports on the recommended use of ADD, and the assessment itself should include details on the impacts of the use of ADD (Danish Energy Agency 2022a).

- Details are provided on the flee speeds that should be used within the assessment, and how, in some instances, animals should be assumed to be at a specific distance from the noise source (Danish Energy Agency 2022a).

2.3.1.6. Examples of underwater assessments in UK waters

Verfuss *et al.* (2023) undertook a review and comparison of impact assessments for nine offshore windfarms built between 2005 and 2017 across the North Sea. The review aimed to compile the approaches taken in the noise assessments and noise field measurements to compare measured data between projects to the respective modelled outputs presented in their assessments. Verfuss *et al.* (2023) highlighted in their conclusions that the lack of standardised reporting across assessments made the comparison between projects difficult with information about key parameters sometimes lacking. Furthermore, although collection of validation data is often a licence condition, the lack of a standardised approach and reporting on the data collection protocol made a comparison between projects challenging (Verfuss *et al.* 2023). The authors highlighted the importance of using such data to inform future assessments and made recommendations on methods of reporting to ensure comparability in future projects.

As part of this literature review, several underwater noise assessments for UK projects were reviewed to compare the level of details included throughout the report. Table 5 summarises the key elements included in each assessment. The review highlighted some initial areas where reporting between projects seems to significantly vary:

- presentation of multiple scenarios (e.g. worst-case and most likely),

- order and level of details included in the results,

- report on additional data collection on background noise levels at the site prior to construction, and

- use of mitigation methods (e.g. ADD use) as part of the modelling approach.

Table 4. A summary of the key requirements for what should be included in construction permit applications in three countries.

Section	**United States** (BOEM 2023)	**Denmark** (Danish Energy Agency 2022a)	**Germany** (Müller & Zerbs 2013)
Description of the model	• Type of model used (e.g. finite element model, ray tracing, parabolic equation, etc.).	• Type of model/s (numerical or semi-empirical) and choice of model/s.	• Distributional model used (e.g. theoretical models, empirical models). • Use of experimental data.
Description of the environment	• Geotechnical information. • Bathymetry. • Substrate layering. • Sound speed profiles.	• Hydrographic condition extremes. • Bathymetry. • Seabed layer. • Sound speed profiles. • Conditions at the surface (e.g. weather or surface roughness).	• Bathymetry. • Wind, wave height, breaking waves and current. • Sound speed profiles. • Acoustic soil properties.

Section	**United States** (BOEM 2023)	**Denmark** (Danish Energy Agency 2022a)	**Germany** (Müller & Zerbs 2013)
Description of the construction scenario	• Sound sources used. • Water depth for each pile type. • Water depth for each modelled location. • Foundation type. • Pile characteristics. • Pile penetration. • Hammer characteristics. • Number of piles over 24 hours.	• Justification for why selected sites are representative of the full array. • Detail of ADD planned to be used in the assessment. • Duration of the pile driving activity and hammer action (hammer energy, number of blows and interval between blows). • Details of three construction scenarios: reference case (unmitigated), planned construction (with noise mitigation) and ADD case.	• Source level (how this is defined and determined). • Consideration given to all noise-intensive construction activities. • Central location to the windfarm can be used for modelling (assume same foundation and homogeneous environment). • All type of foundations should be assessed. • Consider concurrent piling. • Consider other activities ongoing at developments within 30 km. • Presentation of mitigation measures to be used and justification. • Pile driving energy. • Number of driving impacts. • Frequency of impacts. • Three power ranges of operational turbines: low, medium and high rated output.
Description of the Biological elements	• Species potentially present during the construction period. • Seasonality and changes in density and abundance. • Acoustic criteria applied for each species.	• List of species potentially in the concession area.	None

Section	**United States** (BOEM 2023)	**Denmark** (Danish Energy Agency 2022a)	**Germany** (Müller & Zerbs 2013)
Modelling results	• Power spectral sources at 1 m from the source. • Power spectral received levels at 750 m from the source. • Maximum broadband sound level. • Horizontal distances at which sound levels are encountered. • Ensonified area. • Attenuation methods. • Transmission loss approximations.	• Unweighted spectrum of the noise source. • Variation of noise source metrics across water depth. • Variation of noise source metric as a function of pile penetration.	• Average transmission loss at 750 m from the noise source. • Estimates across the whole water column. • Results to be presented at 750 m and 5,000 m from the noise source and for the closest nature conservation site. • Estimates with and without noise mitigation. • Presentation of SEL in relation to the limit values.
Presentation of radial distances	• Distances from the pile for the respective thresholds for all species. • Acoustic ranges as 95% isopleths. • Received levels at 750 m from the noise source.	• Examples provided but requirements less prescriptive.	None
Presentation of exposure estimates	• Agent-based exposure model results. • Exposure estimates without aversion. • Percent of population stock exposed.	• Examples provided but requirements less prescriptive.	None

Table 5. Elements included in three underwater noise impact assessments undertaken for three offshore wind farm projects in UK waters.

Topic	Example 1	Example 2	Example 3
Introduction and review	Review of background information on the units for measuring and assessing underwater noise, underwater noise metrics and criteria for biological receptors.	Detailed review of basic underwater concepts including units for measuring underwater noise, metrics and criteria for biological receptors. Overview of various noise sources associated with construction and operation activities.	Includes introduction to the project and review of basic underwater acoustic concepts. Includes review of baseline ambient noise at the site.
Methods and Approach	Approach, input parameters and assumptions of the noise modelling approach. Details provided on modelling approach and assumptions of the modelling framework. Parameter details provided: • Modelling locations • Piling parameters and scenarios modelled • Source levels used • Environmental conditions: sediment type and bathymetry • Flee speeds used for biological receptors	Overview of modelling approach used. Parameter details provided: • Bathymetry data source • Flee speeds of biological receptors.	Overview of the noise propagation model. Parameter details provided: • Bathymetry data source • Piling parameters and scenarios modelled • Flee speeds used for biological receptors
Results - noise modelling	Measured background noise levels in the area. Methods and details on background noise level measurements and placed results in wider context. Sourced additional data where possible.	Not included.	Not included.

Topic	Example 1	Example 2	Example 3
Results - receptor exposure	Presentation and interpretation of noise modelling with regards to the effects on marine mammals and fish. Tables including ranges for worst-case and most likely scenarios according to the biological receptor thresholds and for construction method (monopile and pin-piles). Results and maps for concurrent and consecutive piling scenarios	Impact ranges provided in tables for all noise sources in order of construction phase. For impact piling: • Some high-level discussion of assumptions. • Tables presenting ranges with and without ADD.	Impact ranges provided in table, figures and maps. Inclusion of review of empirical evidence on the impact of underwater noise on marine mammals. Results and maps for concurrent piling and overall construction footprint. Discussion on the use of mitigation methods.
Additional	Noise modelling of other noise sources expected around construction and operation: cable laying, trenching, rock placement, drilling, dredging, vessel noise, operational WTG noise and UXO detonation.	Additional noise sources are integrated into the main results. A section on proposed mitigation measures and residual impacts is included.	Included noise footprint of the construction phase for the whole wind farm. Included assessment of operational noise and decommissioning. Discussion of potential cumulative impacts in relation to neighbouring projects.
Summary and conclusions	Summary of the key results in the context of worst predicted outcomes.	Summary of key results.	Provides final conclusions.

2.3.2. Sensitivity of biological receptors to noise

Although assessment of underwater noise impacts may not be limited to marine mammal and fish species, these are often considered the taxonomical groups most at risk and are the groups where sufficient noise sensitivity data exists to carry out an assessment. The potential impacts of noise vary between the two groups due to how animals perceive sound. There are two key descriptors of sound to which taxa groups have been identified to have varying sensitivities, which should be considered when screening species for inclusion in assessments:

1) sound pressure, and

2) particle motion.

While all marine mammal species sense underwater sound through sound pressure, there is a large degree of interspecific variation among fish species, which varies from sensing only particle motion, to a mixture of both particle motion and sound pressure.

2.3.2.1. Sound pressure

Sound pressure is sensed by marine mammals (and mammals generally), with some indirect detection by certain fish species (Faulkner *et al.* 2018). Sound pressure acts in all directions, and can be described by temporal and frequency characteristics, as well as magnitude (Popper & Hawkins 2019). Sound pressure is expressed in units of pascals (Pa) or micro-pascals (µPa). Popper and Hawkins (2019) suggests that impulsive sounds (e.g. pile driving) should be presented as the instantaneous peak level (dB $L_{peak,}$ $L_{p,pk}$) when reporting sound exposure. The Sound Exposure Level (SEL, L_E) can be specified for a single strike (SEL_{ss}). For repetitive impulsive sounds such as pile driving over a period, it is appropriate to estimate the cumulative SEL (SEL_{cum}) associated with a series of pile strikes – defined as the total noise energy animals are exposed to over a defined period.

2.3.2.2. Particle motion

Fish and invertebrates primarily sense sound as particle motion (Faulkner *et al.* 2018; Nedelec *et al.* 2016), which can be expressed in terms of particle displacement in metres (typically millimetres), or its time derivative as metres per second (m/s) or particle acceleration (m/s^2) (Popper & Hawkins 2019). Particle motion is a back-and-forth motion, compared to sound pressure which acts in all directions. It is detected by all fishes (including elasmobranchs), even those not sensitive to sound pressure (Popper & Hawkins 2019). Despite so many species sensing sound as particle motion, there is much less information on its effects from anthropogenic sound such as pile driving on receptors. This is largely due to the lack of availability of instruments to measure particle motion, which is more complicated to measure than sound pressure, and a lack of guidance on analytical methodology (Nedelec *et al.* 2016). While particle motion can be estimated from sound pressure levels, the practicality of this is restricted to certain conditions that are rarely met in shelf-seas (e.g. relatively far from reflective boundaries which may influence the shape of the wavefront; Nedelec *et al.* 2016), where many piling assessments are focussed.

While fish primarily sense sound by detecting particle motion, with relatively few detecting sound pressure, there remains a considerable knowledge gap on species' hearing sensitivity to particle motion (Popper & Hawkins 2019). The literature suggests repeatedly that this knowledge gap needs to be addressed, and that the sound from anthropogenic sources should be measured in terms of particle motion, as well as sound pressure. Hawkins and Popper (2017) go as far as to say that assessments cannot be considered satisfactory for fishes and invertebrates unless particle motion is included in addition to sound pressure,

although this conflicts with the lack of availability of criteria in terms of particle motion sensitivity and the means of assessing it. Recent environmental impact assessments have acknowledged that the effects of particle motion are important to consider in noise assessments. However, they are not well understood for fishes and have not been the main consideration in noise impact assessments to date. Due to the lack of knowledge, there is not enough evidence to include any recommendations on how to assess the impacts of particle motion in this report. However, this has been highlighted as an item for future improvement (see Section 4.3.2).

2.3.2.3. Hearing groups

Within each taxonomical group further subgroups have been identified. For marine mammals, these are based on hearing abilities (i.e. frequency range that species are more sensitive to) (Table 6). The marine mammal hearing groups used in recent marine mammal impact assessments were first defined in Southall *et al.* (2007). These groups were created to separate different marine mammal species based on phylogenetic relationships and a combination of auditory, physiological and behavioural characteristics. As more data on these characteristics has become available, the hearing groups have been updated in the NMFS guidance (2016, 2018, 2024) and in Southall *et al.* (2019). Eight distinct hearing groups are now recognised: Low frequency (LF) cetaceans, high frequency (HF) cetaceans, very high frequency (VHF) cetaceans, sirenians, phocid carnivores in water (PCW), phocid carnivores in air (PCA), other marine carnivores in water (OCW) and other marine carnivores in air (OCA). Due to the marine mammal species likely to be present at sites in the UK, only LF, HF and VHF cetaceans and PCW are considered further in this review.

The perception of sound to fish and the impacts of noise exposure are far less understood, compared to the current knowledge for marine mammals. Lucke *et al.* (2024) suggests that research on the effects of sound on fish and invertebrates is approximately 30 years behind research on marine mammals. As such, fish and invertebrates have been broadly grouped anatomically based on how these groups sense sound. The hearing groups are characterised for fish species (Popper & Hawkins 2019), and fish and invertebrates (Lucke *et al.* 2024), and are respectively reproduced in Table 7 and Table 8. The two sets of groupings are similar in that Group One and Group Two as defined by Popper and Hawkins (2019) are primarily sensitive to particle motion (including flatfish, sharks, skates and rays), as for the particle motion sensing groups A2 to A4 as defined by Lucke *et al.* (2024). Groups Three and Four as defined by Popper and Hawkins (2019) include sound pressure sensitive species such as cod, eels, croakers, drums and herring, which are represented in pressure sensitive groups P1 – P3 as defined by Lucke *et al.* (2024).

Table 6. Marine mammal hearing groups relevant to species in UK waters, reproduced from NMFS (2024).

Marine mammal hearing group	Auditory weighting function	Common and scientific names of relevant species
Low-frequency cetaceans	LF	Minke whale (*Balaenoptera acutorostrata*), humpback whale (*Megaptera novaeangliae*) and fin whale (*Balaenoptera physalus*).
High-frequency cetaceans	HF	Bottlenose dolphin (*Tursiops truncatus*), white-beaked dolphin (*Lagenorhynchus albirostris*), Atlantic white-sided dolphin (*Lagenorhynchus acutus*), Risso's dolphin (*Grampus griseus*), killer whale (*Orcinus orca*), sperm whale (*Physeter macrocephalus*), striped dolphin (*Stenella coeruleoalba*), short-beaked common dolphin (*Delphinus delphis*) and long-finned pilot whale (*Globicephala melas*).
Very high-frequency cetaceans	VHF	Harbour porpoise (*Phocoena phocoena*)
Phocid carnivores in water	PCW	Harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*).

Table 7. Generalised fish groups based on sensitivity to noise and hearing capabilities proposed by Popper *et al.* (2014) and presented by Popper and Hawkins (2019).

Group	Characteristics	Examples
One	Lack swim bladders. Sensitive to sound particle motion and a narrow band of frequencies.	Flatfishes (*Pleuronectiformes*) and sharks, skates and rays (*Chrondrichthyes*).
Two	Possess swim bladders, albeit do not appear to play a role in hearing. Sensitive to particle motion only and show sensitivity to a narrow band of frequencies.	Salmonids (*Salmonidae*), some tuna and mackerel (*Scombridae*), and likely many other species.
Three	Possess swim bladders that are close but not intimately connected to the ear. Sensitive to both particle motion and sound pressure. Frequency range extended beyond those of Group one and two, up to approximately 500 Hz.	Cod (*Gadidae*), eels (*Anguillidae*), some drums and croakers (*Sciaenidae*), and others.
Four	Possess special structures mechanically linking the swim bladder to the ear. Primarily sensitive to sound pressure but also detect particle motion. Hearing covers widest frequency range up to several kHz. Generally higher sensitivity to sound pressure than Groups one, two or three.	Squirrelfishes (*Holocentridae*), most drums and croakers (*Sciaenidae*), herrings (*Clupeidae*), and a large group of otophysan fishes.
Five	Eggs and larvae	

Source: Popper and Hawkins (2019).

Table 8. Fish and invertebrate hearing groups proposed by Lucke *et al.* (2024).

Hearing Group	Description	Examples
A	**Acceleration sensitive, non-pressure sensing, particle motion sensing**	
A1	Invertebrates	Cephalopod, crustaceans, bivalves
A2	Cartilaginous fishes	Elasmobranchs: shark, skate, rays, chimaeras (ratfishes)
A3	Bony fishes without a swim bladder	Flatfishes, mackerels, swordfish, tuna, gobies
A4	Bony fishes with a swim bladder not involved in hearing	Sturgeon, salmon, deep sea lanternfishes

Hearing Group	Description	Examples
P	**Known pressure sensitivity in bony fishes with a swim bladder involved in hearing**	
P1	Without adaptation	Cod, haddock, pollack, seabass, croakers, drums
P2	Mechanical connection of swim bladder to inner ear (e.g. Weberian ossicles)	Otophysan: goldfish, zebrafish, catfish, electric eel, knifefish
P3	Ultrasonic adaptation, bubble near ear, or a standard ear	Clupeids: shad, menhaden, herring, sardine

Source: Lucke *et al*. (2024).

2.3.3. Criteria for scoping species and species groups into assessments

An important step in the assessment is identifying the potential sensitive receptors that should be included in the assessment. Sensitive receptors can be scoped into assessments based on their sensitivity to anthropogenic noise generated during construction, temporal and spatial distribution in relation to the proposed development, and modelled effect areas. While some areas will be consistently used through the year others may be linked to seasonally sensitive behaviours. For fish, temporal sensitivity can include spawning and nursery grounds, or migration routes which are not used year-round. For marine mammals, temporal sensitivity can include calving and pupping areas, seasonal haul-outs, nursery grounds, and migration routes which are not used year-round.

Given the conservation status of marine mammal species, they often tend to become the focus of the noise assessment. Faulkner *et al.* (2018) and Hawkins and Popper (2017) suggest that fish and turtles, plus marine crustaceans and elasmobranchs, should also be scoped into Environmental Impact Assessments where relevant and when they are a key component of the local ecosystem (Hawkins & Popper 2017). Species should be scoped into the assessment where the potential impact may affect populations and their sustainability (Hawkins & Popper 2017). Attention should be given to the protection levels of certain species across the different jurisdictions, as for example, certain fish species have designated Marine Protected Areas (MPA) or are considered Priority Marine Features (PMFs). For certain fish species, arguments in support of their inclusion have also been made based on their commercial values. However, Hawkins and Popper (2017) stress that species should not be scoped in purely for commercial interest, and instead susceptibility to

the effects of noise exposure should be considered as well. Another source for information on species that should be considered is the Defra commissioned report, Williams *et al.* (2021), which presents an overview of key marine species likely to be sensitive to anthropogenic noise that are either of high commercial values or have high levels of protection in English waters.

The spatial and temporal distribution of sensitive receptors is normally described as part of a baseline and is generally based on published data and/or model outputs rather than data collected for the project, due to the large extent that must be captured and the difficulties in generating robust datasets for these species. In addition to these, for abundant marine mammal species which can be detected during site-specific surveys such as digital aerial surveys, these data can provide a more detailed occurrence at the site, and an indication of temporal patterns of occurrence. However, the most appropriate sources of information on receptors occurrence at the proposed development site and potential overlap with sensitive areas will be project-specific, and likely to require regular updates as new information is published. Table 9 provides some examples of the types of datasets which could be used to determine potential overlap of distribution and effect zones. While most of these datasets are not temporally explicit, other information captured in baseline reports is often used to identify where overlaps may occur between receptor occurrence and the effect zone.

Hawkins and Popper (2017) advocate for all species present to be considered during assessment to identify those that may be particularly sensitive to noise exposure, and those that play an important ecological role in the ecosystem. Considering proximity of key habitats such as those where reproductive activities take place goes some way to achieving this, by prioritising key life stages. The authors further suggest that sensitivity indices should be devised to help identify fish species that should be assessed.

Table 9. Example datasets commonly used to understand distribution of receptors.

Taxa	Example datasets	Information available
Cetaceans	Small Cetaceans in European Atlantic Waters and the North Sea (SCANS)	Point-estimates for survey blocks, and modelled density surfaces covering the study area – available infrequently and only for summer months.
	Evans & Waggit (2023)	Monthly modelled density surfaces for Wales and surrounding waters.
Seals	Carter *et al.* (2022), (2025)	Modelled relative density of grey and common seals for at-sea distribution around the UK and Ireland, and updated distribution for Scotland only.
Fish	Coull *et al.* (1998); Ellis *et al.* (2012)	Sensitivity and habitat maps covering UK waters, showing nursery and spawning areas.
	International Herring Larvae Survey (IHLS) Data	Larval count and size data which can be used to estimate density to approximate spawning locations to add additional context to Coull *et al.* (1998) and Ellis *et al.* (2012).

2.3.3.1. Marine mammal and fish auditory injury from noise exposure

Once sensitive receptors have been scoped in the assessment, outputs of propagation models are used to determine the extent and magnitude of noise that receptors may be exposed to. Noise exposure thresholds have been used to identify the area from the sound

source within which animals will be exposed to noise levels that may negatively affect them through disturbance or injury. Various sound exposure criteria have been adopted by regulators for the assessment of marine mammals (including for example Lucke *et al.* 2009; NMFS 2018; Southall 2021; Southall *et al.* 2019). These generalise species into hearing groups, with criteria that tend to be revised and implemented in assessments as they are published or superseded. Several criteria also exist for fish with Popper *et al.* (2014) representing the generally accepted source for the past 10 years, but these thresholds are limited in scope and restricted to broad species groups.

Potential auditory injury is often assessed based on exposure to a single instantaneous event or to cumulative exposure over 24 hours (NMFS 2024), with noise exposure thresholds being defined for both assessments. A key parameter to be considered in the cumulative assessment assumes that an animal will move away from the noise source, and the speed at which they will move away will significantly influence for how long they will be exposed to noise levels above the thresholds. Due to the high variability of flee speeds that have been assumed in previous assessments, Section 2.3.4.3 reviews the current evidence behind flee speeds and estimates being used.

At the time of publishing of these recommendations, the most up to date criteria and thresholds are those provided in NMFS (2024) and Popper and Hawkins (2019), and these are currently recommended for use in assessments. However, these have also been recommended as a point for consultation with the relevant regulators as future updates to the thresholds may be published.

2.3.3.2. Marine mammals noise exposure criteria

Noise exposure criteria (i.e. thresholds) for marine mammals typically consist of set sound levels (SPL_{pk} ($L_{p,pk}$) and SEL_{cum} ($L_{E,p,t}$)) above which animals could begin to suffer negative effects to their hearing capabilities. Different thresholds were defined to assess the potential for a Temporary Threshold Shift (TTS) and for a Permanent Threshold Shift (PTS). Species of marine mammals vary significantly in hearing capability across the frequency spectrum, and so a critical step in the definition of these thresholds was to adjust them using auditory-weighted functions (NMFS 2024), based on species-specific or group-specific audiograms (Finneran 2016).

The marine mammal noise exposure thresholds have evolved over time as new information became available. The most used auditory injury guidance in recent years are those provided in National Marine Fisheries Service (NMFS) (2018) and Southall *et al.* (2019). Most recently, updated regulatory guidance in the US has been provided by the NMFS to update and replace their NMFS 2018 Revised Technical Guidance (NMFS, 2024). Two of the three main aspects of the updated guidance covering marine mammal hearing groups and auditory injury onset criteria are summarised in Table 10.

One key update provided in the NMFS (2024) guidance is the change in naming conventions from PTS to Auditory Injury, which is defined as “damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy (Finneran *et al.* 2023; Houser 2021). Auditory injury may or may not result in a permanent threshold shift (PTS).

Table 10. Generalised marine mammal hearing groups, and estimated criteria for auditory injury from impulsive and non-impulsive underwater noise, at received levels.

Hearing group	Example species relevant to UK waters	Generalised hearing range	Auditory injury onset (in water)		
			Impulsive, Flat	Impulsive, Weighted	Non-impulsive ($L_{E,p,24hr}$)
Low-frequency (LF) cetaceans	Baleen whales	7 Hz – 36 kHz	222 dB	183 dB	197 dB
High-frequency (HF) cetaceans	Dolphins, toothed whales, beaked whales, bottlenose whales	150 Hz – 160 kHz	230 dB	193 dB	201 dB
Very High-Frequency (VHF) cetaceans	Harbour porpoise	200 Hz – 165 kHz*	202 dB	159 dB	181 dB
Phocid pinnipeds underwater (PW)	Grey and common seals	40 Hz – 90 kHz	223 dB	183 dB	195 dB

Source: Adapted from NMFS (2024). *Example hearing range given in NMFS (2024) covers additional species not found in UK waters. 'Flat' relates to $L_{p,pk}$, without a frequency weighting. 'Weighted' is the frequency-weighted cumulative SEL $L_{E,p}$ with respect to species hearing groups.

2.3.3.3. Fish noise exposure thresholds

Literature surrounding physical injury to fishes from noise exposure is relatively limited, with a small number of species studied, often undertaken in laboratory conditions that differ from natural soundscapes *in-situ* (Popper & Hawkins 2019).

As limited information is available on criteria for injury arising from particle motion as opposed to sound pressure, interim guidance on levels focus on sound pressure thresholds. This also includes fish species that do not possess swim bladders (Table 11) despite their known sensitivity to particle motion rather than sound pressure. There is evidence that fishes that experience high intensity and particularly impulsive noise can experience damage to body tissues (Popper & Hawkins 2019). This damage appears to result from oscillation of the swim bladder walls, leading to a rapid expansion and subsequent contraction which can damage proximate organs and the swim bladder (Halvorsen *et al.* 2012; Popper & Hawkins 2019). Generally, it is expected that the higher the cumulative level of sound energy that fish are exposed to, the greater the tissue damage will be, with mortal injury a possibility.

Table 11. Proposed interim criteria for mortality and recoverable injury from exposure to pile driving signals.

Type of Animal	Mortality and potential mortal injury	Recoverable injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	> 219 dB SELcum or > 213 dB peak	> 216 dB SELcum or > 213 dB peak	> 186 dB SELcum
Group 2 Fish: swim bladder is not involved in hearing (particle motion detection)	210 dB SELcum or > 207 dB peak	203 dB SELcum or > 207 dB peak	> 186 dB SELcum
Group 3 and 4 Fish: swim bladder involved in hearing (primarily pressure detection)	207 dB SELcum or > 207 dB peak	203 dB SELcum or > 207 dB peak	186 dB SELcum
Sea turtles	210 dB SELcum or > 207 dB peak	(N) High (I) Low (F) Low	-
Eggs and larvae	> 210 dB SELcum or >207 dB peak	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Source: Popper and Hawkins (2019), from Popper *et al*. (2014). Criteria are based on 960 sound events at 1.2 s intervals. The same peak levels are used both for mortality and recoverable injury. Relative risk (high, moderate, low) is given for animals at three broadly defined distances from the source defined in relative terms: N, near; I, intermediate; F, far (from Popper *et al*. 2014). Units for peak and rms sound pressure levels are dB re 1 µPa; SEL dB re 1 $\mu Pa^2 s$. All criteria are presented as sound pressure even for fishes without swim bladders since no data for particle motion exist.

2.3.3.4. Estimating sound exposure

The potential of an effect to biological receptors from noise is generally assessed both as exposure to instantaneous single strikes and to cumulative exposure to sound over a defined period (generally 24 hours). While the former is estimated based only on the sound source levels and transmission loss, the latter needs to consider that certain animals may change position relative to the sound source during the exposure period and thus the sound exposure level that they will receive will vary over time. The method proposed by Lepper *et al.* (2012) was to account for animal movement using an Individual Based Models (IBM) or Agent Based Models (ABM), where individual animals are simulated in time and space to estimate the sound exposure level that they will receive during the exposure period. Note that animals could move away from the sound source or remain stationary, which will depend on the species and their expected behaviour. Within ABM, an agent (i.e. simulated animal) movement is parametrised using reliable data, possibly measured from wild animals, to simulate as accurately as possible how an animal would move. For example, animal flee speed is a critical parameter that was found to be a significant parameter in determining the size of PTS impact ranges. For more details on appropriate selection of flee speeds, see Section 2.3.4.4.

The complexity of ABMs and the number of parameters required varies significantly across assessments. It may be appropriate for the ABM to model animals moving away in a directional manner from the noise source at a constant flee speed or in a more random way. Cumulative exposure over the piling operation is then estimated using the levels of sound exposure that the agent receives at each pile strike depending on their distance to the sound source at any given strike. Models employed to estimate exposure can be also very complex. An example is JASCO's Animal Simulation Model Including Noise Exposure (JASMINE), which also considers animals movement in 3D, accounting for their diving behaviour and how that, in turn, affects the sound exposure levels they are exposed to.

ABM can also take on more complexity by accounting for animal behavioural responses like aversion. This has been recommended within other national guidance (BOEM 2023) to only be considered as an add-on and only when sufficient evidence is available that the species of interest does display aversion towards such stimulus. The main challenge of the additional complexity is how it is parametrised and the reliability of the data that support these parameters. To the best of our knowledge, there is not strong evidence that supports which parameter(s) must be included to appropriately represent animal movement within this scenario. As such this report will not make prescriptive recommendations on the level of complexity that should be included within the model, but it will request that details are provided for all the parameters included and that these will be supported by evidence (Section 3.3).

The application of these methodologies should come with acknowledgement of their limitations. For example, although animal evasive responses directly away from the noise source have been recorded (Graham *et al.* 2023), it is unknown how far animals will support a direct evasive response and whether the assumption of a continuous directional movement is met throughout the piling operation, or whether future simulations should also account for more complex swimming patterns (Matei *et al.* 2024). The presence of vessels at the piling site has been demonstrated to reduce the occurrence of animals and initiate displacement (Benhemma-Le Gall *et al.* 2023), which in addition to the use of mitigation measures such as ADDs to clear instantaneous impact zones, means the assumption that an animal will be present at the piling location is also not realistic. Additional limitations flagged by Matei *et al.* (2024) are that the 2D models assume animals to be in the loudest part of the water column; this is partially overcome by some 3D models, however these are only viable if they can be informed by accurate data and the impact of this additional computational challenge on the resulting impact ranges is still not quantified. Furthermore, Matei *et al.* (2024) also flag the limitation of assuming a constant source level, without considering SEL changes throughout the piling sequence, and recommend the inclusion of hammer energy as a parameter in future models. Finally, it is often acknowledged that movement models do not account for breaks in piling and hearing recovery over this 'quiet' period, a limitation that has been already discussed in Section 2.3.1.3. While currently there are no direct measures that can be applied within the modelling approach that will account for all these limitations, this report encourages users to overcome this however possible or acknowledge them within the assessment (see Section 3.3).

2.3.3.5. Animal responses to underwater noise – flee speeds

During exposure modelling, different swim speeds are assumed for different receptors. Simulations are modelled with animals either stationary (e.g. fish larvae), or swimming away from the noise source, where receptors demonstrate a flee response. At present, there is no overarching national guidance in the UK regarding flee speeds to use in assessments. Environmental impact assessments conventionally use values for marine mammal hearing groups known to be accepted by Statutory Nature Conservation Bodies (SNCBs) in England, Scotland and Wales, which can be different across the nations. There is a need for recommended flee speeds to be included in any guidance developed so that assessments

are consistent across the UK jurisdictions, and to ensure that flee speeds used are based on the most up-to-date understanding of animal responses to pile driving noise or mitigation stimuli such as ADDs. One of the main conservatisms of flee speeds used, often highlighted in assessments, is that in some cases these values represent baseline swimming speeds of animals without external stimuli rather than flee responses, which may not provide true representations of animal behaviour when responding to ADDs or impact-piling activities.

Examples of flee speeds used in recent assessments are presented in Table 12. While not included in submitted planning applications that were reviewed, there are additional flee speeds reported in the literature which could be adopted, potentially leading to reduced conservatism where these speeds are higher than previously used. For example, McGarry (2017) recorded mean and maximum flee speeds of minke whales exposed to an ADD of 4.19 m/s and 5.94 m/s respectively. Comparing these to values of 2.1 m/s (as typically used in underwater noise assessments for Scottish projects), and 2.3 m/s, and 3.25 m/s (as typically used in English and Welsh underwater noise assessments), some consistency is needed (Scottish Natural Heritage 2016; Seiche 2024, 2022; Subacoustech Environmental 2018).

In recent assessments, flee speeds used for harbour porpoise are consistently 1.5 m/s, originating from Otani *et al.* (2001). Despite this consistency in assessments, more recent information is available, with one study reporting a flee speed of 1.97 m/s for harbour porpoise exposed to offshore pile driving sounds (Kastelein *et al.* 2013).

It is generally assumed that fish remain stationary, given little evidence for any sustained flee response to impulsive underwater noise in fish. However, it has been common in assessments to include an additional modelled dataset for fleeing fish at 1.5 m/s (Hirata 1999), to provide another boundary to the envelope, noting that the initial presumption that all fish will remain stationary when exposed to high noise levels likely represents an unrealistic and over-precautionary position.

A small number of recent environmental impact assessments for windfarm consent applications were reviewed to identify the species and groups that are assessed, and flee speeds used in the assessment (Table 12). This highlights the variability of speeds used for the same hearing groups across assessments.

Table 12. Swim speeds assumed for exposure modelling, used in recent environmental impact assessments for proposed offshore windfarms.

Species	Hearing Group	Swim speed (m/s)	Source reference	Assessments
Harbour porpoise	VHF	1.5	Otani (2001)	Green Volt OWF (Seiche 2024), Berwick Bank OWF, (Seiche 2022) Hornsea 3 OWF (Subacoustech Environmental 2018), Dogger Bank South OWF (RWE 2024), Mona OWF (RPS 2025)
		1.4	Westgate (1995)	SNH guidance (2016) for underwater collision risk

Species	Hearing Group	Swim speed (m/s)	Source reference	Assessments
Harbour seal	PCW	1.8	Thompson, (2015)	Green Volt OWF (Seiche 2024), and Berwick Bank OWF (Seiche 2022), Mona OWF (RPS 2025)
		1.5	Otani (2001)	Dogger Bank South OWF (RWE 2024)
Grey seal	PCW	1.8	Thompson, (2015)	Green Volt OWF (Seiche 2024), and Berwick Bank OWF (Seiche 2022), Mona OWF (RPS 2025)
		1.5	Otani (2001)	Dogger Bank South OWF (RWE 2024)
Minke whale	LF	2.3	Boisseau (2021)	Green Volt OWF (Seiche 2024), and Berwick Bank OWF (Seiche 2022), Mona OWF (RPS, 2025)
		3.25	Blix & Folkow (1995)	Hornsea 3 OWF (Subacoustech Environmental 2018), Dogger Bank South OWF (RWE 2024)
		2.1	Perrin 2009	SNH guidance (2016) for underwater collision risk
Bottle-nose dolphin	HF	1.52	Bailey (2010)	Green Volt OWF (Seiche 2024), and Berwick Bank OWF (Seiche 2022), Mona OWF (RPS 2025)
		1.5	Otani (2001) – based on harbour porpoise	Hornsea 3 OWF (Subacoustech Environmental 2018), Dogger Bank South OWF (RWE 2024)
White-beaked dolphin	HF	1.52	Bailey (2010)	Green Volt OWF (Seiche 2024), and Berwick Bank OWF (Seiche 2022)
		1.5	Otani (2001) – based on harbour porpoise	Hornsea 3 OWF (Subacoustech Environmental 2018)
Basking shark	Group 1 fish	1	Sims (2000)	Green Volt OWF (Seiche, 2024), and Berwick Bank OWF (Seiche, 2022), SNH guidance (2016) for underwater collision risk
All fish in group	Group 4 fish	1.5	Hirata (1999)	Hornsea 3 OWF (Subacoustech Environmental 2018)
All fish	All fish	1.5	Hirata (1999)	East Anglia One North OWF (Royal HaskoningDHV 2019)

This report presents a list of possible flee speeds that have been used in previous assessments (see Section 3.3.5.6). It is noted that flee speeds to be used in assessments should be confirmed with the relevant regulators during the consultation process.

3. Recommendations and guidance note

3.1. Introduction

There is broad acceptance among national and international organisations that impact- or percussive-piling activities generate high noise levels in the water, and that this noise is of a magnitude that could harm marine fauna. Impact- or percussive-piling activities often require a licence, and as such developers are often required to carry out an impact assessment in support of their application. In determining whether to recommend to the relevant Secretary of State or Minister that a licence can be granted and a project can proceed, national regulators must be satisfied that the project has identified risks to relevant species in the project's vicinity, and, where adverse effects are identified, that these are suitably addressed or mitigated. The assessment of the levels of underwater noise that could be generated during piling activities in the marine environment therefore represents a critical step in identifying the risks to marine fauna.

There is a benefit in ensuring that the methodology for undertaking such an assessment is consistent between projects, in accordance with the requirements of national regulators in the United Kingdom, and as up to date as practicable. This note presents a summary of recommendations for undertaking underwater noise assessments for impact pile driving activities, to ensure a satisfactory standard is achieved, improving the quality and consistency of reporting and its underlying scientific evidence, and increasing likelihood of acceptance by regulators.

The focus of this guidance note is the calculation of levels of underwater noise produced during impact piling activities, and the levels of noise that marine mammals and fishes are exposed to, plus the prediction of auditory injury on these species. There have been increasing numbers of scientific papers reporting studies on the effects of high noise levels on these species over the last twenty years. Much of the research has focused on auditory impacts, that is, an adverse effect on the hearing capabilities or physiological harm to fishes and marine mammals.

The scientific evidence supporting the assessment of injury from piling noise and this guidance note is not definitive for any of the marine species considered, and species-specific and cross-species research is ongoing. Thus, this guidance note presents recommendations based on the current understanding presented in the scientific literature. Users and regulators are encouraged to be aware of the dynamic nature of the research in the field of environmental impact of underwater noise, and to acknowledge improvements in our understanding in this field following the publication of this report.

3.1.1. Aim

This guidance note was developed to provide recommendations and advice to industry, consultants, regulators and advisors on the assessment of the potential auditory injury to species of marine mammals and fishes from exposure to underwater noise arising from impact-pile driving activities.

This note has been developed by the Joint Nature Conservation Committee (JNCC) in consultation with Natural England, NatureScot, Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Department for Environment Food and Rural Affairs (DEFRA), Department of Agriculture Environment and Rural Affairs of Northern Ireland (DAERA) and Natural Resources Wales (NRW).

3.1.2. Scope

The focus of these recommendations is the assessment of the risk of injury to marine mammals and fish because of underwater noise emitted by impact pile driving activities. As such, the scope of this note is to:

- Provide recommendations on the specifications such as **models and parameters** that need to be assessed and reported within a noise assessment, and the approach used to estimate impact ranges to sound exposure criteria, without placing overly prescriptive requirements on the approach that must be used.
- Provide, where possible, recommendations on **parameters** that should be used, highlighting where parameters should be decided in consultation with the relevant regulators (see Section 3.1.4. “Assessment checklist”).
- Only provide recommendations on the assessment of **impact piling activities**; as such the note will not consider emission or effect of noise from other pile installation techniques, operational noise from wind turbines, any airborne noise or other underwater noise source.
- Provide recommendations for the assessment of **auditory injury or impairment** on relevant species of marine mammal and fishes but will not include disturbance or other behavioural effects.
- Not provide detailed recommendations on **noise monitoring activities**, although it will include details on recommended information to include in the noise risk assessment to assist future validation of the underwater noise modelling study.

3.1.3. Terminology

In addition to the terms and definitions provided in the glossary, the following is provided to explain how terminology is used in this guidance note. ISO 18405:2017 (ISO 2017a), ISO 18406:2017 (ISO 2017b), National Marine Fisheries Services (2024), and many current underwater noise assessment reports have deviated from some terminology to describe criteria for onset of auditory injury or impairment, namely the “peak sound pressure level” (abbreviated peak SPL, PK, SPL_{pk} or SPL_{peak}) in favour of the symbol “$L_{p,pk}$”, and single strike or cumulative sound exposure level (SEL_{ss}, SEL_{cum}) in favour of the symbol “$L_{E,p}$”. ISO 18405:2017 deprecates “peak SPL”. For ease of comprehension, this note will continue to use the familiar SPL_{pk}, SEL_{ss} and SEL_{cum} to aid understanding by the largest audience.

Key unit terminology is described in Table 13 below.

Table 13. Key terminology used in this guidance note.

Quantity	Abbreviation	Symbol	Note
Root mean square sound pressure level	SPL or SPL_{rms}	L_p	-
Peak or zero-to-peak sound pressure level	SPL_{peak} or SPL_{pk}	$L_{p,pk}$	Instantaneous
Sound exposure level	SEL	$L_{E,p}$	-
Single strike or single pulse sound exposure level	SEL_{ss}	$L_{E,ss}$	One pulse

Quantity	Abbreviation	Symbol	Note
Cumulative sound exposure level for a sequence of pulses	SEL_{cum}	$L_{E,p,t}$	Exposure over a period
Cumulative sound exposure level over 24 hours	SEL_{cum}	$L_{E,24hr}$	Exposure over a period

3.1.4. Assessment checklist

To facilitate transparency and comparability, a list of expected parameters as well as points for consultation with regulators are provided below to prompt considerations of modelling parameter requirements prior to the undertaking of the assessment.

3.1.4.1. Required parameters

This guidance note does not prescribe a single, acceptable modelling approach, so the parameter list below is neither exhaustive of all parameters that could be reported, nor are the following parameters all necessarily required. Many modelling approaches can predict the level of piling noise in the water column with a reasonable degree of accuracy, given the correct use of parameters appropriate to that model. The list below provides an indication of parameters that should be included in the assessment, based on a source/path/receiver model. Where possible, the choice of parameters should be supported by references.

Source description:

- Location, coordinates
- Type of foundation pile (e.g. monopile, jacket, mooring for floating turbine structure)
- Pile diameter, m
- Maximum hammer blow energy, kJ
- Low hammer energy to be used at soft start, kJ
- Time at low hammer energy (soft start)
- Piling ramp up sequence: steps and time at each step
- Blow rate, and any variation throughout the piling sequence
- Construction scenarios considered
- Any mitigation at source or any location, and its attenuation performance in decibels
- Any multiple simultaneous noise sources
- The potential for multiple piles to be driven concurrently or sequentially that would add to the total noise exposure
- Description of source noise model.

Acoustic transmission path description:

- Depth of water/bathymetry
- Description of environment (e.g. seabed properties, sediment type, water temperature or temperature variation across season and/or water column)
- Description of noise propagation model
- Sound speed profile for relevant seasons.

Receiver:

- Relevant species or hearing groups of marine mammal and fishes, and thresholds for auditory injury and hearing impairment (e.g. NMFS 2024; Popper & Hawkins 2019) (see Section 3.3.5)
- Input parameters for movement model (including flee speeds – see Section 3.3.5.6)
- Description of animal movement model.

Consultation Prior to Application

To ease the licence application process, it is recommended that certain parameters are confirmed with the relevant regulatory and advisory bodies prior to submission of an application. A recommended list of potential consultation points is listed below:

Construction scenarios:

- definition of worst-case, and optionally most likely, scenarios
- number of locations to be included in the model and justifications for the selected locations
- details on construction scenarios to be included in the assessment
- number of piling days and expected duration of piling activities (days/months/years)
- foundation types considered (e.g. jackets, pin-piles, monopiles, etc.)
- mitigations (e.g. ADD) that maybe considered and how they are planned to be incorporated in the assessment.

Biological receptors:

- list of species considered for the assessment and screening decision, including indication there is a seasonal or year-round occurrence
- noise criteria for the onset of auditory injury and hearing impairment for the species screened into the assessment
- density or occurrence data sources, and/or habitat and distribution for the species screened in the assessment

- process used to identify reference populations and suggested estimates of the reference populations for the species screened in the assessment

- flee speeds to be used in the cumulative sound exposure assessment

- agreement on scope of the assessment in relation to the need for estimating the number of potentially impacted individuals.

3.1.5. Recommendations overview

The guidance note is structured in four main sections (Figure 3):

- The noise **modelling approach**: recommendations are provided on the details, the justification and underlying assumptions that should be included in the selected modelling approach.

- The **input parameters**: recommendations are made on the parameters that should be applied within the assessment both in terms of the envisioned piling activities and on the biological receptors being considered. Users are encouraged to provide the justification for the parameters selected for the assessment, and the underlying assumptions made.

- The **presentation of the impact ranges** (i.e. the results section) to define distances at which injury is predicted: recommendations are made on how the estimated impact ranges should be presented for each hearing group.

- **Additional contextual analysis**: recommendations on contextual analysis that can be provided alongside the main assessment to help reduce excessive conservatism.

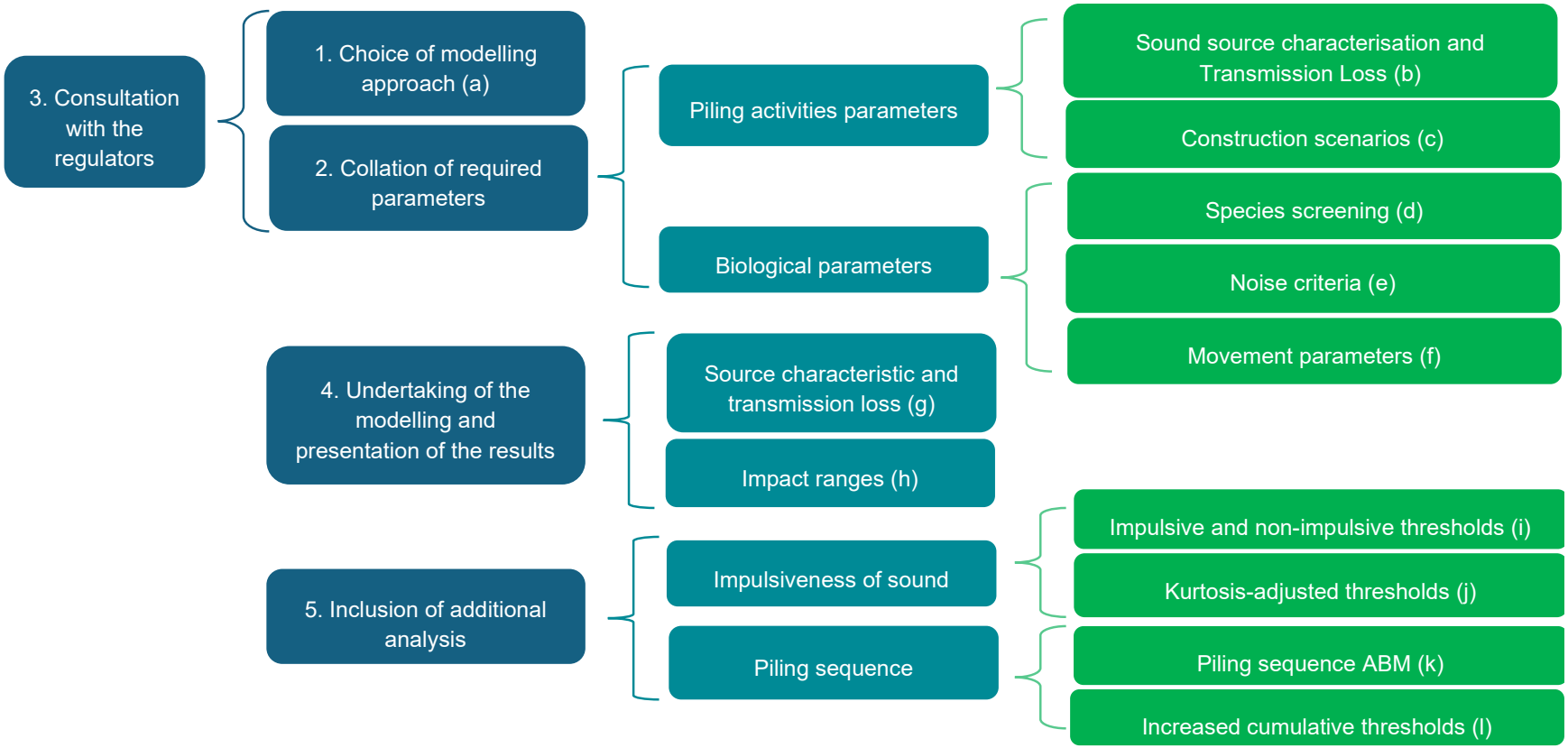


Figure 3. Overview of the main elements of impact-piling underwater noise assessments conisidered in this guidance note. **Assessment overview: a)** Details of the modelling approach selected, with justification on the appropriateness of the model. **b)** Details on the input parameters. **c)** Description of worst-case and most-likely scenarios, foundation types, number of locations modelled, piling sequence, multiple sequential and concurrent pile installation, use of noise abatement systems. **d)** List of relevant species for the assessment and identification of relevant hearing groups. **e)** Noise criteria for mortal, permanent and recoverable auditory injury. **f)** Description of movement model for assessment of cumulative exposure and key parameters. **g)** Sound source levels @ 1 m and 750 m. **h)** Summary tables of hearing group and construction scenario specific impact ranges. **i)** Assessment of magnitude of conservatism based on impulsive thresholds. **j)** Kurtosis bases analysis to account for sound impulsiveness. **k)** Assessment of soft-start and ramp-up sequence influence on impact ranges. **l)** Increased cumulative thresholds accounting for hearing recovery.

3.1.6. Determination of the need for an impact assessment

The principle behind underwater noise impact assessment is to estimate the distance within which biological receptors of a species of interest will be exposed to noise levels at which they may experience adverse impacts, in this instance auditory injury (for more details see Section 3.3.5), and the number of these species that are likely to be affected.

Many developments that involve impact piling activities in water will be required to carry out an underwater noise impact assessment in support of a licence for these activities. However, some developments may not require an in-depth assessment of noise generated using impact piling or detailed underwater noise modelling, due to low environmental sensitivity or because the likelihood of a significant adverse impact is considered low. These will generally be smaller, coastal-based projects. However, it is recommended that agreement is sought from the appropriate regulator, who will determine this through consultation with relevant advisory body.

3.2. Modelling approach

The prediction of underwater noise will typically require the use of a modelling approach which combines two models: one to calculate the noise level at its source (source characterisation), and another to calculate how this noise changes with distance from the source (transmission loss). These two models can be discrete and independent, or integrated, designed to work together.

The assessment should include a brief description and provide evidence in support of the selected approach. The level of detail included should be enough to evaluate the appropriateness of the model for the selected environment. The suitability of the model should be supported by reference to (ideally) peer-reviewed literature describing its validity and/or validation against empirical data. The assessment should include details on the underlying assumptions of the modelling approach. It must be able to calculate SPL_{pk} ($L_{p,pk}$) and SEL_{ss} ($L_{E,p}$) underwater noise metrics as a minimum. It should consider key parameters that affect piling, for example the size of the pile and the hammer's blow energy (see key parameter list in following section). The recent publication by von Pein *et al.* (2022) may assist in prediction of the source level, in the absence of a dedicated model. Further details on this are provided in Section 3.3.1.

Although this guidance note does not provide advice on specific models, both numerical modelling techniques (e.g. parabolic equation, normal mode, or ray tracing models) or empirically derived modelling based on directly measured data, are considered acceptable in principle. It is recommended that example outputs from the selected model are validated by comparison with existing empirical data. Inclusion of any model classes in this guidance note in an assessment should not be considered endorsements of the validity of a model.

The wide variety of acoustic models available and the proprietary nature of some does not allow a full list of acceptable models to be provided. A review of some recognised modelling approaches and their suitability is provided in Farcas *et al.* (2016) and Wang *et al.* (2014). Wang *et al.* (2014) highlight that the suitability of propagation modelling for a specific purpose should be assessed based on: (i) the environment (shallow vs. deep), as this will determine the importance of the interaction with the seabed; (ii) the frequency band of interest, as for example some numerical models such as the parabolic equation are more appropriate for low frequency sound, while ray tracing is more appropriate for high frequency sounds (Etter 2012; see Wang *et al.* 2014 for a matrix assessing appropriateness of numerical models across frequency and environment; Wood *et al.* 2023). As such, it is recommended that within the assessment justifications, the suitability of the model in relation to the environment and frequency band it is applied to is described.

3.3. Input parameters

This section details the input data and parameters that are expected to be important within the selected model and makes recommendations on how they should be presented within the noise assessment. It is split into two main sections that focus on the parameters needed to predict noise levels from the proposed impact-piling activities, and how to estimate the potential impacts to the biological receptors considered within the assessment.

The input parameters used in an assessment will be model-specific, so the following recommendations should not be considered definitive or exhaustive and may not always be applicable. However, the parameters included and used by the chosen model should be specified within the assessment. It is also recommended that the sensitivity of the model to the input parameters is acknowledged and discussed where needed.

3.3.1. Source characterisation

Certain parameters are known to have an influence on the level of underwater noise generated at source and affect sound propagation (see Section 2.3.1.1), which will ultimately determine the magnitude of noise to which a receptor is exposed. Parameters listed in Table 14 should be included.

Table 14. Source characterisation parameters to be included in assessments.

Parameter	Unit	Description
Pile shape and size: pile diameter (width for sheet piles), length in water	Metres (m)	The shape, size and length of the pile will influence the radiating surface area in the water column. Therefore, it is recommended that the shape (e.g. cylindrical or sheet), circumference, diameter or width (depending on the shape) are specified for all the piling scenarios modelled (see Section 3.3.3). The length of the pile in the water column (i.e. associated with penetration depth for subsea piling) should also be clearly detailed, including if- and when piles are driven below the water surface.
Water depth	Metres (m)	Bathymetric data may be used to determine the water depth at the piling location and along the propagation path. The source of the bathymetric data should be specified. Water depth at each piling location modelled should be clearly specified (see Section 3.3.3). Where the state of the tide is also likely to play a significant influence on the noise output, the depth at high and low tide should be specified, indicating which one is being used in the modelling. Additional modelling scenarios for different depths could be considered at sites with large tidal ranges.
Hammer blow energy	Kilojoules (kJ) or Kilo-newton metres (kNm)	The assessment should include the highest blow energy proposed to be used on site, and this should not be exceeded during construction. This energy may be less than the maximum capacity of a proposed hammer, and the value used should be realistic without defaulting to an over-precautionary maximum. Blow energy will often not be constant throughout the piling sequence, and so the variation in energy should be accounted for at each stage in the sequence and specified. To provide an overview of the of the hammer energy throughout a piling sequence (soft start, ramp up, full piling) a percentage or period spent at each energy through ramp up to maximum hammer energy should be presented.
Blow rate	Blows per minute	This often changes throughout the piling sequence; hammers must often drive at higher energy using slower blow rates, meaning faster rates can be possible at lower energies. In modelling cumulative exposure, the blow rate of the hammer is critical where a receptor is moving (see Section 3.3.3.6). The blow rate at each step in the soft start and ramp up (see below, Piling Sequence) and at maximum energy should be specified. Piling engineers commonly specify the number of blows required to drive a pile 25 cm, but the blow rate should be specified in blows per minute.

Parameter	Unit	Description
Piling sequence	Duration in minutes	The assessment should include a detailed description of the piling sequence (soft start, ramp up and piling at the maximum energy), the duration of each part of the sequence and the total duration in a day, and variation of the hammer blow energy and blow rate throughout. *Soft start.* The JNCC mitigation guidelines (2010) states that the soft start should be a minimum of 20 minutes, defining a soft start as any piling at less than the maximum blow energy. For this report, a soft start is defined as a period of piling at the lowest practicable blow energy, at a relatively slow blow rate and ideally with some time in single-blow (not continuous) mode. Note that the lowest practicable blow energy is not necessarily the lowest energy the hammer is cable of delivering, as there may be circumstances where a minimum energy could lead to pile refusal, where the strike does not drive the pile further, which is damaging from an engineering perspective. A minimum period for soft start is not prescribed here but extending this will normally improve impact ranges. A soft start is standard piling practice for the initial phase of installation to ensure the pile is fully vertical before moving to continuous piling. Blow rate and duration for the soft start, should be indicated within the assessment and consulted on with the relevant regulators. *Ramp up*. The period between soft start and maximum energy is known as the ramp up, and the energy may decrease as well as increase depending on the specifics of the seabed/sub-bottom. Where details are not available, a linear ramp up from soft start to maximum can be modelled. The changes in energy and time over which steps occur should be specified.
Location of pile	Coordinates	Include all piling locations considered within the assessment and specify the projection in which coordinates are provided.

3.3.2. Transmission loss

The model used should provide a transmission loss prediction between the source and receiver, suitable for the local environmental conditions. The distance from the source over which the model should calculate noise levels should be sufficient to capture the distance over which receptors could be exposed to sound levels above the relevant noise criteria (see Section 2.3.4).

The calculation of noise attenuation by distance is dependent on numerous variables, and can be affected by frequency, bathymetry, sound speed profiles, ground type and layers, and the size and shape of the source. Such variables can be included explicitly as direct inputs or be implicit in the model. Whichever technique is used, demonstration of the validity of the model should be included, ideally by using a recognised and appropriate numerical sound propagation model (see Farcas *et al.* 2016) or by comparison with suitable empirical data, such as piling noise levels from an appropriate environment. Furthermore, the data source for all the variables included should be specified with associated uncertainty (i.e. quality or suitability of the data for the location).

Where models are spatially dependent on calculation of noise propagation with range (i.e. calculating with respect to changing environmental properties depending on direction), transects should be calculated with a spacing of a maximum of 20° to provide sufficient detail.

It is recommended that unweighted SPL_{pk} ($L_{p,pk}$) and SEL_{ss} ($L_{E,p}$) noise levels at the source and at 750 m are presented in reporting, based on the greatest blow energy as a minimum. The equivalent noise levels at the soft start can also contribute to the context. It is acknowledged that a large, distributed sound source such as from a foundation pile cannot produce a simple ‘source level’ and thus any source level provided is understood as theoretical only for the purpose of modelling. The noise level modelled at 750 m is a standardised value used in many jurisdictions (Verfuss *et al.* 2023) that can be helpful for direct comparisons between projects and field validations.

3.3.3. Construction scenarios

Underwater noise modelling should be undertaken using enough scenario(s) to represent factors that may affect the model outputs, including different options for piling, or the complexity or sensitivity of the site geographically and/or environmentally. A minimum number of scenarios cannot be predefined as this will be case specific. Consideration of the following is recommended to determine the number of scenarios required in the assessment, with further discussion of each below:

- The worst-case and most likely scenario.
- Foundation type or types being installed, or being considered, and types/size of piles.
- The number of representative locations needed.
- Multiple sequential pile installations.
- Whether concurrent piling activities are being considered.
- Use of noise abatement/reduction system(s) and/or different hammer types.

It is noted that inclusion of all possible scenarios may lead to an unnecessarily long and unmanageable quantity presented within the assessment. It is recommended that based on

the above list, an informative number of scenarios are presented for consultation with the regulators along with the justification of why they were selected. Alternatively, a list of all possible scenarios considered can be presented to the regulator to discuss the selection of the most relevant ones for the assessment.

3.3.3.1. Worst-case and most likely scenarios

The worst-case precautionary scenario is required to be presented within the assessments. It is recognised that worst-case scenarios can be unrealistic as they must encompass a combination of all possibilities, however unlikely, to occur together in practice. As such, this guidance note recommends also including 'most likely' scenario(s) where selected piling parameters will more closely represent the expected piling parameters encountered at the site (e.g. lower maximum energy and shorter piling duration or fewer blows). Unlike for the worst-case scenario, there would be no expectation that this most likely scenario would not be exceeded in practice. It is recommended that any design decisions (such as the use or benefit of noise mitigation systems) be based on the worst-case scenario.

The presentation of the two scenarios in comparison allows regulators to assess the degree of precaution associated with the worst-case scenario. Note that while presentation of the worst-case scenario is required, the most likely scenario provides additional context within the assessment and should not be presented alone.

3.3.3.2. Foundation and pile types

Many developments are unlikely to be able to provide definitive piling parameters at the time of modelling, prior to any necessary ground investigation. To allow for further flexibility at the time of construction, this guidance note recommends considering all likely construction scenarios within the modelling envelope, at least as a worst-case. Where a final decision on the design of offshore structures has not been made and several options remain open within the same project, inclusion of different foundation and pile types may be required (e.g. monopile versus pin or jacket piles, Wind Turbine Generator (WTG) foundations and Offshore Substation Platforms (OSP) etc).

All foundation and pile types (e.g. pin-piles, monopiles) should be assessed as different scenarios. Detailed parameters should be presented for each scenario within the assessment.

3.3.3.3. Piling locations

It is recommended that the number of piling locations to be modelled is confirmed during pre-application consultation, and it is supported with suitable justification.

Piling locations should be chosen to represent:

- The variability in depth profile at the site, as, for example, deeper water locations tend to lead to lower sound attenuation, and greater impact ranges.
- Locations for the greatest risk of noise impact on a nearby ecologically sensitive areas, such as a spawning ground or Special Area of Conservation (SAC). If multiple potentially sensitive areas are considered, model a location appropriate for each.
- Considering the geographical variability within or around the site, even for sites with relatively homogenous environmental characteristics, it is worth including enough modelling locations to provide a reasonable estimate for the maximum impact ranges in multiple directions.

- Where, for example, an isolated installation is required in an unknown location, such as an OSP, a central location could be used if locations representative of worst-case for depth or environmental sensitivity have been used for modelling other piling activities (e.g. for WTG foundations).

- Any other piling location close enough to cumulatively contribute to the noise at the site, for example another wind farm due for construction within a similar timeframe.

Piling locations should be chosen in relation to the foundation and pile types being considered. Not all locations within a site may be suitable for all foundation types. For example, if multiple foundations are being considered for the WTG across a site, then at each location multiple foundation types should be modelled.

3.3.3.4. Multiple sequential pile installations

Some pile installations could include the possibility of multiple piles being driven one after another, especially for jacket pile installations. Modelling of multiple operations cumulatively would only be appropriate when these occur in relatively quick succession (of the order of tens of minutes apart).This is because, although PTS or TTS accumulates through multiple exposures, there is recovery of hearing in quiet periods, whether short between pile strikes, or more extended breaks in piling (see also Section 2.3.1.3). Regulators should be consulted on whether cumulative exposure from multiple piling events should be modelled based on available information on the minimum time interval between events. If modelling sequential pile installations is deemed appropriate, where a receptor's movement is modelled during piling it should be clear within the methods how animal movement is accounted for in the gap between sequential piles. A presumption of a receptor remaining stationary during breaks is generally acceptable, although more sophisticated movement modelling can be included with justification. This should be agreed with regulators.

3.3.3.5. Concurrent piling activities

The following recommendations relate to the modelling for impact ranges produced by multiple pulse SEL_{cum} ($L_{E,p,t}$) (see Section 3.3.5.5) from multiple pile driving sources. Where SPL_{peak} thresholds are under consideration, the total impacted area would be equivalent to either the area within the outer boundary of the intersecting contours (Figure 4, left panel), or the sum of the areas of separate contours (Figure 4, right panel).

Where piling activities could occur at the same time at multiple locations within the proposed development, such as where there is the potential for more than one piling barge operating to install piles, these should be assessed as an additional scenario or scenarios so regulators can determine the difference between this and a single piling event. The scenario(s) modelled should represent the maximum number of concurrent piling activities that are envisioned during the project. Justification for the locations selected for concurrent piling should be provided (e.g. deepest water, edge of the site boundary closest to a sensitive location), along with an expectation of the number of locations that could be piled concurrently throughout the project.

Where impact ranges of concurrent piling events combine, the scenario representing the worst-case total impacted area should be used in the modelling. This will often occur at the maximum separation among piling locations because it will represent the minimum or no overlap and the largest combined area. This is demonstrated in Figure 5, right panel. Two piling locations close to one another will have an impacted area overlap and so the combined impacted area would be smaller (such as in Figure 5, left panel). Note that in some cases, modelling concurrent piling may not result in a single linked impact contour, and instead there will be no overlap between the two impacted areas (which would appear

as Figure 4, right panel). This will often only relate to species with lower sensitivity (commonly high frequency cetaceans) so it would be sufficient simply to sum the impacted areas in this case. However, this may not represent the maximum total area and further consultation with regulators may be beneficial to agree the representative worst-case scenario. It may not be possible to choose the worst-case locations to model for all species hearing groups and piling scenarios, in which case a suitable representative concurrent scenario would need to be agreed with regulators.

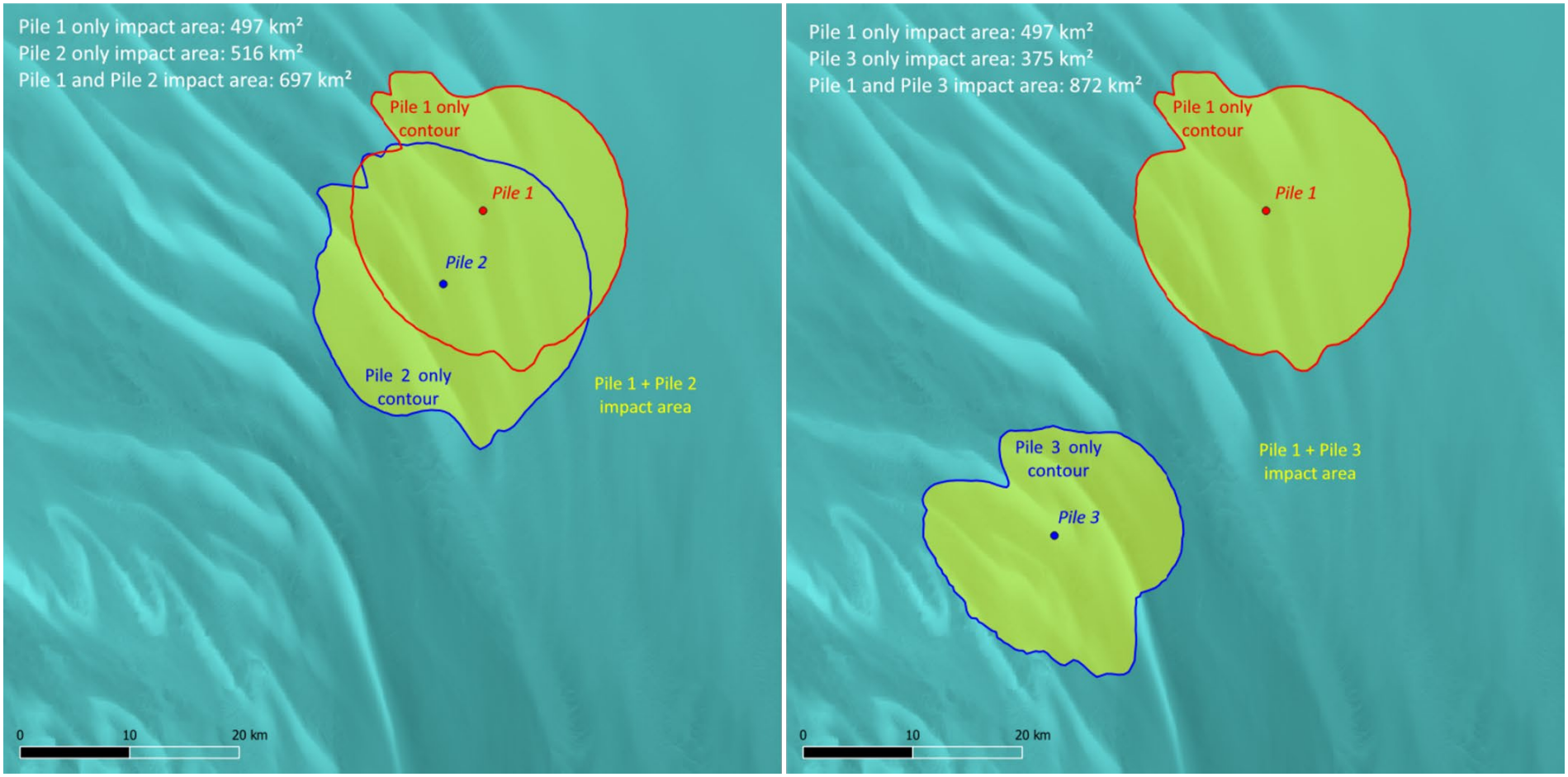


Figure 4. Calculation of impact ranges from piling at two example locations, simultaneously, with different separations. This references the single strike, non-cumulative noise thresholds (i.e. not SEL_{cum}).

In determining a representative scenario, it is not expected that special efforts be made to identify very specific locations that would provide the absolute worst-case scenario, or locations for each receptor category. These would produce an overly precautionary assessment, especially where pile driving at the two absolute worst-case locations would be highly unlikely. Locations showing a small separation in the impacted areas for the largest contours (typically LF or VHF cetaceans, or stationary fish), such that a contour similar to Figure 5 right panel is produced, will provide a reasonably representative worst case.

Modelling cumulative exposure (i.e. the estimated total area of impact arising from repeated, and often overlapping, impulsive sound exposures) requires a starting location for the receptor's position (especially for fleeing receptors). It is recommended that the model is run once per pile location, with a receptor start location at each of the pile locations, and since this will produce different contours for each pile location, that these are overlaid and that the outer boundary of the combined contour is the final contour, as in the right panel of Figure 5.

The example modelling used to derive Figure 5 is based on a receptor fleeing in a straight line from each piling location. Where modelling does not include agent-based avoidance by receptors, a receptor fleeing away from one impact-piling activity would, on some transects, move towards another, so at some distance the noise levels to which they are exposed will start to increase. Linear impact ranges depend on selection of the modelled receptor start point and, in these conditions, could produce excessive and unrealistic ranges. For example, in Figure 5, right panel, the maximum linear impact range would represent a receptor beginning at the position of Pile 1 and swimming past Pile 3 to the southernmost point of the concurrent contour, approximately 2.5 times the linear impact range of the worst-case single location scenario. This is considered extremely unrealistic, primarily as the animal would not be expected to swim towards another high noise pile installation, but also because situations in which piles are installed both simultaneously and in the worst-case locations are highly unlikely.

It is recommended for concurrent piling activities such as these, instead of providing SEL_{cum} impact ranges as radial, linear distances (i.e. a straight-line distance around each piling location in m or km as per single pile source scenarios), the impacted area caused by exposure to the combined sound field from each location is provided as m^2 or km^2. This total combined impacted area would then be used for estimation of the number of affected animal receptors from concurrent piling.

Section 3.3.3 indicates that modelling should include the worst-case scenario for piling parameters as a minimum, but it is acknowledged that almost by definition, this worst-case is unlikely to occur, and even less so in two places simultaneously. Unless there is a realistic expectation that the identified worst-case piling parameters (e.g. maximum hammer energies and durations) may genuinely occur simultaneously at multiple locations, most likely parameters rather than worst-case parameters are considered suitable to be used within the concurrent piling assessment. However, the assumed parameters and the basis for their selection should be justified in the assessment and agreed through consultation.

As only impacted areas (not linear ranges) should be derived for concurrent piling scenarios, the design of mitigation measures, use of ADDs, etc., will still generally be based on worst-case linear impact ranges from a single piling event. As stated above, this is because concurrent scenarios often produce excessive and unrealistic worst-case linear impact ranges.

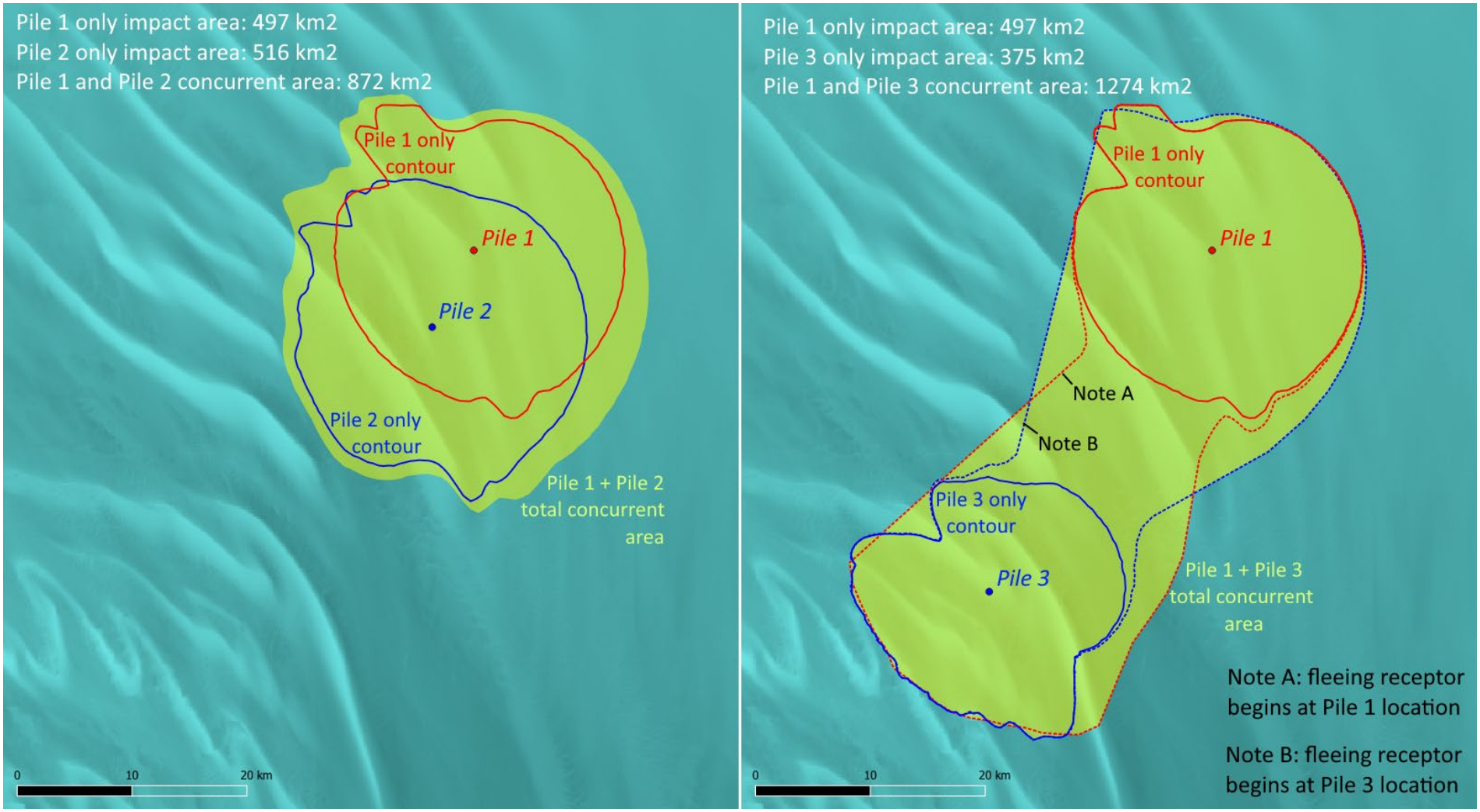


Figure 5. Demonstration of concurrent impact ranges from piling at two example locations, simultaneously, with different separation. In general, the greatest separation (Pile 1 and Pile 3, right panel) will represent the worst case in terms of the number of animals potentially affected. Note that this is not true of the mitigation zone distance since this is generally based on linear impact ranges from a single piling event (see last paragraph of Section 3.3.3.5).

3.3.3.6. Piling sequence

The time component of the piling activity is very important in the assessment of cumulative noise exposure. The piling sequence or timeline needs to be considered at two scales, the piling sequence for each individual pile which is often described by the blow rate and energy, and the overall piling timeline over a 24-hour period, which indicates how many piles could be driven at the site within this period.

The two most relevant components in this instance are the blow energy and the blow rate. The two are often inter-linked and vary throughout the piling sequence. The variation in hammer blow energy and blow rate is often determined by a trade-off between the engineering requirements and the use of the initial blows as “deterrents” to the fauna in the surrounding waters.

The piling sequence describes the anticipated number of blows, blow energy and duration required to drive the pile to its required depth. It is standard practice for the piling sequence to involve a soft start and ramp up before reaching the maximum hammer energy, particularly for large hydraulic hammers used offshore. The maximum energy may not necessarily occur at the end of the piling sequence (although for the purpose of assessments this is usually assumed). A soft start is a period of blows at the lowest practicable energy, at a slow blow rate. This is normally required for engineering purposes and allows receptor species capable of swimming away from high noise sources to do so. The ramp up is a period where the blow energy and blow rate increase up to the maximum hammer energy to be used. The increase in energy is undertaken during no less than 20 minutes to allow animals the time to reach as great a distance as possible to minimise harmful exposure to noise.

The soft start and ramp up of a piling sequence are standard parts of the pile driving sequence, and minimisation of blow energy and the number of blows, and extension of the soft start period can reduce the receptor’s exposure to noise.

Guidance for marine mammal and fish noise exposure criteria (Southall *et al.* 2019; NMFS 2024; Popper *et al.* 2014) recommends that the total exposure of a receptor individual to noise should be assessed over a 24-hour (one day) period. A single pile will not take 24 hours of active piling to drive, but multiple piles within a site could be driven within 24 hours. As such the following points should be considered to determine the number of piles that could be driven within this period and how close in time these piling events will be:

- Time for movement of the piling barge or rig, where multiple piles would be significantly geographically separated.

- A 24-hour period does not need to be midnight to midnight, nor relate to a calendar day, but should account for a sensible start and end time: for example, if daylight-only piling was anticipated, the start time should not be midday.

- Where all piles are driven within a relatively small area, for example a jacket structure, and could potentially be driven within 24-hours, there need not be a specific start or end time, but the timing between piling events is crucial for modelling. Only piles that are driven sequentially in relatively quick succession (of the order of tens of minutes apart) should be included in the cumulative exposure assessment. This is because hearing recovery is expected (see Section 2.3.1.3), and receptors are therefore assumed to have recovered to a greater extent after such a break.

It is recommended that a detailed description of the piling sequence to be included in the modelling is provided within the assessment and that it is discussed with the regulators and advisory bodies during consultation.

3.3.4. Inclusion of mitigation measures

All noise assessments involving impact piling should demonstrate how the underwater noise it generates and the risk of an adverse impact on marine fauna is to be managed. No specific provisions are made in this guidance note on the method of noise reduction that should be used, as multiple techniques or technologies may be used, and different options may or may not be available for a particular site or condition.

The Defra Noise Policy Paper (2025) states “we expect that all offshore wind pile driving activity across all English waters will be required to demonstrate that they have utilised best endeavours to deliver noise reductions through the use of primary and/or secondary noise reduction methods in the first instance.” ‘Primary’ here refers to a reduction of noise at source, for example, by using a quieter hammer or a hammer dampener, ‘secondary’ is a method designed to attenuate noise after its generation, such as a barrier. The Welsh Government has committed to developing a similar policy for managing marine noise in Welsh waters (6 March 2025) although it was not published at the time of publishing this report.

3.3.4.1. Minimum assessment requirements

Within the assessment, the noise reduction methods that are intended to be used can be specified, if known, with the associated minimum level of attenuation expected to be achieved, along with the justification behind the estimated level of attenuation, and references provided. At an early stage, in advance of selection of any specific method or system, it is acceptable to specify a generic value of attenuation that can practically be achieved to be agreed with the regulator and respective SNCBs. Most types of noise abatement system are frequency dependent, that is they will provide different attenuation performance at different sound frequencies. This should be included in the assessment where data are available.

3.3.4.2. Mitigated scenarios

Mitigated modelling scenarios including noise reduction should be included in the assessment. Unmitigated piling scenarios should also be included as a baseline (i.e. offering 0 dB of attenuation), even if such a scenario is not intended to occur, so a comparison can be made, and regulators can see by how much noise levels are expected to be reduced. It should be clear in the assessment how the mitigation measure has been accounted for in the estimation of impact ranges. Note that the unmitigated scenario should use the worst-case scenario.

If it is agreed (with the regulator) reduced noise scenarios are not required, an audit of discussions and explanation of why should be provided in the assessment.

3.3.4.3. Using an Acoustic Deterrent Device (ADD)

If the use of one or more types of ADD is being considered as part of the mitigation plan for marine mammals, details, if available, of the model of the ADD(s), including output level, frequency and duty cycle, should be included within the assessment. Further information on ADDs can be found in Phillips *et al*. (2025).

Underwater noise modelling should be undertaken in the first instance without the benefit of any noise reduction or use of an ADD. The need for an ADD (or potentially some other mitigation) will be informed by this modelling.

An ADD can be incorporated into the underwater noise assessment using data from published literature on the species-specific distance at which ADDs have been demonstrated to displace a marine mammal – this is considered an upper flee limit; it should not be assumed that ADDs are effective over any distance. However, the way to include the ADD in an assessment is determined by this upper flee limit.

1. If the upper flee limit is smaller than the impact range to be mitigated (for example, if an ADD is shown to be effective over a distance of 1 km and the impact range is 2 km) then the ADD cannot be assumed to reduce the number of animals within the impact contour when piling begins, since animals moving away from the ADD cannot be expected to continue to travel beyond the upper flee limit. However, the ADD will still have a benefit since, although the animals will still be within the impact range, they will be further away from the source and so the risk in terms of noise level and impulsivity will be reduced, if not fully eliminated. The impact will therefore be partially mitigated.

2. If the upper flee limit is greater than the impact range, then the ADD can fully mitigate the impact, provided the flee distance travelled by the animals during ADD operation, calculated as the product of the duration of ADD operation and a suitable, citable flee speed (ideally measured under exposure to ADD noise), is greater than the impact range.

The flee distance to clear the impact range should be calculated using the distance from the pile to the edge of the range as a worst case, unless there is cause to expect any animals to be further away from the pile at the start (e.g. MMO, other disturbance such as vessel noise, etc.).

Underwater noise modelling should only be used to determine the effectiveness of an ADD, or to reduce impact ranges, if the model can account for the ADD upper flee limit as described above. Otherwise, the simple calculation of flee distance and the area over which a marine mammal is displaced is acceptable.

ADDs are not considered effective for fish.

3.3.5. Biological parameters

To assess risks to marine mammal and fish arising from sound exposure, there should be a prediction of impact ranges from the noise source. The area surrounding the piling activities where animals would be exposed to sound levels likely to cause injury should be modelled or calculated. Although out of the scope of this guidance note, further prediction of behavioural impacts or disturbance because of underwater noise may also be required.

This section of the guidance note makes recommendations on how to identify animals that may be at risk of injury from piling noise and the biological parameters that should be used within the assessment to estimate the impact ranges for permanent or recoverable auditory injury.

Note that different provisions may apply for sea turtles and some fish species (e.g. basking sharks) if these species require assessment. The requirement for this should be confirmed during pre-application consultation with the relevant regulator and their advisors.

Further, this guidance note provides advice on the assessment of impacts to fish species based on their exposure to sound pressure level only. Particle motion is also a concern for this taxonomic group, but current knowledge on the impacts of particle motion is not currently sufficient to allow for recommendations to be provided on this topic.

3.3.5.1. Screening of species

The presence of relevant species within a potentially impacted area (from piling noise) to be considered in an assessment should be identified by using:

- Relevant literature sources.
- Publicly available datasets.
- Site-specific survey data where available.

Williams *et al.* (2021), for example, presents an overview of key marine species likely to be sensitive to anthropogenic noise that are either of high commercial value or have high levels of protection in English waters. Attention should be given to protected species, and protected sites (e.g. Special Area of Conservation (SAC) or Marine Protected Areas (MPA)) (e.g. Atlantic salmon and/or areas dedicated to sensitive activities e.g. nursery and spawning grounds for sensitive fish species such as herring). The timing of the operations should be taken into consideration when identifying the species that may be present and any overlap with key life stages that may be relevant for the noise risk assessment.

It is recommended that the final list of species to be assessed is agreed pre-application with the relevant regulators and their advisors. If species are likely to be present within the area, but they are not considered to be at risk, justification should be provided during the consultation and be agreed upon with the relevant regulators and/or consultees.

A list of all the species considered within the assessment should be presented.

Although the broader noise assessment may require further estimation of potentially impacted individuals for each species/population, this is not covered by the current guidance note. To complete this component of the assessment, it is recommended that the most up-to-date data sources for species' densities and abundances are confirmed in consultation with the relevant regulators.

3.3.5.2. Hearing groups

Due to the large variability in hearing capabilities, and availability of data relating to many or indeed most species' hearing, within the two taxonomic groups, species within them have been subdivided further into hearing groups, and these should be applied as relevant to ensure that assessment considers this variability.

Marine mammals are split into seven hearing groups in NMFS (2024): Low frequency (LF) cetaceans, high frequency (HF) cetaceans, very high frequency (VHF) cetaceans, sirenians (SI), phocid carnivores in water (PCW), phocid carnivores in air (PCA), other marine carnivores in water (OCW) and other marine carnivores in air (OCA). In UK waters, underwater noise assessments would not typically require assessment to SI, PCA, OCW and OCA categories as these species do not occur in British waters or represent threshold for noise exposure in air. Airborne noise impacts would be considered in a separate assessment.

Hearing groups for fishes have been defined by Popper and Hawkins (2019) based on their physiology: Group 1 (no swim bladder), Group 2 (swim bladder not involved in hearing), Group 3 and 4 (swim bladder involved in hearing), Sea turtles, and Eggs and Larvae. It should be noted that while impact ranges should be presented for all hearing groups, sea turtles may not always be relevant for assessments of activities in the British Isles. Thus, this should be confirmed in consultation with the relevant regulators.

While noise criteria presented in the following sections represent the most up-to-date thresholds at the time of publication of this report, thresholds to be used within the assessment should be confirmed during pre-application consultation with the relevant regulators and their advisers.

3.3.5.3. Noise criteria for assessment (i.e. auditory injury thresholds)

Potential adverse impacts from impact-piling activities are assessed both as exposure to instantaneous single strikes as SPL_{pk} ($L_{p,pk}$) and exposure to repetitive sound over a prolonged period as SEL_{cum} ($L_{E,p}$). To assess potential impacts from noise exposure, noise thresholds have been identified, above which exposure could lead to onset of the impact. Specifically, noise criteria for onset of permanent or recoverable auditory injury have been defined in publicly available literature, which are further detailed as species-specific thresholds.

This guidance note considers the risk of mortality or recoverable injury to fish, and permanent or recoverable auditory injury to marine mammals.

For marine mammals, the guidance note follows the definitions provided in NMFS (2024), reported below. Note that these reflect a change in terminology from previously used criteria (Southall *et al.* 2019).

- *Temporary Threshold Shift (TTS)* = “A temporary, reversible increase in the threshold of audibility at a specified frequency or portion of an individual’s hearing range above a previously established reference level (ANSI 1995; Yost 2007).”

- *Auditory Injury* = “Damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy (Finneran *et al.* 2023; Houser 2021). Auditory injury may or may not result in a permanent threshold shift (PTS).”

- *Permanent Threshold Shift (PTS)* = “A permanent, irreversible increase in the threshold of audibility at a specified frequency or portion of an individual’s hearing range above a previously established reference level (ANSI 1995; Yost 2007).”

In the UK, PTS onset has been used to assess auditory injury impacts and determine mitigation requirements. The criteria for Auditory Injury under NMFS (2024) will be equivalent. It is noted that some regulators may also request impact ranges to be reported for TTS for context, this should be confirmed during the consultation process.

It is worth highlighting the term ‘onset’. This means that at the specified threshold, the effect will begin to be seen in a population. It makes clear that exceedance of this threshold does not mean that all individuals will be subject to the effect.

For fishes, exposure to impulsive sound is assessed based on risk of mortality or potential for a mortal injury, recoverable injury, or TTS. Popper and Hawkins (2019) found that while exposure to SPL_{pk} ($L_{p,pk}$) above certain thresholds always resulted in mortality or some degree of permanent and recoverable injuries, cumulative exposures for certain species

showed more of a gradient in the responses. These are reflected in the cumulative exposure criteria presented below (see Table 18).

It is recommended that clear definitions of the impacts considered are provided within the assessment, and if those deviate from the ones provided above, this should be agreed in consultation with the relevant regulators and their advisers.

3.3.5.4. Instantaneous single strikes (SPL_{pk} or $L_{p,pk}$)

This guidance note reports the most up-to-date auditory injury and hearing impairment onset criteria at the time of publication for marine mammals, extracted from the NMFS (2024) (see Table 15).

Currently recommended criteria for fishes are those developed by Popper and Hawkins (2019) (see Table 16). Note that the same SPL_{pk} ($L_{p,pk}$) levels are used both for mortality and recoverable injury in some categories (Popper & Hawkins 2019).

Instantaneous single strike impact ranges for marine mammals at risk of Auditory Injury and TTS based on SPL_{pk} ($L_{p,pk}$), and impact ranges for fishes at risk of mortality and recoverable injury based on SPL_{pk} ($L_{p,pk}$) should be presented for all relevant hearing groups.

Table 15. Generalised marine mammal hearing groups, Auditory Injury and TTS thresholds for impulsive single strikes (SPL_{pk} or $L_{p,pk}$) (NMFS 2024). * Example hearing range given in NMFS (2024) covers additional species not found in UK waters.

Hearing group	Example species relevant to UK waters	Generalised hearing range	Unweighted SPL_{pk} (dB re 1 µPa)	
			Impulsive - Auditory Injury	Impulsive - TTS
Low-frequency (LF) cetaceans	Baleen whales	7 Hz – 36 kHz	222 dB	216 dB
High-frequency (HF) cetaceans	Dolphins, toothed whales, beaked whales, bottlenose whales	150 Hz – 160 kHz	230 dB	224 dB
Very High-Frequency (VHF) cetaceans	Harbour porpoise	200 Hz – 165 kHz*	202 dB	196 dB
Phocid pinnipeds underwater (PCW)	Grey and common seals	40 Hz – 90 kHz	223 dB	217 dB

Table 16. Generalised fish groups mortality and recoverable injury thresholds for impulsive single strikes (SPL_{pk} or $L_{p,pk}$) (Popper & Hawkins 2019).

Type of Animal	Mortality and potential mortal injury (SPL_{pk})	Recoverable injury (SPL_{pk})
Group 1 Fish: no swim bladder (particle motion detection)	> 219 dB	> 213 dB
Group 2 Fish: swim bladder is not involved in hearing (particle motion detection)	> 207 dB	> 207 dB
Group 3 and 4 Fish: swim bladder involved in hearing (primarily pressure detection)	> 207 dB	> 207 dB
Sea turtles	> 207 dB	-
Eggs and larvae	>207 dB	-

3.3.5.5. Cumulative Sound Exposure Levels (SEL_{cum} or $L_{E,p}$)

Cumulative SEL ($L_{E,p}$) considers both the received levels and the duration of exposure (generally estimated within a 24-hour period). In its basic form the approach to estimate cumulative sound exposure level should be described as:

$$SEL_{cum} = SEL_{SS} + 10\log(number\ of\ strikes\ over\ 24\ hour\ period)$$

The SEL_{SS} in the equation will strongly depend on the distance at which a receptor is from the source during the piling period. While for stationary species this will be vary only with the changes in piling noise output, it is assumed that all marine mammal species and some fish species will move away from the noise source or potentially hide. For species that are assumed to flee from the disturbance, the SEL_{cum} ($L_{E,p}$) impact range represents the start position at which a receptor would receive the exact exposure threshold if the animal was to flee away from the source at the start of piling.

The most up-to-date SEL_{cum} ($L_{E,p}$) criteria for marine mammal and fish groups at the time of publication of this note are presented in Table 17 (extracted from NMFS 2024) for marine mammal hearing groups and Table 18 (extracted from Popper & Hawkins 2019) for fish hearing groups. Thresholds to be used within the assessment should be confirmed during the consultation with the relevant regulators and advisers. It should be reiterated that these criteria are based on the onset of an impacts; that is, beyond this noise exposure threshold, the impact would start to be detected, and the benefit of recovery between impulses is not accounted for.

Table 17. Generalised marine mammal hearing groups Auditory Injury and TTS thresholds for cumulative sound exposure levels (SEL_{cum} or $L_{E,p}$) (NMFS 2024).

Hearing group	Example species relevant to UK waters	Weighted SEL_{cum} (dB re 1 μPa^2s)			
		Impulsive		Non-impulsive	
		Auditory injury	TTS	Auditory injury	TTS
Low-frequency (LF) cetaceans	Baleen whales	183 dB	168 dB	197 dB	177 dB
High-frequency (HF) cetaceans	Dolphins, toothed whales, beaked whales, bottlenose whales	193 dB	178 dB	201 dB	181 dB
Very High-Frequency (VHF) cetaceans	Harbour porpoise	159 dB	144 dB	181 dB	161 dB
Phocid pinnipeds underwater (PW)	Grey and common seals	183 dB	168 dB	195 dB	175 dB

Table 18. Generalised fish groups mortality and recoverable injury thresholds for cumulative sound exposure levels (SEL_{cum} or $L_{E,p}$) (Popper & Hawkins 2019). Relative risk (high, moderate, low) is given for animals at three broadly-defined distances from the source defined in relative terms: N, near; I, intermediate; F, far (from Popper *et al.* 2014).

Type of Animal	Mortality and potential mortal injury (SEL_{cum})	Recoverable injury (SEL_{cum})	TTS (SEL_{cum})
Group 1 Fish: no swim bladder (particle motion detection)	> 219 dB	> 216 dB	> 186 dB
Group 2 Fish: swim bladder is not involved in hearing (particle motion detection)	210 dB	203 dB	> 186 dB
Group 3 and 4 Fish: swim bladder involved in hearing (primarily pressure detection)	207 dB	203 dB	186 dB
Sea turtles	210 dB	(N) High (I) Low (F) Low	-

Type of Animal	Mortality and potential mortal injury (SEL_{cum})	Recoverable injury (SEL_{cum})	TTS (SEL_{cum})
Eggs and larvae	> 210 dB	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

To estimate the sound exposure levels that fleeing animals are exposed to, their movement is often simulated using an Agent or Individual Based Model (ABM/IBM). These models can have varying degrees of complexity depending on the level of detail at which they are trying to simulate an individual movement. In their simplest form, they should represent an individual moving away from the source in a straight line. These models will then be used to estimate the changing single strikes levels to which individuals are exposed at each pile strike as they move further from the source.

3.3.5.6. Swim speeds

Swim speed is a critical parameter within ABM and IBM, and it will significantly influence the resulting ranges. Table 19 presents a range of swim speeds that have been recommended by regulators across the UK, and a range of speeds arising from more recent literature. It should be noted that the ranges of swim speeds presented often arise from the context in which an animal's swim speed was measured, whether it was a mean travelling speed or a startle response due an external stimulus. As such, it is recommended that the set of swim speeds used in the assessment is agreed in consultation with the relevant regulators and advisors' pre-application. Fishes should be assumed to remain stationary as a default but should also be assessed as fleeing where relevant (see Table 19).

Table 19. Swim speeds assumed for cumulative sound exposure modelling, used in recent environmental impact assessments for proposed offshore windfarms.

Species	Hearing Group	Type	Swim speed (m/s)	Source reference
Harbour porpoise	VHF	Regulatory – SNH (2016)	1.4	Westgate *et al.* (1995)
		Regulatory – Parker *et al.* (2022)	1.5	Otani *et al.* (2001)
		Additional	1.97	Kastelein *et al.* (2018)
Harbour seal	PCW	Regulatory – SNH (2016)	1.8	Thompson (2015)
Grey seal	PCW	Regulatory – SNH (2016)	1.8	Thompson (2015)
Minke whale	LF	Regulatory – SNH (2016)	2.1	Perrin *et al.* (2009)
		Additional	2.3	Boisseau *et al.* (2021)
		Regulatory - Parker *et al.* (2022)	3.25	Blix & Folkow (1995)
		Additional	4.19	McGarry *et al.* (2017)

Species	Hearing Group	Type	Swim speed (m/s)	Source reference
Bottlenose dolphin	HF	Accepted in previous assessments	1.52	Bailey *et al.* (2010)
		Regulatory - Parker *et al.* (2022)	1.5	Otani *et al.* (2001) – harbour porpoise
White-beaked dolphin	HF	Accepted in previous assessments	1.52	Bailey *et al.* (2010)
		Regulatory - Parker *et al.* (2022)	1.5	Otani *et al.* (2001) – harbour porpoise
Basking shark	Group 1 fish	Stationary	0	-
		Additional	1	Sims *et al.* (2000)
Fish groups	Group 4 fish	Stationary	0	-
		Additional	1.5	Hirata (1999)
All fish	All fish	Stationary	0	-
		Additional	1.5	Hirata (1999)

3.3.5.7. Minimum requirements for reporting

The assessment should include details on the approach used to calculate cumulative impact, including but not limited to:

- The basic functionality of the IBM/ABM, including justifications in support of the chosen approach
- Underlying assumptions of the approach regarding animal movements or remaining stationary during the assessed period
- Specification of the movement model used and movement parameters (e.g. flee speed and/or site fidelity). Parameters should be supported by references where possible
- For species where evidence supports aversion of the activities, details need to be provided on how this is accounted for in the model. Parameters should be supported by references where possible
- Whether a 2D or 3D animal movement model was used when accounting for sound exposure through the water column
- Where an ADD use is proposed, results should be presented without any ADD in the first instance, but additional results can also be reported to include ADD use.

Note that cumulative exposure is usually calculated over a 24 hour period. Where the proposed activity has a shorter duration (i.e. less than 24 hours), exposure should be calculated over the period of activity. The worst-case cumulative exposure should include the maximum activity that could occur within a period of 24 hours but considering the time interval between events (see Section 3.3.3.4).

It is acknowledged that there are several assumptions that can be made within a noise assessment, which have been discussed within the Section 2.3.4.3. As such it is recommended that assumptions made about animal movement are included within the assessment and their implications on the results acknowledged.

3.3.6. Concurrent piling activities

Cumulative exposure criteria impact ranges are based on exposure to and distance from a single noise source. The approach used to estimate cumulative exposure from concurrent piling activities are often complex. This guidance note does not provide an in-depth prescriptive approach; however detailed information on the approach taken, along with any assumptions made on animal movements in response to exposure to multiple sound sources, should be included in the assessment.

Cumulative exposure modelling should calculate a sound field set up by all contributory noise sources operating within the proposed project concurrently. The exposure is calculated with a receptor travelling through this combined sound field. A noise impact contour should be calculated to identify the distance from all contributory sources where an animal would just receive the relevant noise exposure criteria. In practice, this can include the maximum number of concurrent impact-piling sources at the development site.

There are several complexities in the movement a receptor between multiple sound sources, which cannot be described by a simple linear impact range, as the calculated noise impact contour of one noise source will often extend beyond the position of a secondary noise source, thus misrepresenting the maximum and average impact ranges. The total combined exposure impact area should be presented in the assessment.

Single strike impact predictions do not need to consider combined noise sources, since the likelihood of a peak crossing at the same time as another at the precise location of a receptor at a similar noise level is negligible.

3.4. Presentation of results

The results section of the assessment should cover relevant outputs of the source characterisation and transmission loss models and the estimated injury ranges for all hearing groups across construction scenarios.

3.4.1. Source characterisation and transmission loss

It is recommended that as a minimum, the following are presented within the assessment:

- Sound source levels (SEL_{ss} and SPL_{peak} or $L_{E,p}$ and $L_{p,pk}$) and sound levels at 750 m (SEL_{ss} and SPL_{peak} or $L_{E,p}$ and $L_{p,pk}$).
- A quantification and visualisation of the transmission loss over distance. As a minimum, a sound level vs range plot of the maximum hammer blow energy to be used on the worst-case transect.

Examples of additional results that can be included:

- Source level at an octave band or 1/3 octave band frequency spectrum.
- Propagation as a function of water depth.
- Transmission loss at various hammer energies.

All results for source description and noise levels at 750 m should be included in tables. Table 20 provides an example layout.

Table 20. Summary of the maximum predicted $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) noise levels at 1 m / a range of 750 m used for modelling.

Source level / Level at 750m	Modelling location	$L_{p,pk}$ @ 1m/750m	$L_{E,p,ss}$ @ 1m/750m
Foundation Type 1	Location A	X dB re 1 µPa	A dB re 1 µPa^{2}s
	Location B	Y dB re 1 µPa	B dB re 1 µPa^{2}s
	Location C	Z dB re 1 µPa	C dB re 1 µPa^{2}s
Foundation Type 2	Location A	X dB re 1 µPa	A dB re 1 µPa^{2}s
	Location B	Y dB re 1 µPa	B dB re 1 µPa^{2}s
	Location C	Z dB re 1 µPa	C dB re 1 µPa^{2}s

As future monitoring of underwater noise levels at the site may be required as part of the licence condition. It is recommended that suitable modelling outputs are presented which will enable meaningful comparison with measured data once made available. This could include, for example, provision of spreadsheets depicting sound level vs range data from each modelled location.

3.4.2. Estimates of sound exposure ranges for each species and/or hearing group

The underwater noise assessment for marine mammals and fishes should be based on the impact ranges for auditory injury. The results section should present as a minimum the impact ranges estimated for each hearing group for the two noise criteria (SPL_{peak} or $L_{p,pk}$ and SEL_{cum} or $L_{E,p}$) for all the construction scenarios and locations considered. For cumulative impacts the swim speed or movement model used to estimate impact ranges should be clearly labelled. The layout in Table 21 can be used as an example for presentation of results. Tables should be presented separately for worst-case and most likely scenarios or side-by-side with clear labels on the scenario that each value represent. The latter option may facilitate comparison of the results. It is recommended that wherever possible, if comparison between scenarios (e.g. mitigated vs unmitigated) is an important part of the interpretation the results, such comparison is facilitated with combined or near-by tables.

Impact ranges in reference to TTS or other lower auditory impact (e.g. disturbance, out of scope of this note) should also be presented as additional information for regulators and advisors. Presentations of results in relation to impacts other than auditory injury should be confirmed in consultation with the regulators.

Table 21. Summary of the predicted $L_{p,pk}$ / $L_{E,p,24hr}$ marine mammal impact ranges, in Location A.

Marine mammal criteria $L_{p,pk}$ / $L_{E,p,24hr}$			Foundation Type 1			
			Area	Maximum range	Minimum range	Mean range
PTS	LF	S dB	km^2	m	m	m
	HF	T dB				
	VHF	U dB				
	PCW	V dB				
TTS	LF	W dB				
	HF	X dB				
	VHF	Y dB				
	PCW	Z dB				

Where appropriate, graphical representations of the extents of the impact ranges in relation to the piling location can be included. These would present loci or contours representing the position of the modelled impact ranges, which would demonstrate how they are affected by the local environment, and the direction of the greatest extents. This may be particularly useful where there is a sensitive location that would be affected, and an overlap of the impact contour with the location is an important result. If concurrent piling is being considered, providing further clarification on how this is being assessed (see Section 3.3.3). 'Heat map' style coloured/shaded plots are not recommended for identification of defined impact ranges as it can be difficult to distinguish impact levels.

Examples of additional results that can be included:

- If ADD use is being considered and not directly included in the model, the duration of ADD operation required to clear the predicted impact ranges.
- Graphical representation of calculated SEL_{cum} ($L_{E,p}$) as a function of distance from the source.

3.5. Additional contextual analysis

To overcome some of the conservatism associated with impact piling noise exposure impact assessments, a few additional methods are shown for analysis that can be included within the assessment to provide further context to the results. These are based on active areas of research at the time of publication, and so are optional at this time, and would be additional to the main assessment. They should not be presented instead of the results stated in Section 3 and are only presented as additional context, although this does not preclude this additional context becoming standard or routine in the future.

The optional analysis presented below are:

1. Impact range estimates accounting for transition from impulsive to non-impulsive sound (two options).
2. Impact ranges accounting for auditory recovery during the piling sequence (two options).

Consultation with regulatory bodies on these is advised prior to commencement of analysis and assessment.

3.5.1. Estimates accounting for impulsiveness of sound (optional)

Although different thresholds exist to define impulsive and non-impulsive sounds, impact pile driving assessments generally focus on impulsive noise. Both Popper *et al.* (2014) and Popper and Hawkins (2019), and NMFS (2024) separate sounds and respective criteria by impulsive and non-impulsive sound. Recent work (e.g. Lucke *et al.* 2024; Matei *et al.* 2024) has focused on interpreting the transition towards non-impulsivity that occurs over distance and time. Although it is recognised that impact piling activities produce impulsive sounds near the source, sound is expected to lose energy at greater distances and become more non-impulsive. However, identifying the point when an impulsive sound transitions to non-impulsive (Hastie *et al.* 2019; Matei *et al.* 2024) has proven challenging.

Two methods are suggested here that can be presented alongside the onset range for cumulative auditory injury to provide additional context. While national regulators and statutory nature conservation bodies (SNCBs) do not currently advise their use within the main assessment, it may be appropriate to do so when sufficient evidence and data is available. The objective of including this additional analysis is to provide more contextual information on the conservatism that are often highlighted within underwater assessments. As such alongside precautionary statements on the results of the analysis based on the assumptions of full impulsivity, the first additional analysis suggests that changes to the impact ranges are somewhat quantified if the transition to non-impulsive sounds is account for. The objective of this first analysis is to provide context on the magnitude of conservatisms included in the analysis. While the second can be used as a complement to a fully impulsive assessment methodology, where kurtosis data is available.

- Following the evidence presented by Hastie *et al*. (2019), where using the rise time and the quotient of peak pressure over duration the impulsive to non-impulsive transition is identified around 3.5 km, and the evidence presented in Matei *et al.* (2024) where kurtosis dropped below 40 between the first 0.6 to 3.3 km, we suggest that non-impulsive thresholds could be used beyond 3.5 km, in those instances where a modelled non-impulsive impact range extends beyond 3.5 km.

Or:

- Lucke *et al.* (2024) suggests dispensing with the impulsive and non-impulsive binary and instead use the principle of a kurtosis-adjusted SEL ($L_{E,p}$), which would present a single value corrected by its impulsivity and still enable comparison with recognised criteria. Specifically, Lucke *et al.* (2024) suggest that auditory injury thresholds can be interpolated in the impulsive/non-impulsive transition area (kurtosis levels between 3–40). As such, kurtosis-adjusted onset auditory injury cumulative ranges can be presented utilising the methodology in Lucke *et al.* (2024), to account for the area where a presumption of full-impulsivity (kurtosis > 40) is not predicted. It is further recommended that visual representations can be included showing the impact ranges based on the auditory injury criteria in the context of the ranges when kurtosis drops below 40 and subsequently below 3.

Both analyses can provide regulators with an indication of how the presented results in the assessment are influenced by the assumptions and potential conservatism of the analysis. While the first analysis will provide a direct comparison to the impact ranges provided in the main assessment, the second analysis will provide impact ranges for a series of thresholds from impulsive to non-impulsive.

3.5.2. Estimates accounting for piling sequence (optional)

Another significant conservatism that is often highlighted in impact-piling assessment has been the equal energy hypothesis, which assumes that the amount of sound energy animals will be exposed to will have the same impact on its auditory system whether it was received gradually or all at once. Based on the literature review undertaken to support this guidance (Section 2), two approaches are recommended that could be used to account for auditory recovery during breaks in piling (short or long-term). The first approach recommends the use of an ABM tool to assess how different piling sequences affect the resulting impact ranges. These results could be used by the applicant and regulators to investigate how estimated impact ranges can be minimised by adjusting the initial piling sequence. While the second analysis suggest presenting additional impact ranges for slightly higher sound exposure thresholds, resulting from assumed hearing recovery between piling breaks.

A) Accounting for piling sequence (soft start, etc.)

As part of the RaDIN (Range-dependent nature of impulsive noise, Matei *et al.* 2024) study, an ABM was developed to assess how impact ranges varied across different scenarios (source levels, transmission loss, piling timeline, swim speed, and impulsive-to-non-impulsive transition distance). Modifications to the piling timeline by using different hammer logs (i.e. the change in piling energy, blow rate, etc. over the pile installation period) was identified as a major factor in reducing impact ranges. The RaDIN ABM tool may be used to identify optimal piling timelines that will reduce impact ranges and effectively act as a mitigation tool.

The RaDIN tool and respective user helpfile is available here: https://github.com/SMRU-Consulting-Github/RADIN-framework-development.

B) Increase in cumulative threshold to allow for short-term hearing recovery between pile strikes

Based on the evidence of hearing recovery due to breaks in noise exposure presented by Kastelein *et al.* (2014), Sinclair and Verfuss (2021) and Sinclair *et al.* (2023) suggest that a piling duty-cycle of 25% (i.e. piling pulses are present for 25% of the time during active piling) would support increasing the auditory injury cumulative threshold by 2 or 3 dB. Thus, using the minimum adjustment for, for example, the VHF PTS criterion as per Southall *et al.* the threshold would become:

$$155 \text{ dB re } 1 \text{ } \mu Pa^2s \text{ } L_{E,p,t} + \text{dB} = 157 \text{ dB re } 1 \text{ } \mu Pa^2s \text{ } L_{E,p,t}$$

This guidance proposes that these thresholds may be used to provide additional context to the estimated ranges. These additional ranges could be provided within a figure or a table to allow comparison with the estimated ranges based on the impulsive threshold.

4. Future improvements

4.1. Introduction

Through the literature review (Section 2) and guidance note (Section 3), several knowledge gaps have been identified within the current knowledge that underpins underwater noise assessments for pile driving. Where possible, the recommendations and guidance note has attempted to integrate recent evidence to overcome some of these limitations, but many remain. This final section provides a summary of the knowledge gaps and future improvements that were identified, and that can be integrated in future iterations of the guidance when more evidence becomes available. Another aim of this last objective is to support prioritisation of funding for future research, by highlighting the impacts that upcoming research may have on current underwater noise impact assessments.

4.2. Methods

This section is organised so that specific knowledge gaps are first identified followed by a summary on the current state of knowledge, and the implications that each new evidence will have on the guidance. Research gaps are scored using a traffic light system to inform future funding prioritisation based on the following definitions:

- Significant improvement to the assessment but currently key parameters/knowledge lacking for implementation – **fundamental research required**
- Significant improvement to the assessment, initial evidence available but some knowledge gaps need to be addressed before implementation – **supplementary research required**
- Evidence to support improvement being addressed by ongoing research, implementation should be available in the short-term – **improvements should become standard approach**

Following the review of knowledge gaps directly affecting future iterations of pile-driving underwater noise impact assessments, this section presents some broader considerations for the industry and the regulators on the context surrounding underwater impact assessments and dissemination of results and information.

4.3. Future improvements

The tables below summarise key knowledge gaps that were identified through the literature review and guidance note. Knowledge gaps have been grouped under the following themes:

(i) advances in offshore impact-piling,

(ii) understanding impacts of underwater noise and

(iii) ongoing research. The knowledge gaps discussed are summarised in Table 22.

Table 22. Summary of the knowledge gaps presented alongside their traffic light evaluation.

Theme	Knowledge gap	Evaluation
Advances in offshore impact-piling	Deep water piling transmission	
	Piling at other developments	
	Large piles and hammers	
	Piling at floating offshore wind projects	
	Mitigation	
Understanding impacts of underwater noise	Low frequency cetaceans hearing range	
	Marine mammal flee speeds	
	Impulsive noise ranges	
	Equal energy hypothesis (i.e. hearing recovery)	
	Marine mammal auditory injury and TTS criteria	
	Proportion of animals developing PTS	
	Particle motion	
	Sound exposure through the water column	
Ongoing research	Scottish Passive Acoustic Network (SPAN)	

4.3.1. Advances in offshore impact piling

These sections consider how future advances in offshore impact piling may lead to a requirement for additional considerations at the assessment stage.

Deep water piling and transmission

Current knowledge gap:
Much of the underwater noise modelling undertaken in support of impact assessment uses empirically derived models, based significantly on existing data from offshore wind farms in relatively shallow water, typically 20–40 m depth. Many offshore wind farms currently in the assessment phase, and future developments, are planned to be constructed in much deeper water. Models are designed to extrapolate beyond the bounds of existing data, but there will be lower confidence where piling noise transmission data in deep water is not generally available.

Deep water piling and transmission

It is likely that underwater noise monitoring will be required during the installation of foundations or moorings for wind turbines situated in deeper water. Validation of existing models must be undertaken, and further development of models may be required to provide confidence in modelling in these environments. The field studies that will be necessary will require specially designed moorings.

Currently there is a justifiable lower confidence in empirically derived models where the predictions are made using parameters that are outside of the existing data used as inputs, although this has always been the case in the development of offshore wind. There should be a focus on exploiting opportunities to study the effects of transmission loss in deeper water in future studies for impact piling.

Improvement to future guidance:

Based on the validation of upcoming assessments for projects in deeper waters, the guidance could be updated to include specific provisions for empirically derived models being applied to areas beyond the existing data, especially in water 50–100 m and deeper.

Piling at other developments

Current knowledge gap:

The distance over which underwater noise spreads around a piling location is substantial and can potentially reach other neighbouring projects under construction. With an increasing number of offshore wind projects in development and due for construction, some may be under construction concurrently and there is therefore a risk that piling noise from multiple sources could act synergistically, contributing to larger overall exposure to noise. This risk is not included in current guidance, and a better understanding is needed on how these noise sources may interact and influence animal movement and thus, exposure to cumulative noise above auditory injury or disturbance thresholds.

Improvement to future guidance:

It is recommended that future guidance includes recommendations for inclusion of the cumulative exposure effects of multiple piling instances that could occur outside of as well as inside the development under consideration.

Large piles and hammers

Current knowledge gap:

Models for prediction of the noise level at the pile location for input into a transmission loss model largely rely on empirical data. Predictions of noise levels for future offshore wind farms frequently include predictions based on piling hammers that are much bigger than those that have been used to date, and some that are purely theoretical. There are limited studies (e.g. Von Pein *et al.* 2022) that contribute to addressing this data gap.

Opportunities should be sought to investigate the noise output of larger hammers, which may be more efficient at a given blow energy. For example, would a 2,400 kJ hammer operating at maximum capacity produce the same noise level as a 5,500 kJ hammer operating at 2,400 kJ? There may be noise benefits where a hammer is not operating at 100% of its capacity. If this could be demonstrated, this would be indicative of over-precaution in assessments.

Large piles and hammers

Research to date has also indicated that hammers' noise output appears to approach an asymptote at higher energies, and so the noise of larger capacity hammers at high energies may not produce substantial increases over lower energies, potentially due to improved efficiency.

Improvement to future guidance:
The improved understanding on the relationship between noise levels and hammer size and not just in relation to hammer energy, may support inclusion of more detailed provisions on ramp-up and soft-start requirements in the guidance.

Piling at floating offshore wind projects

Current knowledge gap:
To date, few, small floating offshore wind farms have been installed (e.g. Kincardine, Hywind) and there are therefore few data available on underwater noise associated with piling for floating wind designs. Floating designs involve a larger number of piles per turbine than fixed foundation turbines and their typical siting in deep water also provides additional complexity.

Improvement to future guidance:
The different designs proposed for floating offshore wind developments will benefit from detailed study to determine their noise impact. Impact piling remains an option for the floating turbine moorings, and the number of piles required per turbine can be more than for fixed designs which, combined with the deep-water environment, may be harder to apply traditional piling noise abatement to. Further field studies for impulsive noise generated in the construction of floating developments should be considered a priority. Further research into noise mitigation from offshore wind construction should be undertaken specifically for floating offshore wind.

Mitigation

Current knowledge gap:
The risks associated with underwater noise from wind farm construction are well known and the offshore industry is developing more options for systems to reduce the noise. The efficacy of these can change with many factors affecting the noise production (e.g. size of the pile affects its noise frequency, which is critical in the performance of some systems) and its location (deeper water tends to lead to challenges with near- and far-field systems), so predicting the benefits of the use of such systems is often difficult. The industry generally is not open in sharing noise attenuation performance data, which makes it hard to make recommendations for the systems. Although some studies have provided data on mitigation performance (Bellmann *et al.* 2020; Verfuss *et al.* 2019) there is still limited data on many systems, especially in conjunction with larger piles and environments with conditions where no or limited piling has been undertaken in the past.

Industry using noise abatement systems, and sites where they are tested, should be encouraged to share performance data with the wider industry.

Improvement to future guidance:
More detailed information on the performance and success of mitigation measures could inform guidance on future recommendations and how best to include them, or noise abatement systems generally.

4.3.2. Understanding impacts of underwater noise

This section highlights knowledge gaps relevant to understanding the implications of underwater noise exposure to biological receptors (in this report limited to marine mammals and fish), which represent critical information in the interpretation of underwater impact assessments.

Low frequency cetacean hearing range



Current knowledge gap:

Often species-specific hearing ranges are not available and thus are inferred from one species to another. Very recent evidence has been published that minke whales hearing may extend into much higher frequencies than previously assumed (Houser *et al.* 2024).

Improvement to future guidance:

Guidance should be updated once this new evidence is integrated into onset criteria for minke whales.

Marine mammal flee speeds



Current knowledge gap:

The importance of flee speeds as a parameter within movement models to estimate cumulative exposure was highlighted in Section 2.3.1.2 of the literature review. Including evidence-based faster flees speeds was a recommendation made to the steering group, and it was agreed that faster flee speeds can be included as additional context within assessments.

However, some significant knowledge gaps remain before these faster flee speeds can be fully adopted. While recent research has provided new evidence on flee speeds of minke whale (Phillips *et al.* 2025) and harbour porpoise (Kastelein *et al.* 2018) no evidence has been published for other species. Furthermore, it remains unknown the maximum duration for which animals may be able to sustain such higher speeds.

Improvement to future guidance:

While the present guidance incorporated some of this recent evidence and recommended that analysis can be presented using this faster flee speeds alongside the slower speeds, there is not yet enough evidence (measurements only available from a few animals and for some species) to adopt only the faster flees speeds within assessments. Furthermore, it should be noted that including both speeds within assessments allows comparison of results with previous assessments.

On the other hand, without a clearer understanding for how long animals may sustain such faster flee speeds, future ABMs could also allow the incorporation of multiple flee speeds, to account for a change in animal behaviour as they move further away from the noise source.

Impulsive noise ranges

Current knowledge gap:

The impulsiveness of pile driving noise has been a topic of interest within research over the last few years. Within Section 2.3.1.2 of the literature review, an overview of the key findings has been provided. While this guidance has attempted to make provision to overcome some of the conservatisms in relation to the assumption of noise retaining its impulsivity (see Section 3.5.1), key knowledge gaps remain to be filled before definitive updates to underwater noise assessments can be fully supported:

1. A clear threshold to identify the transition from impulsive to non-impulsive sound has not be identified, with different definitions of impulsivity resulting in different transition ranges.
2. Based on the current onset criteria, it is unclear how transition areas (i.e. when sound should not be considered impulsive, but it is not yet under the non-impulsive thresholds) should be treated within assessments, and more importantly what risks animals may still face within these transition areas. While Lucke *et al.* (2024) has made suggestions on how onset thresholds could be interpolated along the impulsiveness gradient (see Section 2.3.1.2 for more details), no evidence is currently available to support how interpolated thresholds translate into TTS or PTS elicitation in the receptors, and how the PTS and TTS onset criteria relate to the metrics used to measure impulsive to non-impulsive transition (e.g. kurtosis).

Improvement to future guidance:

Identification of parameters and criteria to identify the transition from impulsive to non-impulsive noise could support future application of different noise criteria based on said thresholds. However, considerations should be made based on the findings of Matei *et al*. (2024), whose ABM results suggest that accounting for impulsiveness transition did not significantly affect the size of the impact ranges. As such, caution is warranted on the extent of the implications that further research in this area may have on future iterations of the guidance.

Equal energy hypothesis (i.e. hearing recovery)

Current knowledge gap:

The assumption of the equal energy hypothesis and the fact that current methods applied in underwater assessment do not consider the possibility of hearing recovery between breaks is detailed in Section 2.3.1.2 of the literature review. The presented guidance suggests two possible additional analyses that can be presented within assessments that aim at overcoming some of the current conservatism:

1) using the ABM developed as part of the RaDIN project to assess the impact of piling timelines on impact ranges (Matei *et al.* 2024), and
2) follow the methods presented by Sinclair *et al.* (2023), and Sinclair and Verfuss (2021) (reviewed in Section 2.3.1.3 of the guidance) by increasing the cumulative PTS onset criteria by 2 or 3 dB.

Despite these suggestions, there are still significant knowledge gaps that remain to be filled before this additional analysis can replace current assessment practices:

- More evidence is required to understand how piling timelines reduce impact ranges by allowing hearing recovery and how this can be incorporated into cumulative PTS criteria.
- The evidence demonstrating that cumulative exposure to intermittent compared to continuous sound results in different amounts of TTS is generally accepted, however quantification of difference in resulting TTS and the amount that onset criteria should be changed by is still uncertain and currently derived only by calculations rather than evidence and data.

Improvement to future guidance:

Cumulative PTS onset ranges may be updated in the future to account for hearing recovery during piling breaks, and this could be adjusted depending on each specific project planned piling schedule. This will also allow projects to vary their piling schedule to minimise the impact of the proposed development.

Marine mammal auditory injury and TTS criteria

Current knowledge gap:

Auditory injury and TTS onset criteria have evolved since their first publication in Southall *et al.* (2007). While significant advances have been made, it is acknowledged by Southall (2021) that the evidence behind onset criteria is continuously evolving as our understanding of marine mammal hearing improves.

Improvement to future guidance:

As such, onset criteria should be seen as an outstanding knowledge gap, and guidance should be responsive to adjust those based on new evidence being published. It is noted that the NMFS (2024) onset criteria have been included in this guidance note (see Section 3.3.5.3), however the criteria to be used in the assessment have been recommended as a consultation point (see Section 3.1.4) to ensure that future updates to criteria will be considered during the consultation process even if updates to the guidance have not been made available yet.

Proportion of animals developing PTS

Current knowledge gap:

One of the current assumptions made within underwater noise impact assessments is that all the animals exposed to sound levels above onset threshold criteria will develop TTS or PTS. Research carried out by Donovan *et al.* (2017), based on the data presented by Finneran *et al*. (2005), suggested that only 18–19% of the animals exposed to noise above PTS onset threshold are predicted to actually experience PTS. However, this evidence is still quite limited as it is only based on a simulation output.

Improvement to future guidance:

Obtaining more evidence on the probability of individuals developing PTS and TTS when exposed at sound levels above the thresholds will reduce the level of conservatisms currently present within assessments.

Note: it is recognised that experiments aimed at assessing PTS on animals are unethical and it is expected that all results on PTS are derived from knowledge of TTS.

Particle motion

Current knowledge gap:

All fish can detect particle motion, however there is a large gap surrounding particle motion research and evidence. Sound pressure levels have defined criteria against which noise and fish responses can be modelled but this level of detail is lacking for particle motion due to the difficulty in measuring it. This is an area acknowledged by Regulators and Key Consultees, as requiring additional research.

Improvement to future guidance:

Research is needed on particle motion and the effects on different hearing Group species and how this can be modelled in a representative way, which would prove useful in assessments.

Sound exposure across the water column

Current knowledge gap:

A current limitation of sound exposure levels is that they report impact ranges in a two-dimensional manner, assuming that animals are found within the loudest part of the water column. The knowledge gap on this issue is two-fold:

1. Future research should aim at better understanding sound exposure levels along the water column and incorporate this knowledge into future modelling tools which in turn could consider estimating impacts ranges at different depths.
2. More information is needed on animal behavioural responses (specifically in relation to their diving behaviour) to account for animal exposure across the water column. This limitation was also flagged by Matei *et al.* (2024) in relation to accounting for diving behaviour within movement models.

Improvement to future guidance:

Once more evidence is available on noise exposure across the water column, guidance should make provisions on how this information should be incorporated into underwater noise assessments, by for example highlighting depth brackets that may be more relevant for certain species (e.g. deep-diver species).

Sound exposure across the water column

On the other hand, if guidance will push for more consideration of the diving behaviour into movement models this should be done alongside a review of current species-specific diving data availability and with provisions on which parameters should be used.

4.3.3. Ongoing research

This section provides some insights into the results of some ongoing research projects, the results of which may have implications in future iterations of the guidance.

Scottish Passive Acoustic Network (SPAN)

Current knowledge gap:

SPAN's overarching aim is to fill the knowledge gaps on cetacean occurrence across Scottish waters and measure underwater noise profiles throughout the life cycle of renewable energy development.

Improvement to future guidance:

While SPAN is not directly aimed at recording impact-piling activities, data collected through this project will include far-field recordings of several windfarm piling operations and may be used to validate modelled estimates of received sound levels. Validation of modelled estimates is not currently included in the guidance but may be incorporated in the future. Model validation guidance is included by other national guidelines (BOEM 2023; Danish Energy Agency 2022b).

4.4. Additional considerations and future opportunities

On top of reviews of the specific knowledge gaps presented in Section 4.3, there are two additional broader recommendations that users of this guidance should consider.

First, regulators should highly encourage data sharing from developers to start addressing some of the knowledge gaps highlighted. These should be agreed during discussion on model validation and monitoring during the construction phase. The ReCON project recommendations on data and information required for validation should be considered (Verfuss *et al.* 2023).

The final recommendation relates to the dissemination of this guidance, its future updates, and relevant publications within the industry. The authors of this guidance believe that these should be better disseminated and circulated between the relevant stakeholders. An extremely successful example of active community on the dissemination of results is the marine mammal community which through the email list of MARMAM (Marine Mammal Research and Conservation Discussion) updates interested parties worldwide on new publications, legislation and conferences. There is a need for better communication and dissemination of information across the various stakeholders within the industry. This will strongly benefit uptake of this and future guidance and recommendations from regulators.

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Glossary

Definition of acoustic metrics and terms from ISO 18405

Metrics definitions are summarised from ISO 18405:2017 (ISO 2017a).

Metric	Definition
Sound pressure (ISO 3.1.2.1)	Contribution to total pressure caused by the action of sound and it is expressed in pascals (Pa).
Peak sound pressure	Greatest magnitude of the sound pressure during a specified time interval, for a specified frequency range.
Mean-square sound pressure (p^2) (ISO 3.1.3.1)	Integral over a specified time interval of squared sound pressure, divided by the duration of the time interval for a specified frequency range. $$p^2 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} p^2(t)dt$$
Mean-square sound pressure level (ISO 3.2.1.1)	Ten times the logarithm to the base 10 of the ratio of the mean-square sound pressure to the specified reference value in decibels (dB). $$L_p = 10log_{10}(\frac{p^2}{p_0^2}$$
Zero-to-peak sound pressure level (SPLpk) (ISO 3.2.2.1)	Twenty times the logarithm to the base 10 of the ratio of the zero-to-peak sound pressure to the specified reference value in decibels (dB). $$L_{p,pk} = 20log_{10}(\frac{p_{pk}}{p_0})$$ In underwater acoustic the reference value is 1µPa. Note this terminology updates the deprecated terminology of peak sound pressure level (i.e. peak SPL).
Sound exposure (ISO 3.1.3.5)	Integral of the square of the sound pressure (p) over a specified time interval or event, for a specified frequency range. $$E_{p,T} = \int_{t_1}^{t_2} p^2(t)dt$$ Where t_1 and t_2 are the start and end times of the time interval or event.

Metric	Definition
Sound exposure level (SEL) (ISO 3.1.3.5)	Ten times the logarithm to the base 10 of the ratio of the sound exposure, to the specified reference value in decibels. $$L_{E,p} = 10log_{10}(\frac{E_p}{E_{p,0}})$$ In underwater acoustic the reference value is 1μPa. When reporting SEL the time duration and frequency range should be specified.
Transmission loss	Reduction in source level (L) between two specified points (x1 and x2). Transmission loss is expressed in decibels (dB). $$N_{PL} = L_{(x1)} - L_{(x2)}$$

Other terms

Table 23: Glossary of terms.

Term	Definition
Agent-based model	A computational method that simulates interactions of 'agents' to understand how a system behaves. Also known as individual-based model (IBM).
Auditory injury	Damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy. May or may not result in permanent threshold shift (NMFS, 2024).
Biological receptor	An organism that is expected to be sensitive to a pressure
Blow/hammer energy	The energy in kilojoules, equivalent to kilonewton-metres, at which a piling hammer strikes a pile at a stroke.
Blow rate	The repetition rate at which a hammer can strike a pile. This typically is measured in blows per minute and is likely to change with the blow energy.
Crest factor	The measurement of the discrepancy between average peak sound pressure levels within a pulse
Dose response	Describes the magnitude of a response, as a function of exposure
Environmental Baseline	The description of the baseline environment, often reported on in Environmental Impact Assessments prior to development
Exposure duty cycle	The ratio of time a device is on, to the time it is off
Flee speed	The speed that animals are assumed to swim away when eliciting an avoidance response
Kurtosis	A summary of the temporal structure of a signal and directly relates by how variable a sound is in pressure amplitudes

Term	Definition
Isopleths	Lines on a map connecting points having equal value.
Particle motion	Changes in the position of particles over time.
Peak sound pressure level	The highest instantaneous sound level, without time weighting
Permanent Threshold Shift	The permanent reduction in the sensitivity of the ear to sound
Pile driving	The process of using hammers to drive piles into the ground during construction
PTS onset range	The range from a noise source that permanent threshold shift may occur
Pulse duration	The length of a sound pulse
Ramp up	Progressive increase in piling hammer blow energy through a piling sequence
Rise time	The time taken by a signal to reach its maximum pressure, generally from 10% to 90% of the highest peak value.
Soft start	A period at the commencement of a piling sequence where the blow energy is minimised, allowing biological receptors capable of moving away from the noise to do so before the blow energy and noise levels increase in a ramp up.
Temporary Threshold Shift	A temporary decrease in hearing sensitivity, usually caused by exposure to noise

Acronym and abbreviations

Table 24. List of acronyms and abbreviations and their meanings.

Acronym / Abbreviation	Meaning
ABM	Agent-based model
ADD	Acoustic Deterrent Device
BOEM	Bureau of Ocean Energy Management
DAS	Digital Aerial Survey
ECF	Energy Conversion Factor
EIA	Environmental Impact Assessment
HF	High Frequency
IBM	Individual-based models
JNCC	Joint Nature Conservation Committee
LF	Low Frequency
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
OCW	Other marine Carnivores in Water
OSP	Offshore Substation Platform
PCA	Phocid Carnivores in Air
PCW	Phocid Carnivore in Water
PTS	Permanent Threshold Shift
SCANS	Small Cetaceans in European Atlantic Waters and the North Sea
SEL	Sound Exposure Level
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High Frequency
WTG	Wind Turbine Generator

Appendix 1

Overview of the literature sources considered for the literature review.

Table 25. Summary table of references included in the literature review. Sources originally requested by JNCC to be included in the review process are marked as "required" (R), while those identified as part of the literature review process are marked as "additional" (A).

Source	Scientific publication in peer-reviewed journals
R	Farcas *et al.* (2014) – Underwater Noise Modelling for Environmental Impact Assessment
R	Faulkner *et al.* (2018) – Guiding Principles for Assessing the Impact of Underwater Noise
A	Hastie *et al.* (2019) - Effects of Impulsive Noise on Marine Mammals: Investigating Range-dependent Risk
A	Hawkins & Popper (2017) – A Sound Approach to Assessing the Impact of Underwater Noise on Marine Fishes and Invertebrates
R	Herbert-Read *et al.* (2017) – Anthropogenic Noise Pollution from Pile-Driving Disrupts the Structure and Dynamics of Fish Shoals
R	Kastelein *et al.* (2014) – Effect of Level, Duration, and Inter-Pulse Interval of 1–2 kHz Sonar Signal Exposures on Harbor Porpoise Hearing
A	Nedelec *et al.* (2016) – Particle Motion: The Missing Link in Underwater Acoustic Ecology
R	Popper & Hawkins (2019) – An Overview of Fish Bioacoustics and the Impacts of Anthropogenic Sounds on Fishes
R	Popper *et al.* (2014) - Sound Exposure Guidelines
A	Southall *et al.* (2021) – Marine Mammal Noise Exposure Criteria: Assessing the Severity of Marine Mammal Behavioral Responses to Human Noise
A	Southall *et al.* (2019) – Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects
R	Southall *et al.* (2008) – Marine mammal noise-exposure criteria: initial scientific recommendations
R	von Benda-Beckmann *et al.* (2022) – Evaluation of Kurtosis-Corrected Sound Exposure Level as a Metric for Predicting Onset of Hearing Threshold Shifts in Harbor Porpoises (*Phocoena Phocoena*)
R	Von Pein *et al.* (2022) – Scaling Laws for Unmitigated Pile Driving: Dependence of Underwater Noise on Strike Energy, Pile Diameter, Ram Weight, and Water Depth

Source	Report published by statutory bodies and national guidelines
A	Andersson *et al.* (2017) – A Framework for Regulating Underwater Noise during Pile Driving
R	Bureau of Ocean Energy Management (BOEM) (2022) – Nationwide Recommendations for Impact Pile Driving Sound Exposure Modelling and Sound Field Measurement for Offshore Wind Construction and Operations Plans (Marine Acoustic Modelling and Measurement Guideline)

Source	Report published by statutory bodies and national guidelines
R	Danish Energy Agency (2022) – Guideline for Underwater Noise: Installation of Impact or Vibratory Driven Piles
R	Matei *et al.* (2024) – Range-Dependent Nature of Impulsive Noise (RADIN). Final Report
A	Müeller & Zerbs (2013) – Offshore Wind Farms Prediction of Underwater Sound - Minimum Requirements on Documentation
A	National Marine Fisheries Services (NMFS) (2018) - 2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts
A	National Marine Fisheries Services (NMFS) (2023) – National Marine Fisheries Service: summary of Endangered Species Act Acoustic Thresholds (Marine Mammals, Fishes and Sea Turtles)
A	National Marine Fisheries Services (NMFS) (2024) - 2024 Update to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing
A	Persohn *et al.* (2020) – Recommendations to Limit the Impacts of Manmade Underwater Acoustic Emissions on Marine Wildlife
A	Scottish Natural Heritage (SNH) (2016) - Assessing Collision Risk between Underwater Turbines and Marine Wildlife
R	Verfuss *et al.* (2023) – Reducing Uncertainty in Underwater Noise Assessments (ReCon)
R	Wood *et al.* (2023) – Energy Conversion Factors in Underwater Radiated Sound from Marine Piling: Review of Method and Recommendations"

Source	Publicly available underwater noise assessments
A	Royal HaskoningDHV (2019) – East Anglia ONE North Offshore Windfarm. Appendix 11.4. Underwater Noise Assessment
A	Seiche (2024) - Green Volt Offshore Wind Farm. Technical Appendix 9.1. Underwater Noise Technical Report
A	Seiche (2022) – Berwick Bank Wind Farm Appendix 10.1. Subsea Noise Technical Report"
A	Subacoustech Environmental (2018) – Hornsea 3 Offshore Wind Farm. Annex 3.1 - Subsea Noise Technical Report