**JNCC Report 799**

# Evidence review of harbour porpoise disturbance ranges in the context of the assessment and management of impulsive noise in Special Areas of Conservation: impact piling

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# Preface

This is a JNCC-commissioned report completed by SMRU Consulting. The primary intended audience is the JNCC and other statutory nature conservation bodies, to provide a resource to inform development of their guidance.

This report represents one of two complementary reports in contribution to an evidence review of harbour porpoise disturbance ranges in the context of the assessment and management of impulsive noise in Special Areas of Conservation. The current report covers impact piling. The second report covers all other relevant noise sources (Majewska *et al.* 2025). Each report has been written to be stand-alone, so some introductory material is duplicated between the two reports.

# Summary

In 2020, the Joint Nature Conservation Committee (JNCC), Natural England and the Department of Agriculture, Environment and Rural Affairs published guidance on the management of impulsive noise within harbour porpoise Special Areas of Conservation (SACs) (JNCC 2020). A key feature of this guidance was the recommendation of default effective deterrence ranges (EDRs) for specific categories of impulsive noise-generating activities, to assess the spatio-temporal extent of disturbance within SACs in English, Northern Irish and Welsh offshore waters. EDRs provide a radius around activities within which it is assumed that animals are disturbed. Where available, EDRs are based on empirical evidence of harbour porpoise responses to relevant activities. This radius is not equivalent to 100% deterrence/disturbance, but the range within the which the bulk of the effect had been detected (JNCC 2020). The extent of evidence supporting EDRs varies between activities, is very limited for some, and continues to grow over time. As such, periodic review of default recommended EDRs is required to ensure that guidance remains current and is based on the best available evidence.

To inform the development of updated guidance on noise management in harbour porpoise SACs, a review was undertaken of evidence relating to harbour porpoise disturbance to impulsive noise sources. Specifically, the review aimed to:

(i) review the evidence underpinning the current EDRs and subsequently published studies,

(ii) where possible, revisit existing data with the aim of defining default EDRs in a more standardised way,

(iii) recommend default EDRs; and

(iv) recommend priorities for filling evidence gaps.

The current report covers impact piling, including the percussive installation of monopiles, pin piles, sheet piles and conductor piles. A complementary report covers all other relevant noise sources (Majewska *et al.* 2025).

Due to the considerable number of empirical studies of harbour porpoise responses to monopile or pin pile driving in the context of offshore wind farm (OWF) construction, these were the focus of our review for this noise source. Studies which predicted response ranges from predictive noise modelling or field measurements of underwater noise were only considered for conductor and sheet piling due to the lack of empirical response studies for these activities. Building on earlier reviews, relevant studies were summarised, scrutinised and tabulated to include a summary of the reported response ranges along with key attributes such as location, pile type and diameter, hammer energy, acoustic deterrent device use, number of piling events monitored and reported noise levels. Each piece of evidence was also assigned a score based on specific evaluation criteria, including the type of study (empirical response, noise measurement or modelling), a study's ability to estimate an EDR, and several additional criteria relating to the relevance of the study to current UK piling practices and limitations of the study design or analysis.

A total of 21 studies of piling at OWFs were reviewed; one related to sheet piles, while all others covered monopiles and/or pin piles. These studies covered waters of the UK, Netherlands, Germany, Belgium and Denmark, and a variety of piling parameters (e.g. pile diameters, hammer energies) and levels of noise abatement. Evidence is dominated by passive acoustic monitoring (PAM) studies, with some also provided by aerial surveys. Two noise measurement studies were reviewed for conductor piling. Where possible, data and plots presented in existing studies were examined to estimated EDRs according to a

common definition, that being a distance representing the average habitat loss per individual. This exercise was supplemented by an additional analysis performed on data from the three OWFs in the Moray Firth. These efforts, combined with EDRs already reported in studies, resulted in a total of 13 estimated EDRs for monopiles and/or pin piles. Lastly, weighted averages of reported effects ranges were generated (favouring estimated EDRs over values reported in studies, where possible) using evidence scores as weights. These weighted averages provided further context to general patterns observed across studies where recommending default EDRs.

Overall, the review confirmed previous observations: that among studies, there is considerable variation in the approach to data collection, analysis and reporting of results, which complicates comparison of results and adds considerable uncertainty to the estimation of effects ranges. While this does not preclude refinement of the current recommended EDRs for harbour porpoise SAC management, it does:

(i) limit the extent to which EDRs can be recommended for anything other than broad categories of piling activity (e.g. with vs without noise abatement),

(ii) limit the extent to which extrapolations can be made from existing studies to current piling practices in the UK (e.g. acoustic deterrent device (ADD) durations, hammer energies); and, ultimately

(iii) limit the extent to which conservatism can be confidently reduced.

Among the evidence reviewed, there was not strong support for different EDRs for monopiles and pin piles; reported effects ranges showed almost complete overlap for the two pile types. By contrast, there was strong support for smaller EDRs for piling with noise abatement than unabated piling. Recommended EDRs follow consideration of all the evidence reviewed in the current study, including reported effects ranges and estimated EDRs, but also the limitations and relevance of specific evidence.

For **monopiles or pin piles *without* noise abatement**, a majority of evidence points towards an EDR in the region of 15 - 20 km. The weighted average of reported effects ranges across 14 studies (included 8 estimated EDRs) in this category was 17.4 km. It is noted that EDRs of < 15 km have been reported for unabated piling, including from recent analyses of highly relevant projects, and that comparable data collection is planned for several projects in UK waters in 2025. It is recommended that this suggested EDR for unabated piling should be reviewed as soon as such data are available.

For **monopiles or pin piles *with* noise abatement**, a majority of evidence points towards an EDR in the region of 10 - 15 km. The weighted average of reported effects ranges across seven relevant studies (including four estimated EDRs) in this category was 10.8 km. It is important to note that an EDR of 10 - 15 km assumes a reduction in broadband $SEL_{SS}$ @ 750 m of approximately 10 dB or more. While noise modelling and dose-response assumptions may support a graduated approach of smaller EDRs within this range for increasing dB reductions, the empirical evidence does not provide strong support for such an approach.

For **conductor piling or sheet piling**, the evidence base is limited but the nature of the activity and associated noise levels suggest that an EDR not exceeding the lower bound of those considered for abated monopiles or pin piles would be appropriate (i.e. an EDR ≤ 10 km). Should sheet or conductor piling occur without the use of an ADD, then an EDR in the range 5 - 10 km may be appropriate.

Priorities are recommended for filling evidence gaps. Foremost among these is a reiteration of an earlier such review: that there is a need to conduct a true meta-analysis of existing

PAM data which standardises as many elements of the analysis and reporting as possible, to facilitate more accurate investigation of the spatial extent of porpoise responses to pile-driving, and the factors influencing these responses. Additional priorities include empirical studies of porpoise responses to piling with moderate levels of noise abatement; studies of the influence of ADDs on porpoise responses in a OWF construction context (including different ADD types); and studies of noise levels and animals' responses to pin piling of anchors for floating OWF.

# Contents

# 1. Introduction

## 1.1. Overview: Harbour porpoise SAC management and Effective Deterrence Ranges

Special Areas of Conservation (SACs) have been designated for harbour porpoise (*Phocoena phocoena*) in UK waters with the main aims of protecting recognised important habitats for the species and avoiding significant disturbance in order to allow those habitats to contribute in the best possible way to supporting the species (JNCC 2020). Conservation objectives for harbour porpoise SACs in waters of England, Wales and Northern Ireland are provided in Table 1, one of which is ensuring that there is no significant disturbance of the species.

**Table 1.** Conservation objectives for harbour porpoise SACs in waters of England, Wales and Northern Ireland.

| To ensure that the integrity of the site is maintained and that it makes an appropriate contribution to maintaining Favourable Conservation Status (FCS) for harbour porpoise in UK waters. In the context of natural change, this will be achieved by ensuring that: | |
|---|---|
| **Objective** | **Requirement** |
| Objective 1 | Harbour porpoise is a viable component of the site. |
| Objective 2 | There is no significant disturbance of the species. |
| Objective 3 | The condition of the supporting habitats and processes, and the availability of prey is maintained. |

Harbour porpoise are considered sensitive to underwater noise associated with industrial activities (e.g. impulsive noise associated with pile driving for construction of offshore wind farms (OWFs)) and field studies have shown that animals respond to such activities. Given the scale of noise-generating activity planned within and adjacent to some SACs, an approach to managing the extent of noise disturbance within these sites was developed.

Guidance on the management of impulsive noise within harbour porpoise SACs in waters of England, Wales and Northern Ireland (JNCC 2020) defines significant disturbance through quantitative time-area thresholds for the spatio-temporal extent of disturbance within the SAC. The method of estimating the spatial extent of disturbance advised for SACs in English, Northern Irish and Welsh offshore waters is by using effective deterrence ranges (EDRs) for specific impulsive noise-generating activities (Table 2). EDRs assume a fixed disturbance range for harbour porpoise for different activities, which equates to the average habitat lost by individual animals. Other methods of estimating the spatial extent of disturbance include the use of noise propagation modelling and response thresholds, with such an approach recommended by Natural Resources Wales for SACs in Welsh waters (NRW 2023).

This approach is strongly influenced by the size of activity-specific EDRs - for which there are considerable uncertainties. The Joint Nature Conservation Committee (JNCC) 2020 guidance provided recommended EDRs for several categories of impulsive noise-generating activities, including: impact pile-driving (monopiles and pin pile, with and without noise abatement, and conductor piling), unexploded ordnance (UXO) detonation, seismic (airgun) survey and high-resolution geophysical survey. More recently, default EDRs have been recommended for all activities listed in the UK Marine Noise Registry (MNR) (JNCC 2023a, b), including further sub-categories of those presented in JNCC 2020. A Department for Environment Food and Rural Affairs (Defra)-commissioned review of the evidence underlying the EDRs, published in 2023, identified that empirical data of harbour porpoise responses were only available for impact-piling of wind farm foundations and, to a lesser extent, for seismic surveys and Acoustic Deterrent Devices (ADDs) (Brown *et al.* 2023). A summary of key findings from that review is provided in Section 1.2.

### 1.1.1. Impact piling - description of activity

During impact pile-driving, hollow steel piles are driven into the seabed using a hydraulic hammer to secure infrastructure such as wind turbine foundations, offshore platforms, subsea manifolds or anchors. Pile-driven wind turbine foundations are either secured to the seabed by a single large diameter **monopile** or several smaller diameter **pin piles**; other infrastructure typically uses pin piles. This process results in the production of high intensity sounds of an impulsive nature. The short broadband impulses are dominated by energy at low frequencies, with source levels of $SPL_{pk}$ > 230 dB re 1 µPa @ 1 m, and a blow typically every 1–2 seconds (Jiménez-Arranz *et al.* 2020a). Received noise levels and noise propagation are heavily dependent on a range of parameters, with influential factors including pile diameter and type, hammer energy, depth of pile in substrate, seabed substrate type, water depth, current strength, sound speed profiles, and bathymetry (Bellmann *et al.* 2020). It can take between approximately one and several hours to install a single pile, with foundations requiring multiple pin piles generally taking longer to install than monopiles. Piling programmes can last several months for a commercial-scale wind farm. ADDs are widely used in advance of piling operations to deter harbour porpoise and other marine mammals from zones of potential auditory injury. The duration of ADD use varies according to the size of predicted impact zones and the advice of regulatory authorities.

In addition to hollow steel piles, **sheet piles** may also be driven into the seabed using a hydraulic hammer, resulting in impulsive noise 'sheet piling'). Sheet piling is used where there is a need for earth retention and/or creation of a cofferdam to generate a dry working area. It is common in coastal construction around ports but less common offshore (being used in just one of the OWF empirical porpoise response studies reviewed here, Carstensen *et al.* 2006). Impact piling of sheet piles produces a relatively broadband sound in the range of 25 - 4,000 Hz, with a higher relative high-frequency content than steel pipes but considerably lower sound pressure levels than the pin piles and monopiles typically used for wind turbine foundations (Jiménez-Arranz *et al.* 2020b), with the latter requiring much higher hammer energies to install.

**Conductor piling** is a non-routine activity associated with drilling wells for hydrocarbon exploration in certain circumstances (BEIS 2019). It is a type of impact pile-driving of a conductor pipe (essentially a narrow pin pile) into the seabed to provide a stable hole through which upper sections of a well are drilled in certain sediment types. The diameter of the conductor pipe is usually < 1 m and therefore requires considerably lower hammer energy than that used for pin piles or monopiles for wind turbine foundations which are several metres in diameter. Direct measurements of underwater sound generated during conductor piling are limited; mean broadband noise levels of ≤ 156 dB re 1 µPa at 750 m from source, with peak frequency around 200 Hz, were recorded at conductor piling in shallow water in the North Sea (Jiang *et al.* 2015). Conductor piling events generally last several hours.

**Noise abatement systems (NAS)** can be used to reduce the transmission of piling noise into the marine environment and have been widely deployed for approximately a decade during OWF construction off mainland Europe. Systems are varied (see reviews in Verfuss *et al.* 2019; Bellmann *et al.* 2020; Barber *et al.* 2024), with some of the most widely used in OWF applications including single or double bubble curtains, or sleeves deployed around the pile. Many systems can be used in combination to achieve greater noise reductions.

### 1.1.2. Current EDRs for piling noise

The current recommended activity-specific EDRs (Table 2) are based on empirical evidence from field studies of porpoise responses to those noise sources (where such data exist), as opposed to disturbance ranges estimated from noise modelling. The JNCC (2020) guidance explains the preference for empirically-derived EDRs over modelled disturbance ranges due to the following uncertainties applicable to the latter: a lack of consensus on quantitative thresholds for disturbance; considerable variability among predicted noise levels depending on the choice of modelling approach; that other characteristics of sounds (i.e. more than just received levels) will influence how an animal perceives sound; and that factors such as behavioural context and prior exposure to sound will also influence how animals respond.

**Table 2.** Activity-specific effective deterrence ranges (EDRs) for impact piling as currently recommended in the guidance on the management of impulsive noise within harbour porpoise SACs in waters of England, Wales and Northern Ireland (JNCC 2020, 2023a). [1] Activity categories match those as presented most recently in the MNR guidance (JNCC 2023a). [2] Additional references are cited in the main text of (JNCC 2020). [3] An EDR was not assigned specifically to sheet piles in JNCC (2020) but was subsequently assigned in JNCC (2023a).

| **Activity [1]** | | **EDR (km)** | **References from which EDRs were based [2]** |
|---|---|---|---|
| *Without noise abatement* | Monopiles | 26 | Tougaard *et al.* (2013); Dähne *et al.* (2013) |
| | Pin piles | 15 | Graham *et al.* (2019) |
| | Conductor piles for oil and gas | 15 | Jiang *et al.* (2015); MacGillivray (2018); Graham *et al.* (2019) |
| | Sheet piles | 15 | N/A[3] |
| *With noise abatement* | All pile types | 15 | Dähne *et al.* (2017); Rose *et al.* (2019) |

The recommended EDRs were based on empirically derived ranges "*where the bulk of the effect (reduction in porpoise vocal activity or sightings) had been detected*", noting that:

- The EDRs do not represent 100% disturbance in an associated area, nor do they represent the maximum range at which disturbance effects can be detected.
- Only the most detectable effects on the animals are observed by those studies informing the EDRs.
- The observed disturbance effects reported in the different studies were not derived in a comparable way.

The latter point is particularly important in terms of how suitable the reported disturbance effects are for deriving an EDR according to the definition of the *"average level of habitat loss"*. Among the studies cited, it is only Tougaard *et al.* (2013) who provided a clear definition of EDR that related to average temporary habitat loss per individual, noting that for this to be estimated results need to include a suitable deterrence function - a gradient of decreasing deterrence effect with increasing distance to source (see Section 2.2 for further details). The JNCC (2020) guidance refers to Tougaard *et al.* (2013) and that approach to estimating an EDR from a specific dataset. However, the JNCC's review of studies to inform recommendations for activity-specific EDRs did not attempt to apply the same approach to any deterrence functions presented in other studies. Different projects have reported the observed effects differently, meaning it is not straightforward to use a standard way of deriving an EDR. Instead, the recommended default EDRs were informed by the published ranges where the bulk of the effect had been detected, being neither equivalent to 100% deterrence nor the limit at which effects have been detected (JNCC 2020).

For monopiles without noise abatement systems (NAS), an EDR of 26 km is recommended in the JNCC (2020) guidance. A key basis for the 26 km EDR for monopiles is the review of several studies presented by Tougaard *et al.* (2013), who used data from Dähne *et al.* (2013) at the Alpha Ventus OWF (Germany) to estimate a deterrence function which indicated an EDR of 26 km (this distance representing the overall temporary loss of habitat).

For monopiles with NAS, the JNCC (2020) guidance recommends a 15 km EDR, based on the average of the observed maximum distances in field studies, citing deterrence ranges between 12 and 17 km reported for different types of piling with NAS (Dähne *et al.* 2017; Brandt *et al.* 2018; Rose *et al.* 2019).

For pin piling (with or without noise abatement), the JNCC (2020) guidance recommends an EDR of 15 km. This was largely based on pin piling without noise abatement at the Beatrice OWF (UK), with responses of porpoise presented in Graham *et al.* (2019). Early in the construction period, Graham *et al.* (2019) found a 50% probability of harbour porpoise behavioural response within 7.4 km in the 12 hours after the piling had ended (the deterrence distance during piling was not reported). The study also showed a 25% probability of response within approximately 18 km. These distances decreased over the course of the construction programme, suggesting potential habituation to the noise source. Therefore, the guidance selected a 15 km EDR to account for *"the fact that the bulk of the effects while piling was occurring would have likely been detected at distances greater than 7.4 km"*.

### 1.1.3. Review of EDRs

The JNCC (2020) guidance notes that the default recommended EDRs for piling and other noise sources will be under regular review considering emerging evidence such as that gathered through monitoring associated with licensed activities. The need for consideration of emerging evidence and additional review of existing evidence is a key driver of the EDR evidence review presented in this current report.

## 1.2. The Defra-commissioned review of evidence underlying EDRs (Brown *et al.* 2023)

In 2023, a Defra-commissioned review of evidence supporting the management of disturbance in harbour porpoise SACs was published, which included a review of the evidence underlying the current EDRs used in porpoise SAC management (Brown *et al.* 2023). The review provided a detailed examination of 19 studies published on the effect of pile driving on harbour porpoise, with a particular focus on the reported spatial extent of responses. Key findings of this review included:

- Studies on the response of harbour porpoise to pile-driving have generally illustrated a commonality in terms of temporary displacement to distances of c. 10–20 km, regardless of pile type or the use of noise abatement.
- The current 26 km EDR applied to monopiles without noise abatement is largely based on a study conducted at Alpha Ventus OWF which was only installed with pin piles on jacket or tripod foundations.

- For the pile dimensions and hammer energies studied to date, it does not appear that there is sufficient evidence to support such a large difference in EDR between pin piles (15 km) and unabated monopiles (26 km). There is considerable overlap in the ranges of reported effects among the two pile types, and 26 km exceeds the range at which the bulk of effects are reported in a majority of studies of either pin piles or monopiles.
- Among studies, there was considerable variation in the approach to data analysis and reporting of results, which complicates the comparison of results and adds considerable uncertainty to the estimation of the ranges of effects.
- Only one study (Tougaard *et al.* 2013) provided a clear definition of the approach to estimating EDRs: this being the average habitat loss per individual. Other studies rarely reported results in a way that this approach could be applied. As such, it can be difficult to interpret effect ranges with greater resolution than the maximum distance of detectable effect, or a wide range of distances over which effects appear to plateau.

To enable a more robust assessment of porpoise responses to pile-driving, including the estimation of EDRs according to a clear definition, Brown *et al.* (2023) recommended a **meta-analysis** of existing data. Such an exercise would seek to standardise as many elements of the analysis and reporting as possible, to facilitate more accurate investigation of the spatial extent of porpoise responses to pile-driving, and the factors influencing these responses. Such a meta-analysis would require a compilation and re-analysis of data from as many available relevant datasets as possible.

## 1.3. Objectives

The overall aim of this study is to review empirical evidence on harbour porpoise disturbance ranges from impact piling and put forward recommendations for updated EDRs. This will be achieved through four specific objectives:

1. Review literature (grey and peer-reviewed) for empirical evidence of harbour porpoise disturbance in relation to impulsive noise for piling.
2. Conduct a meta-analysis of existing porpoise disturbance data with the aim of defining default EDRs in a more standardised way.
3. Recommend default EDRs for impact piling, listing respective underpinning evidence and limitations.
4. Recommend priorities for filling evidence gaps on harbour porpoise disturbance from piling.

# 2. Literature Review

## 2.1. Approach (summary of literature review process)

In the current study, we build upon the literature review undertaken by Brown *et al.* (2023) to identify and review new relevant empirical studies of harbour porpoise responses to impact piling. Our approach to identifying new studies included the following:

- Drawing upon SMRU Consulting's internal database of literature and general awareness of relevant studies.
- Engaging with relevant external research groups to identify any new evidence.
- Google scholar search, utilising 'cited by' function on key references (e.g. Graham *et al.* 2019).
- PNNL Tethys Knowledge Base.
- Royal Belgian Institute of Natural Sciences offshore wind monitoring reports.

Due to the considerable number of empirical studies of harbour porpoise responses to monopile or pin pile driving in the context of OWF construction, these were the focus of our review for this noise source. Studies which predicted response ranges from predictive noise modelling or field measurements of underwater noise were only considered for conductor and sheet piling due to the lack of empirical response studies to these activities. Such noise modelling and measurement studies carry additional uncertainty over empirical response studies (see Section 1.1.1) and so were only considered where they represented the only data sources available.

### 2.1.1. Evidence scoring

Evidence scoring methodology was developed so that recommended default EDRs could be accompanied by a measure of confidence associated with the robustness of the evidence, its relevance to harbour porpoise in UK waters and the volume of underlying evidence. This process involves two key steps: (i) evaluating individual studies across various criteria, and (ii) aggregating these scores across all studies. Empirical studies of animal responses, such as direct observations or acoustic detections, receive the highest confidence scores (all studies reviewed for impact piling in this report are based on empirical evidence). Additional scoring adjustments consider a study's ability to estimate an EDR, species relevance, environmental characteristics, and alignment with UK-specific activity parameters. Minor penalties apply for limitations such as small datasets or lack of statistical analysis. The scoring framework follows a decision-tree approach, where all studies are initially assigned a baseline score and penalties can be subsequently applied under each criterion. Details are provided in Appendix 1.

## 2.2. Defining the EDR

As described by Brown *et al.* (2023), while all studies of porpoise responses to piling report on the spatial extent of responses, it is uncommon for such studies to estimate the EDR. Therefore, it is challenging to determine if reported response ranges are under- or over-estimating response ranges in terms of the average habitat loss per individual.

Where possible, we consider the results of the reviewed literature in the context of the definition of an EDR as developed from a deterrence function (response vs distance), as per Tougaard *et al.* (2013) and analogous to the Effective Response Range described in Tyack and Thomas (2019). This provides a measure of the average temporary habitat loss per individual, and accounts for individual differences in responses of animals at a given range from the source, with some not responding at closer ranges (losing less habitat) and some responding at larger ranges (losing more habitat). The EDR is a threshold distance: beyond this distance the number of animals responding to the disturbance equals the number of animals not responding within that distance (Figure 1).

The aforementioned EDR metric is preferred to alternative metrics such as $R_{50}$ (the distance at which there is a 50% probability of response), which fails to account for the exponential increase in size of disturbed area with range from source and, therefore, underestimates the number of animals responding and the average habitat loss (Tyack & Thomas 2019).

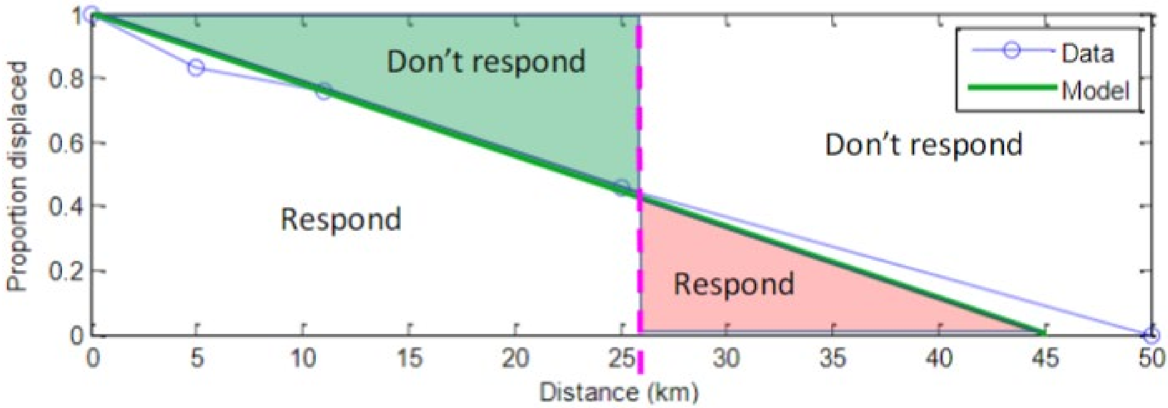


**Figure 1.** A modification of Figure 7 from Tougaard *et al.* (2013) to illustrate how the EDR (pink dashed line at 26 km) relates to a deterrence function. By assuming a uniform density of animals across the area of impact and that the deterrence function is symmetrical in all directions, the proportion displaced (or probability of response) is used to estimate the cumulative number of animals responding and not responding with increasing range from source. The EDR is a threshold distance: beyond this distance the number of animals *responding* to the disturbance (represented by the red triangle) equals the number of animals *not responding* within that distance (green triangle).

## 2.3. Evidence

Section 2.3.1 below provides summary reviews of relevant empirical studies identified supplementary to those reviewed in Brown *et al.* (2023). These studies primarily utilise passive acoustic monitoring (PAM) data to assess harbour porpoise responses, and this review focusses on how porpoise respond as a function of distance to piling, rather than received noise levels, as it is empirical evidence of response ranges which are currently favoured in harbour porpoise SAC noise management (JNCC 2020).

Following this, Section 2.3.2, provides summary reviews of all available empirical studies of harbour porpoise responses to piling based on aerial survey data. These are included as an alternative source of information on the spatial extent of porpoise responses to piling which, while typically of a coarse spatio-temporal resolution, are less influenced by variability in analytical methods than PAM data and do not assume that vocalisation rates are directly related to porpoise occurrence.

Section 2.3.4 provides a tabulation of all reviewed empirical response studies from both Brown *et al.* (2023) and the current study, including features of the associated OWFs (e.g. region, water depth, piling characteristics, ADD use, use of NAS, reported noise levels) and the reported spatial extent or deterrence effects. This section also includes a figure plotting the reported spatial extent or deterrence effects for different pile types and with/without noise abatement. Plots of the reported spatial extent of deterrence vs selected features of OWFs are provided in Appendix 3. For further detail on those studies which did not undergo a detailed review in the current study (see Section 2.3.1), see Appendix 1 of Brown *et al.* (2023).

### 2.3.1. Empirical response studies - PAM

#### 2.3.1.1. Benhemma-Le Gall *et al.* (2024)

Benhemma-Le Gall *et al.* (2024) used PAM at Moray West OWF, in the Moray Firth (eastern Scotland), to evaluate the response of harbour porpoises to monopile driving during construction. Baseline data were collected over one month, followed by three months of monitoring during the installation of 18 monopiles (9.5 to 10 m diameter) using a 4,400 kJ hydraulic impact hammer. Noise abatement measures were not applied and ADDs were used for 10 minutes immediately prior to piling commencing to deter marine mammals from the zone of potential injury. An array of 60 Cetacean Porpoise Detectors (CPODs, Chelonia Limited, UK), deployed up to 33.4 km from piling locations, captured detection data.

Data were analysed to assess, for each CPOD location, the proportional change in porpoise Detection Positive Hours (DPH) between a response period (24-h post-piling) and a baseline period (a period of 24-h starting 48-h before piling). Following the approach taken by Graham *et al.* (2019) for Beatrice OWF, porpoise were considered to have exhibited a behavioural response to piling when the proportional decrease in occurrence was greater than 0.5. The value of 0.5 was selected based on an analysis of baseline data collected within the Moray Firth in 2017 when no piling or other known loud impulsive noise-generating activities were taking place. Within this baseline period, a null distribution of proportional change in occurrence (DPH) was generated by randomly sampling two 24-h periods two days apart and determining the proportional change in the number of DPH. A 0.5 decrease in the proportion of DPH was the 1$^{st}$ percentile of this distribution.

This ‘pre-processing’ type approach simplifies the subsequent modelling methodology by establishing a binary response variable: for each monitoring location and piling event, porpoise either respond (1) or do not respond (0) (i.e. are disturbed or not disturbed). By setting such a high threshold (99% confidence) for assigning a positive behavioural response (i.e. a ‘1’), the probability of mis-classifying a stochastic change in porpoise occurrence (i.e. unrelated to piling) as a response to piling is very low. This should reduce the likelihood of false positives at large distances from stretching out the deterrence function, resulting in a higher EDR. Conversely, this approach also has the potential to underestimate genuine responses of a lesser magnitude, as all proportional changes in occurrence smaller than 0.5 will be assigned a zero response. However, as the deterrence function is a model fit between a binary response variable and not a step-function, then moderate-level responses at intermediate distances are still predicted.

From the binary response data, Generalised Linear Mixed Models (GLMMs) were developed for a subset of the monitored piling events where there was sufficient time between piling events to establish an appropriate baseline period. It is noted that vessel traffic was also factored into the analyses as a covariate, with the influence of vessels in close proximity to CPODs on detection rates assessed and accounted for to isolate responses to piling and not vessels. All models included a random factor that combined the CPOD and deployment location identifiers to control for variation in device sensitivity or any site-specific environmental differences. Piling order and duration were also included as candidate covariates.

Models for the first two piling events indicated a ≥ 50% probability of response within 5 km of piling and an EDR of 9.4 km (following the definitions of Tougaard *et al.* 2013, and Tyack &

Thomas 2019). Models were also developed for a subset of seven piling events, but only limited results were presented for these; more pronounced responses were observed for the first two piling events. Focusing on the first two piles was favoured by the authors as it was considered more conservative (responses were greater than for seven piles combined). The authors reported that the extent of porpoise responses to monopiles at Moray West OWF were broadly similar to those reported by Graham *et al.* (2019) for pin piles at the Beatrice OWF. However, authors highlighted that the reduced use of ADDs in this study (10 minutes) may have contributed to a weaker observed response compared to Beatrice OWF (where an ADD was used for 15 minutes). In Section 2.3.5, the data for piling at OWFs within the Moray Firth is revisited using an alternative approach (e.g. shorter 12-h response period).

#### 2.3.1.2. Rose *et al.* (2024)

Rose *et al.* (2024) utilised PAM to assess the effects of various noise sources, including ship traffic, vibropiling and impact pile driving, on harbour porpoise presence before and during the construction phase at the Kaskasi II OWF in the German North Sea. Data were collected from 17 CPOD stations from June 2021 to May 2022, with construction taking place over two months in 2022. A total of 25 monopile foundations were installed using impact pile driving or a combination of vibration hammering and impact pile driving. Noise mitigation techniques such as bubble curtains and hydro sound absorbers were employed at turbines installed using impact pile driving. ADDs were used for 30 minutes before piling commenced.

Generalised Additive Models (GAMs) or Generalised Additive Mixed Models (GAMMs) were applied to the hourly porpoise detection data to identify factors that influenced detection rates. The dependent variable in the GAMs was the hourly porpoise detection rate (Porpoise Positive Minutes, PPM), and the explanatory variables included sound levels, shipping activity, distance from pile driving and time of day.

The results of the gradient analysis showed that the number of harbour porpoise detections increased as distance from the turbines increased. This was the case during baseline as well as construction phases. The GAMs highlighted that for noise-mitigated impact piling, porpoises were deterred up to distances of 7 to 14 km, with deterrence lasting approximately 30 - 40 h. In contrast, unmitigated impact piling caused more severe deterrence, with porpoises avoiding the area up to 15 to 20 km. However, the authors noted that the exact maximum distance could not be determined with precision due to a limited dataset.

Cumulative effects analyses (using an approach which did not seek to isolate responses specifically to piling activity) showed that, unlike the GAM results, relatively low harbour porpoise detection rates were observed at a considerable distance (approximately 18 km) even before the construction phase, with little further decline during the construction phase (in contrast to changes in detection rates < 18 km). As such, the study concluded that the low detection rates beyond 18 km from the construction sites did not seem to be linked to the pile-driving activities. The GAMM analysis showed that ship traffic, particularly when ships were within 2 km of CPODs, negatively impacted porpoise detection rates, with effects extending up to 3 km for dynamic positioning vessels.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2. Instead, these represent the average distance at which porpoise detections were predicted to be lower during periods of piling than non-piling and are, therefore, akin to the maximum distance of detectable effect. These results, as currently presented, were not considered suitable for estimation of an EDR (see Section 3.2).

#### 2.3.1.3. Van Geel *et al* 2023

van Geel *et al.* (2023) presented the results of PAM during construction of the East Anglia ONE OWF in the southern North Sea. A total of 102 wind turbine jacket foundations were installed with 2.5 m diameter pin piles (total 310 pin piles installed) without the use of noise abatement. Maximum hammer energy reached was 1,169 kJ. A Lofitech seal scarer ADD was used to deter marine mammals from the zone of potential injury, although the ADD duration was not provided. Using an array of 12 CPODs deployed out to ~20 km from piling locations, porpoise detection rates were compared between days with piling ('piling') and days without piling ('non-piling'), with the exclusion of the 48-h pre- and post-piling from non-piling period. GAMs were developed to predict the probability of porpoise detection within the piling and non-piling periods, given a variety of covariates.

Distance to piling was the first and second most important covariate in the piling and non-piling models, respectively. A posterior simulation indicated that when uncertainty around all model coefficients were incorporated, the median probability of detecting porpoises was lower during piling than in the non-piling period up to 14 km from piling activity. The authors noted that, while results indicated that piling impacted porpoise detections, other potentially concurrent noise sources such as vessel traffic, ADDs, and UXO clearance could also have contributed to deterrence. In interpreting the results, it is important to note that harbour porpoise detection rates at the most distant monitoring site to the wind farm area (approx. 20 km) were higher than those closer to the farm even during non-piling periods. This pattern was also apparent in the months before and after the construction period, suggesting that the most distant monitoring site (which was closer to the coast) may have represented more favourable habitat than sites closer to the wind farm.

It is noted that 14 km does not meet the definition of an EDR as described in Section 2.2. Instead, it represents the average distance at which porpoise detections were predicted to be lower during days with piling than days without piling and is therefore akin to the maximum distance of detectable effect. In Section 3.3, these results are revisited with a view to estimating a corresponding EDR.

#### 2.3.1.4. De Jong *et al.* (2022)

***Gemini***

The study by de Jong *et al.* (2022) used passive acoustic monitoring to evaluate the dose-response relationship between harbour porpoises and the noise generated by monopile installation at the Gemini OWF in the Dutch North Sea. The project involved the installation of 150 monopile foundation turbines (7.5 m diameter) over seven months without noise abatement measures. FaunaGuard ADDs (see Voss *et al.* 2021) were used for an average of 73 minutes. Fifteen CPODs were deployed within and around the wind farm, extending out to 40 km and additional acoustic recorders were installed at two CPOD locations.

Analysis of porpoise echolocation detections (PPM) revealed that porpoises were detected less frequently during pile-driving at distances of at least 15 km from the source, with this distance corresponding to where the upper 95% CI of the mean response was equal to the reference level. The authors noted that the observed avoidance distance may have been limited by the relatively short duration of piling events, which did not allow enough time for harbour porpoise to move further away.

It is noted that 15 km does not meet the definition of an EDR as described in Section 2.2. Instead, it represents the average distance at which porpoise detections were predicted to be lower during periods of piling than non-piling and is, therefore, akin to the maximum distance of detectable effect. In Section 3.3, these results are revisited with a view to estimating a corresponding EDR.

***Borssele***

de Jong *et al.* (2022) also investigated the relationship between harbour porpoise and monopile installation noise at the Borssele OWF in the Dutch North Sea. The study monitored porpoise click detections with 16 CPODs and recorded underwater noise with seven recorders during the installation of 94 turbines at Borssele I & II and 77 turbines at Borssele III & IV. Noise abatement measures included a Double Big Bubble Curtain (DBBC) and a sleeve system of either a HydroSound Damper (HSD) or the AdBm system.

Analysis incorporated noise modelling to calibrate piling strike data to Sound Exposure Level (SEL) and applied Bernoulli GAMMs to evaluate the effects of weighted and unweighted SEL, as well as distance to piling, on porpoise presence. A dose-response relationship was estimated based on the results of the GAMM analysis.

Key findings in relation to distance showed that harbour porpoise presence (PPM) declined with increasing sound pressure levels, and that porpoises were detected less frequently during pile driving at distances of at least 7 km from the source, with this distance corresponding to where the upper 95% CI of the mean response was equal to the reference level. Less frequent detections were also noticeable up to 15 km from piling. The authors reported that clear piling noise detection was limited to 10 km from piling as beyond that distance piling noise was masked by ship traffic and noise mitigation measures. The study also reported that analysis showed that further away than 15 km, piling sound did not affect the probability of PPM. Probability of detection reduced significantly when the weighted SEL was ≥ 55 dB re 1 $\mu Pa^2 s$, and the unweighted broadband SEL was ≥ 130 dB re 1 $\mu Pa^2 s$.

It is noted that the reported values of 7 km and 15 km do not meet the definition of an EDR as described in Section 2.2. Instead, these values represent the extent of distances at which porpoise detections were predicted to be lower during periods of piling than non-piling. The distance of 7 km is akin to the maximum significant effect (at the 95% level). In Section 3.3, results are revisited with a view to estimating a corresponding EDR.

#### 2.3.1.5. Rumes *et al.* (2022)

Rumes *et al.* (2022) investigated the factors influencing harbour porpoise detections before, during, and after pile driving activities associated with construction of three OWFs (Norther, Northwester 2, and SeaMade) in the Belgian North Sea from 2018 to 2020. See Table 3 for further details of each OWF.

The analysis used PAM data from CPODs deployed at 19 locations up to 30 km from piling locations, albeit with limited data > 20 km. Data excluded periods immediately before and after piling itself in attempt to exclude the effects of ADDs on porpoise presence. A GAM model was fitted and included both piling- and noise-related variables as well as time and space related variables. The effects of relative time and distance were only evaluated in combination.

The GAM model indicated the strongest reduction in the likelihood of porpoise detections during pile-driving compared to 48 h prior within 10 km of the source, with minor reductions / no effect in the range of approximately 10 - 20 km. The authors noted that predictions beyond 20 km carry significant uncertainties due to limited data and should be interpreted with caution. Within approximately 5 km of the piling site, the model also revealed a decrease in porpoise detections several hours before piling, likely linked to heightened vessel noise and other preparatory activities.

It is noted that the values presented in this study do not meet the definition of an EDR as described in Section 2.2. Instead, these represent the average distance at which porpoise detections were predicted to be lower during periods of piling than non-piling and are therefore akin to the maximum distance of detectable effect. These results, as currently presented, were not considered suitable for estimation of an EDR (see Section 3.2).

Rumes and Zupan (2021) assessed the impact of noise mitigation measures on the likelihood of detecting harbour porpoises during OWF construction in the Belgian North Sea. The analysis draws from PAM data collected during the construction of three OWFs: Nobelwind (2016), Northwester 2 (2019), and SeaMade (2019). See Table 3 for further details of each OWF.

Given that pile driving activities for Northwester 2 and SeaMade overlapped, and both projects used similar noise mitigation technology, the study combined data from both projects. The analysis categorised detection data into three phases: Impact (during ADD use and piling), Aftermath (1 - 6 h post-pile driving), and Recovery (48 - 96 h post-pile-driving). Due to limited time between piling events, a baseline period (48 - 24 h before the disturbance) was not considered.

In 2016, at piles installed without noise mitigation, between 0 - 5 km from the pile porpoise detection rates were significantly lower during (Impact) and immediately after pile driving (Aftermath) compared to the Recovery phase (63% and 53% reductions respectively), with the difference diminishing at greater distances. Mean detection rates of porpoises reduced in all distance categories up to 15 - 20 km from the pile-driving. In contrast, with noise mitigation in 2019, detection rates were less affected by pile-driving noise, with smaller reductions observed at distances of 0 - 5 km and 5 - 10 km during (impact phase) and immediately after pile driving (Aftermath) compared to the Recovery phase (11% and 31% respectively). In both years, the furthest distance class (> 20 km) showed no change in mean detection rates between different phases. Overall, detections were approximately 25% lower in 2016 (no noise mitigation) than in 2019 (with noise mitigation).

It is noted that the values reported in this study do not meet the definition of an EDR as described in Section 2.2. Instead, these represent the average distances at which porpoise detections were predicted to be lower during periods of piling than non-piling and are, therefore, akin to the maximum distance of detectable effect. These results, as currently presented, were not considered suitable for estimation of an EDR (see Section 3.2).

### 2.3.2. Empirical response studies - Aerial surveys

The review in Brown *et al.* (2023) largely omitted studies which used aerial surveys to assess responses of harbour porpoise to impact piling, instead focusing on PAM studies which were better-suited to assessing responses on a gradient of distances and over a larger number of piling events. Nonetheless, aerial surveys in close temporal proximity to piling events can provide a useful alternative data source on porpoise occurrence relative to the piling location and add support to PAM results. Therefore, in the tabulation of studies presented in Section 2.3.4, results for aerial surveys are also included. These include a single study which exclusively used aerial surveys (Haelters *et al.* 2015), and three studies which reported limited aerial survey results in addition to PAM (Dähne *et al.* 2013; Geelhoed *et al.* 2018; Rose *et al.* 2019).

### 2.3.3. Noise measurement studies - Conductor piling

Two noise measurement studies relating to conductor piling were reviewed at a high-level in Brown *et al.* (2023): one in deep water off the west coast of the US (MacGillivray 2018) and one in shallower water in the Central North Sea (Jiang *et al.* 2015). Summary details of both studies are provided in Table 4.

#### 2.3.3.1. MacGillivray (2018) - California, USA

MacGillivray (2018) analysed the measurement of underwater noise from piling of six conductor casings at a deep offshore oil platform off the coast of California, USA. Conductors were 0.66 m diameter, 512 m length and piled to a total penetration depth of 91 m over a period of 2.5 - 3.5 h each. A hydraulic hammer was used, with energy ranging from 31±67 kJ per strike at the start of the sequence to 59±67 kJ per strike at the end. A Polypenco cushion between the hammer and the conductor was used to dampen the impact force of the hammer, which was estimated to reduce the generated noise by $SPL_{pk}$ 3.3 dB re 1 µPa, $SPL_{rms}$ 1.5 dB re 1 µPa and $SEL_{SS}$ 1.8 dB re 1 µPa. Acoustic data were collected using six recorders located between 10 - 1,475 m from the platform. The hydrophones were located at depths of 20 - 430 m in water depths ranging from 365 - 436 m.

Underwater noise measurements at 20 m depth showed a surface shadow zone where broadband sound levels were 10 - 15 dB lower than at deeper receivers at a measurement range of 300 - 750 m. This difference was suggested to be a result of soft seabed sediments. Plots of sound levels versus horizontal distance from the conductor for different depths showed that a noise level of $SPL_{rms}$ 160 dB re 1 µPa was exceeded at distances of up to 480 m for recording stations located at significant depths (> 300 m). Measurements at approximately 1,500 km suggest that the maximum distance at which the potential behavioural response threshold ('Level B harassment', NOAA 2005) of $SPL_{rms}$ 160 dB re 1 µPa was exceeded was in the range of 500 - 1,000 m. Sound levels in the range $SEL_{SS}$ 140-150 dB re 1µPa$^2$s, which have been reported to be concurrent with deterrence of porpoise among various empirical studies at OWFs, were not exceeded beyond approximately 2 km. As noted by MacGillivray (2018), the noise levels measured from conductor piling close to the source are within the range of those measured for hammering of similar diameter piles in shallower water associated with coastal infrastructure projects (see review in Caltrans 2009).

#### 2.3.3.2. Jiang *et al.* (2015) - Central North Sea

A study conducted by Jiang *et al.* (2015) presents noise measurements taken in the Central North Sea, near an exploration jack-up rig attached to a gas production platform, during routine conductor hammering procedures. Conductor diameter, length and penetration depth was not reported, nor was the use of any cushions or noise abatement. Piling lasted approximately 2 h. A hydraulic hammer was used, with energy ranging from 80 - 85 kJ per strike. Water depth was 48 m.

Underwater noise measurements were conducted from an offshore support vessel, stationed at distances of 750 m, 1 km, and 2 km away from the conductor hammering operation site. Noise measurements were carried out before and during piling operations and at hydrophone depths of 12 m, 24 m and 36 m. Three noise level indicators were chosen, including $SPL_{rms}$ (5 s averaging time), $SPL_{pk}$ and 1/3 octave band $SEL_{SS}$. The data analysed in the study showed two frequency peaks - a low-frequency peak at 200 Hz and a high-frequency peak at 1,250 Hz; however, the authors could not determine the reason for the dual peak in the pulse spectrum, as information regarding the source was limited. $SPL_{pk}$ noise levels were reported at each measurement distance, being up to 156.0, 137.7 and 134.5 dB re 1 µPa at 750 m, 1 km and 2 km respectively. Broadband $SEL_{SS}$ was not reported for each measurement range but based on 1/3 octave band levels (none of which exceeded 150 dB re 1 μPa$^2$s @ 750 m), the authors concluded that noise levels did not exceed a German regulatory $SEL_{SS}$ 160 dB @ 750 m limit. Based on measured sound levels, a transmission loss model was applied to predict $SPL_{rms}$ between 0 - 5 km from the piling source. The model estimated that a threshold of $SPL_{rms}$ 160 dB re 1 μPa threshold ('Level B harassment', NOAA 2005) was unlikely to be exceeded beyond a distance of approximately 250 m from source (interpreted from Figure 4 of Jiang *et al.* 2015). However, it is noted that the long 5 s integration time will have biased $SPL_{rms}$ values low compared to a shorter integration time more appropriate for a highly impulsive signal.

### 2.3.4. Tabulation of empirical response study and associated OWF features, including the reported spatial extent of deterrence effects

Table 3 and Table 4 provide a tabulation of all reviewed studies relevant to impact piling, including those described in detail above and also those reviewed in Brown *et al.* (2023). Figure 2 plots the reported spatial extent or deterrence effects for different pile types and with/without noise abatement for empirical response studies relating to impact piling at OWFs. Plots of the reported spatial extent of deterrence vs selected features of OWFs are provided in Appendix 3.

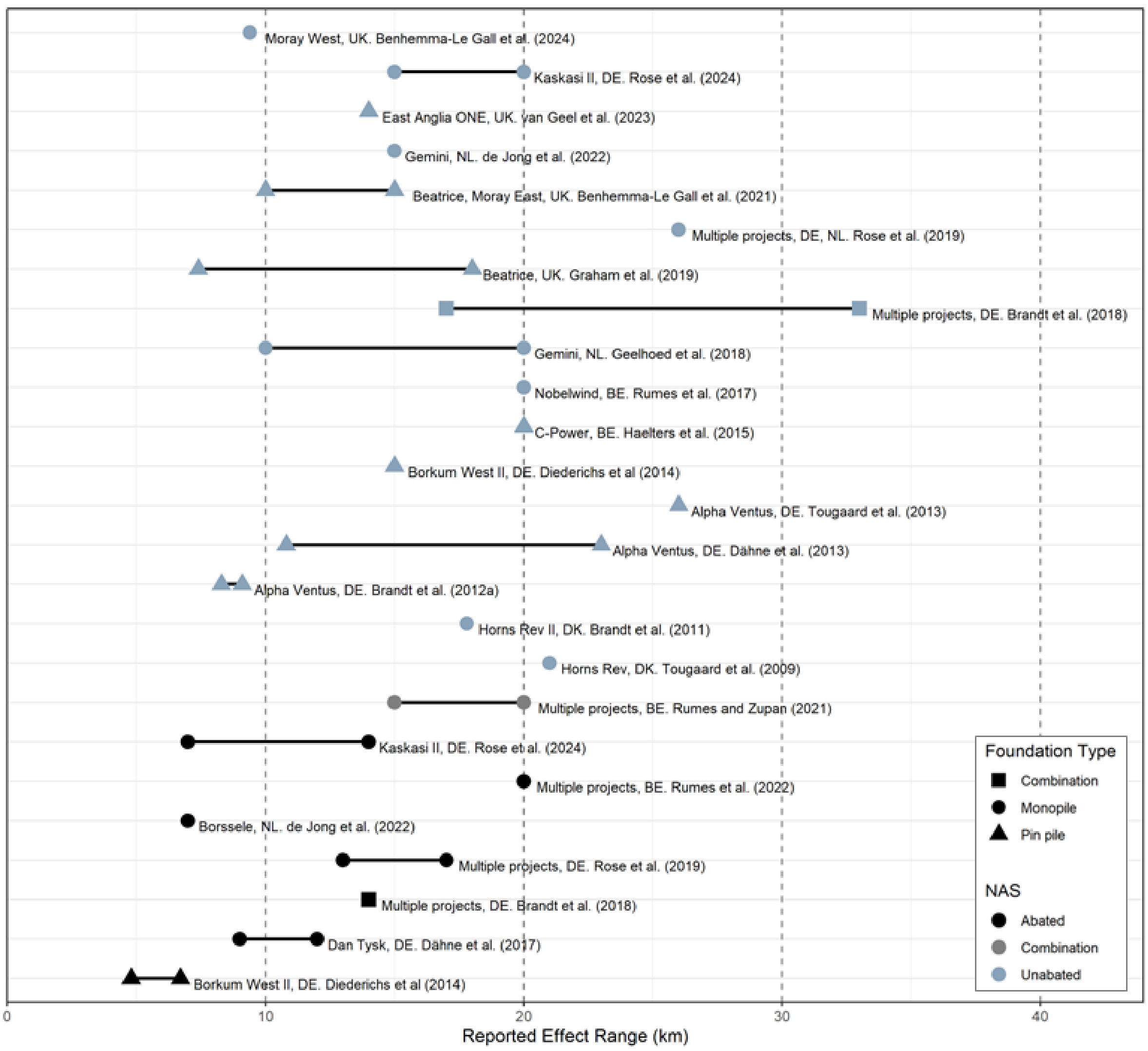


**Figure 2.** Reported effect ranges of harbour porpoises to impact pile driving in relation to OWFs with and without noise abatement as reported in the studies considered in this review and as listed in Table 3 (below). It is noted that comparisons in reported effects ranges are complicated by different approaches in data collection, analyses and definitions of effects. Studies reported either a single value (dots) or a range of values (dots connected with line). Where a study presented results of both PAM and aerial surveys, only the result for PAM is plotted; results for aerial surveys are included below in Table 3 where applicable.

**Table 3.** Relevant empirical studies of porpoise responses to pile driving associated with offshore wind farm construction identified in the literature review, in reverse chronological order of publication, including those reviewed in Brown *et al.* (2023). Further information on each study is provided above in Section 2.3 or Appendix 1 of Brown *et al.* (2023).

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Benhemma-Le Gall *et al.* (2024) | Moray Firth, North Sea (UK)<br>36–47 m | Moray West | Mono, 9.5 - 10 | 2.8 h [1]<br>≤ 4,400 kJ | 10 | None | **5 km** (R50). ≥ 50% probability of response in the 24 h period after piling).<br>**9.4 km** (EDR). Average radius habitat loss estimated from the probability of response in the 24 h period after piling vs distance (see Section 2.2). [2] | # piling events analysed: Seven, although the impact ranges reported relate to the first two piles only.<br>Reported noise levels: Preliminary results indicate broadband SEL @ 750 m from the first two piling events were 179 dB re 1μPa$^2$s.<br>[1] Average time. [2] A maximum deterrence distance was not reported. |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Rose *et al.* (2024) | Southern North Sea (DE)<br>18–26 m | Kaskasi II | Mono, 6.5 [1] | Not reported<br>≤ 3,000 kJ | 30[2] | None | **15 - 20 km** [3] The distance at which there is a combined effect of time and distance on the hourly porpoise detection rate, PPM/h (GAM model). Responses relate to impact piling (not vibropiling). | # piling events analysed: 18<br>Reported noise levels: Broadband $SEL_{SS}$ @ 750 m ranged between 153-179 dB re 1μPa$^2$s.<br>[1] Only results for impact piling are considered here (noting that the study also explored responses to vibropiling). [2] The ADD used was a FaunaGuard device, in contrast to many other projects which used a Lofitech Seal Scarer. [3] Noting that Rose *et al.* (2024) concluded that the low detection rates beyond 18 km from the construction sites did not seem to be linked to the pile-driving activities but cumulative effects of shipping activity and increase in low-frequency noise. |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Rose *et al.* (2024) | Southern North Sea (DE)<br>18–26 m | Kaskasi II | Mono, 6.5 [1] | Not reported<br>≤ 3,000 kJ | 30[2] | DBBC + HSD; or Big Bubble Curtain (BBC) + HSD | **7 - 14 km** | - |
| van Geel *et al.* (2023) | Southern North Sea (UK)<br>30–40 m | East Anglia One | Pin, 2.5 | "Several hours"<br>475 - 1,169 kJ | Used pre-piling but duration not reported | None | **14 km** = Distance at which the median probability of detecting porpoises was the same on piling days compared to non-piling days. | # piling events analysed: 310.<br>Noise levels: Not reported for close to source. Mean noise level at 14 km (VHF frequency-weighted) was $SEL_{SS}$ 103 dB re $1 \mu Pa^2 s$. |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| de Jong *et al.* (2022) | Southern North Sea (NL)<br>28–36 m | Gemini | Mono, 7.5 | 2.1 h<br>1,400 kJ | 73 [1] | None | **15 km** = Distance at which there is a 95% probability (based on upper CI) that porpoise activity is reduced relative to a reference level (periods without piling) | # piling events analysed: 142.<br>Reported noise levels: Maximum measured broadband SEL @ 750 m was 182 dB re 1μPa²s.<br>[1] The ADD used at Gemini was a FaunaGuard, in contrast to the majority of other projects which used a Lofitech Seal Scarer. |
| de Jong *et al.* (2022) | Southern North Sea (NL)<br>14–40 m | Borssele (1, 2, 3 & 4) | Mono, 6.5 - 8.3 | 2 - 5 h<br>2,000 kJ | 40 - 101 | DBBC and HSD or DBBC and AdBm | **7 km** = Distance at which there is a 95% probability (based on upper CI) that porpoise activity is reduced relative to a reference level (periods without piling) | # piling events analysed: 171.<br>Reported noise levels: Not reported but had to adhere to a dB limit of broadband SEL 172 dB re 1μPa²s.<br>Note: Additional details on piling and ADD duration from Brasseur *et al.* (2022) |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Rumes *et al.* (2022) | Southern North Sea (BE)<br>≤ 45 m | Norther NV | Mono, 7.2 - 8.0 | 0.87 - 3.72 h<br>3,028 ±456 kJ | 150 [5] | BBC | **10 - 20 km.** 10 km = Strongest reduction in the probability of porpoise detections relative to > 48 h prior to piling. 10-20 km = minor reductions / no effect in the range of approximately 10 - 20 km (GAM model). | # piling events analysed: 129 (Norther NV = 45, Northwester 2 = 24, Seamade = 60)<br>Reported noise levels: Not reported but noted that they remained below the national dB limit of broadband $SPL_{pk}$ @ 750 m of 185 dB re 1µPa. |
| | | Northwester 2 | Mono, 7.4 - 8.0 | 1.06 - 3.67 h<br>1,942 ±406 kJ | 60 | DBBC | | |
| | | SeaMade | Mono, 7.5 - 8.0 | 1.08 - 3.43 h<br>1,930 ±423 kJ | 40 | DBBC | | |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Rumes and Zupan (2021) | Southern North Sea (BE)<br>≤ 45 m | Nobelwind | Mono, 4.5 - 6.8 | 1.45 - 4.52 h<br>1,254 ±114 kJ | 150 | None | **15 - 20 km** = The maximum distance class at which there was a reduction in mean porpoise detection rates of > 2% (12.0–17.7%) reported during impact compared to a reference period. No statistical tests performed. % reductions at projects with NAS were generally smaller than the project without NAS, most notably in the 0–5 km range, but also at 15–20 km. | # piling events analysed: 135 (Nobelwind = 51, Northwester 2 = 24, Seamade = 60)<br>Reported noise levels: Not reported. |
| | | Northwester 2 | Mono, 7.4 - 8.0 | 1.06 - 3.67 h<br>1,942 ±406 kJ | 60 | DBBC | | |
| | | Sea Made | Mono, 7.5 - 8.0 | 1.08 - 3.43 h<br>1,930 ±423 kJ | 40 | DBBC | | |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Benhemma-Le Gall *et al.* (2021) | Moray Firth, North Sea (UK)<br>40–50 m | Beatrice, Moray East | Pin, 2.2 - 2.5 | 2.5 - 5.15 h<br>Beatrice: 1,800–2,400 kJ<br>Moray East: 1,033–1,748 kJ | 6 - 15 | None | **10 - 15 km** = Distance within which the modelled probability of harbour porpoise occurrence/buzzing during piling is less than the probability during non-piling. | # piling events analysed: 176 (Beatrice 86, Moray East 90)<br>Reported noise levels: Beatrice: Broadband SEL @ 800 m of up to ~166 dB re 1µPa$^2$s (one of 4 focal piles) (Graham *et al.*, 2019). Moray East: not reported but approximately 3dB higher than Beatrice (Benhemma-Le Gall, pers. comm.). |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Graham *et al.* (2019) | Moray Firth, North Sea (UK)<br>40–50 m | Beatrice | Pin, 2.2 | 5.0 (range 2.9 - 8.8 h)<br>1,800–2,400 kJ | 15 | None | **7.4 km** (R50) = ≥ 50% probability of response in the 24 h period after piling)<br>**18.0 km** (R25) = ≥ 25% probability of response in the 24 h period after piling)<br>The authors also state that, according to their results, harbour porpoise are unlikely to respond beyond 20 km. | # piling events analysed: 17 (of 86 foundations)<br>Reported noise levels: Broadband SEL @ 800 m of up to ~166 dB re $1\mu Pa^2s$ (one of 4 focal piles). |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Rose *et al.* (2019) | Southern North Sea (DE)<br>17–39 m | Seven projects (‘GESCHA 2’) [1] | Mono, 5.9 - 8.1 | Predominately ≤ 3.5 h<br>1,883 kJ[2] | Used but duration not reported | 2 - 3 systems [3] | **13 - 17 km**. PAM data. 13 km = Distance to 20% reduction in detection rate during piling (“reference-type” models). 17 km = distance at which acoustic activity during piling equals the average of all fitted values (“classical-type” models)<br>**14.4 km.** Aerial survey data. Mean distance at which porpoise sightings were below the expected average, based on a GAM analysis of aerial survey data. | # piling events analysed: GESCHA 2: 770, incl 181 (unabated) and 589 (abated) (‘classical-type’ models); 160 (abated, ‘reference-type’). GESCHA1&2: 366 (unabated, ‘reference-type’) Gemini: 160 (unabated, ‘classical-type’).<br>Reported noise levels: Broadband SEL @ 750 m was 158-162 dB re $1 \mu Pa^2 s$ (GESCHA2, abated) and 172 dB re $1 \mu Pa^2 s$ (GESCHA1&2, unabated).<br>[1] Amrumbank West (ABW), Borkum Riffgrund 1 (BR), Butendiek (BU), Godewind 1&2 (GW), Nordsee One (N1), Sandbank (SB), Veja Mate (VM). |
| | Southern North Sea (DE, NL)<br>17–41 m | 14 projects (‘GESCHA 1 & 2’) [5] | Mono, 5.5 - 8.1 | Predominately ≤ 3.5 h<br>Blow energy not reported | Used but duration not reported | None | **26 km**. Distance to 20% reduction in detection rate during piling (“reference-type” models). | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rose *et al.* (2019) | Southern North Sea (NL)<br>28–36 m | Gemini | Mono, 7.5 | 2.1 h<br>1,400 kJ | 73 [6] | None | **13 km**. Distance at which acoustic activity during piling equals the average of all fitted values (“classical-type” model) | [2] 1,883 kJ was the highest blow energy among the projects included for which data could be found (see von Pein *et al.*, 2022).<br>[3] Typically a BBC and/or DBBC and a resonator (e.g. HSD) or casing (e.g. IHC-NMS).<br>[4] ‘Classical-type’ models assessed changes in porpoise detections over 48 h before and after piling, allowing for the inclusion of all piling events, but responses could be influenced by the cumulative effects of often closely sequenced pile driving. Conversely, the reported response range (zero line in GAM plots) represents an average of the fitted values and so is already affected by piling effects and not a true zero-response range. |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Rose *et al.* (2019) | | | | | | | | 'Reference-type' models assessed the change in DPH during piling relative to a reference period combining hours pre- and post-piling with sufficient temporal separation as to be considered uninfluenced by piling.<br>[5] As [1] plus Gemini (NL), Dan Tysk, Borkum West II, Global Tech I, Riffgat, Nordsee Ost, Meerwind Süd/Ost<br>[6] A FaunaGuard ADD was used, instead of the typical Lofitech seal scarer. The FaunaGuard is known to deter porpoise from a smaller area around piling (Voss *et al.* 2023). |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Geelhoed *et al.* (2018) | Southern North Sea (NL)<br><br>28–36 m | Gemini | Mono, 7.5 | 2.1 h<br><br>1,400 kJ | 73 [5] | None | **10 - 20 km.** PAM data: decrease in porpoise detections to 10 km; increase at 20 km<br><br>**15 - 25 km**. Aerial survey data: surveys showed a lack of porpoise sightings in a radius around the piling location, with the radius varying between < 15 km to ~25 km within each specific survey. | # piling events analysed: 166 (PAM).<br><br>Reported noise levels: Maximum measured broadband SEL @ 750 m was 182 dB re 1μPa$^2$s (reported in de Jong *et al.* 2022). |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Brandt *et al.* (2018) | Southern North Sea (DE)<br>18–41 m | Six projects (‘GESCHA 1’) [1] | Mono, 5.5 - 6.5<br>Pin, 2.4 - 2.5 | Mono 1 - 1.9 h<br>Pin, 3.1 - 8.3 h<br>1,883[2] | Used but duration not reported (Dan Tysk was 66 min) | BBC (5 OWFs)<br>IHC-NMS (1 OWF: Riffgat) | **14 km.** Distance at which ‘global overall average’ reached. | # piling events analysed: ~350 (abated), ~200 (unabated)<br>Reported noise levels: Broadband $SEL_{SS}$ @ 750 m of 168-180 dB (unabated) and 163-169 dB (abated) dB re $1 \mu Pa^2 s$.<br>[1] Dan Tysk, Borkum West II, Global Tech I, Riffgat, Nordsee Ost, Meerwind Süd/Ost. Total ~ 350 piling events.<br>[2] 1,883 kJ was the highest blow energy among the projects included for which data could be found (see von Pein *et al.*, 2022).<br>[3] Includes 80 foundations at BARD, 11 at Borkum West II and 0-2 at others. Total ~200 piling events. |
| | | Primarily BARD and Borkum West II [3] | Pin, 2.5 - 3.4 (BARD and BWII) | 3.1 - 5.0 h (BARD and BWII)<br>1,400 kJ (BARD) | Used but duration not reported | None | **17 - 33 km**. ‘Global overall average’ reached at 33 km; detection rates did not substantially differ between 17 km to 33 km. No well-defined limit for effect range. | |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Dähne *et al.* (2017) | Southern North Sea (DE)<br>21–29 m | DanTysk | Mono, 6 | 1.95 h (range 1.65 - 3.45 h)<br>1,883 kJ | 66 (range 37 - 235) | BBC or DBBC | **9 - 12 km.** Maximum distance bin with significant lower porpoise activity compared to baseline | # piling events analysed: 85.<br>Reported noise levels: Broadband SEL @ 750 m of 157 dB re 1µPa2s. |
| Rumes *et al.* (2017) | Southern North Sea (BE)<br>8–31 m | Nobelwind | Mono, 4.5 - 6.8 | 1.45 - 4.52 h<br>1,254 ±114 kJ | 150 | None | **20 km.** Observed decrease in DPM/day and DPM10/hr, no mention of significance | # piling events analysed: 10 (of total 51)<br>Reported noise levels: Broadband SEL @ 750 m of 174 dB re $1 \mu Pa^2 s$. |
| Haelters *et al.* (2015) | Southern North Sea (BE)<br>12–27 m | C-Power | Pin, 1.83 | 1.6 h<br>800 kJ | ~120 | None | **20 km.** Displacement up to 20 km during piling observed by aerial surveys | # piling events analysed: one (study was based on the results of two surveys: one before and one during piling).<br>Reported noise levels: Broadband $SPL_{pk}$ @ 750 m of 172-189 dB re $1 \mu Pa^2$. |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Diederichs *et al.* (2014), Nehls *et al.* (2015) | Southern North Sea (DE)<br>27–32 m | Borkum West II | Pin, 2.5 | 5.0 h<br>1,000–1,200 kJ | Used but duration not reported | None | **15 km** Approximate distance to the 144 dB SEL (unweighted) contour, which was shown to be the lowest noise level at which reduction in PPM/h relative to a reference period could be detected with statistical significance. | # piling events analysed: 40 (foundations, total 120 piles)<br>Reported noise levels: Broadband SEL @ 750 m of 174 (unabated) and 163 (abated) dB re 1μPa$^2$s. Approximate values interpreted from plots in Diederichs *et al.* (2014). |
| | | | | | | BBC | **4.8 - 6.7 km** | |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Dähne *et al.* (2013) | Southern North Sea (DE)<br>30 m | Alpha Ventus | Pin, 2.4 - 2.6 | 6 - 13 h<br>≤ 500 kJ | ~ 300<br>(≥ 30, inc. for entire piling sequence for 50% of piles) | None | **10.8 - 23 km. PAM data.** Significant effect of pile driving on DPH/hr. Gap in monitoring stations between 10.8 km and 23 km; small increase in detections at 23 km, therefore extent of reduction in porpoise occurrence lies between 10.8 and < 23 km.<br>**25 km**. Radius around piling within which only three porpoises were sighted during one survey which coincided with piling. | # piling events analysed: PAM: 12 (foundations, each with 3-4 piles installed). Aerial survey data: 1 (with good spatio-temporal overlap with piling).<br>Reported noise levels: Broadband SEL @ 750 m of 167-170 dB re $1\mu Pa^2s$ (based on measurements at greater distance). |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Tougaard *et al.* (2013) | Southern North Sea (DE)<br>30 m | Alpha Ventus | Pin, 2.4 - 2.6 | 6 - 13 h<br>≤ 500 kJ | ~ 300<br>(≥ 30, inc. for entire piling sequence for 50% of piles) | None | **26 km** = EDR, representing average habitat loss per individual (see Section 2.2). The EDR was estimated from a linear deterrence function (proportion of porpoise displaced by distance to piling) based on the difference between models of porpoise acoustic activity with and without piling presented in Dähne *et al*. (2013). | # piling events analysed: 12 (foundations, each with 3-4 piles installed)<br>Reported noise levels: Broadband SEL @ 750 m of 167-170 dB re 1μPa$^2$s (based on measurements at greater distance) |
| Brandt *et al.* (2012) | Southern North Sea (DE)<br>30 m | Alpha Ventus | Pin, 2.4 - 2.6 | 6 - 13 h<br>≤ 500 kJ | ~ 300<br>(≥ 30, inc. for entire piling sequence for 50% of piles) | None | **8.3 - 9.1 km** = Significant effect of hour after pile driving on PPM/H | # piling events analysed: 12 (foundations, each with 3-4 piles installed)<br>Reported noise levels: Broadband SEL @ 750 m of 167-170 dB re 1μPa$^2$s (based on measurements at greater distance) |

| **Study** | **Region (country); water depth** | **OWF** | **Pile type; diameter (m)** | **Piling duration (per foundation); max blow energy** | **ADD average duration (min)** | **NAS** | **Reported spatial extent of effect and description** | **Notes** |
|---|---|---|---|---|---|---|---|---|
| Brandt *et al.* (2011) | Southern North Sea (DK)<br>4–14 m | Horns Rev II | Mono, 3.9 | 0.76 h<br>900 kJ | 255 (163 pre-piling, 47 during piling, 46 post-piling) | None | 17.8 km = Mean max detectable decline | # piling events analysed: 91.<br>Reported noise levels: Broadband SEL @ 750 m of 176 dB re $1 \mu Pa^2 s$ (one pile only). |
| Tougaard *et al.* (2009) | Southern North Sea (DK)<br>6–12 m | Horns Rev | Mono, 4 | 0.5 - 2.5 h<br>360 - 450 kJ | Not reported | None | **21 km** = Extent of significant increase in first inter encounter interval after pile driving | # piling events analysed: 80<br>Reported noise levels: Broadband $SPL_{pk\text{-}pk}$ @ 930 m of ~ 184 dB re $1 \mu Pa^2$ (one pile only). |

| Study | Region (country); water depth | OWF | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| Carstensen *et al.* (2006) | Baltic Sea (DK)<br>6–10 m | Nysted | Sheet, NA | 1.5 - 10 h<br>Not reported | 120 - 630 (30 min + piling duration) | None | **15.7 km** = Maximum distance at which there was a significant change in wait time between porpoise acoustic detections between baseline and following bouts of piling. 15.7 km was the maximum monitored distance, so responses may have extended beyond this distance. | # piling events analysed: not reported, but sheet piling only used at one foundation.<br>Reported noise levels: Not reported. |

**Table 4.** Noise measurement and modelling studies of relevance to porpoise responses to conductor pile driving identified in the literature review, in reverse chronological order of publication, including those reviewed in Brown *et al.* (2023). Further information on each study is provided above in Section 2.3.

| Study | Region (country); water depth | Project | Pile type; diameter (m) | Piling duration (per foundation); max blow energy | ADD average duration (min) | NAS | Reported spatial extent of effect and description | Notes |
|---|---|---|---|---|---|---|---|---|
| MacGillivray (2018) | Santa Barbara Channel (US); 365 m | ExxonMobil Harmony platform | Conductor<br>0.66 | 2.5 - 3.5 h<br>59±67 kJ | Not reported | "Polypenco" pile cushion | **0.5 - 1.0 km** = Approximate maximum distance to $SPL_{rms}$ 160 dB 'Level B harassment' (NOAA 2005) | # piling events analysed: 6<br>Reported noise levels: Broadband $SPL_{pk}$ @ 480 m of ≤ ~180 dB re 1μPa; broadband SEL @ 480 m of ≤ ~155 dB re 1μPa$^2$s. |
| Jiang *et al.* (2015) | Central North Sea; 48 m | Exploration jack-up rig attached to a gas production platform | Conductor<br>Not reported | ~ 2 h<br>85 kJ | Not reported | None | **250 m** = Approximate distance to $SPL_{rms}$ 160 dB 'Level B harassment' (NOAA 2005) | # piling events analysed: Not reported.<br>Reported noise levels: Broadband $SPL_{pk}$ @ 750 m of 150.9 - 156.0 dB re 1μPa; broadband SEL @ 750 m of < 160 dB re 1μPa$^2$s. |

### 2.3.5. EDRs from existing data were estimated through the following approaches: Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 1; a summary is provided here. A total of 21 empirical response studies (OWFs) and two noise measurement studies (conductor piles) were reviewed and assigned scores based on specific evaluation criteria (Figure 9, Appendix 1). All studies were assigned an initial score of 10, with penalties subsequently applied as appropriate for criteria including: the study's suitability for estimating an EDR; the relevance of the species studied (no penalties applied in this instance), the relevance of the study area to the UK (i.e. water depth); the relevance of the activity to current and near-future UK OWF construction (e.g. piling characteristics, ADD use); and, other study limitations (e.g. limited baseline data, potential for biases). The reviewed studies focused on impact piling of monopiles and pin piles without noise abatement, piling with abatement, or both scenarios. When summarising scores, those studies which reported a single spatial extent for both abated and unabated piling combined were excluded to ensure a clear distinction between the two scenarios.

For piling of **monopiles or pin piles without noise abatement**, there were a total of 17 studies which received scores ranging from 5 to 9 (out of a maximum of 10), with an average score of 7.0. These studies were conducted during the construction of 23 OWFs.

For piling **monopiles or pin piles with noise abatement**, there were a total of seven studies which received scores ranging from 6 to 8, with an average score of 7.1. These studies were conducted during the construction of 16 OWFs.

For piling of **sheet piles without noise abatement**, there was one study which received a score of 5.

For **conductor piling**, there were two studies which received scores of 4 and 5, with an average score of 4.5. One of the two studies used a pile cushion which provided limited noise abatement.

The limited differentiation between the scores of impact piling studies reflects that they are all empirical studies of porpoise responses and, therefore, do not receive any of the penalties associated with relying upon noise measurement or modelling data.

# 3. Estimation of EDRs from existing data ('meta-analysis')

## 3.1. Introduction

As emphasised in Brown *et al.* (2023), to derive methodologically comparable estimates of EDR and robustly explore the factors which may be driving different levels of porpoise response between studies, a meta-analysis is required which involves the acquisition and re-analysis of data according to a common approach (Brown *et al.* 2023). As such an exercise is beyond the scope of the current study, instead an attempt to introduce greater comparability between existing studies is made by examining their results to estimate EDRs according to a consistent definition (the range at which the total number of animals not disturbed equals those disturbed beyond that range (Tougaard *et al.* 2013) - see Section 2.2)

## 3.2. General approach

**Examination/Interpretation of deterrence functions** (magnitude/ probability of response vs distance to piling) Within published studies, as was performed by Tougaard *et al.* (2013) on data presented in Dähne *et al.* (2013). This involved extracting values from published studies, either directly from data tables or by using the 'graphreader' online tool to extract values from plots. In some cases, trend lines were fitted to data points to provide a deterrence function. Further details are provided in the study-specific sections below. For each study, we estimated three values: the distance at which there was a 50% probability of response (R50), the EDR, and the probability of response at the EDR. The latter was estimated to see if there was any consistency among this value between studies, while the R50 was estimated to compare relative to the EDR and noting that this is a parameter commonly reported in studies of animal responses to sources of disturbance.

While the values extracted from plots are an approximation of the data underlying the plots, a validation exercise (Appendix 2) on plots where the underlying data are known showed them to be accurate for this application.

Studies for which this approach was applied were those which met the following requirements:

i. the study included a data table or figure which presented the change in porpoise detections function of distance to piling,

ii. the reported change in porpoise detections could be interpreted as proportional change relative to a reference period,

iii. values were provided along a gradient of distances from the piling source, covering a minimum of three discrete distances/distance bins,

iv. results were presented over a sufficient distance from the piling source to reasonably estimate the distance at which zero change in porpoise detections.

The studies identified as meeting these requirements included:

- van Geel *et al.* (2023): East Anglia ONE, UK
- de Jong *et al.* (2022): Gemini and Borssele, Netherlands
- Brandt *et al.* (2018): A meta-analysis of seven OWFs, Germany
- Dähne *et al.* (2017): Dan Tysk, Germany

- Diederichs *et al.* (2014); Nehls *et al.* (2015): Borkum West II, Germany
- Brandt *et al.* (2011); Thompson *et al.* (2013): Horns Rev II, Denmark.

**Additional modelling of published data** from OWF projects in the Moray Firth, Scotland (Graham *et al.* 2019; Benhemma-Le Gall *et al.* 2021; Benhemma-Le Gall *et al.* 2024). Efforts were also made to estimate EDRs from the meta-analysis of projects in Germany and the Netherlands included in the Gescha 1 and 2 studies (Rose *et al.* 2019); however, it was not possible to obtain model outputs from which a suitable deterrence function could be derived for EDR estimation. This was primarily due to changes in porpoise detections at specific CPOD locations/projects being absolute rather than proportional. Further, the models developed on these data included many covariates other than distance for which it was not possible to select meaningful values when generating predictions of responses vs distance (A Rose, pers. comm.).

The approach taken here to estimate EDRs by approaches (1) and (2) described above varies somewhat between the different studies and datasets included. As such, details of the approach and corresponding results are presented below in study-specific sections.

## 3.3. Approach details and results

### 3.3.1. van Geel *et al.* (2023)

A summary of the van Geel *et al.* (2023) study is provided in Section 2.3.1.2, and key features are listed in Table 5. Based on GAMs which predicted the probability of porpoise detection within the piling and non-piling days, a plot was provided for each GAM, showing the median probability of detecting porpoises on piling days and non-piling days as a function of distance. Values from this plot were extracted using graphreader. For 100 m increments of distance, the difference in probability of porpoise presence between piling and non-piling days was estimated. At each distance increment, the difference was then divided by the difference at the minimum distance (1 km) to provide a proxy probability of response (*p(response)*) with distance which ranged between 1.0 at 1.0 km and 0.0 at 13.8 km where the probability of porpoise presence between piling and non-piling days became equal. The proxy *p(response)* with distance thereby provided a deterrence function from which an EDR could be estimated. The estimated EDR at East Anglia ONE from these data was **9.5 km** (no noise abatement).

**Table 5.** Key features of the van Geel *et al.* (2023) study.

| Wind farms studied | Location | Pile type(s) | Noise abatement |
|---|---|---|---|
| East Anglia ONE | UK Southern North Sea | Pin piles | None |

**Table 6.** Estimated EDRs from the van Geel *et al.* (2023) study. [1] The distance at which there is a 50% proxy p(response).

| Distance piling period median crosses non-piling reference (km) | R50[1] (km) | Distance upper 95% CI crosses non-piling reference (km) | EDR (km) [*p(response)* at EDR] |
|---|---|---|---|
| 13.8 | 8.1 | n/a | 9.5 [0.43] |

### 3.3.2. de Jong *et al.* (2022) - Gemini and Borssele

Table 7 summarises key features of the de Jong *et al.* (2022) study. Using PAM data (CPODs), a variety of models were developed to assess porpoise responses as a function of noise levels or distance. Distance model outputs include the probability of presence of porpoise positive minutes within a monitored hour (p(PPM/h>0)) during hours of piling as a function of distance to piling (see Figures 23 (Borssele) and 25 (Gemini) in de Jong *et al.* (2022)). On these plots, a horizontal reference line was also plotted which represented the mean p(PPM/h>0) when no piling was taking place (no piling at the wind farm of interest or adjacent projects).

**Table 7.** Key features of the de Jong *et al.* (2022) study.

| Wind farms studied | Location | Pile type(s) | Noise abatement |
|---|---|---|---|
| Gemini | Netherlands North Sea | Monopiles | None |
| Borssele | Netherlands North Sea | Monopiles | DBBC and either HSD or AdbM |

Using graphreader, values of the two plotted lines were extracted from each of the two plots in distance increments of 0.1 km. For each distance increment, the difference between the p(PPM/h>0) during piling and non-piling was calculated up to the distance at which the difference became zero. At each distance increment, the difference was then divided by the difference in p(PPM/h>0) at distance zero to provide a proxy probability of response (*p(response)*) with distance which ranged between 1.0 at the piling location (distance 0.0 km) and 0.0 where the p(PPM/h>0) during piling became equal to the non-piling reference line. The proxy *p(response)* with distance thereby provided a deterrence function from which an EDR could be estimated.

At **Gemini**, the increase in p(PPM/h>0) during piling with distance to piling was fairly linear, with the median p(PPM/h>0) during piling crossing the reference line at 38.6 km. The upper 95% CI crossed the reference line at 15 km, indicating a 95% probability of porpoise activity being reduced within ≤ 15 km of piling. The estimated EDR at Gemini from these data was **24.0 km** (no noise abatement).

At **Borssele**, the increase in p(PPM/h>0) during piling with distance to piling showed a more logarithmic trend, with a plateau in p(PPM/h>0) approximately equal to the reference value between approximately 15 - 20 km from piling. The upper 95% CI crossed the reference line at 7 km, indicating a 95% probability of porpoise activity being reduced within ≤ 7 km of piling. The start of the plateau of the median p(PPM/h>0) during piling (which extracted values indicated to be at 16.5 km), was taken as the distance at which the proxy *p(response)* was equal to zero. The estimated EDR at Borssele from these data was **8.3 km** (with noise abatement).

The contrasting shapes of the deterrence functions at Gemini and Borssele are important, as the more linear function at Gemini results in a far larger number of porpoise responding at intermediate to far distances where, despite the probability of responding being quite low, the areas are large. It is noted that the estimated EDR of 24.0 km at Gemini from the models developed by de Jong *et al.* (2022) is considerably larger than the estimated extent of deterrence effects reported in previous analyses of these data; for example, 13 km (Rose *et al.* 2019) and 10 - 20 km (Geelhoed *et al.* 2018). Reasons for this particularly large estimated EDR are not clear, but it is noted that the extracted deterrence function was fairly linear in nature, and only reached a *p(response)* of zero at a large distance to piling of

38.6 km. This resulted in a *p(response)* >0 over a very large area, resulting in many animals predicted to respond in total and therefore a high EDR. Considering the reported maximum spatial extent of effects reported for other studies of the Gemini OWF, and other projects with unabated piling, this maximum distance to reference levels and the resulting EDR may be overly-conservative.

**Table 8.** Estimated EDRs from the de Jong *et al.* (2022) study. [1] The distance at which there is a 50% proxy p(response).

| Dataset / model | Distance at which median modelled detection rate becomes the same for both piling and non-piling periods (km) | R50[1] (km) | Distance at which upper 95% CI of modelled detection rate for piling period exceeds non-piling periods (km) | EDR (km) [*p(response)* at EDR] |
|---|---|---|---|---|
| Gemini (unabated) | 38.6 | 22.4 | 15.0 | 24.0 [0.46] |
| Borssele (abated) | 16.5 | 6.3 | 7.0 | 8.3 [0.36] |

### 3.3.1. Brandt *et al.* (2018)

Table 9 summarises key features of the Brandt *et al.* (2018) study. The study was a meta-analysis combining PAM data from the construction of seven OWFs in German waters. A mixture of pin piles and monopiles were used across different foundation types. Active NAS, mostly single BBCs, were applied for most foundations at 6 of the 7 OWFs. While some piling without NAS occurred across all foundation and pile types, most piling events without NAS were pin piles for tripod foundation types.

**Table 9.** Key features of the Brandt *et al.* (2018) study.

| Wind farms studied | Location | Pile type(s) | Noise abatement |
|---|---|---|---|
| The first seven commercial-scale OWFs constructed in German waters | German North Sea | Mixture of pin piles and monopiles between different wind farms | At 6/7 OWFs for most foundations |

GAMs with DPH as a binary response variable were developed. From an EDR perspective, the models of interest were those including an interaction term of distance with hour relative to piling (HRP) as a predictor variable ('distance model'). Such models were developed for all piling events combined, and with and without NAS. From each model, plots were generated of the predicted deviance in DPH from the overall mean, given HRP and distance to piling (see Figures 5 and 6 in Brandt *et al.* 2018).

The relevant plots in Brandt *et al.* (2018) provided contours (and 95% CIs) for deviance in overall mean DPH in increments of 0.2. For specific values of HRP, distance values were extracted (using graphreader) for deviance from overall mean DPH from 0.0 to the highest negative value plotted (-0.8 or -0.6), which provided the data points from which to draw a deterrence function. Wherever HRP was zero (i.e. active piling), it was assumed that at 0 km the deviance from overall mean DPH was -1.0 (no detections), as mitigation measures implemented close to the piling site would have ensured that no animals were present in very close proximity to the piling location. While this results in an assumed rate of decay in porpoise presence within the first few km which may not reflect reality, the overall influence on EDR estimation is minimal due to the small areas in consideration at close ranges to piling.

Extracted values were then used to plot approximate deterrence functions illustrating deviance in DPH from the overall mean for selected values of HRP (Figure 3). Rather than fit smoothed trendlines to the data, the rate of decay in response with distance was assumed to be linear between each data point (i.e. straight lines drawn between data points). From the deterrence function, a data frame was developed to estimate the cumulative numbers of animals responding and not responding throughout the total impacted area, from which an EDR could be estimated (Figure 4).

The estimated EDRs and other spatial response metrics are provided in Table 10. The EDRs during active piling were estimated to be 14 km without noise abatement, and 7 km with noise abatement. It is important to remember that this study measured changes in porpoise acoustic activity relative to an overall mean. As this overall mean is calculated over all available data, including impact data (i.e. hours during and adjacent to piling), response ranges and EDRs could be underestimated relative to a true undisturbed baseline state. Some of the OWFs included were located where disturbance effects from individual OWFs might be expected to overlap; however, the study did not report the exact dates of construction of each OWF and, therefore, it is not known if there were interactions between OWFs influencing disturbance ranges.

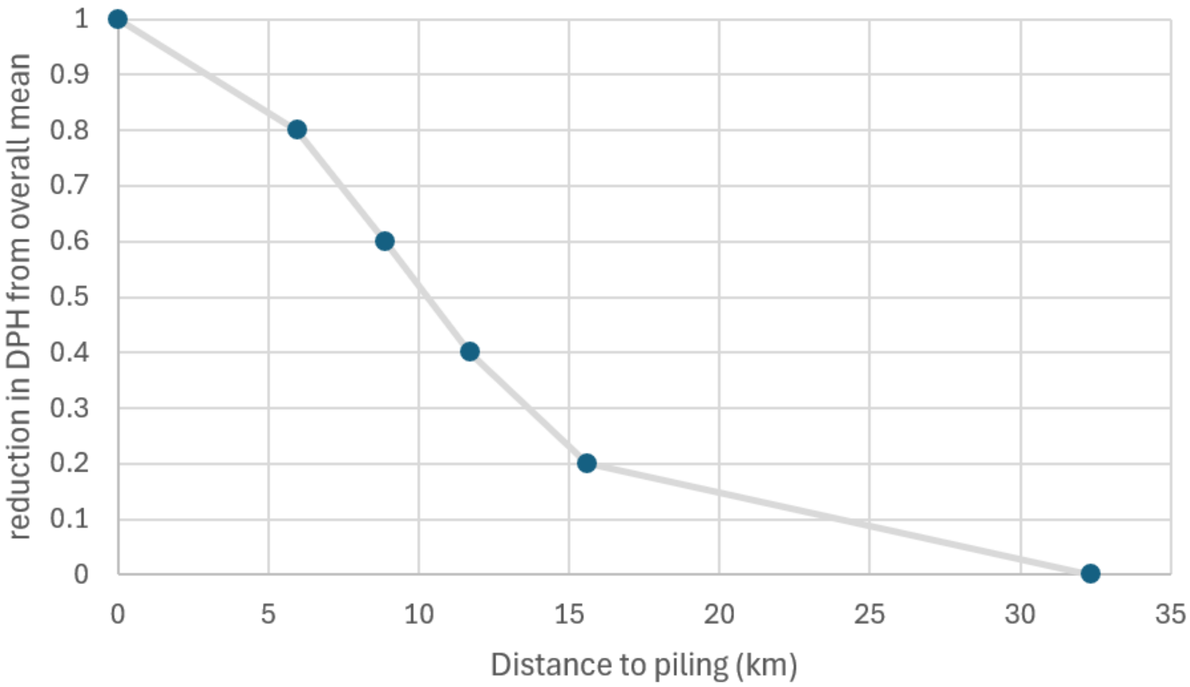


**Figure 3.** An approximate deterrence function extracted from results presented in Brandt et al. (2018) illustrating the reduction in detection positive hours (DPH) from the overall mean during hours of active piling (hour relative to piling = 0) without noise abatement.

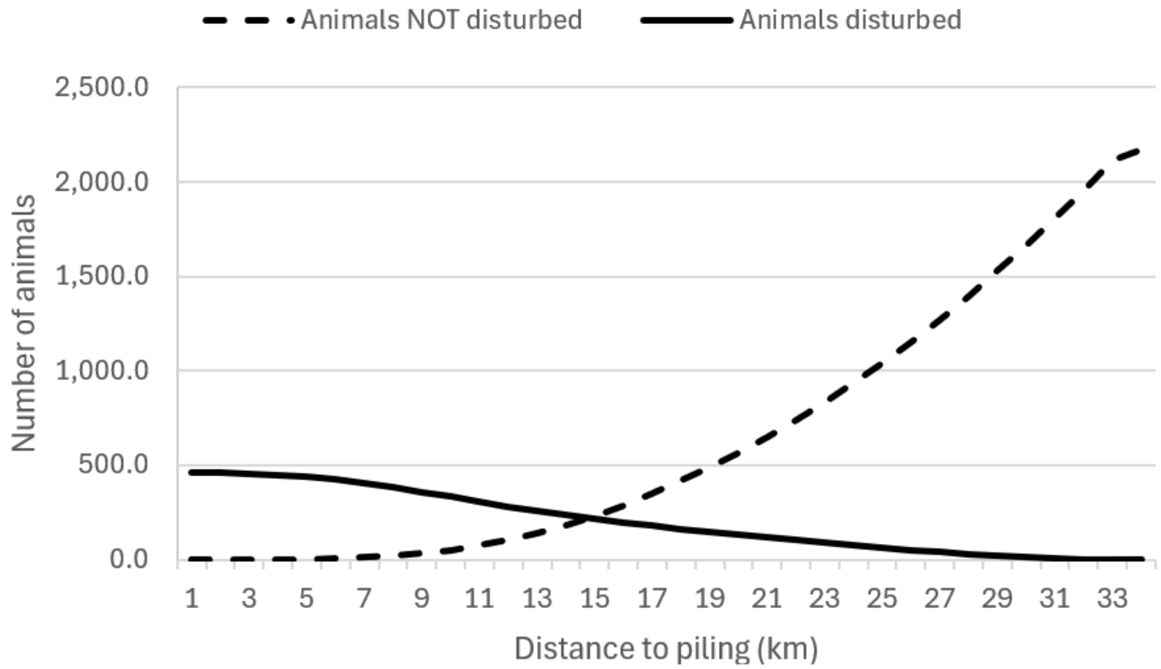


**Figure 4.** An illustration of the cumulative number of animals disturbed and not disturbed with distance to piling, assuming a uniform density of 0.8 harbour porpoise/ km2, estimated from models presented in in Brandt et al. (2018) for piling without noise abatement and during active piling (i.e. hour relative to piling = 0). The EDR is where the two plotted lines meet; in this case, at 14 km.

**Table 10.** Estimated EDRs from the Brandt et al. (2018) study. [1] The distance at which there is a 50% proxy p(response).

| Dataset / model | Hour relative to piling | Distance to overall mean DPH across the entire dataset | R50[1] (km) | EDR [*p(response)* at EDR] |
|---|---|---|---|---|
| No noise abatement | 0 | 32.4 | 10 - 11 | 14 [0.28] |
| With noise abatement | 0 | 13.9 | 5 | 7 [0.308] |

### 3.3.1. Dähne *et al.* (2017)

Dähne *et al.* (2017) reported acoustic detection rates of harbour porpoise at PAM stations between 1.5 - 18.0 km from impact piling at the Dan Tysk OWF in the German North Sea. Table 11 summarises key features of the Dähne *et al.* (2017) study.

**Table 11.** Key features of the Dähne *et al.* (2017) study.

| Wind farm studied | Location | Pile type(s) | Noise abatement |
|---|---|---|---|
| Dan Tysk | German North Sea | Monopiles | Yes: BBC or DBBC |

The foundation type was monopiles of 6 m diameter, all installed with noise abatement comprising either a single or double big bubble curtain. Piling lasted between 99 - 207 min (mean = 117 min) and was preceded by a period of ADD use of between 37 - 235 min (median = 66 min) duration (Table 3). The study analysed porpoise detection rates between a baseline period (3 h prior to ADD activation) and three 'impact' period categories: the period when the ADD was active, during piling, and then up to 24 h post-piling in 1 h increments. The analysis was performed for six distance bins, extending between 1.5 - 18 km from piling. Statistically significant reductions in porpoise detections between baseline and both ADD and piling periods were observed for distance bins up to 9 - 12 km from piling, a pattern which extended to 4 - 5 h post-piling for some distance categories.

The plots provided for each of the six distance bins (Figure 2 in Dähne *et al.* (2017)) allow development of deterrence functions for piling activities. graphreader was used to extract %PPM values from the relevant plots in Dähne *et al.* (2017), then calculated the proportional reduction in %PPM between baseline and both ADD and piling periods for each of the distance bins as a proxy for the probability of response, *p(response)*. Values of *p(response)* were plotted vs distance to piling, taking the mid-point of each distance bin (e.g. 4.5 km for the 3 - 6 km bin) (Figure 5a). Two additional data points were plotted to complete the deterrence function: a *p(response)* of 1.0 at 0 km to account for the assumption that all animals were deterred from the immediate vicinity of piling, and a *p(response)* of zero at 19.5 km based on the assumption that animals were not responding to the noise source at this range. The latter is considered a reasonable assumption given the small and non-significant reductions in %PPM recorded at all distances between 12 - 18 km from piling. A non-linear least squares model was fit to these data using the 'nls' package in *R* (R-Core-Team 2023), with the model fit digitised in graphreader. The model did not fit exactly through the added values at 0 km and 19.5 km, and adding a weighting to these values to force a fit resulted in a compromise to the fit to the other values. Therefore, to avoid abrupt step changes in the deterrence function at 0 and 19.5 km, we assumed a linear function between the model fit and the added values between 0 - 2.25 km and 16.5 - 19.5 km (Figure 5b).

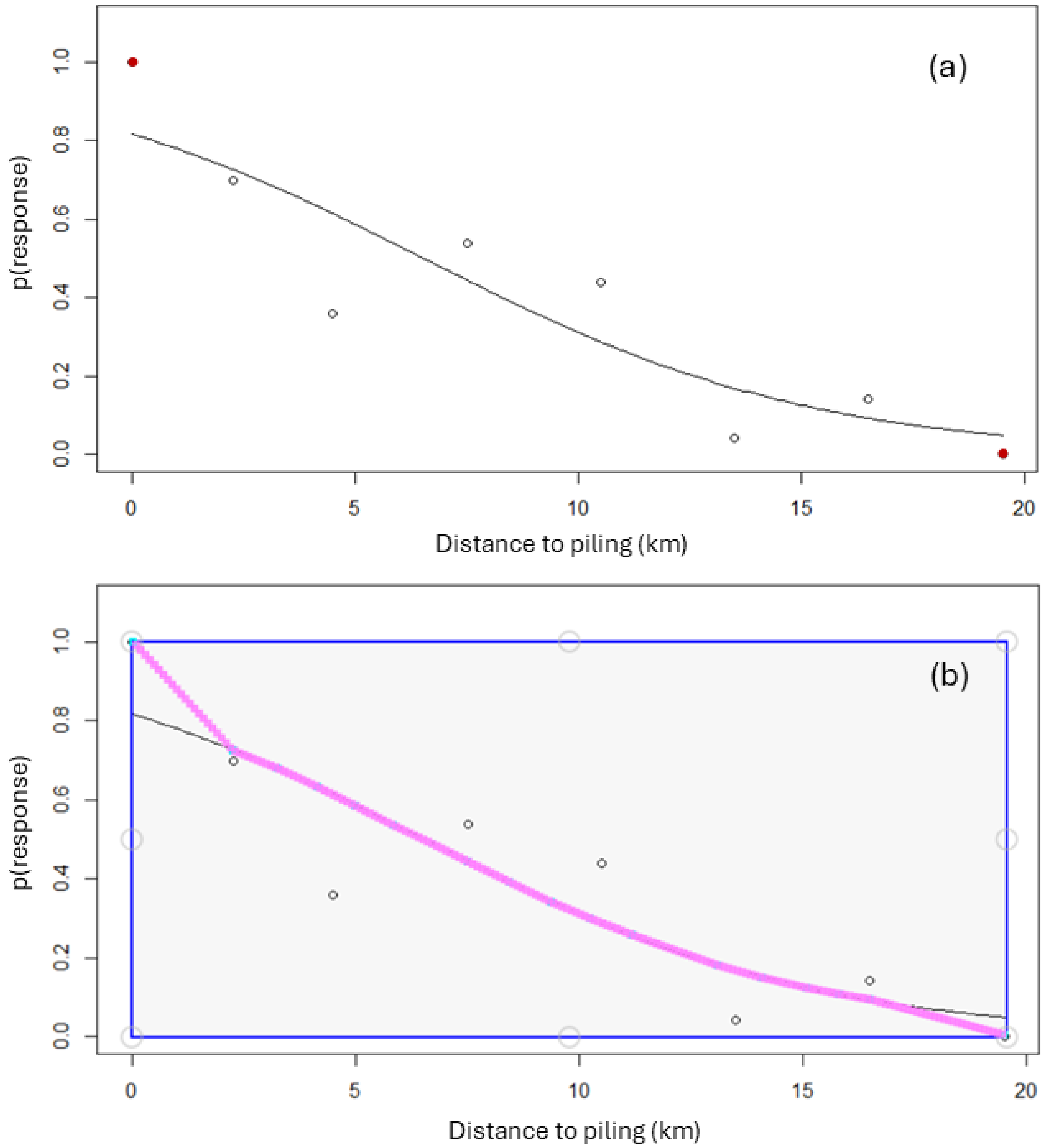


**Figure 5.** A deterrence function for harbour porpoises responding to pile driving at the Dan Tysk OWF, as reported in Dähne et al. (2017), showing a proxy for probability of response 'p(response)'. Plot (a) shows data from Figure 2 of Dähne et al. (2017) (open circles), added values at distance of 0 and 19.5 km, and a non-linear least squares model fit. Plot (b) is a screenshot from graphreader illustrating the curve from which values were extracted for estimating the EDR (purple line).

From the resulting deterrence function, an EDR of 10.5 km was estimated. The distance to the 50% probability of response (R50) was 6.5 km (Table 12). This EDR lies within the reported maximum extent of a statistically significant reduction in %PPM of 9 to 12 km. The sensitivity of this EDR to assumptions made with regard to the distance at which *p(response)* reached zero was also explored by repeating the approach described above but assuming zero response at the mid-point of the 15 to 18 km distance bin. (Both the 12 - 15 and 15 - 18 km distance bins reported no statistically significant reduction in %PPM.) This 'shortening' of the deterrence function provided an estimated EDR of 9.6 km and an R50 of 6.4 km.

**Table 12.** Estimated EDR from the Dähne *et al.* (2017). [1] The distance at which there is a 50% proxy p(response).

| R50[1] (km) | EDR (km) [*p(response)* at EDR] |
|---|---|
| 6.5 | 10.5 [0.29] |

### 3.3.2. Diederichs *et al.* (2014), Nehls *et al.* (2015) - Borkum West II OWF

The results of monitoring using CPODs and broadband acoustic recorders during construction of the Borkum West II OWF in the German North Sea are presented in Diederichs *et al.* (2014) and Nehls *et al.* (2015). The foundation type was pin piles of 2.5 m diameter, some with no noise abatement, and some with noise abatement comprising two single big bubble curtain configurations. The piling duration was not reported in either study. ADDs were used (pingers and Lofitech seal scarer), but the duration of their use was not reported (Table 3). Monitoring devices were deployed at up to approximately 30 km from piling locations.

**Table 13.** Key features of the Diederichs *et al.* (2014) and Nehls *et al.* (2015) studies.

| Wind farm studied | Location | Pile type(s) | Noise abatement |
|---|---|---|---|
| Borkum West II | German North Sea | Pin piles | BBC (two configurations) at some piles |

Porpoise responses were not directly assessed as a function of distance to piling. Rather, they were analysed as a function of received noise levels. Responses were presented as the change in PPM/h relative to a reference period (defined as a period of nine hours before piling (full hours *T-10h* to *T-2h*), under the condition that no piling took place in the preceding 24 (until *T-34h*). The change in PPM/h during piling was then explored for 5 dB bins of unweighted SEL (50$^{th}$ percentile, and therefore somewhat lower than the typical 95$^{th}$ percentile values reported in other studies) from < 135 dB to > 160 dB. Significant reductions in PPM/h were observed from received levels of 145 - 150 dB and higher, albeit with some (non-statistically significant) lesser reductions above 135 dB. From these data, it is possible to reference all reductions to that of the maximum received level category of > 160 dB to derive a dose-response function with a probability of response, *p(response)*, spanning 1.0 to zero. *p(response)* was set to zero for SEL < 135 dB as a non-significant increase in PPM/h reported (Table 14).

To provide a single value for received level, the mid-point of each category was taken (e.g. 157.5 dB for the 155 - 160 dB category), with upper and lower bounds taken as 162.5 dB and 132.5 dB, respectively (Table 14). Graphreader was then used to extract values of measured $SEL_5$ at distance from plots of measure noise levels vs distance presented in Diederichs *et al.* (2014). Separate plots were provided for measured piles with different levels of noise abatement, including no noise abatement (n = 8 piles) and two BBC configurations (BBC1, n = 6 piles; BBC2 (optimised), n = 10 piles) (Table 14).

**Table 14.** Reported reduction in PPM/h relative to a reference period for categories of received unweighted SEL (Diederichs *et al.* 2014; Nehls *et al.* 2015), corresponding derived probability of response used in the current study, and reported distances to relevant sound levels for different levels of noise abatement (Diederichs *et al.* 2014). * indicates statistical significance. [1] Artificially adjusted to zero as non-significant increase in PPM/h reported. [2] Noise levels were taken to be the 50th percentile fit of values across the piles where noise levels were extensively measured. [3] Noise levels did not exceed 160 dB at the closest monitoring distance of 750 m, so it was assumed that a probability of response of 1.0 was only achieved at 0 km.

| Sound level ($SEL_{50}$ dB) | Sound level (SEL dB) category mid-point | Reduction in PPM/h relative to reference period | Probability of response | Reported distance (km) to sound level category mid-point (SEL) | | |
|---|---|---|---|---|---|---|
| | | | | none | BBC1 | BBC2 |
| > 160 | 162.5 | -4.86* | 1.000 | 2.5 | 0.7 | 0.00[3] |
| 155 - 160 | 157.5 | -4.13* | 0.850 | 4.0 | 1.5 | 0.8 |
| 150 - 155 | 152.5 | -3.74* | 0.769 | 7.1 | 2.7 | 1.7 |
| 145 - 150 | 147.5 | -2.52* | 0.518 | 11.5 | 4.7 | 3.3 |
| 140 - 145 | 142.5 | -1.27 | 0.261 | 17.3 | 8.0 | 5.5 |
| 135 - 140 | 137.5 | -0.88 | 0.180 | 24.2 | 12.9 | 8.9 |
| < 135 | 132.5 | 0.31 | 0.000[1] | 34.1 | 18.3 | 14.0 |

For each level of noise abatement, a non-linear least squares model was fit using the 'nls' package in *R* (R-Core-Team 2023), with the model fit digitised in graphreader. The model did not fit exactly through the added values at 0 km; therefore, we assumed a linear function between the model fit at the closest reported distance to 0 km and a *p(response)* of 1.0 at 0 km.

From the resulting deterrence functions, EDR and R50 values were estimated for each different level of noise abatement (Table 15). The EDR for piling with no noise abatement was estimated to be 17.8 km, while the estimated EDR for the optimised BBC (BBC2), which achieved an average noise reduction of SEL 11 dB re 1μPa$^2$s (range 9 - 13 dB re 1μPa$^2$s), was 6.2 km. Both these estimated EDRs are slightly larger than the effects ranges of 15 km (unabated) and 4.8 - 6.7 km (BBC1 and BBC2) reported in the associated publications (Diederichs *et al.* 2014; Nehls *et al.* 2015). For all three noise abatement levels, the measured SEL at the distance of the estimated EDR was between SEL 141 - 142 dB re 1μPa$^2$s.

**Table 15.** Estimated EDRs from the Diederichs *et al.* (2014) studies for different levels of noise abatement. [1] The distance at which there is a 50% proxy p(response).

| R50[1] (km) | | | EDR (km) [*p(response)* at EDR] | | |
|---|---|---|---|---|---|
| No noise abatement | BBC1 | BBC 2 | No noise abatement | BBC1 | BBC 2 |
| 12.8 | 5.5 | 3.8 | 17.8 [0.25] | 8.4 [0.21] | 6.2 [0.20] |

### 3.3.3. Thompson *et al.* (2013), Brandt *et al.* (2011)

Thompson *et al.* (2013) plotted a deterrence function through data on harbour porpoise responses to piling at the Hornsea Rev II OWF in Danish waters presented in Brandt *et al.* (2011). Table 9 summarises key features of the Brandt *et al.* (2018) study. The foundation type was monopiles of 3.9 m diameter, all installed without noise abatement. Piling lasted an average of 46 min. ADD use was extensive, with an average of 163 min pre-piling (range 0 - 461 min), throughout piling, and an average of 46 min post-piling (range 0 - 279 min) (Table 3).

Thompson *et al.* (2013) fitted a binomial function through six data points, each of which provided the mean proportional reduction in PPM/h between the hour immediately following piling and the overall mean PPM/h at that location throughout the entire study period. The mean distances between piling and each of the six TPOD locations were 2.6, 3.2, 4.8, 10.1, 17.8 and 21.7 km. In addition to plotting the best fit, lower and upper bounds were also plotted, based on the standard error (lower) or a line weighted to include all data points (upper). Values for the best fit and upper bounds were extracted using graphreader and used to estimate the corresponding EDR and R50 values.

**Table 16.** Key features of the Brandt *et al.* (2011) study.

| Wind farm studied | Location | Pile type(s) | Noise abatement |
|---|---|---|---|
| Horns Rev II | Danish North Sea | Monopiles | None |

An EDR of 14.3 km was estimated for the best fit, and 16.8 km for the upper bound (Table 12). These EDRs are smaller than the reported maximum distance to a detectable decline of 17.8 km previously reported for these data (Brandt *et al.* 2011).

As noted by Brandt *et al.* (2011), the reported changes in porpoise acoustic activity are relative to an overall average which includes all available data and so include data that are influenced by pile driving. As such, porpoise activity during this 'baseline' will already be reduced relative to a true undisturbed state, and so the results may underestimate the true extent of responses. As such, use of the EDR upper bound (16.8 km) is advised, as the additional conservatism of encompassing all data points should reduce the extent to which responses may be underestimated.

**Table 17.** Estimated EDRs from the Thompson *et al.* (2013) study based on data presented in Brandt *et al.* (2011). [1] The distance at which there is a 50% proxy p(response).

| R50[1] (km) | | EDR (km) [*p(response)* at EDR] | |
|---|---|---|---|
| Best fit | Upper bound | Best fit | Upper bound |
| 12.2 | 15.1 | 14.3 [0.34] | 16.8 [0.36] |

### 3.3.4. Moray Firth OWFs

#### 3.3.4.1. Approach

Existing data from three OWFs in the Moray Firth were revisited to estimate EDRs from both models presented in existing studies and from new models developed for the current study to provide additional insight. The three OWF were:

- Beatrice OWF ('Beatrice') (see Graham *et al.* 2019).
- Moray East OWF ('Moray East') (see Benhemma-Le Gall *et al.* 2021).

- Moray West OWF ('Moray West') (see Benhemma-Le Gall *et al.* 2024).

Key attributes of the three Moray Firth OWFs are provided in Table 18. All wind farms utilised a large-scale PAM array of up to ~60 CPODs and a similar analytical approach which is described in detail in Graham *et al.* (2019) and summarised in Section 2.3.1.1. While CPODs were deployed up to ~60 km from piling locations during construction at Beatrice and Moray East, the maximum CPOD distance to piling at Moray West was ~ 35 km. Therefore, for the purpose of comparison between wind farms, the current study considered models for Beatrice and Moray East OWFs using data up to 60 km from piling, as previously presented (Graham *et al.* 2019; Benhemma-Le Gall *et al.* 2021), and also developed models using data only up to 35 km from piling. Additionally, for each truncation distance (35 km or 60 km), models were developed for both 12-h and 24-h response periods (post-piling).

The models provide predictions of the mean (and 95% CI) probability of porpoise responding, *p(response)*, as a function of distance to piling, on a logarithmic scale, and specified values of other covariates (e.g. ADD use, piling duration, piling sequence, hammer energy, number of vessels). Using the different models available, deterrence functions were developed from predictions of *p(response)* in 50 m distance increments between 0 - 35 km or 0 - 60 km from the piling location. From the deterrence functions, the range to a 50% probability of response (R50) was extracted and EDRs were estimated according to the definition presented in Section 2.2. For EDR estimation, where the predicted *p(response)* was > 0 at the maximum distance, it was assumed to be zero at the next distance increment.

**Table 18.** Key features of the Moray Firth OWFs.

| Wind farm studied | Pile type(s) | Noise abatement |
|---|---|---|
| Beatrice | Pin piles | None |
| Moray East | Pin piles | None |
| Moray West | Monopiles | None |

#### 3.3.4.2. Results and discussion

Model parameters, R50 values and estimated EDRs for the three Moray Firth OWFs are presented in Table 19 to Table 21. Deterrence functions for Moray East and Moray West are presented in Figure 6 and Figure 7. A few general patterns are apparent:

- Estimated EDRs were considerably larger when based on data up to 60 km from piling compared to 35 km from piling.
- Estimated EDRs appeared to be influenced by how close to zero the predicted *p(response)* was at the maximum distance modelled.
- Estimated EDRs based on models on Beatrice data were considerably larger when predicted *with* ADD use compared to without ADD use.
- The pattern of diminishing responses with piling sequence at Beatrice indicated by R50 estimates was not apparent in the estimated EDRs.
- When considering only 12-h response models based on data up to 35 km from piling, estimated EDRs at Moray East and Moray West were similar (12 - 13 km) but larger at Beatrice (15 - 20 km, with ADD use).

The differences in porpoise response to piling activities between these three OWFs may be due to variations in the pile installation techniques, mitigation measures implemented, vessel traffic and behaviour around these construction sites pre- and post-piling. The heavy lift piling vessel was anchored at Beatrice, jacked up at Moray East and dynamically positioned at Moray West. These different piling vessel types would have generated varying levels of noise throughout the preparation, installation and post-installation activities. The number and behaviour of support vessels also varied between the piling campaigns of these three OWFs. For example, increased levels of vessel intensity were already observed during the baseline periods (48 h to 24 h prior to piling) at Beatrice in comparison to Moray East (see Figure 5.B in Benhemma-Le Gall *et al.* (2023)). In future analyses of these data (beyond the scope of the current review), a metric that accounts for levels of vessel activities (e.g. vessel intensity) will be estimated for both the baseline and response periods.

**Table 19.** Beatrice: model configurations, parameters, R50 values and estimated EDRs. Shaded rows are those where predictions were made for no ADD use, which is atypical to current practise in the UK. [1] Value forced to 1.0 in EDR estimation. [2] Predicted p(response) was 1.0 at 0 km but dropped steeply to 0.4 at 50 m distance.

| Piling order or N piling bouts | Response type | Covariates selected | Values used for predictions | Predicted over distance (km) | R50 (km) | Range of p(resp) values | EDR (km) | Predicted over distance (km) | r50 (km) | Range of p(resp) values | EDR (km) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st | 24-h | log(distance) * order + vessels_1km | piling order = 1, no vessels | 0-35 | 6.8 | 0.045 - 1 | 13.3 | 0 - 60 | 7.0 | 0.040 - 1 | 19.7 |
| 47th | 24-h | | piling order = 47, no vessels | 0-35 | 4.1 | 0.081 - 1 | 13.7 | 0 - 60 | 4.0 | 0.052 - 1 | 19.2 |
| 86th | 24-h | | piling order = 86, no vessels | 0-35 | 1.1 | 0.128 - 1 | 14.4 | 0 - 60 | 1.5 | 0.067 - 1 | 19.1 |
| 1st | 12-h | log(distance) * order + vessels_500m + ADD | piling order = 1, no vessels, no ADD | 0-35 | 2.1 | 0.003 - 1 | 5.6 | 0 - 60 | 3.1 | 0.002 - 1 | 8.7 |
| | | | piling order = 1, no vessels, with ADD | 0-35 | 8.3 | 0.083 - 1 | 15.7 | 0 - 60 | 8.4 | 0.031 - 1 | 19.5 |
| 47th | 12-h | | piling order = 47, no vessels, no ADD | 0-35 | 0.7 | 0.01 - 1 | 5.8 | 0 - 60 | 1.4 | 0.01 - 0.99 [1] | 10.1 |
| | | | piling order = 47, no vessels, with ADD | 0-35 | 6.6 | 0.162 - 1 | 17.6 | 0 - 60 | 6.4 | 0.082 - 0.99 [1] | 23.3 |
| 86th | 12-h | | piling order = 86, no vessels, no ADD | 0-35 | 0.0 [1] | 0.024 - 1 | 6.5 | 0 - 60 | 0.2 | 0.027 - 0.90 [1] | 12.3 |

| Piling order or N piling bouts | Response type | Covariates selected | Values used for predictions | Predicted over distance (km) | R50 (km) | Range of p(resp) values | EDR (km) | Predicted over distance (km) | r50 (km) | Range of p(resp) values | EDR (km) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | piling order = 86, no vessels, with ADD | 0-35 | 3.2 | 0.262 - 1 | 19.4 | 0 - 60 | 3.5 | 0.161 - 0.989 [1] | 27.5 |

**Table 20.** Moray East: model configurations, parameters, R50 values and estimated EDRs. * Value forced to 1.0 in EDR estimation.

| Piling order or N piling bouts | Response type | Covariates selected | Values used for predictions | Predicted over distance (km) | R50 (km) | Range of p(resp) values | EDR (km) | Predicted over distance (km) | R50 (km) | Range of p(resp) values | EDR (km) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N=12 | 24-h | log(distance) * duration + vessels_1km | piling duration = 2.5 h, no vessels | 0-35 | 1 | 0.026 - 0.958* | 7.7 | 0 - 60 | 1.3 | 0.015 - 0.997* | 10.4 |
| N =19 | 12-h | log(distance) + duration + max hammer energy | piling duration = 3.1 h, mean max hammer energy = 1,165 kJ | 0-35 | 2.15 | 0.076 - 1 | 12.5 | 0 - 60 | 2 | 0.051 - 1 | 17.8 |

**Table 21.** Moray West: model configurations, parameters, r50 values and estimated EDRs.

| Piling order or N piling bouts | Response type | Covariates selected | Values used for predictions | Predicted over distance (km) | R50 (km) | Range of p(resp) values | EDR (km) |
|---|---|---|---|---|---|---|---|
| 1st & 2nd | 24-h | log(distance) * duration | piling duration = 3 h | 0 - 35 | 4.9 | 0.02 - 1 | 9.4 |
| N = 7 | 24-h | log(distance) * duration | piling duration = 3 h | 0 - 35 | 1.1 | 0.036 - 1 | 8.6 |
| 1st & 2nd | 12-h | log(distance) * duration + Bvessels_1km | piling duration = 3 h, no vessels | 0 - 35 | 6.3 | 0.053 - 1 | 12.9 |
| N = 9 | 12-h | log(distance) * duration + sandeel density | piling duration = 3 h, scaled sandeel density = 0, (eq. mean sandeel density = 73.8 $N/m^2$) | 0 - 35 | 0.5 | 0.095 - 1 | 12.1 |

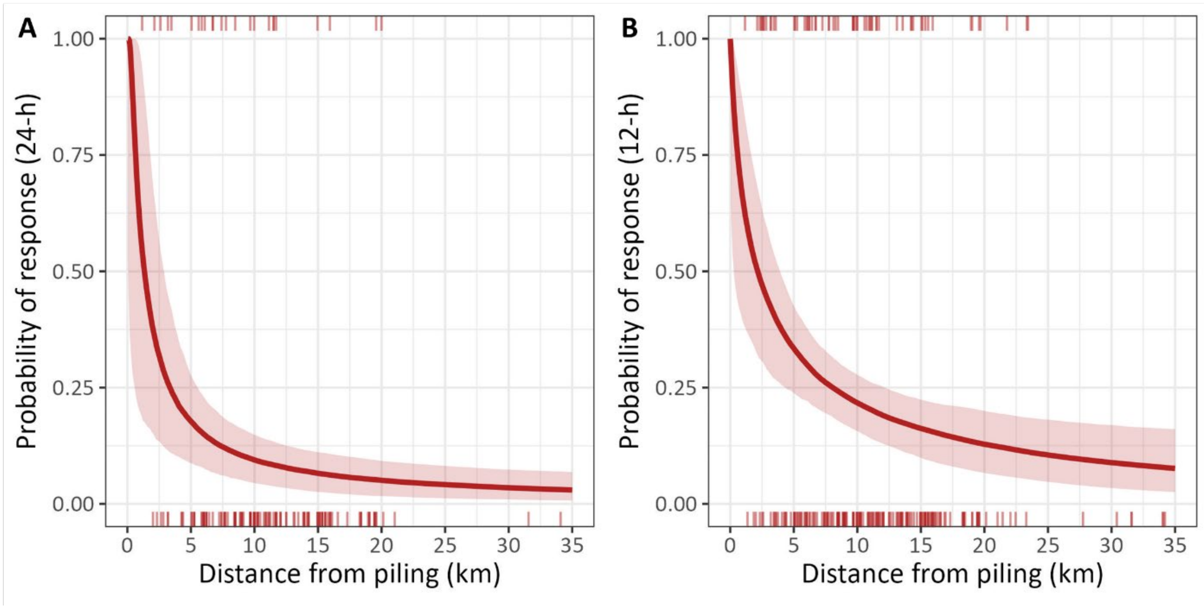


**Figure 6.** Probability of a) 24-h and B) 12-h harbour porpoise responses in relation to the partial contribution of distance from piling at a subset of piling events (solid red line) at Moray East OWF. The 95% confidence intervals (shaded areas) highlight uncertainty in fixed effects only. Rug plots show actual response data.

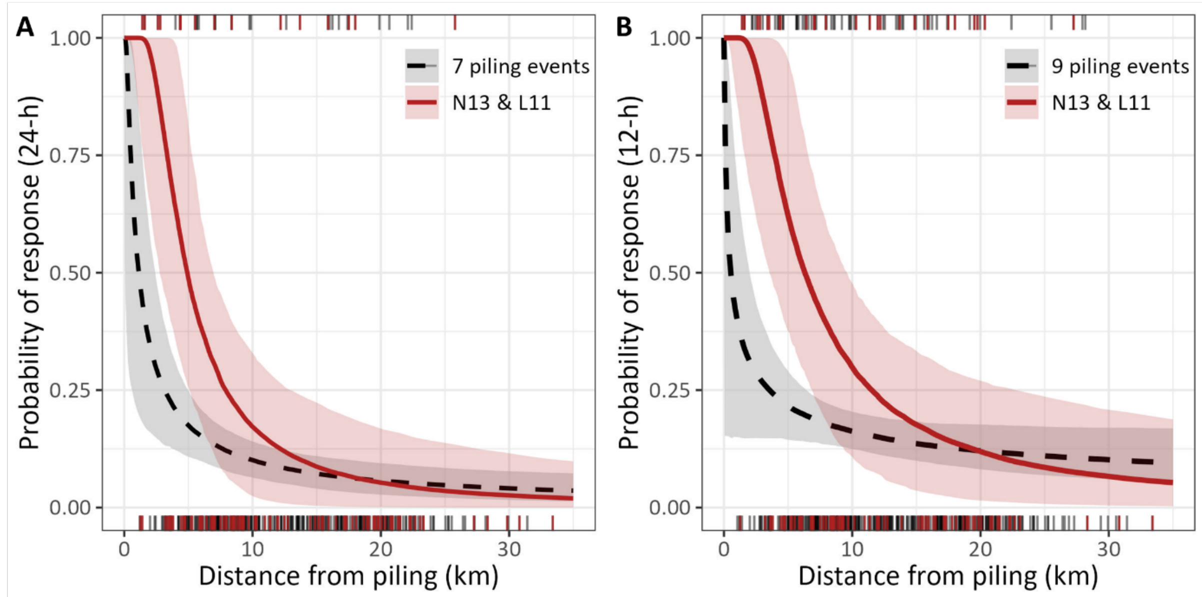


**Figure 7.** Probability of A) 24-h and B) 12-h harbour porpoise responses in relation to the partial contribution of distance from piling at the first two piling events (N13 & L11; solid red lines) or at a subset of piling events (dashed black lines) at Moray West OWF. The 95% confidence intervals (shaded areas) highlight uncertainty in fixed effects only. Rug plots show actual response data.

Given that piling order was not retained in the Moray East models, the EDR estimates are based on the averaged porpoise response to a subset of piling events (n=12 for the 24-h response model; n=19 for the 12-h response model). This could explain the lower values of EDRs observed at Moray East in comparison to Beatrice.

The use of ADD-based mitigation measures prior to pile installation increased the level of porpoise response within a 12-h period after piling cessation at Beatrice, which led to higher

EDR estimates in comparison to pilings event without ADD use. Further, the variation in ADD duration between the three Moray Firth OWFs may also have contributed to the weaker responses observed in Moray East and Moray West in comparison to Beatrice.

It also noted that noise levels recorded during Moray West monopile installation (Ocean Winds, Unpublished Data, cited in Benhemma-Le Gall *et al.* (2024)) were louder than those reported during the Beatrice pin pile installation activities (see Graham *et al.* 2019; Thompson *et al.* 2020), and so the reasons for the lower level of porpoise response at Moray West remain unclear (see Discussion section of Benhemma-Le Gall *et al.* (2024). These differences highlight the need to consider, in larger comparative analyses, the contextual factors such as seasonal variation in individual energetic needs and prey availability, previous exposure to similar anthropogenic noise but also the differences in sampling design and in construction and mitigation activities.

It is important to be mindful of caveats in the analytical approach and the influence this may have on results. For example, porpoise responses to each Moray Firth OWF's piling activities were modelled separately; this leads to different covariates being retained in each model, and consequently comparisons between OWFs have to be drawn carefully.

Additionally, EDR estimates can vary widely with the shape of the deterrence function curves, especially the tail. EDR estimates can also vary with the extent of the PAM array. As an example, for similar range of *p(response)* values, EDR estimates tend to be higher for the 0 - 60 km dataset than for the 0 - 35 km dataset. Unlike the EDR estimates, the R50 estimates do not seem to vary as much with the shape of the deterrence function curve, nor with the extent of the PAM array, as these are largely dictated by how steeply the *p(response)* drops over the first 5 - 10 km from the piling location. The influence of the shape of the deterrence function and extent of the PAM array are not considered to be unique features of the Moray Firth study and are relevant considerations for all such PAM studies.

Table 22 summarises the specific estimated EDRs for each of the three Moray Firth projects which we consider to be the most representative values to use to inform default recommended EDRs for piling. These each use 12-h response periods to minimise the inclusion of recovery, and data to 35 km from piling to reduce the effect of distant positive responses unlikely to be caused by piling. For Beatrice, the 47$^{th}$ piling event is selected (middle of the construction period) and for Moray East the model for 19 piling events is included to maximum the same size. While the Moray West model for 9 piling events may be more representative than the selected one for 2 piling events, the latter is favoured as the deterrence function showed a very steep drop in *p(response)* at close distances (resulting in an R50 of only 0.5 km) and a *p(response)* of approximately 10% even at 35 km, and so was considered less reliable than the 2-pile model for EDR estimation.

**Table 22.** Summary of the most representative estimated EDRs from the Moray Firth data. [1] The distance at which there is a 50% proxy p(response).

| OWF | Data and model configuration | R50[1] (km) | EDR (km) [*p(response)* at EDR] |
|---|---|---|---|
| Beatrice | 12-h response period, 47th pile, with ADD, 35 km data | 6.6 | 17.6 [0.30] |
| Moray East | 12-h response period, 19 piling events, with ADD, 35 km data | 2.15 | 12.5 [0.18] |
| Moray West | 12-h response period, 2 piling events, 35 km data | 6.3 | 12.9 [0.15] |

## 3.4. Summary of estimated EDRs

Estimated EDRs from data extracted from existing studies on the responses of harbour porpoises to impact pile driving are plotted in Figure 8 and tabulated in Table 23. These also include the EDR of 26 km estimated by Tougaard *et al.* (2013) for Alpha Ventus, but the EDR presented for Moray West in Benhemma-Le Gall *et al.* (2024) (24-h response) has been replaced by that estimated in Section 3.3.4 (12-h response).

Based on the studies and data scrutinised to date, estimated EDRs (using the EDRs selected as most representative from the three Moray Firth OWFs – see Table 22), range from:

- 12.9 - 24.0 km for monopiles without noise abatement (noting that for 24-h response models on Moray West, estimated EDRs were in the range 8.6 - 9.4 km).
- 6.2 – 10.5 km for monopiles and/or pin piles with noise abatement
- 9.5 - 26.0 km for pin piles without noise abatement

The estimated EDRs are also presented as a percentage of the spatial extent of effects as reported in each study (taking the upper bound where a range was provided). For studies which reported spatial extent of effects corresponding to the maximum range of deterrence effect (such as where detection rates equal those of a non-piling baseline), their corresponding estimated EDRs are smaller than these maximum ranges, and corresponding estimated R50s are smaller still. For studies reporting a spatial extent of effects which was the upper bound of statistical significance, their corresponding estimated EDR was larger than the reported spatial extent of effects.

From the estimated deterrence functions, we also reported the proxy *p(response)* at the estimated EDR. This value is presented out of interest in exploring if there was consistency in the *p(response)* / the proportional reduction in detection rates at the estimate EDR. The *p(response)* at the EDR ranged between 0.15 - 0.46, with a mean and median value of 0.3. The highest estimated values of *p(response)* corresponded to smaller EDRs and/or detection functions which were more linear in nature. The lowest estimated values of *p(response)* corresponded to larger EDRs and/or detection functions with a logistic shape and long tail.

It is important to note that the shape of the deterrence function has a large influence on estimated EDRs. More linear functions or those with a 'long tail' of low probability of response extending to many tens of kilometres generally result in much larger EDRs. It is unclear how decisions made in modelling approaches can influence the resulting EDR. It is possible that, for some modelling approaches, a small change in the degrees of freedom (dictating the ‘wiggliness’ of a deterrence function) may have a large influence on the EDR, even though the effect on model fit may be minor.

Model predictions from the Moray Firth projects often feature a *p(response)* of > 0.05, up to 0.25 in some cases, at the maximum monitored distance to piling. When estimating the EDR, *p(response)* beyond this distance is assumed to be zero. It is not currently known whether such an assumption is biasing EDRs low, or a feature of the modelling process (such as a few distant non-piling-related positive responses) is biasing EDRs high by resulting in this ‘long tail’ in the deterrence function. It is likely that including data up to 60 km from a piling location will, to some extent, result in overly conservative EDRs. This is supported by multiple studies providing evidence of porpoise acoustic activity reaching a baseline value within 35 km (e.g. Brandt *et al.* 2018; Rose *et al.* 2019; de Jong *et al.* 2022). However, the relationship between the spatial extent of monitoring and EDRs is currently unquantified. Choosing an appropriate distance at which to truncate data is critical and requires further investigation. It is noted that such efforts are currently underway within elements of the PrePARED project, by using piling noise measurement data to assess the harbour porpoise frequency-weighted signal-to-noise ratio as a function of distance to piling. This will help to understand the spatial limits to which piling noise is audible to and/or likely to cause a response in harbour porpoise. Outputs from this work are expected in the latter half of 2025.

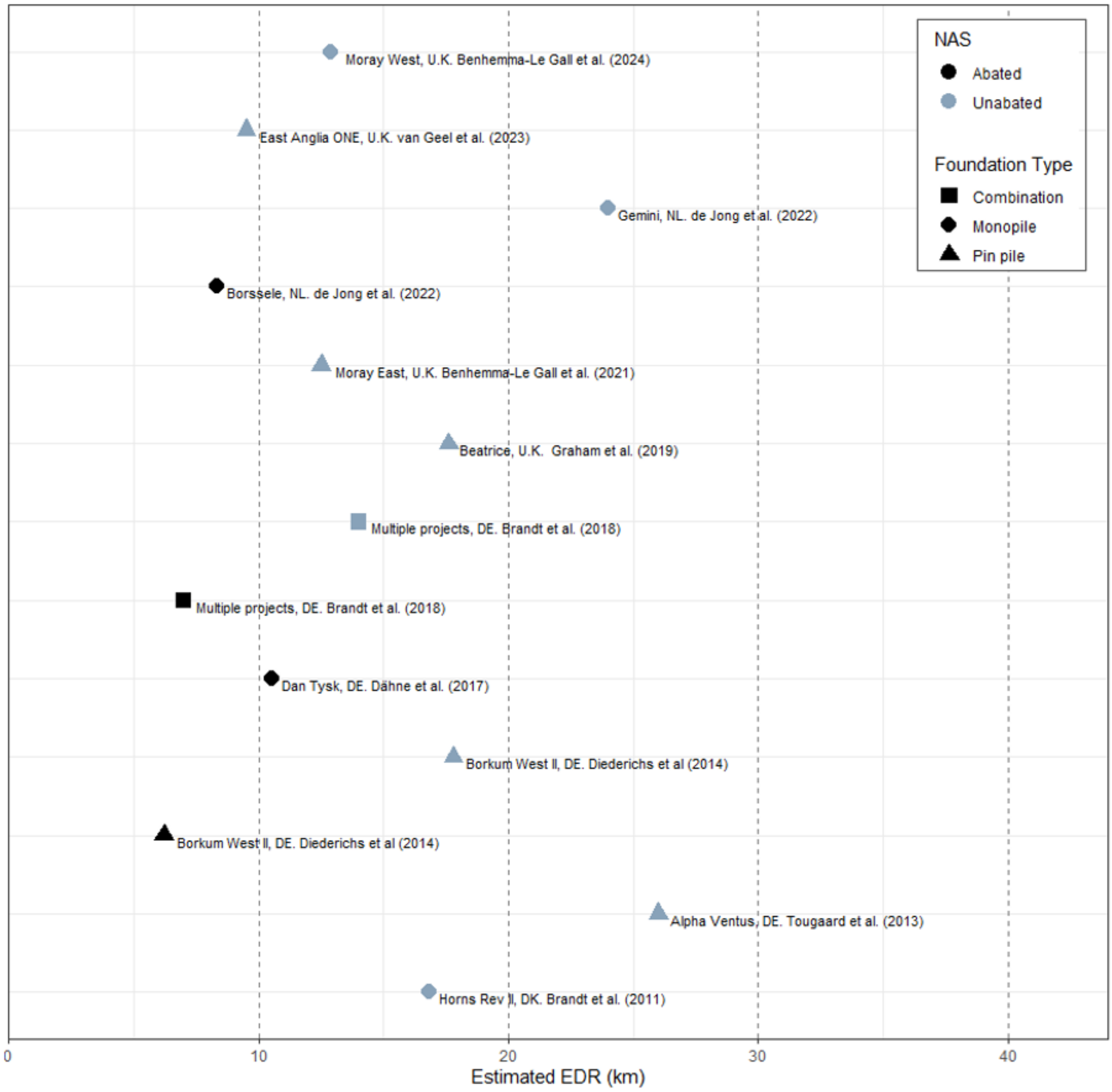


**Figure 8.** Estimated EDRs from existing studies on the responses of harbour porpoises to impact pile driving with and without noise abatement, as described in Section 2.3.5. While the same definition of EDR was interpreted from each study, comparisons of EDRs between studies is complicated by different approaches to the underlying analyses and their influence on the deterrence functions from which EDRs were estimated.

**Table 23**. Relevant empirical studies of porpoise responses to pile driving from which an EDR was estimated as described in Section 3.3 from data presented in these publications. Also included is Tougaard *et al.* (2013) which already estimated an EDR based on a comparable approach. “Mono” = Monopile, “Pin” = Pin pile, “N/A” = Not Applicable, “-“ = Not Available. For additional details on the SEL @750 m, ADD use and description of reported spatial extent of effect, see Table 3. [1] While Benhemma-Le Gall *et al.* (2024) reported an EDR of 9.4 km for Moray West based on the first two piles and a 24-h response, the EDR of 12.9 km was based a 12-h response, as presented in Section 3.3.4. [2] The analysis presented in Benhemma-Le Gall *et al.* (2021) was very different to that undertaken here (see Section 3.3.4) from which EDRs were estimated.

| Reference | Wind Farm | Pile type, max diameter (m) | NAS type used | SEL @ 750 m | Average ADD duration (min) | Reported spatial extent of effect (km) | Estimates based on additional analysis | | | EDR as % of maximum reported spatial extent of effect |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | R50 | EDR | *p(response)* at the EDR | |
| Benhemma-Le Gall *et al.* (2024) | Moray West, UK | Mono, 10.0 | N/A | 179 | 10 | 5 (R50), 9.4 (EDR) | 0.5 | 12.9 [1] | 0.15 | 129 |
| van Geel *et al.* (2023) | East Anglia ONE, UK | Pin, 2.5 | N/A | - | - | 14 | 8.1 | 9.5 | 0.43 | 68 |
| de Jong *et al.* (2022) | Gemini, NL | Mono, 7.5 | N/A | 182 | 73 | 15 | 22.4 | 24.0 | 0.46 | 160 |
| | Borssele, NL | Mono, 8.3 | DBBC and HSD or AdBm | 172 | 70 | 7 | 6.3 | 8.3 | 0.36 | 119 |
| Benhemma-Le Gall *et al.* (2021) | Moray East, UK | Pin, 2.5 | N/A | - | 15 | 10 - 15 [2] | 2.15 | 12.5 | 0.18 | 83 |
| | Beatrice, UK | Pin, 2.2 | N/A | 166 | 15 | | 6.6 | 17.6 | 0.3 | 117 |
| Graham *et al.* (2019) | Beatrice, UK | Pin, 2.2 | N/A | 166 | 15 | 7.4 (R50), 18.0 (R25) | 6.6 | 17.6 | 0.3 | 98 |

| Reference | Wind Farm | Pile type, max diameter (m) | NAS type used | SEL @ 750 m | Average ADD duration (min) | Reported spatial extent of effect (km) | Estimates based on additional analysis | | | EDR as % of maximum reported spatial extent of effect |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **R50** | **EDR** | ***p(response)* at the EDR** | |
| Brandt *et al.* (2018) | Seven projects, DE | Pin, 3.4 | N/A | 180 | - | 17 - 33 | 10 - 11 | 14.0 | 0.28 | 42 |
| | Seven projects, DE | Mono, 6.5<br>Pin, 2.5 | BBC, IHC-NMS | 169 | - | 14 | 5 | 7.0 | 0.308 | 50 |
| Dähne *et al.* (2017) | Dan Tysk, De | Mono, 6.0 | BBC or DBBC | 157 | 66 | 9 - 12 | 6.5 | 10.5 | 0.29 | 88 |
| Diederichs *et al.* (2014); Nehls *et al.* (2015) | Borkum West II, DE | Pin, 2.5 | N/A | 174 | - | 15 | 12.8 | 17.8 | 0.25 | 119 |
| | Borkum West II, DE | Pin, 2.5 | BBC | 163 | - | 4.8 | 3.8 | 6.2 | 0.2 | 129 |
| Tougaard *et al.* (2013) | Alpha Ventus. DE | Pin, 2.4 - 2.6 | N/A | 170 | ~300 | 26 (EDR) | ~20 | 26 | ~0.36 | N/A |
| Brandt *et al.* (2011) | Horns Rev II, DK | Mono, 3.9 | N/A | 176 | 255 | 17.8 | 15.1 | 16.8 | 0.36 | 94 |

# 4. Weighted averages of reported effects ranges

It is recognised that comparisons between studies of porpoise responses to impact piling are challenging due to differences in study design, analysis and reporting. Nonetheless, to assist in interpreting the evidence base for the purposes of EDR recommendation, weighted averages of reported effects ranges were generated using the assigned evidence scores as weights. This allows some measure of the suitability, relevance and quality of the evidence to be factored into recommendations.

## 4.1. Approach

For all empirical response studies relating to monopile or pin piling at OWFs, a hierarchy of reported effects ranges was assigned:

- Where an EDR could be estimated, this was assigned to the study. The specific EDR assigned was that determined to be most suitable (as described in Section 3).
- Where an EDR could not be estimated, and a single response distance was reported, this was assigned to the study.
- Where an EDR could not be estimated, and a range of response distances was reported, the minimum, maximum, and mid-point of the range were assigned to the study.

As some of the 20 such studies reviewed presented values for piling both with and without noise abatement, this resulted in a total 26 data points for which at least one reported response range was available. This was reduced to 25 with the exclusion of Rumes and Zupan (2021) which provided a single result for abated and unabated piling. Weighted averages were then estimated for the following categories of piling: unabated; abated; unabated monopiles, unabated pin piles. No average was estimated for abated pin piles as only one study fell into this category.

The dataset included three different studies which provided reported effects ranges specifically for Alpha Ventus OWF, and a further three for Gemini OWF. To avoid bias towards these projects among weighted averages, the study with the highest score was selected for Alpha Ventus (Tougaard *et al.* 2013, EDR of 26 km, study score of 8). As all three studies of Gemini scored 7, the study with the intermediate reported effect range was selected (Geelhoed *et al.* 2018, reported effect range of 10 - 20 km, mid-point of 15 km).

For each category of piling type, weighted averages were generated using the min, max and mid-point of reported effects ranges, where applicable. Results are presented in Table 24. The weighted mean was calculated as:

$$\bar{x}_w = \frac{\sum_{i=1}^{n} w_i \, x_i}{\sum_{i=1}^{n} w_i}$$

Where $\bar{x}_w$ is the weighted mean, $x_i$ are the reported effects ranges, $w_i$ are the scores and $n$ is the number of reported effects ranges.

**Table 24**. Weighted averages of effects ranges for different categories of monopile or pin piling at OWFs. [1] Results from Brandt et al. (2018) were excluded from these categories as they included a combination of monopiles and pin piles.

| **Piling category** | **Number of studies (of which an EDR was estimated)** | **Weighted average effect range (km): mid-point (min-max)** |
|---|---|---|
| Piling without noise abatement (monopile or pin pile) | 14 (8) | 17.4 (16.9 - 18.0) |
| Piling with noise abatement (monopile or pin pile) | 7 (4) | 10.8 (10.0 - 11.6) |
| Monopiles without noise abatement | 7 (2) [1] | 18.2 (17.0 - 19.3) |
| Pin piles without noise abatement | 6 (5) [1] | 17.1 (17.1 - 17.1) |
| Monopiles with noise abatement | 5 (2) [1] | 12.6 (11.5 - 13.7) |

# 5. Recommending default EDRs

## 5.1. Overview: Evidence base

Since the publication of Brown *et al.* (2023), a few additional empirical studies of harbour porpoise responses have been completed, which have added to the evidence base. Furthermore, our attempts in the current study to estimate EDRs from existing study outputs and data have provided additional insight on the response ranges of harbour porpoise to impact pile driving.

Reported effects ranges, estimated EDRs and weighted averages of effects ranges among the 21 studies of **piling at OWFs** reviewed are summarised in Table 25. These are separated by pile type and with/without noise abatement, where possible, in line with the current recommended default EDRs (JNCC 2020). With the exception of Alpha Ventus OWF at 26 km (which included long piling and ADD durations) and Gemini OWF at 24.0 km (which is conservative relative to other reported effects ranges for this project - see Section 3.3.2), all estimated EDRs for unabated piling are ≤ 17.8 km (n = 7). All estimated EDRs for abated piling are ≤ 10.5 km (n = 4).

The single empirical response study relating to **sheet piling** reported a maximum effect range of 15.7 km. However, this study was associated with very long duration of ADD use concurrent with piling in this study, which limits the interpretation of porpoise responses to the activity of sheet piling itself. It is unlikely that this study is representative of sheet piling in UK waters, which is largely restricted to the construction of cofferdams close to shore (e.g. in coastal infrastructure development).

Two noise measurement studies of **conductor piling** reported distances to a potential disturbance threshold level of $SPL_{rms}$ 160 dB re 1µPa of up to approximately 0.5 - 1.0 km. While this evidence base is very limited and likely underestimates the disturbance effect which may occur over multiple hours of piling, it does indicate the much lower noise emissions associated with this activity and the lower potential for disturbance.

**Table 25**. Summary of reported effects ranges and estimated EDRs among the 20 studies reviewed. [1] Results for Rumes and Zupan (2021) are omitted due to their inclusion of a mixture of monopiles with and without noise abatement, but their reported effects range of 15 - 20 km is within the range of both categories. [2] Results from Brandt *et al*. (2018) were excluded from these categories as they included a combination of monopiles and pin piles. [3] While Benhemma-Le Gall *et al*. (2024) reported an EDR of 9.4 km for Moray West based on the first two piles and a 24-h response, the EDR of 12.9 km based on a 12-h response (as presented in the current study) is favoured here.

| Piling category | Pile diameters represented in evidence (m) | Max hammer energies represented in evidence (kJ) | Reported effects range, km (n= number of studies) | Estimated EDR, km (n= number of studies) | Weighted average effect range (km): mid-point (min-max) |
|---|---|---|---|---|---|
| Piling without noise abatement (monopile or pin pile) [1] | Mono: 3.9 - 10.0<br>Pin: 1.8 - 2.6 | Mono: 450 - 4,400<br>Pin: 500 - 2,400 | 7.4 - 33.0 (n = 17) | 9.5 - 26.0 (n = 9) | 17.4 (16.9 - 18.0) |
| Piling with noise abatement (monopile or pin pile) [1] | Mono: 5.0 - 8.3<br>Pin: 2.5 | Mono: 1,400 - 3,028<br>Pin: 1,200 | 4.8 - 20.0 (n = 7) | 6.2 - 10.5 (n = 4) | 10.8 (10.0 - 11.6) |
| Monopiles without noise abatement [1, 2] | Mono: 3.9 - 10.0 | Mono: 450 - 4,400 | 9.4 - 26.0 (n = 7) | 12.9[3] - 24.0 (n = 3) | 18.2 (17.0 - 19.3) |
| Monopiles with noise abatement [1, 2] | Mono: 5.0 - 8.3 | Mono: 1,400 - 3,028 | 7.0 - 20.0 (n = 5) | 8.3 - 10.5 (n = 2) | 12.6 (11.5 - 13.7) |
| Pin piles without noise abatement | Pin: 1.8 - 2.6 | Pin: 500 - 2,400 | 8.3 - 26.0 (n = 8) | 9.5 - 26.0 (n = 5) | 17.1 (17.1 - 17.1) |
| Pin piles with noise abatement | Pin: 2.5 | Pin: 1,200 | 4.8 - 6.7 (n = 1) | 6.2 (n = 1) | NA |
| Sheet piling without noise abatement | NA | NA | 15.7 (n = 1) | NA | NA |

It is emphasised that the observations of Brown *et al.* (2023) remain valid: that among studies, there is considerable variation in the approach to data collection, analysis and reporting of results, which complicates comparison of results and adds considerable uncertainty to the estimation of effects ranges. While this does not preclude refinement of the current recommended EDRs for harbour porpoise SAC management, it does: (i) limit the extent to which EDRs can be recommended for anything other than broad categories of piling activity (e.g. with vs without noise abatement); (ii) limit the extent to which extrapolations can be made from existing studies to current piling practices in the UK (e.g. ADD durations, hammer energies); and, ultimately, (iii) limit the extent to which conservatism can be confidently reduced.

In the sections below, we discuss the findings of the review and identify considerations when interpreting the evidence base to recommend default EDRs.

### 5.1.1. Influence of construction characteristics on reported effects ranges

The current recommended default EDRs for piling without noise abatement are 26 km for monopiles and 15 km for pin piles. The current evidence review has found that there is not a strong evidence base to support a higher EDR for unabated monopiles than pin piles (Table 25), which aligns with the findings of an earlier review (Brown *et al.* 2023). We found that there was almost complete overlap between the two categories among reported effects ranges, and that the estimated EDRs for monopiles without noise abatement all fell within the range of those estimated for pin piles without noise abatement. The highest estimated EDR of any studies where this was reported or could be estimated from the data presented, was for unabated pin piling at the Alpha Ventus OWF in Germany (Dähne *et al.* 2013; Tougaard *et al.* 2013).

Despite pile diameters, hammer energies and reported broadband noise levels generally being higher for monopiles than pin piles (Figure 4, Appendix 3), reported effects ranges were not larger. The duration of piling is generally much longer for a jacket (or other foundation requiring multiple pin piles) than a monopile, which may result in larger deterrence ranges than predicted based on noise levels alone, due to a longer total period of deterrence.

Similarly, the duration of ADD use varies considerably between projects. At some earlier projects, the duration could be several hours (e.g. Brandt *et al.* 2011; Dähne *et al.* 2013), which was likely a substantial contributor to the overall disturbance effect and resulted in greater deterrence ranges over piling alone and/or with a much reduced ADD duration. Among the studies which reported ADD durations, only four (three Moray First projects and Kaskasi II in Germany) used average ADD durations of less than 60 minutes; estimated EDRs among the three Moray Firth OWFs (which included unabated monopiles and pin piles) were 12.5, 12.9 and 17.6 km. The most commonly reported ADD type was the Lofitech seal scarer, which is known to result in far-reaching deterrence to harbour porpoise (Brandt *et al.* 2013; Thompson *et al.* 2020; Voss *et al.* 2023). While an alternative device, the FaunaGaurd, has been reported to cause only more localised deterrence (Voss *et al.* 2023), the reported effects ranges from the two OWFs where a FaunaGuard ADD was used (Gemini, Kaskasi II) were within the range of those for other OWFs (Table 23).

Overall, plots of reported effects ranges vs blow energy, piling duration, broadband noise levels at 750 m and ADD duration did not reveal any obvious patterns (Appendix 3). However, it is likely that any patterns are, at least to some extent, being obscured by differences in how each study has analysed and reported an effect range. A comprehensive meta-analysis of original data which standardises analysis between studies would facilitate a robust exploration of relationships between these factors and effect ranges.

### 5.1.2. Considering duration of response and recovery

Most studies report deterrence during piling activity itself; however, some have included an interaction term between distance and hour relative to piling (HRP) therefore providing predictions of deterrence either during piling (HRP = 0), or at specified values of HRP post-piling. Furthermore, an important subset of studies (all those in the Moray Firth, Scotland) exclusively report deterrence in the 12-h or 24-h post-piling. As such, these include a certain amount of recovery within the response metric, with 24-h post piling models providing smaller deterrence ranges than 12-h models. We suggest using the more precautionary 12-h models when estimating response ranges, as these are more comparable to those of other studies. EDRs are currently applied on a daily basis, and so inclusion of some recovery would be acceptable in terms of the average habitat loss per day, particularly where the duration of piling is typically only a few hours, as is the case with modern monopile installation.

### 5.1.3. Influence of the shape of the deterrence function and maximum spatial extent of monitoring/analysed data

The shape of the deterrence function has a large influence on estimated EDRs. More linear functions or those with a 'long tail' of low probability of response extending to many tens of kilometres generally result in much larger EDRs. It is unclear how decisions made in modelling approaches can influence the resulting EDR. It is possible that, for some modelling approaches, a small change in the degrees of freedom may have a large influence on the EDR, even though effects on model fit are minor.

Model predictions from the Moray Firth projects often feature a *p(response)* of >0.05, up to 0.25 in some cases, at the maximum distance to piling. When estimating the EDR, *p(response)* beyond this distance is assumed to be zero. It is not currently known whether such an assumption is biasing EDRs low, or a feature of the modelling process (such as a few distant non-piling related positive responses) is biasing EDRs high by resulting in this 'long tail' in the deterrence function.

Similar to the above, the distance from piling to which monitoring took place, and subsequently the spatial extent of the data used in models, appears to have an important influence on estimated EDRs. At least in the case of data from the Beatrice and Moray East projects in the Moray Firth, where estimated EDRs using data to 60 km were 24 - 48% larger than those using data to 35 km (see Section 3.3.4). Choosing an appropriate distance at which to truncate data is critical and requires further investigation.

### 5.1.4. Piling of anchors for floating offshore wind

While there are a considerable number of empirical studies on the responses of harbour porpoise to impact piling of pin pile for jacket-type OWF foundations, there are none for pin-piling of anchors for floating OWFs. A review of the piling parameters in several floating OWF projects revealed that the planned pile diameters and hammer energies are within the range of those for which empirical studies of responses exist (Appendix 4). However, it is unknown how animals may respond differently given the deeper water of floating projects and the differences to piling methods (e.g. the pile never spanning the full length of the water column). As such, using current empirical response evidence to inform EDRs for piling of floating turbine anchors carries additional uncertainty over their use to inform EDRs for fixed foundations. While predictions of disturbance can be made based on depth-specific predictive noise modelling and a fixed response threshold or dose-response function, opportunities to collect empirical data on noise levels and animal responses to piling of anchors should be a priority.

### 5.1.5. Level of noise abatement / number of systems used

While increasing levels of noise abatement (i.e. two or more systems) result in lower noise levels, there is not currently a strong evidence base to support smaller EDRs for harbour porpoise when multiple NAS are used. Results from PAM at Borkum West II OWF in Germany (Diederichs *et al.* 2014; Nehls *et al.* 2015) suggested smaller impact ranges with an improved BBC system. However, this result was inferred from noise levels and a dose-response function developed across all piling events, not a direct comparison of responses vs distance to piling between different levels of abatement and so should be interpreted with caution. In contrast, a primary objective of Rose *et al.* (2019) was to compare the findings of spatial displacement associated with OWFs piled using a single abatement system (almost exclusively a BBC, 'GESCHA 1 projects') with those using 2 - 3 systems to achieve a noise limit of a broadband $SEL_{ss}$ 160 dB re 1µPa$^2$s @ 750 m ('GESCHA 2' projects). Using the same modelling approaches across the two datasets, effects ranges were within 2 km of each other, and that effect durations were also similar (slightly longer for GESCHA 2). The authors provide a lengthy discussion of multiple possible reasons for this finding, including the possibility of a stereotypical response to piling and/or ADD noise: whereby exceedance of noise levels initiating this stereotypical response causes animals to swim away for a certain time and distance, irrespective of the source noise level within a certain range of noise (Rose *et al.* 2019). Other suggested possible reasons included responses to construction noise and habitat-related influences on response. With regard to the latter, Rose *et al.* (2019) noted the large differences in effects ranges between individual projects, which could not be explained by received noise levels.

As described in Section 3.2, it was not possible to estimate EDRs from the data presented in Rose *et al.* (2019). However, from the four studies with noise abatement where EDRs were estimated from reported data, those three with a single system (BBC or DBBC) provided estimated EDRs of between 6.2 - 10.5 km, while the single OWF with two systems (Borssele, DBBC plus resonator) provided an estimated EDRs of 8.3 km.

It is noted that those studies reporting noise levels for the same projects with/without abatement showed approximately a 10 dB reduction in SEL @750 m when abatement was used (see Table 3). Based on these studies and reviews of reported and expected dB reductions from different NAS, a 10 dB broadband SEL reduction is typically achievable in waters up to 40 m deep with an effective BBC, DBBC or resonator casing (Appendix 5). A review of model-predicted reductions in behavioural response ranges for different levels of broadband dB reduction as presented in US OWF applications suggested an average ~50% reduction in the radius of behavioural response ranges for a 10 dB reduction over unabated piling (references provided in Appendix 5). While the current review is not focussed on evidence from model-predictions, it is noted that a similar reduction was reported in the empirical evidence. The two empirical studies reviewed here which compared response ranges with/without abatement from more or less the same datasets/projects also showed as ~ 50% reduction in reported effects ranges when noise abatement was applied: 14 km vs 7 km in Brandt *et al.* (2018) and 26 km vs 13 km in Rose *et al.* (2019).

### 5.1.6. Recommendations for default EDRs

Recommended default EDRs are presented below. These follow consideration of all the evidence reviewed in the current study, including reported effects ranges and estimated EDRs, but also the limitations and relevance of specific evidence.

For **monopiles or pin piles *without* noise abatement**, a majority of evidence points towards an EDR in the region of 15 - 20 km.

- It is noted that EDRs of < 15 km have been reported for unabated piling, including from recent analyses of highly relevant projects, and that comparable data collection is planned for several projects in UK waters in 2025. It is recommended that this suggested EDR for unabated piling should be reviewed as soon as such data are available.
- The weighted average of reported effects ranges across 14 studies (included 8 estimated EDRs) was 17.4 km.

For **monopiles or pin piles *with* noise abatement**, a majority of evidence points towards an EDR in the region of 10 - 15 km.

- The weighted average of reported effects ranges across seven relevant studies (including four estimated EDRs) was 10.8 km.
- Note that an EDR of 10 - 15 km assumes a reduction in broadband $SEL_{SS}$ @750 m of approximately 10 dB or more.
- While noise modelling and dose-response assumptions may support a graduated approach of smaller EDRs within this range for increasing dB reductions, the empirical evidence does not provide strong support for such an approach.

For the two EDR categories recommended above, it is noted that a 'balance of evidence' approach has been taken, considering all available studies from the UK and elsewhere spanning the last 20 years. An alternative approach could be to base EDRs on a smaller number of the most relevant studies, such as those which best reflect current and near-future piling practices in the UK. Such an approach could be considered in the near future when several additional studies occurring in the UK in 2025 provide results. Efforts to make these results as comparable as possible (in terms of analytical approach) are recommended.

For **conductor piling**, the evidence base is limited but the associated noise levels suggest that an EDR not exceeding the lower bound of those considered for abated monopiles or pin piles would be appropriate (i.e. an EDR ≤ 10 km).

- Should conductor piling occur without the use of an ADD, then an EDR in the range 5–10 km may be appropriate.

For **sheet piling**, the evidence base is limited but the nature of the activity is such that an EDR not exceeding the lower bound of those considered for abated monopiles or pin piles would be appropriate (i.e. an EDR ≤ 10 km).

- The single empirical response study related to sheet piling at an OWF involved lengthy ADD use and is not considered to be representative of the nature of sheet piling likely to occur in UK waters or anticipated porpoise responses.
- Should sheet piling occur without the use of an ADD, then an EDR in the range 5–10 km may be appropriate.

# 6. Recommended priorities for filling evidence gaps

Based on the evidence review performed, we reiterate the recommendations of Brown *et al.* (2023) to conduct a true **meta-analysis** of existing PAM data which standardises as many elements of the analysis and reporting as possible, to facilitate more accurate investigation of the spatial extent of porpoise responses to pile-driving, and the factors influencing these responses. Such an effort, which was well-beyond the scope of the current review, would be a valuable exercise to run in parallel to targeted new data collection, noting that one output of the meta-analysis would be to develop a framework and guiding principles for analysis of PAM data on responses of harbour porpoise to pile driving. It is noted that a Defra-funded scoping exercise for such a meta-analysis was completed in 2023 (Verfuss *et al.* 2023), and that further scoping efforts are currently underway to facilitate such a project commencing in 2025.

Additional priorities relating to impact piling include:

- **Empirical studies of responses to piling with moderate levels of noise abatement.** Studies of porpoise responses to abated piling have generally been associated with 10 dB of broadband noise abatement or greater. It is currently unknown how animals may respond to lesser levels of noise abatement, such as those associated with the use on-pile systems. Such systems may have fewer operational constraints than other systems such as BBCs or resonators and so understanding their effectiveness in terms of porpoise responses should be a priority.
- **More empirical studies of the influence of ADDs in an OWF construction context.** The relative contribution of ADDs is still uncertain but appears to be important. Only one study has provided a direct comparison of porpoise responses to piling with/without the use of ADDs (Graham *et al.* 2019); opportunities to conduct similar comparisons at forthcoming monitored OWFs should be explored.
- **Further exploration of the effects of the FaunaGuard vs Lofitech ADDs in an OWF construction setting** should be pursued, particularly given the recent policy development in the UK favouring the use of noise abatement and the associated lower risk of injury and need for deterrence.
- **Noise levels and animal responses to piling of anchors for floating offshore wind.** While there are a considerable number of empirical studies on the responses of harbour porpoise to impact piling of pin pile for jacket-type OWF foundations, there are none for pin-piling of anchors for floating OWFs. Collecting empirical data on noise levels and animal responses to piling of anchors, to see if these are indeed comparable to those from piling of fixed foundations, should be a priority.
- **Sampling at sufficient range.** In future empirical response studies, important to sample beyond the maximum extent of effects and collect noise data at larger distance to help determine where to truncate data for analyses. This is important for reducing the likelihood of biases in the deterrence function and associated EDR estimates.
- **Adjusting for the effects of vessel disturbance.** Studies rarely incorporate Automatic Identification System data to understand vessel movements - this can lead to misassignment of responses to piling activity and influence the deterrence function where vessels may be distributed at distance from piling and cause localised deterrence.

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# Glossary

**Table 26.** Glossary of terms, acronyms and abbreviations.

| Term | Definition |
|---|---|
| AdBm | A sleeve-type noise abatement system. |
| ADD | Acoustic Deterrent Device. A device that emits pulses of high frequency sound to deter marine mammals from an area. |
| BBC | Big Bubble Curtain |
| BOEM | Bureau of Ocean and Energy Management (US) |
| CIS MU | Celtic and Irish Seas Management Unit |
| CPOD | Cetacean Porpoise Detector |
| DBBC | Double Big Bubble Curtain |
| Defra | Department of Environment, Food and Rural Affairs. |
| DPH | Detection Positive Hours |
| EDR | Effective Deterrence Range. A radius from a source of disturbance (i.e. noise source), with the associated area representing the the overall estimated loss of habitat to animals. If all animals vacated the circle of radius EDR around the noise source, then this would be equivalent to the mean loss of habitat per animal (Tougaard *et al.* 2013) |
| EIA | Environmental Impact Assessment. A statutory process by which certain planned projects must be assessed before a formal decision to proceed can be made. It involves the collection and consideration of environmental information, which fulfils the assessment requirements of the EIA Directive and EIA Regulations, including the publication of an Environmental Statement (ES) or Environmental Impact Assessment Report (EIAR). |
| $ER_{95}$ | Exposure Range. The $95^{th}$ percentile of the closest point of approaches to piling of simulated animals (based on an animal movement model with no aversive movement) which are exposed to a certain threshold noise level. |
| FCS | Favourable Conservation Status |
| GAM | Generalised Additive Model |
| GAMM | Generalised Additive Mixed Model |
| GLMM | Generalised Linear Mixed Model |
| HRA | Habitats Regulation Assessment |
| HRP | Hours relative to piling |
| HRGS | High-resolution Geophysical Surveys |

| Term | Definition |
| --- | --- |
| HSD | HydroSound Damper. A sleeve-type noise abatement system. |
| Impulsive noise | Noise characterised by a short duration and steep rise in sound pressure, such that the majority of the energy is delivered in a very short period of time. Examples of underwater impulsive noise sources include explosions, airgun pulses and impact pile-driving. For a given sound energy level, impulsive noise is more injurious to marine life than non-impulsive noise. |
| JNCC | Joint Nature Conservation Committee |
| MNR | Marine Noise Registry. The UK MNR is a resource managed by the JNCC which documents reported low-frequency impulsive noise from licenced activities in UK waters, generally at the scale of UK Oil and Gas Licensing Blocks or as points for point noise sources (such as piling or explosions). |
| Mitigation measures | Measure implemented to reduce impacts associated with activities. Typically embedded within the assessment at the relevant point in the EIA and specified in consent conditions. |
| MNR | Marine Noise Registry |
| MU | Management Unit |
| NMFS | National Marine Fisheries Service (US) |
| NAS | Noise Abatement System. Systems designed to reduce the propagation of noise into the marine environment from a noise source. |
| OWF | Offshore wind farm |
| PAM | Passive acoustic monitoring |
| PPM | Porpoise Positive Minutes |
| R50 | The distance at which there is a 50% probability of response |
| SAC | Special Area of Conservation. Protected sites designated under Article 3 of the Habitats Directive for habitats listed on Annex I and Animals listed on Annex II of the Directive. |
| SEL | Sound Exposure Level. May be presented as $L_{E,p}$. |
| $SEL_{cum}$ | Accumulated sound exposure level (across multiple pulses). May be presented as $L_{E,24}$. |
| $SEL_{SS}$ | Single strike sound exposure level (in contrast to a measure of accumulated sound such as $SEL_{cum}$). May be presented as $L_{E,p}$. |
| SL | Source Level |

| Term | Definition |
|---|---|
| SPL | Sound pressure level. In the absence of further information, this is usually assumed to be the $SPL_{rms}$ metric. |
| $SPL_{pk}$ | Peak (or zero-to-peak) sound pressure level. May be presented as $L_{p,\mathrm{pk}}$ or $L_{p,\mathrm{0\text{-}pk}}$. |
| $SPL_{pk\text{-}pk}$ | Peak-to-peak sound pressure level. May be presented as $L_{p,\mathrm{pk\text{-}pk}}$. |
| $SPL_{rms}$ | Root-mean-squared sound pressure level. May be presented as $L_p$ or $L_{p,rms}$. |
| UXO | Unexploded ordnance. Explosive weapons (e.g. bombs, shells, mines) that did not explode when they were employed and still pose a risk of detonation. Numerous UXO associated with WWI and WWII are present on the seabed in the North Sea, which may require disposal to ensure the safe construction of offshore infrastructure. |

# Appendix 1 - Evidence scoring

## Introduction

An evidence-scoring methodology was developed so that recommended default EDRs could be accompanied by a measure confidence associated with the robustness, relevance to harbour porpoise in UK waters and volume of underlying evidence. This process involves two key steps:

(i) evaluating individual studies across various criteria, and

(ii) aggregating these scores across all studies.

The scoring framework follows a decision-tree approach (Figure 9), where all studies are initially assigned a baseline score and penalties can be subsequently applied under each criterion.

## Differentiating empirical response, noise measurement and modelling studies

At the first stage, studies are scored according to the type of data they include. **Empirical studies** of animal responses, be it through direct observation (e.g. aerial surveys) or acoustic detections, provide direct data on animals' responses to activities; therefore, they are the most robust category of evidence available, and no penalties are applied.

The alternative to empirical studies of animal responses are those which make inferences about how animals may respond, using **fixed response thresholds** applied to either measured noise levels or model-predicted noise. This type of evidence is included where empirical studies of responses are limited or lacking. Both noise measurement and modelling studies carry a substantial penalty over empirical response studies due to the uncertainty over how animals may respond.

**Noise measurement studies** refer to those that directly recorded real-world underwater noise levels during activities, where noise levels at different distances to the source were measured and the range to behavioural effect thresholds could be estimated. While all behavioural effect thresholds are subject to considerable uncertainty, and no universally accepted criteria exist, when applied to field noise measurements there is at least greater confidence in the noise levels which animals will experience. No further penalties are applied to noise measurement studies at this stage in the decision-tree.

By contrast, **modelling studies** rely on computational simulations using input parameters and assumptions to predict noise levels and estimate distances to behavioural effect thresholds. As noise measurement and modelling studies are associated with greater uncertainty in estimating distances to fixed thresholds, they incur a penalty.

### Empirical studies scoring

Empirical studies receive additional scoring adjustments based on their capacity to estimate EDR and the relevance of species studied. Given that this review aims to identify EDRs (which differ from the maximum observed behavioural response distances), studies are scored as follows:

- No penalty if the study directly estimates EDR.
- A minor penalty if the study provides data from which EDR can be extracted.

- A major penalty if the data cannot be used to extract EDR.

Additionally, as the primary focus is on harbour porpoise responses, data collected for other species receive lower scores (Figure 9).

### Consideration of environmental characteristics

As noise propagation varies with bathymetry, studies are scored based on their relevance to the bathymetric conditions typical of UK harbour porpoise SACs. The average site depths in the UK SACs range from 10 - 50 m, with a maximum depth in the Southern North Sea of 75 m. Studies conducted in similar bathymetric environments do not lose points.

### Relevance to Activity Parameters

A further scoring criterion assesses the relevance of the study to the specific activity under review. The key consideration is how closely the study parameters align with current and near-future UK activities, such as pile type, diameter, piling duration, ADD type and activation duration, and other operational factors (e.g. most common parameters were verified using Stone (2023a, 2023b, 2024) and Marine Noise Registry data). Scoring is adjusted as follows:

- Studies closely matching recent UK parameters score highest.
- Points are deducted for studies with significantly different parameters (e.g. ADD duration exceeding 60 minutes).
- Studies using proxy noise sources receive penalties (UXO clearance used as a proxy for decommissioning explosives).

### Other limiting factors

Further minor penalties may be applied if studies had other limiting factors, such as limited datasets or a lack of statistical analysis.

## Summarising scores

To account for differences in the number and type of studies (empirical, noise measurement and modelling), scores are averaged by study type.

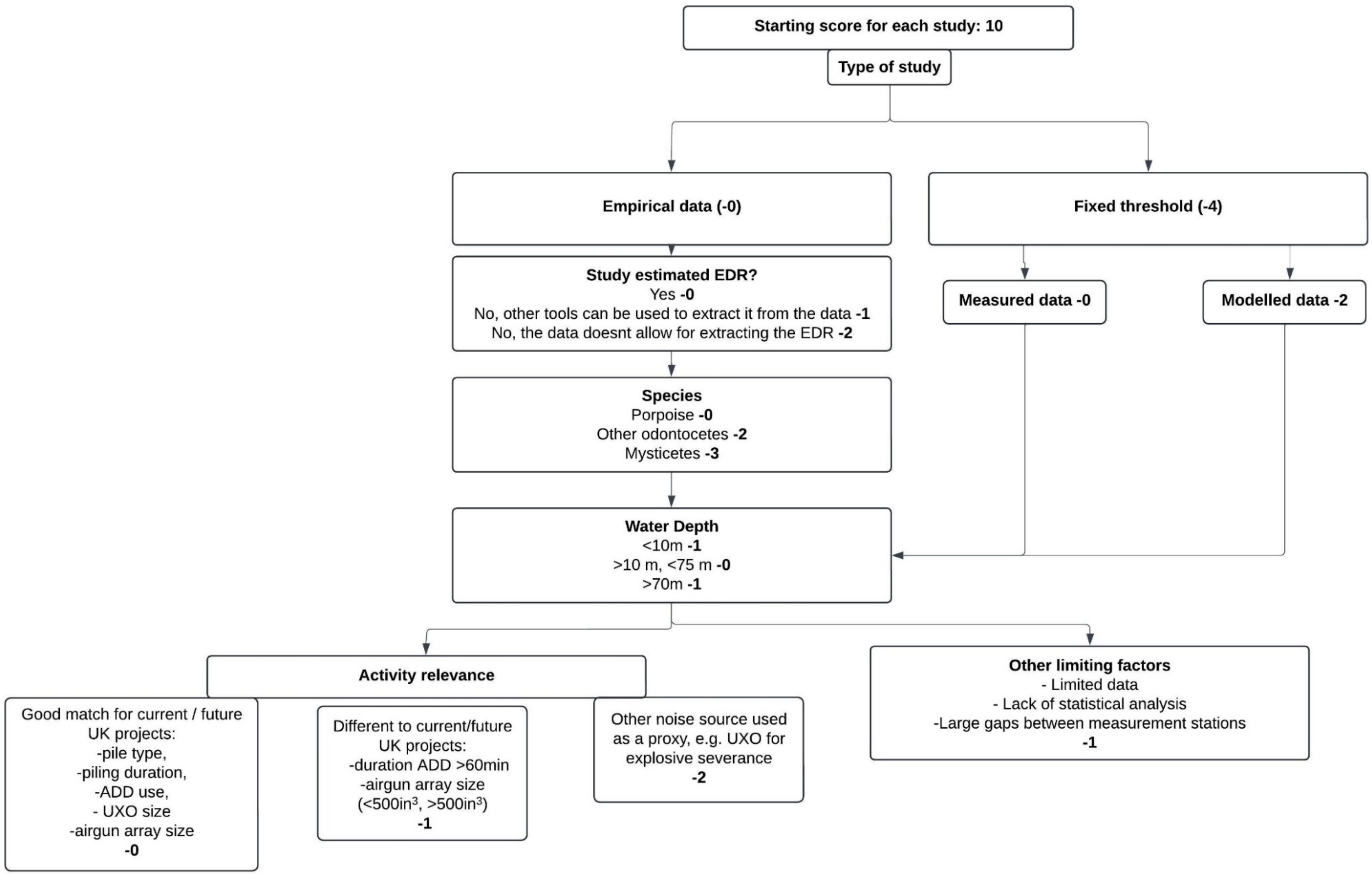


**Figure 9.** Decision tree used to score individual studies within this evidence review.

## Study-specific scores for impact piling

**Table 27.** Study-specific scores assigned to impact piling studies. Mono = Monopile; Pin = Pin pile; Cond. = conductor; Y = Yes, penalty points received (the number of points deducted indicated in brackets); No = No penalty received in this category.

| Study characteristics | | | | Score penalties | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Study *Piling of OWFs*** | **OWF / Project** | **Pile type** | **NAS** | **Study type** | **Estimated EDR?** | **Species** | **Water depth** | **Relevance** | **Other limitations** | **Final score** | **Notes** |
| Benhemma-Le Gall *et al.* (2024) | Moray West | Mono | None | N | N | N | N | N | Y (1) | 9 | Rigorous approach but high threshold for assigning a positive behavioural response may underestimate lower-level responses; reported EDR is based on 24-h post-piling response. |
| Rose *et al.* (2024) | Kaskasi II | Mono | None<br>Yes | N | Y (2) | N | N | N | N | 8 | The data presented in the report did not allow for EDR quantification. |
| van Geel *et al.* (2023) | East Anglia One | Pin | None | N | Y (1) | N | N | Y (1) | Y (1) | 7 | The study did not report EDR, but other tools were used to estimate it; lack of details about the ADD duration; large confidence intervals resulting from GAMs. |
| de Jong *et al.* (2022) | Gemini | Mono | None | N | Y (1) | N | N | Y (1) | Y (1) | 7 | The study did not report EDR, but other tools were used to estimate it; ADD type (FaunaGuard) not currently used in UK; reference period not spatially explicit. |

| **Study characteristics** | | | | **Score penalties** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Study *Piling of OWFs*** | **OWF / Project** | **Pile type** | **NAS** | **Study type** | **Estimated EDR?** | **Species** | **Water depth** | **Relevance** | **Other limitations** | **Final score** | **Notes** |
| de Jong *et al.* (2022) | Borssele (1, 2, 3 & 4) | Mono | Yes | N | Y (1) | N | N | Y (1) | Y (1) | 7 | The study did not report EDR, but other tools were used to estimate it; lack of details about ADD duration; reference period not spatially explicit and piling started in the wider area prior to the start of monitoring. |
| Rumes *et al.* (2022) | Norther NV, Northwester 2, SeaMade | Mono | Yes | N | Y (2) | N | N | Y (1) | Y (1) | 6 | The data presented in the report did not allow for EDR quantification; long ADD duration; Northwester 2 was the only project to successfully use NAS. |
| Rumes and Zupan (2021) | Nobelwind | Mono | None | N | Y (2) | N | N | Y (1) | Y (2) | 5 | The data presented in the report did not allow for EDR quantification; long ADD duration; Northwester 2 was the only project to successfully use NAS; no statistical tests were performed; no baseline considered, only aftermath and recovery for comparison with impact phase. |
| | Northwester 2, SeaMade | Mono | Yes | | | | | | | | |
| Benhemma-Le Gall *et al.* (2021) | Beatrice, Moray East | Pin | None | N | Y (1) | N | N | N | N | 9 | The study did not report EDR, but data provided for purposes of this report were analysed to estimate it. |

| Study characteristics | | | | Score penalties | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Study *Piling of OWFs*** | **OWF / Project** | **Pile type** | **NAS** | **Study type** | **Estimated EDR?** | **Species** | **Water depth** | **Relevance** | **Other limitations** | **Final score** | |
| Graham *et al.* (2019) | Beatrice | Pin | None | N | Y (1) | N | N | N | Y (1) | 8 | The study did not report EDR, but data provided for purposes of this report were analysed to estimate it; rigorous approach but high threshold for assigning a positive behavioural response may underestimate lower-level responses; main results reported are based on 24-h post-piling response. |
| Rose *et al.* (2019) | Seven projects ('GESCHA II') | Mono | Yes | N | Y (2) | N | N | Y (1) | Y (1) | 6 | The data presented in the report did not allow for EDR quantification; lack of details about ADD duration; maximum reported extent of responses may be influenced by the cumulative effects of closely sequenced pile driving and a reference level which includes piling periods. |
| | 14 projects ('GESCHA I & II') | Mono | None | N | Y (2) | N | N | Y (1) | N | 7 | The data presented in the report did not allow for EDR quantification; lack of details about ADD duration but suspect long durations given those reported for other projects in Germany at that time. |

| **Study characteristics** | | | | **Score penalties** | | | | | | | **Notes** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Study *Piling of OWFs*** | **OWF / Project** | **Pile type** | **NAS** | **Study type** | **Estimated EDR?** | **Species** | **Water depth** | **Relevance** | **Other limitations** | **Final score** | |
| | Gemini | Mono | None | N | Y (2) | N | N | Y (1) | N(Y) | 6 | The data presented in the report did not allow for EDR quantification; ADD type (FaunaGuard) not currently used in UK; maximum reported extent of responses may be influenced by the cumulative effects of closely sequenced pile driving and a reference level which includes piling periods. |
| Geelhoed *et al.* (2018) | Gemini | Mono | None | N | Y (2) | N | N | Y (1) | N | 7 | The data presented in the report did not allow for EDR quantification; ADD type (FaunaGuard) not currently used in UK |
| MacGillivray (2018) | Oil and gas platform, California | Cond. | Yes | Y (4) | - | - | Y (1) | N | Y (1) | 4 | Deeper waters than those in UK SACs; there was a spatial gap in the location of noise monitoring stations. |
| Brandt *et al.* (2018) | Six projects (‘GESCHA I’) [1] | Mono Pin | Yes | N | Y (1) | N | N | Y (1) | Y (1) | 7 | The study did not report EDR, but other tools were used to estimate it; lack of details about ADD duration but suspect long durations given those reported for other projects in Germany at that time; maximum reported extent of responses may be influenced by the cumulative effects of closely sequenced pile driving and a reference level which includes piling periods. |
| | Primarily BARD and Borkum West II [2] | Pin | None | N | Y (1) | N | N | Y (1) | Y (1) | 7 | |

| Study characteristics | | | | Score penalties | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Study *Piling of OWFs*** | **OWF / Project** | **Pile type** | **NAS** | **Study type** | **Estimated EDR?** | **Species** | **Water depth** | **Relevance** | **Other limitations** | **Final score** | |
| Dähne *et al.* (2017) | DanTysk | Mono | Yes | N | Y (1) | N | N | Y (1) | Y (1) | 7 | The study did not report EDR, but other tools were used to estimate it; long ADD duration; short reference period quite close to ADD activation. |
| Rumes *et al.* (2017) | Nobelwind | Mono | None | N | Y (2) | N | N | Y (1) | N | 7 | The data presented in the report did not allow for EDR quantification; long ADD duration. |
| Haelters *et al.* (2015) | C-Power | Pin | None | N | Y (2) | N | N | Y (1) | Y (2) | 5 | The data presented in the report did not allow for EDR quantification; lack of details about ADD duration; very limited data (two surveys, one before and one during piling). |
| Jiang *et al.* (2015) | Central North Sea | Cond. | None | Y (4) | - | - | N | N | Y (1) | 5 | Limited information about piling parameters; $SPL_{rms}$ values based on a long integration time and likely to be biased low. |
| Diederichs *et al.* (2014); Nehls *et al.* (2015) | Borkum West II | Pin | None / Yes | N | Y (1) | N | N | Y (1) | Y (1) | 7 | The study did not report EDR, but other tools were used to estimate it; lack of details about ADD duration; responses were not directly assessed as a function of distance to piling, but by received level and then extrapolated to distance. |

| Study characteristics | | | | Score penalties | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Study** ***Piling of OWFs*** | **OWF / Project** | **Pile type** | **NAS** | **Study type** | **Estimated EDR?** | **Species** | **Water depth** | **Relevance** | **Other limitations** | **Final score** | |
| Dähne *et al.* (2013) | Alpha Ventus | Pin | None | N | Y (1) | N | N | Y (2) | N | 7 | The study did not report EDR, but subsequent authors did with these data; long ADD duration; long piling duration per foundation. |
| Tougaard *et al.* (2013) | Alpha Ventus | Pin | None | N | N | N | N | Y (2) | N | 8 | Long ADD duration, long piling duration per foundation. |
| Brandt *et al.* (2012) | Alpha Ventus | Pin | None | N | Y (1) | N | N | Y (2) | N | 7 | The study did not report EDR, but subsequent authors did; long ADD duration; long piling duration per foundation. |
| Brandt *et al.* (2011) | Horns Rev II | Mono | None | N | Y (1) | N | Y (1) | Y (2) | Y (1) | 5 | The study did not report EDR, but other tools were used to estimate it; small pile diameter and low hammer energy; very shallow water depth; long ADD duration; the reported changes in porpoise acoustic activity are relative to an average that includes data influenced by pile driving, meaning the 'baseline' activity may already be reduced compared to a true undisturbed state. |
| Tougaard *et al.* (2009) | Horns Rev | Mono | None | N | Y (2) | N | Y (1) | Y (2) | N | 5 | The data presented in the report did not allow for EDR quantification; small pile diameter and low hammer energy; very shallow water depth; lack of details about ADD duration. |

| Study characteristics | | | | Score penalties | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Study *Piling of OWFs*** | **OWF / Project** | **Pile type** | **NAS** | **Study type** | **Estimated EDR?** | **Species** | **Water depth** | **Relevance** | **Other limitations** | **Final score** | |
| Carstensen *et al.* (2006) | Nysted | Sheet | None | N | Y (2) | N | Y (1) | Y (1) | Y (1) | 5 | The data presented in the report did not allow for EDR quantification; very shallow water depth; long ADD duration and two devices used concurrently; study design was such that the maximum extent of porpoise responses could not be estimated. |

# Appendix 2 - graphreader validation exercise

This section presents a brief validation exercise using the graphreader online tool, which was employed in this review to extract numerical values from plots in published studies (e.g. Brandt *et al.* (2011); Diederichs *et al.* (2014); Nehls *et al.* (2015); Dähne *et al.* (2017); Brandt *et al.* (2018); de Jong *et al.* (2022); van Geel *et al.* (2023); see Section 3.3).

For this validation, a plot from Graham *et al.* (2019) was used, specifically the probability of a harbour porpoise response (24 h post-piling) as a function of distance from the piling location for both the 1st and final (86th) piling locations, using a truncation distance of 60 km. The dose-response plots for these locations are represented in Figure 6a of Graham *et al.* (2019) by a solid navy line (1st location) and a dashed blue line (86th location). A screenshot of Figure 6a was uploaded to graphreader, and data points were manually marked on both curves (Figure 10). In the graphreader tool, the axis limits were set to 0 - 1 on the y-axis and 0 - 60 km on the x-axis. The minimum sampling interval was constrained to 150 m due to the tool's limit of 500 sampling points.

Figure 11 shows two curves (for the 1st and 86th locations) based on extracted graphreader points. The sampled curve data were exported as a CSV file. For 150 m increments of distance, the number of porpoises disturbed vs non-disturbed was estimated (assuming a theoretical uniform density of 0.8 animals per $km^2$). The distance at which the number of porpoises disturbed was equal to non-disturbed has been then estimated using the sampled curve and presented as an EDR in Table 28. The resulting EDR values using the graphreader tool are presented alongside those derived from the original study data (for 24-h response and 60 km truncation distance for 1st and 86th location). The observed deviations are minimal and are likely attributable to differences in sampling resolution, as graphreader samples at 150 m intervals, whereas the original study used a 5 m interval.

**Table 28.** Validation exercise - EDR values estimated using the graphreader tool and the original study data for the 1st and 86th piling location at Beatrice OWF.

| Piling location | EDR value (km) | |
|---|---|---|
| | graphreader tool | Original study data |
| 1st location | 19.80 | 20.00 |
| 86th (last) location | 19.65 | 19.74 |

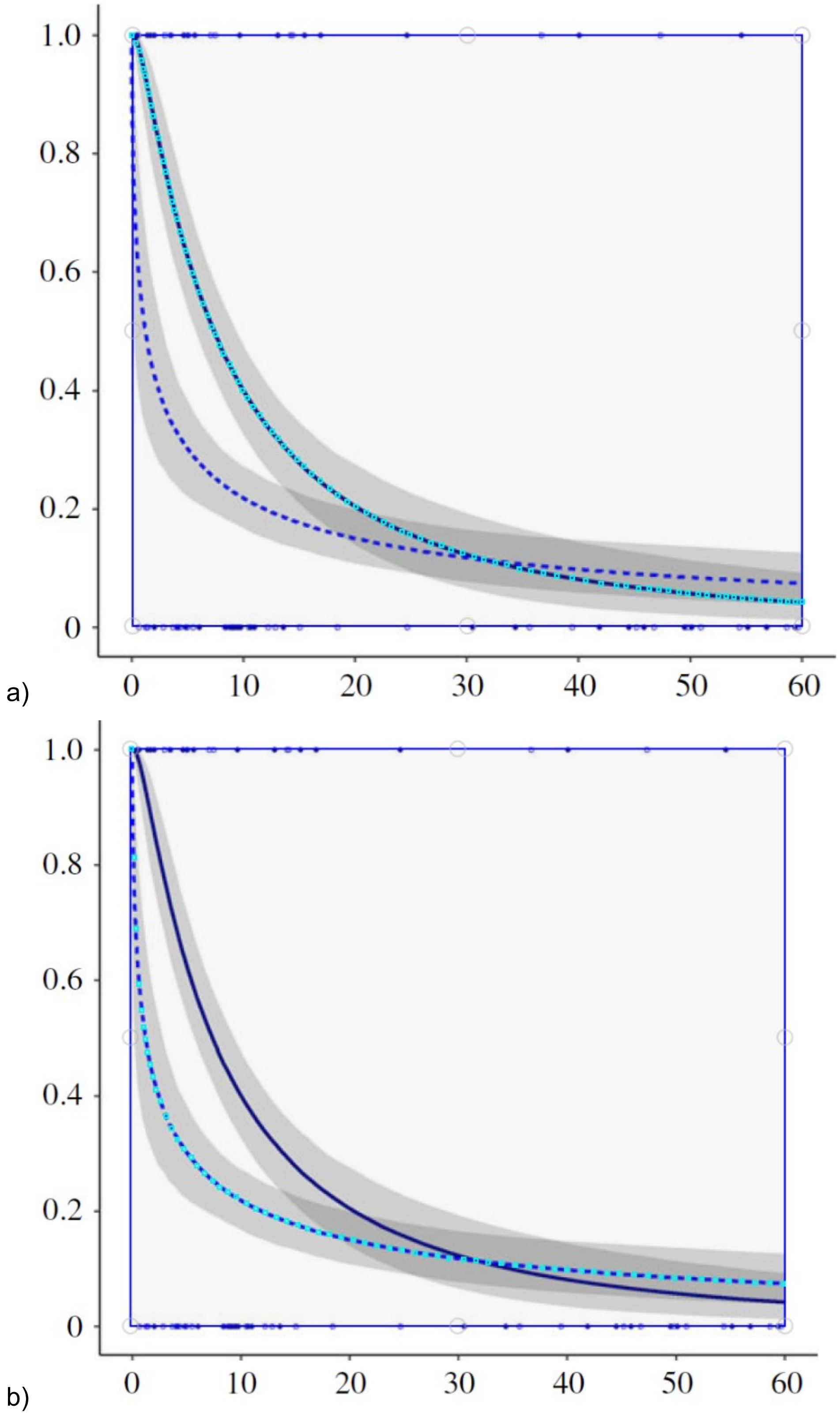


**Figure 10.** Points marked on the probability of harbour porpoise response in relation to distance from piling for a) 1st location and b) 86th (last) location, using the graphreader tool.

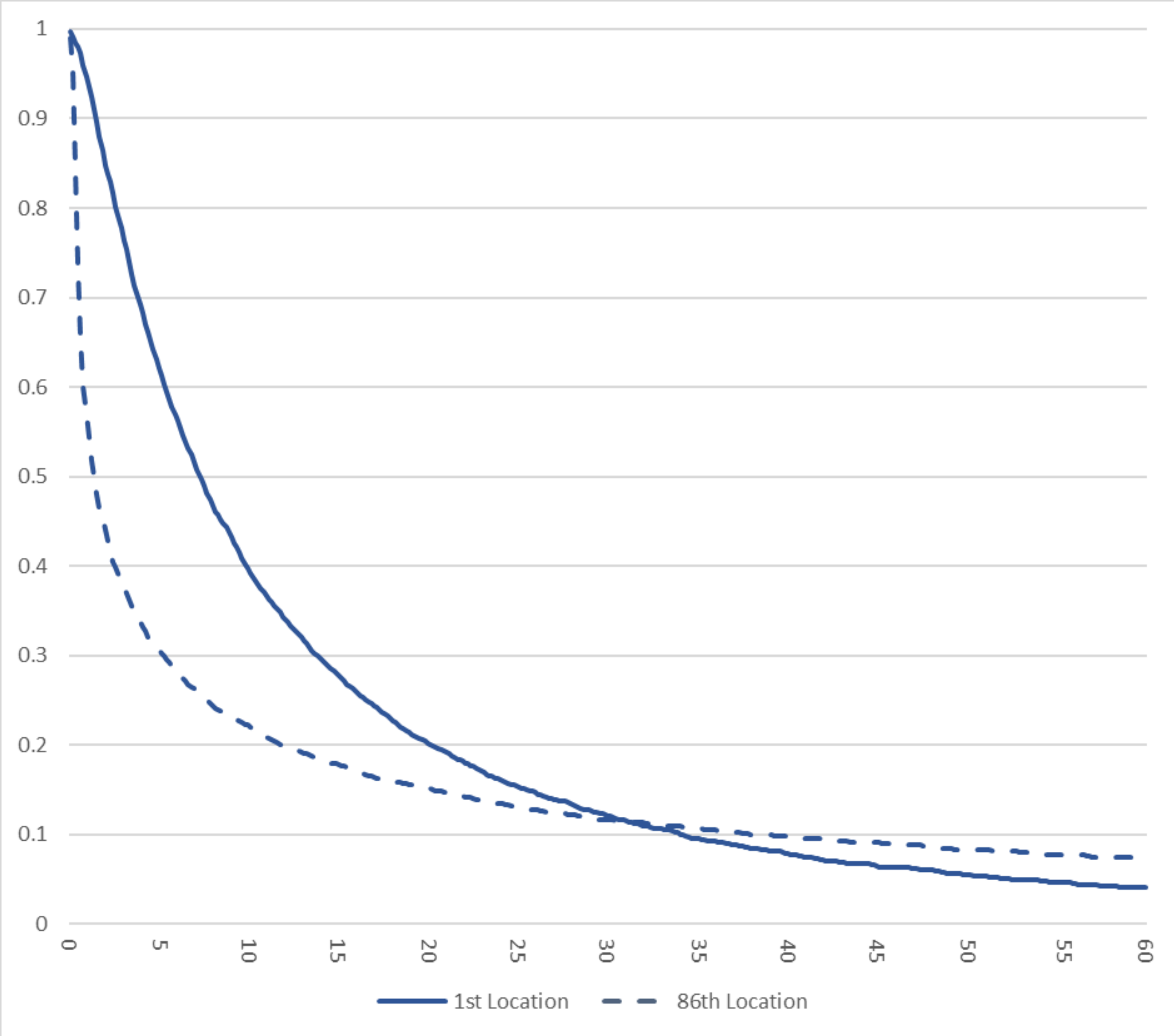


**Figure 11.** The probability of harbour porpoise response (24hrs) in relation to distance from piling for the 1st location and 86th location using data points extracted in the graphreader tool.

# Appendix 3 - Plots of reported effects ranges vs project characteristics

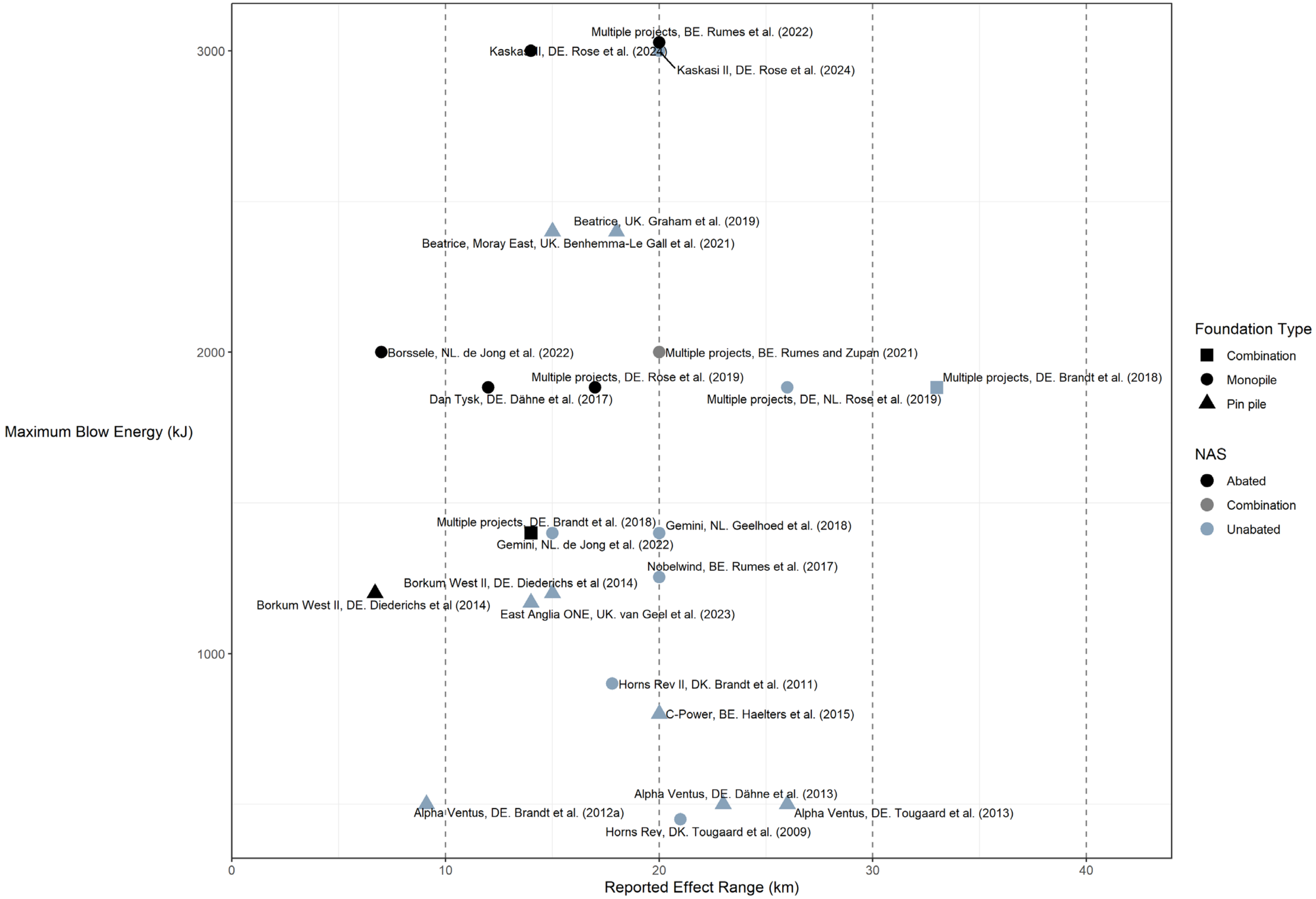


**Figure 12.** Effect ranges of harbour porpoises to impact pile driving with and without noise abatement as reported in the studies considered in this review vs blow energy. It is noted that comparisons in reported effects ranges are complicated by different approaches data collection, analyses and definitions of effects. Where studies reported effects as a range of distance values, the mid-point is plotted.

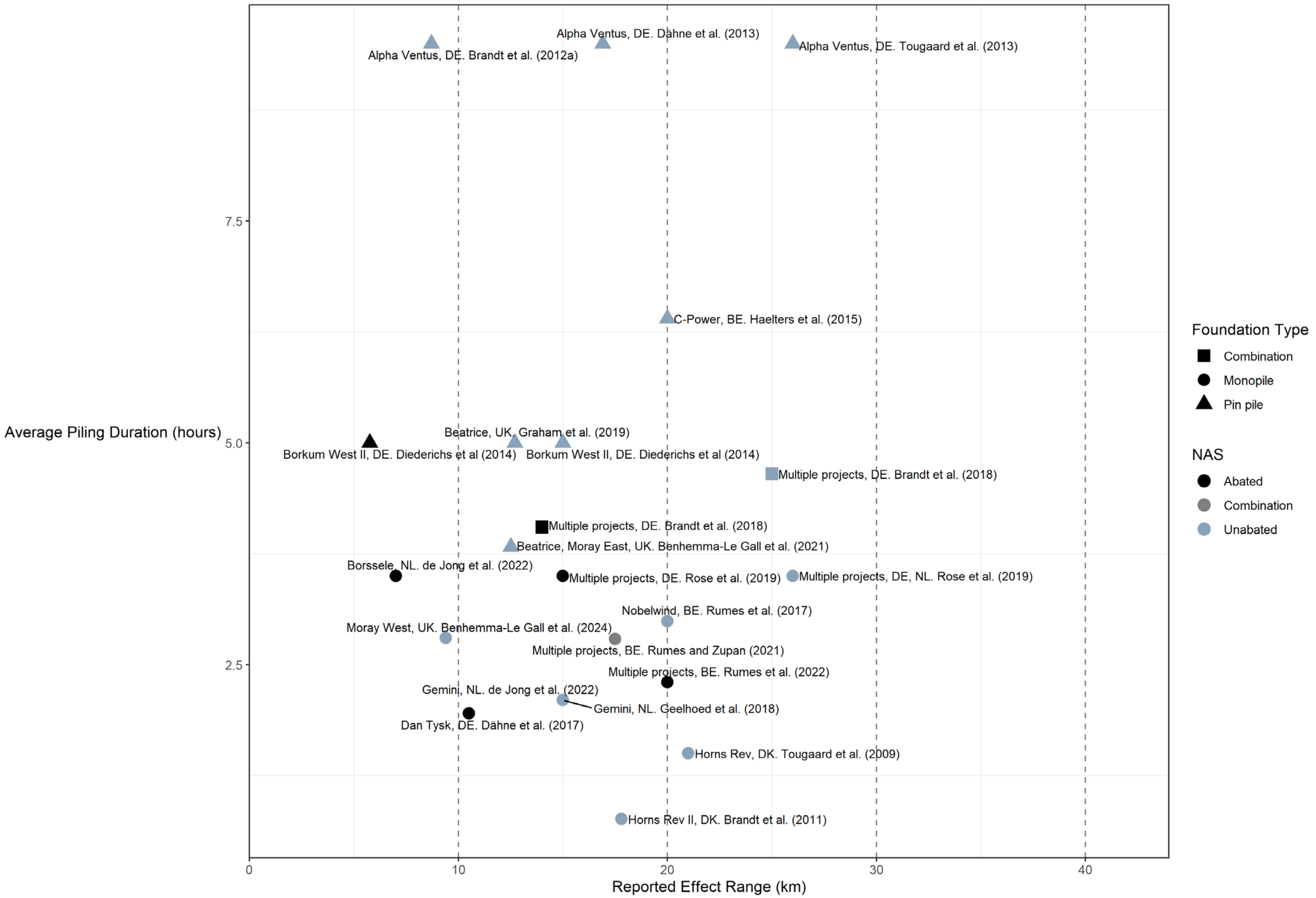


**Figure 13.** Effect ranges of harbour porpoises to impact pile driving with and without noise abatement as reported in the studies considered in this review vs piling duration. It is noted that comparisons in reported effects ranges are complicated by different approaches data collection, analyses and definitions of effects. Where studies reported effects as a range of distance values, the mid-point is plotted.

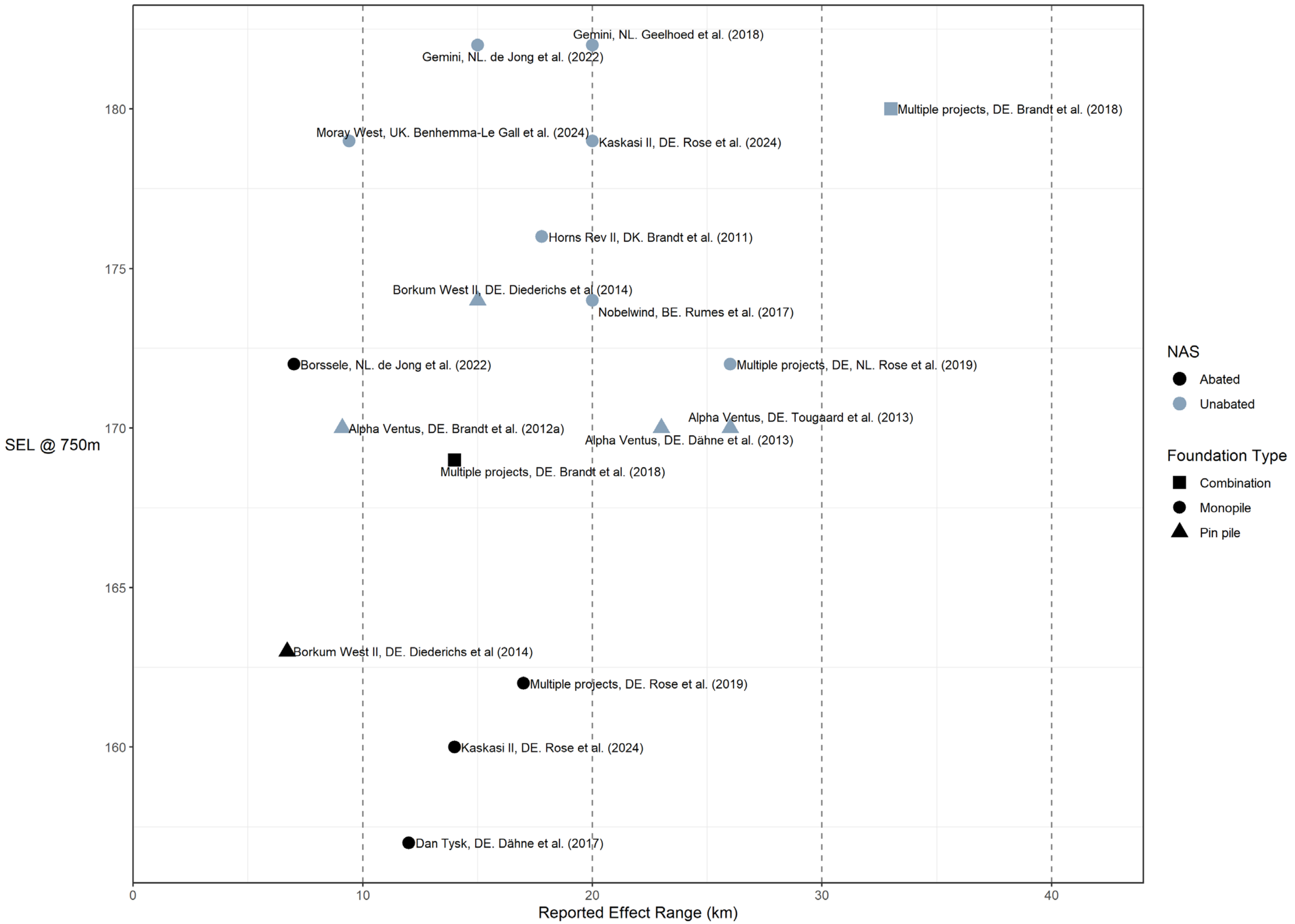


**Figure 14.** Effect ranges of harbour porpoises to impact pile driving with and without noise abatement as reported in the studies considered in this review vs unweighted SEL @ 750 m. Studies which did not report SEL @ 750 m are not plotted. It is noted that comparisons in reported effects ranges are complicated by different approaches data collection, analyses and definitions of effects. Where studies reported effects as a range of distance values, the mid-point is plotted.

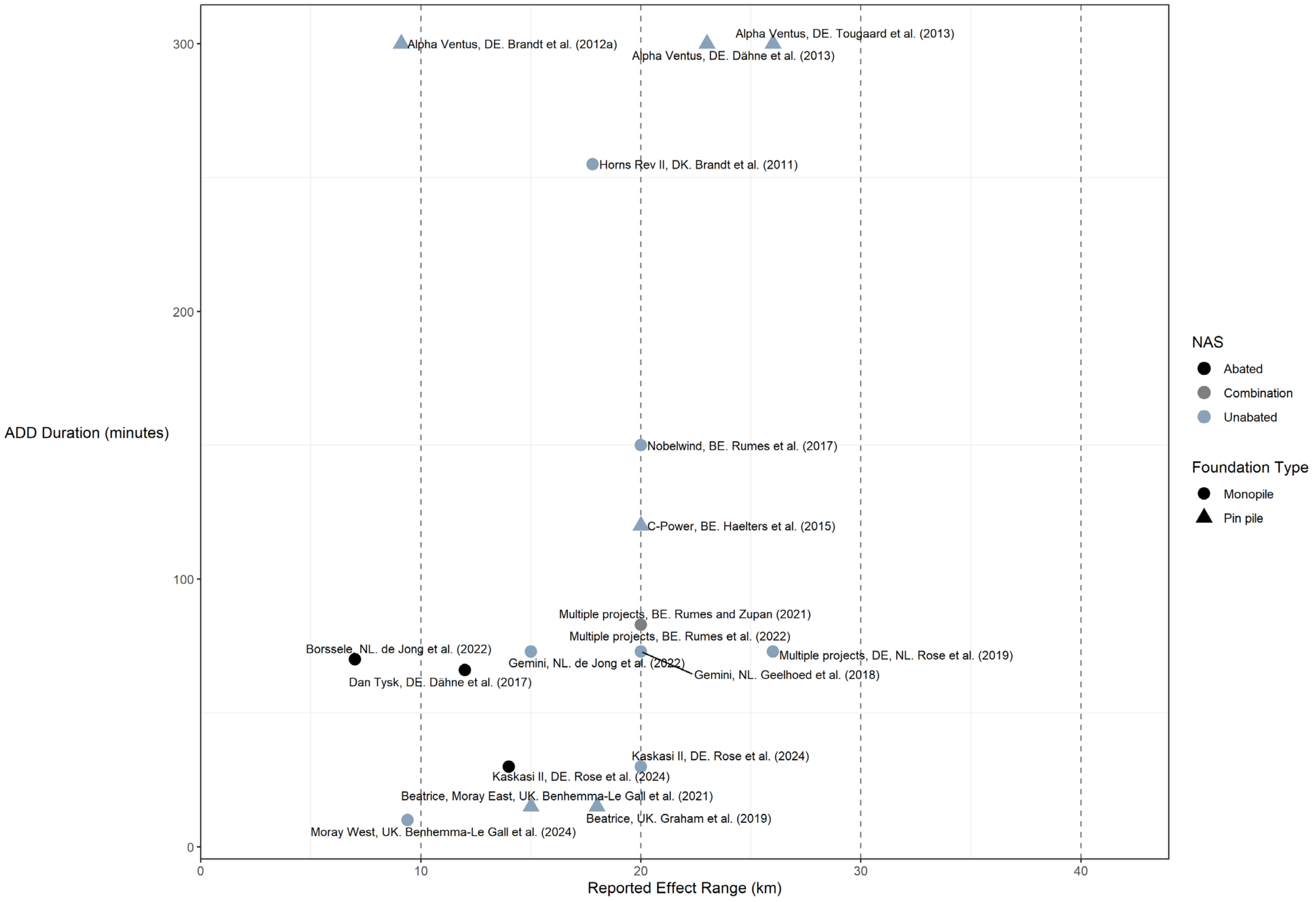


**Figure 15.** Effect ranges of harbour porpoises to impact pile driving with and without noise abatement as reported in the studies considered in this review vs ADD duration (average). Studies which did not report ADD duration are not plotted. It is noted that comparisons in reported effects ranges are complicated by different approaches data collection, analyses and definitions of effects. Where studies reported effects as a range of distance values, the mid-point is plotted.

# Appendix 4 - Example piling parameters for piling of anchors for floating offshore wind

The underwater noise maximum-design scenario assumed for floating OWFs is the potential for pile driven anchors to secure the mooring lines for the floating turbines. To date, no floating turbines have been installed in the UK using pile driven anchors. Therefore, there is no as-built data to compare against the maximum design scenario assessed in EIAs. The size of the anchor piles (up to 4.8 m diameter) and the maximum hammer energy (up to 2,500 kJ) assumed in the recent EIAs for floating turbines WTGs are comparable to the size of pin piles used in jacket foundations for fixed WTGs (for example, the Moray East OWF installed 2.5 m diameter pin piles for jackets with a maximum hammer energy of 2,071 kJ).

**Table 29.** Piling parameters from EIAs for example floating OWF projects. [1] Caledonia Offshore Wind Farm. Volume 1 Overview Chapters Chapter 3 Proposed Development Description (Offshore). October 2024. [2] Muir Mhor Offshore Wind Farm. Environmental Impact Assessment Report. Volume 1, Chapter 3: Project Description. November 2024. [3] Salamander Offshore Wind Farm. Offshore EIA Report. Volume ER.A.2, Chapter 4: Project Description. April 2024. [4] Project Erebus Environmental Statement. Chapter 4: Proposed Development Description.

| Parameter | Project | | | |
|---|---|---|---|---|
| | **Caledonia, Moray Firth[1]** | **Muir Mhor, North Sea[2]** | **Salamander, North Sea[3]** | **Erebus, Celtic Sea[4]** |
| Pile diameter (m) | 4.8 | 4 | 3 | 2.5 |
| Pile penetration depth (m) | 40 | 60 | 70 | 52 |
| Max hammer energy (kJ) | 2,000 | 2,400 | 2,500 | 800 |
| Water depth (m) | 39 - 88 | 62 - 97.7 | 86 - 102 | 65 - 85 |
| Piles per anchor | 2-3 | 1 | 1 | 1 - 2 |
| Anchors per turbine | 12-18 | 9 | 3 - 8 | 3 - 5 |

# Appendix 5 - Expected dB reductions from different NAS, and associated % reductions in effect ranges

Reviews of empirical data and manufacturer claims for dB reductions from different noise systems are provided in Verfuss *et al.* (2019), Bellmann *et al.* (2020) and Barber *et al.* (2024). These are summarised below in Table 30. Note that the dB reductions are almost exclusively based on measurements from waters < 40 m deep. To provide an indication of the potential reduction in modelled impact ranges associated with specific dB reductions, we have compiled results from documents supporting several OWF consent applications in the US. There, it is routine to present modelled impact ranges, based on the fixed threshold of $SPL_{rms}$ 160 dB re 1µPa, for a variety of dB reductions representing different levels of noise abatement (Table 31). The 160 dB threshold is unweighted and used by the National Marine Fisheries Service as a behavioural response threshold for all species of marine mammal. The modelled impact ranges are represented by the metric $ER_{95}$. The $ER_{95}$ this is the 95$^{th}$ percentile of the closest point of approaches to piling of simulated animals (based on an animal movement model with no aversive movement) which are exposed to the $SPL_{rms}$ 160 dB re 1µPa level at some point during a piling sequence. The $ER_{95}$ is not a parameter typically estimated in UK OWF assessments and is generally smaller than the modelled radial distance to the $SPL_{rms}$ 160 dB isopleth; however, the relative reductions associated with different levels of noise abatement are broadly relevant.

**Table 30.** Sound level (in dB) reduction reported empirically or by the manufacturer based on Verfuss *et al.* (2019), Bellmann *et al.* (2020) and Barber *et al.* (2024).

| **Noise abatement type** | | **Reported/claimed dB reduction (broadband SEL)** |
|---|---|---|
| *Bubble curtains* | BBC | 7 - 15 |
| | DBBC | 8 - 18 |
| *Near-field systems* | Isolation casing (e.g. IHC-NMS) | 5 - 43 (typically 13 - 17) |
| | Resonator (e.g. HSD, AdBm) | 10 - 12 |
| *Combination systems* | Isolation casing + BBC | 17 - 20 |
| | Isolation casing + DBBC | 19 - 25 |
| | Resonator + DBBC | 15 - 28 |
| *On-pile systems* | Pile cushion | 5 - 26 |
| | IHC PULSE | 6 - 10 |
| | Menck MNRU | 9 |
| *Alternative hammers* | BLUE hammer | 19 - 24 |
| | Vibro hammer | 12 - 20 |

**Table 31.** For selected US OWF applications: modelled distance ($ER_{95}$) to $SPL_{rms}$ 160 dB threshold (NMFS Level B harassment) for harbour porpoise assuming no noise abatement (km) and predicted % reduction in radius predicted by different levels of noise abatement. [1] Project names include URL links to the resource from which values were extracted. [2] ER95 is the 95th percentile of the closest point of approaches to piling of simulated animals (based on an animal movement model with no aversive movement) which are exposed to the SPLrms 160 dB level at some point during a piling sequence.

| **Project [1]** | | **Pile type, diameter (m)** | **$ER_{95}$ range to $SPL_{rms}$ 160 dB threshold, assuming no noise abatement (km) [2]** | **% reduction in radius of $ER_{95}$ at different level of modelled broadband dB reduction by noise abatement** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **6 dB** | **10 dB** | **12 dB** | **15 dB** |
| *Monopiles* | Atlantic Shores South | Mono, 15 | 6.36 | **27** | **41** | **-** | **55** |
| | Atlantic Shores North | Mono, 10 | 6.59 | **28** | **43** | **-** | **61** |
| | Atlantic Shores North | Mono, 15 | 6.95 | **30** | **43** | **-** | **61** |
| | Maryland | Mono, 11 | 13.65 | **-** | **62** | **-** | **-** |
| | Mayflower | Mono, 11 | 10.51 | **37** | **57** | **-** | **70** |
| | South Fork | Mono, 8 | 9.126 | **44** | **-** | **63** | **-** |
| *Pin piles* | Atlantic Shores South | Pin, 5 (4/day) | 5.24 | **32** | **45** | **-** | **63** |
| | Atlantic Shores North | Pin, 5 | 2.56 | **41** | **59** | **-** | **78** |
| | Mayflower | Pin, 2.9 | 8.29 | **45** | **63** | **-** | **71** |
| | Mayflower | Pin, 4.5 | 10.92 | **39** | **58** | **-** | **72** |
| *Mean [+/- SE] % reduction* | | | | *36 [2.3]* | *52 [3.0]* | - | *66 [2.7]* |