

OFFSHORE RENEWABLES JOINT INDUSTRY  
PROGRAMME (ORJIP) FOR OFFSHORE WIND



# Best practice advice for designing impact pile driving profiles to reduce impacts to marine mammals

October 2026



working to accelerate  
offshore consenting



# ORJIP Offshore Wind

The Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind is a collaborative initiative that aims to:

- Fund research to improve our understanding of the effects of offshore wind on the marine environment.
- Reduce the risk of not getting, or delaying consent for, offshore wind developments.
- Reduce the risk of getting consent with conditions that reduce viability of the project.

The programme pools resources from the private sector and public sector bodies to fund projects that provide empirical data to support consenting authorities in evaluating the environmental risk of offshore wind. Projects are prioritised and informed by the ORJIP Advisory Network which includes key stakeholders, including statutory nature conservation bodies, academics, non-governmental organisations and others.

ORJIP Stage 2 was a collaboration between the Carbon Trust, EDF Energy Renewables Limited, Ocean Winds UK Limited, Equinor ASA, Ørsted Power (UK) Limited, RWE Offshore Wind GmbH, Shell Global Solutions International B.V., SSE Renewables Services (UK) Limited, TotalEnergies OneTech, Crown Estate Scotland, Scottish Government (acting through the Offshore Wind Directorate and the Marine Directorate) and The Crown Estate Commissioners.

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# Glossary

| Term                     | Description                                                                                                              |
|--------------------------|--------------------------------------------------------------------------------------------------------------------------|
| <b>ABM</b>               | Agent-Based Model                                                                                                        |
| <b>animat</b>            | a virtual animal used within simulations and modelling                                                                   |
| <b>EIA</b>               | Environmental Impact Assessment                                                                                          |
| <b>HF</b>                | High frequency cetaceans – functional hearing group from Southall et al. (2019) and NMFS (2024)                          |
| <b>LF</b>                | Low frequency cetaceans – functional hearing group from Southall et al. (2019) and NMFS (2024)                           |
| <b>RSafe</b>             | minimum safe starting distance an animal must be at the start of piling in order to remain below the PTS-onset threshold |
| <b>OWF</b>               | Offshore Wind Farm                                                                                                       |
| <b>PCW</b>               | Phocids in water – functional hearing group from Southall et al. (2019) and NMFS (2024)                                  |
| <b>PTS</b>               | Permanent Threshold Shift (auditory injury)                                                                              |
| <b>RaDIN</b>             | Range Dependent nature of Impulsive Noise                                                                                |
| <b>SD</b>                | Standard deviation                                                                                                       |
| <b>SEL</b>               | Sound Exposure Level [dB re 1 $\mu\text{Pa}^2\text{s}$ ]                                                                 |
| <b>SEL<sub>cum</sub></b> | Cumulative Sound Exposure Level [dB re 1 $\mu\text{Pa}^2\text{s}$ ]                                                      |
| <b>SL</b>                | Source Level [dB re 1 $\mu\text{Pa}$ ]                                                                                   |
| <b>SPL</b>               | Sound Pressure Level [dB re 1 $\mu\text{Pa}$ ]                                                                           |
| <b>TTS</b>               | Temporary Threshold Shift                                                                                                |
| <b>VHF</b>               | Very high frequency cetaceans – functional hearing group from Southall et al. (2019) and NMFS (2024)                     |

## Executive summary

The RaDIN project (Matei et al., 2024) developed a simulation tool to estimate relative auditory injury (Permanent Threshold Shift, PTS) impact ranges from impact pile driving under different scenarios, and demonstrated that the factors that most influenced the cumulative PTS ranges were animal swim speed and piling blow rate. It was shown that a high inter-blow-interval (slow blow rates) in the first 45 minutes of a piling event resulted in much smaller cumulative PTS ranges and concluded that the piling parameters assessed in EIAs may result in substantial overestimation of PTS ranges. The RaDIN project concluded with a set of recommendations which led to the RaDIN2 project. The purpose of this RaDIN2 study was to build upon the findings of the RaDIN study to further investigate how piling profiles and other physical or biological evidence can improve the realism of cumulative PTS impact ranges.

**Task 1 RaDIN Movement Tool improvements:** The RaDIN2 Movement Tool now implements more realistic movements of the animats as well as introducing a range of possible behavioural responses, with the possibility for animats to move with a variable speed with three avoidance triggers: distance, duration, or received sound level. The tool was also improved to include a relationship between hammer energy and source level to allow for a ramp up of the sound source, and frequency-dependent sound attenuation was incorporated for specific distance bins, available for both monopiles and pin piles to allow for improved sound propagation.

**Task 2 Census of real-world piling profiles:** The purpose of this task was to collate real piling logs from a wide range of representative wind farm construction activities (all using impact piling). With this information, the intent was to calculate summary statistics that capture real-world piling installation operations. Piling log data was collated for 1,448 piles from nine OWF in the UK (764 monopiles, 684 pin piles). These were investigated to understand the active piling duration per pile, the total installation duration per pile, gaps in piling, hammer energy in the soft-start, hammer energy throughout all piling, blow-rates in the soft-start and blow rates throughout all piling. There was considerable variability in the real piling profiles, in terms of the blow rate, hammer energy and overall duration of piling. Across the OWFs analysed, only 12.5% of the piles reached or exceeded the maximum hammer energy defined in the EIA and only 0.55% of the piles reached or exceeded the maximum hammer energy defined in the MMMP. Blow rates varied substantially among projects and foundation types, demonstrating considerable variation in soft-start and piling practices across OWFs. The vast majority of piles were installed in under 2 hours, though piling profiles also varied considerably within and between OWFs, with no consistent installation pattern observed across projects. Collectively, these findings highlight the considerable variability in real-world piling schedules and indicate that a conservative single worst-case piling profile is unlikely to capture the full range of installation conditions encountered across offshore wind farm projects.

**Task 3 Comparison of real vs EIA piling profiles:** The aim of this task was to compare the cumulative PTS impact ranges produced using the EIA piling profiles, with the cumulative PTS impact ranges produced using the real piling logs. This study showed that for harbour porpoise:

- 50% of the real pin pile logs had cumulative PTS impact ranges that were <50% of the range predicted using the EIA piling profile
- 96% of the real monopile logs had cumulative PTS impact ranges that were <50% of the range predicted using the EIA piling profile

And for minke whales:

- 89% of the real pin pile logs had cumulative PTS- impact ranges that were <50% of the range using the EIA piling profile
- 100% of the real monopile logs had PTS-impact ranges that were <30% of the range using the EIA piling profile

This was also investigated for the MMMP phase, where it was expected that predicted ranges would align more with real piling logs due to the availability of detailed geophysical data and refined piling parameters. However, this made very little difference, and the MMMP piling profiles still substantially over-predicted cumulative PTS ranges compared to real piling logs.

**Task 4 Piling schedule workshop:** we delivered a 3 hour workshop to update stakeholders on the RaDIN2 project outcomes and to provide facilitated engagement between engineers, regulatory advisors, EIA and Consenting experts, acousticians, and marine mammal specialists to develop practical solutions to streamline EIA processes. The goal was that we would also gather feedback and stimulate discussion on how to collaboratively improve consenting processes, highlight limitations of the project's proposed approach and suggest next steps for follow-up analyses. There was much discussion on the technical feasibility of implementing different soft start procedure, and that it is often difficult to perfectly control hammer energy and blow rate in high precision. A key theme raised at the workshop was the importance of continued dialogue between developers, engineers, regulators, advisors, and contractors throughout EIA and MMMP process. Participants identified a need for improved communication and collaboration before formal approval of mitigation plans, particularly regarding soft-starts, pile refusals, and realistic installation scenarios. There were concerns that current modelling approaches can compound multiple worst-case assumptions, potentially resulting in unrealistic PTS ranges that may overstate environmental risk. EIA and MMMP piling profiles often differ from actual installation practices because they are based on conservative, worst-case assumptions designed to support consenting and regulatory compliance, and there was agreement that it would be better to move beyond strictly worst-case impact assessments towards incorporating a more proportionate approach to mitigation.

Following the piling schedule workshop, it was clear that a longer dedicated workshop is required to help refine practical and agree Best Practice Guidance for soft-starts and piling profiles that balances both technical and consenting risks. Recommendations for this future workshop have been provided, and both engineers and regulators/SNCBs have agreed the importance of this.

| Recommendations from RaDIN                                                                                                                                                                              | Addressed in RaDIN2                                                                                                                                                                                                                                                                                                                                                                                                           |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Threshold shift playback experiments to known sounds with known impulsiveness characteristics to better understand the impulsiveness points at which sounds become less damaging to the auditory system | <i>Not part of RADIN2 scope – remains a recommendation following RaDIN2</i>                                                                                                                                                                                                                                                                                                                                                   |
| Further development of the framework to address potential conservatism within the current formation to better understand PTS risks                                                                      | <ul style="list-style-type: none"> <li>• Variable animal speed and response mechanisms</li> <li>• Source level calculated from hammer energies</li> <li>• Frequency-dependent sound attenuation</li> <li>• Adjustable blow rates and hammer energies for soft start and ramp up</li> </ul>                                                                                                                                    |
| Census of real world hammer logs (as constructed) and comparison to EIA assumptions (design envelope) to understand how often worst case assumptions are realised                                       | <ul style="list-style-type: none"> <li>• Piling log data from 1,448 piles from 9 OWF</li> <li>• Comparison cumulative PTS ranges produced using EIA or MMMP piling schedules vs real piling logs</li> </ul>                                                                                                                                                                                                                   |
| Swim speed is important to better understand. A complete review or dedicated behavioural response studies would be needed to support this.                                                              | <ul style="list-style-type: none"> <li>• Literature review of animal swimming and fleeing speeds provided</li> </ul>                                                                                                                                                                                                                                                                                                          |
| Facilitated engagement between engineers, regulatory advisors, acousticians, and marine mammal specialists to develop solutions to streamline EIA processes.                                            | <ul style="list-style-type: none"> <li>• Workshop with engineers, regulatory advisors, EIA and consenting experts, acousticians, and marine mammal specialists</li> </ul>                                                                                                                                                                                                                                                     |
| Use framework to explicitly design hammer logs that can minimize impact ranges and coordinate with engineers to ensure feasibility.                                                                     | <p>Discussed at workshop</p> <ul style="list-style-type: none"> <li>• Model most likely case as well as worst case</li> <li>• Need to define a realistic range for hammer energy, blow rate, and ramp-up behaviour</li> <li>• Need better pile-specific drivability, pile logs, geotechnical insight, and measured installation data</li> <li>• Need new guidance and definitions on what constitutes a soft-start</li> </ul> |
| Carry out studies of swim speeds of animals relative to pile driving activities.                                                                                                                        | <i>Not part of RADIN2 scope – remains a recommendation following RaDIN2</i>                                                                                                                                                                                                                                                                                                                                                   |

# 1. Introduction

## 1.1. RaDIN

The RaDIN project (Range Dependent nature of Impulsive Noise) (Matei et al., 2024) aimed to:

- review literature on the impulsiveness of sound and its effect on the auditory system of mammals,
- use real piling underwater noise recordings to investigate how impulsiveness changes with distance from pile,
- provide a simulation tool to estimate relative auditory injury (Permanent Threshold Shift, PTS) impact ranges from impact pile driving under different scenarios,
- use real piling logs to investigate whether assumptions in Environmental Impact Assessment Report (EIAs) may result in significant overestimate of cumulative PTS ( $SEL_{cum}$ ) impact ranges.

The main findings of the project were:

- There was a clear decrease in impulsiveness with distance from source. Kurtosis values decreased rapidly over 0-1 km from the source, and other metrics of impulsiveness (crest factor, peak sound pressure level, and high frequency content) all markedly decreased within 5 km from the pile.
- Simulations using the RaDIN tool showed that the factors that influence the cumulative PTS impact range the most are animal swimming speed away from the pile and blow rate. These factors were much more influential than the range at which sound transitioned from impulsive to non-impulsive. A high inter-blow-interval (slow blow rates) in the first 45 minutes of a piling event resulted in much smaller PTS ranges. As is expected, the faster the animal swims, the smaller the cumulative PTS impact range is.
- Overall, the results of the study highlighted that the piling parameters assessed in EIAs may result in substantial overestimation of PTS ranges. EIAs must present and assess the worst-case scenarios, without any assessment of how likely the worst case is to be realised. Increasingly, the use of Noise Mitigation Systems (NMS) (including quieter installation methods and noise abatement methods) to reduce impacts on marine mammals is being discussed (see UK Govt Policy Paper: Reducing Marine Noise, 2025). Understanding conservatism in impact assessments is a critical and pressing need to help proportionality in assessments and discussions.

## 1.2. RaDIN2

The purpose of this study was to build upon the findings of the RaDIN study to further investigate how piling profiles and other physical or biological evidence can improve the realism of cumulative PTS impact ranges. The key tasks within this project were:

- Further development of the RaDIN tool to enhance realism (and reduce conservatism)

- A census of real-world piling profiles: collation of piling logs from multiple offshore windfarms to understand construction patterns
- A comparison of real-world construction vs EIA piling modelling: assessing variations between EIA and as-built piling logs for multiple offshore windfarms.
- A multidisciplinary workshop to explore the co-development of piling profiles to balance technical and consenting risks.

## 2. Task 1: RaDIN movement tool improvements

The RaDIN project generated a Movement Tool model which is a one-spatial-dimension (1D) agent-based model (ABM) simulating movement of animals (referred to as animats) moving through a soundscape (set with a constant source level and point transmission loss model for pile driving noise) away from the source location in a straight line at a user defined speed. PTS onset ranges are calculated based on established noise exposure criteria, with animats accumulating  $SEL_{ss}$  following individual pile strikes. For each animat that accumulates enough  $SEL_{cum}$  to experience a TTS onset, an analysis routine continues to accumulate all additional measurements of  $SEL_{ss}$  until a 40 dB TTS is reached (i.e., the animal accumulates enough threshold shift to reach the PTS onset). The 40 dB TTS is presumed to be a PTS onset level (Southall et al., 2019). When a TTS value of 40 dB is reached, the given animat is considered to have experienced PTS and their starting distance from the piling location (the first patch in the 1D simulation) is recorded.

The RaDIN project identified that resulting PTS impact ranges are dependent on a number of assumptions regarding the source level, blow rate and animal movement.

In the RaDIN2 Movement Tool we implemented more realistic movements of the animats as well as introducing a range of possible behavioural responses. We also introduced a relationship between hammer energy and source level to allow for a ramp up of the sound source.

### 2.1. Overview

Similarly to the original RaDIN Movement Tool, the RaDIN2 Movement Tool is an individual-based model to simulate marine mammal movement and acoustic exposure during offshore pile driving. The model tracks individual animats as they move away from a sound source and calculates cumulative sound exposure levels ( $SEL_{cum}$ ) to assess risk of temporary (TTS) and permanent (PTS) threshold shift. Below we present a general overview of the model.

#### 2.1.1. Spatial and Temporal Domain

Animats are simulated to move in one direction over time, specifically away from the pile driving location. The number of animats is established by the user and their starting positions are non-uniformly distributed between 0 m and the maximum distance from the source (user-specified), with a higher density of animats near the pile driving location. It is worth noting that the user can define the strength of the placement bias towards the pile driving location. The bias was introduced to make sure more animats are placed closer to the source, as these are the individuals which are more likely to experience threshold shifts. Simulations progressed in 1-second time steps, with the piling duration being determined by the piling schedule.

#### 2.1.2. Movement

Animats move away from the source, in a straight line. In the absence of pile strikes, animats move at a user-specified 'normal' travelling, species-specific speed. To increase realism (i.e. animals do not actually move at a precise speed in a straight line), movement speed for each individual is drawn from a normal distribution with mean and standard deviation (SD) specified by the user. This allows some variance in speed between time-steps to be incorporated within an individual and between individuals.

Speed can therefore be 0 m/s to account for the fact that some animals could be stationary for a period of time.

When a pile strike occurs, animats in the RaDIN2 model can switch from “normal” to “fleeing speed”. When fleeing is triggered, the distance or time over which this lasts depends on the user specified behavioural response mechanisms (mechanism described below). Table 1 provides examples of “normal” and “fleeing” swimming speeds for the five key marine mammal species in the UK, noting those most commonly used in piling assessments. It is important to note that fleeing speeds and animal responses to pile driving noise is unknown. From this brief literature review, it is evident that the “normal” and “fleeing” speeds for different species varies greatly. For example, there is considerable difference in the swimming speed recommended in EIA modelling for minke whales in Scotland (2.1 m/s) and England (3.25 m/s). Of note, is that the “normal” swimming speed for porpoise ranges between 0.46 - 1.6 m/s and the “fleeing” speed ranges between 1.6 – 4+ m/s, which doesn’t align with the “fleeing” speeds typically advised and used in underwater noise impact assessments (1.4 – 1.5 m/s). This indicates that the fleeing speeds and subsequent impact ranges currently modelled for harbour porpoise are highly conservative. It is noted, that the guidance in England (Parker et al., 2025) acknowledges this: **“these fleeing speeds are precautionary, as there have been more recent studies which have shown harbour porpoise and minke whale fleeing at higher speeds from loud impulsive noise sources (e.g. Kastelein et al. 2018; van Beest et al. 2018; McGarry et al. 2017). However, it cannot be assumed that an animal will swim directly away from a noise source at a constant speed. Therefore, it is important to retain conservatism in the assessment, based upon the best available evidence, to ensure that the worst-case scenario has been assessed”**.

**Table 1. Summary of hearing group specific normal and fleeing speeds. Values most commonly used in piling noise impact assessments are marked in blue.**

| Species         | Type   | Speed (m/s) | Notes                                                                               | Reference                                   |
|-----------------|--------|-------------|-------------------------------------------------------------------------------------|---------------------------------------------|
| Harbor porpoise | normal | 0.9         | Mean swim speed                                                                     | Otani et al. (2000)                         |
|                 |        | 1.4         | Average of descent and ascent swim speeds<br>Swimming speed recommended in Scotland | Westgate et al. (1995)<br>SNH (2016)        |
|                 |        | 1.19        | Mean speed during baseline quiet periods                                            | Kastelein et al. (2018)                     |
|                 |        | 1.3 - 1.5   | Average swim speed                                                                  | Otani et al. (2001)                         |
|                 |        | 1.5         | Swimming speed recommended in England                                               | Otani et al. (2001)<br>Parker et al. (2025) |
|                 |        | 0.46        | Mean swimming speed without exposure                                                | Hiley et al. (2021)                         |
|                 |        | 1.6         | Swim speed before AHD exposure (no tag)                                             | Elmegaard et al. (2023)                     |

|                           |         |               |                                                                                                   |                                                |
|---------------------------|---------|---------------|---------------------------------------------------------------------------------------------------|------------------------------------------------|
|                           |         | 1.3-1.4       | Swim speed pre- AHD exposure (tagged animals)                                                     | Elmegaard et al. (2023)                        |
|                           | fleeing | 1.97          | Mean fleeing speed when exposed to piling at SPL 154 dB re 1 $\mu$ Pa, sustained speed for 30 min | Kastelein et al. (2018)                        |
|                           |         | 6.2           | Reported speeds that porpoise can swim                                                            | Leatherwood et al. (1982)                      |
|                           |         | 2.2           | Mean speed during VHF sound exposure                                                              | Hiley et al. (2021)                            |
|                           |         | 2.3           | Mean speed during first long dive after VHF sound exposure                                        | Hiley et al. (2021)                            |
|                           |         | 4.0           | First 30 seconds after AHD exposure, no tag                                                       | Elmegaard et al. (2023)                        |
|                           |         | 1.4-1.9       | During AHD exposure, tagged animals                                                               | Elmegaard et al. (2023)                        |
|                           |         | 1.6 (1.3-3.2) | Average observed in reaction to a seal scarer (min-max)                                           | Brandt et al. (2013)                           |
| <b>Bottlenose dolphin</b> | normal  | 1.5           | Swimming speed recommended in England                                                             | Parker et al. (2025)                           |
|                           |         | 2.18          | Mean speed through the water                                                                      | Bailey and Thompson (2010)                     |
|                           |         | 1.52          | Mean swim speed $1.52 \pm 0.17$<br>Swimming speed recommended in Scotland                         | Bailey and Thompson (2006)                     |
|                           | fleeing | N/A           | No data available                                                                                 |                                                |
| <b>Small cetacean</b>     | normal  | 2.0 – 4.0     | Routine swimming speed                                                                            | Williams (2009)                                |
|                           | fleeing | 10.0          | Sprint speed                                                                                      |                                                |
| <b>Minke whale</b>        | normal  | 2.1           | Swimming speed recommended in Scotland                                                            | Williams (2009)<br>SNH (2016)                  |
|                           |         | 2.3           | Control speed: mean 8.4 km/h (4.2 – 12.1), SD 1.9, n=15                                           | (Boisseau et al., 2021)                        |
|                           |         | 3.25          | Optimum swimming speed, obtained from metabolic rate<br>Swimming speed recommended in England     | Blix and Folkow (1995)<br>Parker et al. (2025) |
|                           | fleeing | 4.19          | ADD treatment speed: mean 15.1 km/h (6.6 – 21.4), SD 4.7, n=10                                    | (Boisseau et al., 2021)                        |
|                           | normal  | 2.1 – 2.6     | Routine swimming speed                                                                            | Williams (2009)                                |

|                        |         |            |                                         |                               |
|------------------------|---------|------------|-----------------------------------------|-------------------------------|
| <b>Mysticete whale</b> | fleeing | 4.1 – 13.3 | Range of sprinting speeds               |                               |
| <b>Phocid</b>          | normal  | 1.2 - 2.0  | Routine swimming speed                  | Williams (2009)               |
|                        | fleeing | 4.0        | Sprints                                 |                               |
| <b>Harbor seal</b>     | normal  | 1.8        | Swimming speed recommended in Scotland  | Thompson (2015)<br>SNH (2016) |
|                        |         | 1.5        | Swimming speed used in EIAs in England  |                               |
| <b>Grey seal</b>       | normal  | 1.8        | Swimming speed recommended in Scotland  | Thompson (2015)<br>SNH (2016) |
|                        |         | 1.5        | Swimming speed used in EIAs in England  |                               |
|                        |         | 1.71       | Mean descent speeds $1.71 \pm 0.41$ m/s | Gallon et al. (2007)          |
|                        |         | 1.37       | Mean ascent speeds $1.37 \pm 0.36$ m/s  |                               |

### 2.1.3. Behavioural Response Mechanisms

We implemented three alternative, mutually exclusive behavioural response mechanisms to represent different hypotheses about how marine mammals respond to pile driving (in addition to a response of no change in swimming speed) (Figure 1).

#### 2.1.3.1. Distance-based response

Animals respond to the first pile strike and flee until reaching a user specified threshold distance from the source, after which they switch to normal traveling speed (i.e. animals slow down once they get a certain distance from the source). Animals starting beyond the threshold distance maintain normal speed throughout. Distance-based response allows for multiple flee events throughout the simulation.

#### 2.1.3.2. Duration-based response

Animals flee for a fixed duration following the first strike, then return to normal speed regardless of their position relative to the source. Duration-based response allows for multiple flee events throughout the simulation.

#### 2.1.3.3. Noise-triggered response

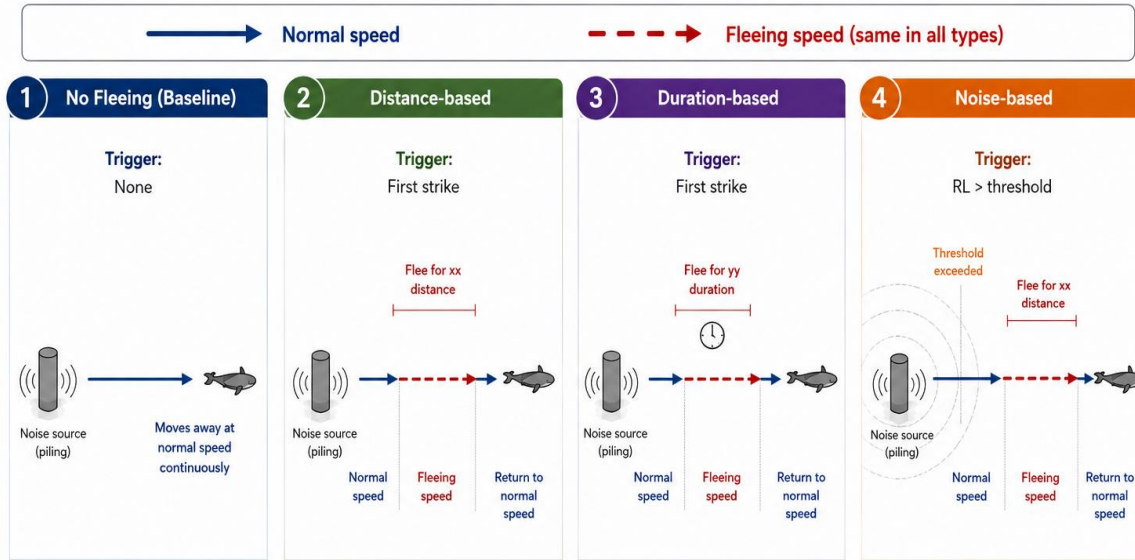
Animals flee whenever their received sound level (dB re 1  $\mu\text{Pa}^2\text{s}$ ,  $\text{SEL}_{\text{ss}}$ ) exceeds a threshold (dB re 1  $\mu\text{Pa}^2\text{s}$ ,  $\text{SEL}_{\text{threshold}}$ ), switching between fleeing speed and normal speed based on two possible mechanisms: (1) fleeing for a fixed distance, or (2) fleeing for a distance proportional to the difference between received level and the threshold before slowing down. In the latter case, the fleeing distance is defined by the following equations, based on the fleeing mechanisms implemented in DEPONS model (Nabe-Nielsen, 2019):

### Equation 1

$$Distance_{fleeing} = 10^{\frac{SEL_{ss} - SEL_{threshold}}{x}}$$

where  $SEL_{ss}$  is a single strike sound exposure level (dB) at the time fleeing was triggered and  $x$  is a  $\log_{10}$  multiplier used in calculation of transmission loss (see Equation 2).

Noise-triggered response allows for multiple flee events throughout the simulation.



**Figure 1. Graphical representation of behavioural response mechanisms implemented in the tool.**  
RL – received level ( $SEL_{ss}$ ).

### 2.1.4. Acoustic Model

Received sound levels are calculated using the following series of equations:

### Equation 2

$$SEL_{ss} = SL_{ss} - x * \log_{10} r + \alpha * \left(\frac{r}{1000}\right)$$

where  $SL_{ss}$  is single strike source level (dB re 1  $\mu Pa^2s$ ),  $x$  is the log multiplier,  $r$  – distance from the source (km), and  $\alpha$  attenuation coefficient (dB/km).

Source levels ( $SL_{ss}$ ) at 1 m (dB re 1  $\mu Pa^2s$ ) are calculated from the hammer energy following the method of De Jong and Ainslie (2008). The equation relates hammer energy to acoustic output:

### Equation 3

$$SL_{ss} = 120 + 10 \log_{10} * \left(\frac{\beta * E * c * \rho}{4 * \pi}\right)$$

where  $E$  is hammer energy [J],  $\beta$  is acoustic energy conversion efficiency (0.05),  $c$  is speed of sound in seawater (1520  $m s^{-1}$ ), and  $\rho$  is water density (1,027  $kg m^{-3}$ ). This formulation assumes that a fraction  $\beta$  of the mechanical energy is converted to acoustic energy, which then spreads from a point source. During inter-strike intervals when no piling occurred, source level was set to ambient noise level (0 dB re 1  $\mu Pa^2s$ ).

The time step in the model is one second, therefore, SEL<sub>ss</sub> for each strike is quantified over one second, which results in a value equal to the sound pressure level (SPL) for that strike.

### 2.1.5. Thresholds and frequency weighting corrections

The received SEL<sub>ss</sub> calculated for each animal at each time step must be adjusted to account for the frequency-dependent hearing sensitivity of marine mammals. This adjustment is critical because marine mammals in different hearing groups have evolved hearing sensitivities optimised for their ecological niches and communication ranges. Southall et al. (2019) categorises marine mammals into the following functional hearing groups:

- Very high frequency cetaceans (VHF, such as the harbour porpoise (*Phocoena phocoena*))
- High frequency cetaceans (HF, including species like sperm whales (*Physeteridae*) and delphinids (*Delphinus*))
- Low frequency cetaceans (LF, e. g., minke whale (*Balaenoptera acutorostrata*))
- Phocid carnivores in water (PCW, e. g., harbour seal (*Phoca vitulina*)).

Additionally, sound frequency content changes as it propagates through seawater due to frequency-dependent absorption, with high-frequency sounds being preferentially attenuated over distance. Since pile driving generates a broad frequency spectrum, different frequencies contribute differently to the perceived loudness and biological impact depending on propagation distance.

Rather than applying a single fixed frequency correction to all received sound levels (as was implemented in the RaDIN1 tool), the RaDIN2 tool implements distance-specific frequency weighting based on the animal's instantaneous distance from the source. This approach is more biologically and physically realistic because high-frequency components attenuate rapidly during propagation due to frequency-dependent absorption in seawater (Ainslie and McColm, 1998).

For each animal at each time step, the RaDIN2 tool calculates the instantaneous distance from the source and selects an appropriate frequency weighting correction from nine distance bins: 0–249 m, 250–499 m, 500–749 m, 750–1,499 m, 1,500–2,999 m, 3,000–4,499 m, 4,500–5,999 m, 6,000–7,499 m, 7,500–8,999 m, and ≥9,000 m. Each bin contains distance-specific and hearing-group-specific correction factors that account for frequency-dependent propagation loss (Southall et al., 2019). These corrections are also differentiated by pile foundation type (monopile versus pin-pile), as the acoustic signatures and frequency spectra differ between foundation types (Verfuss et al., 2023). The frequency-weighted SEL is then calculated as the unweighted received level minus the distance-specific correction factor.

Cumulative SEL (SEL<sub>cum</sub>) is then calculated by summing weighted SEL over time. Animals are considered to experience TTS when weighted SEL<sub>cum</sub> reaches the TTS threshold as per the NMFS (2024) guidance. Similarly, animals are considered to experience PTS when weighted SEL<sub>cum</sub> reaches the PTS threshold as per the NMFS (2024) guidance (Table 2). Animals in the simulation do not experience any recovery in threshold shifts in between pile strikes.

**Table 2. TTS and PTS thresholds in NMFS (2024). SEL thresholds are in dB re 1  $\mu$ Pa<sup>2</sup>s.**

| Group | TTS threshold | PTS threshold |
|-------|---------------|---------------|
|-------|---------------|---------------|

|     | (SEL weighted) | (SEL weighted) |
|-----|----------------|----------------|
| LF  | 168            | 183            |
| HF  | 178            | 193            |
| VHF | 144            | 159            |
| PCW | 168            | 183            |

### 2.1.6. Model Outputs

The primary model output is the PTS-onset impact range, or minimum safe starting distance ( $R_{safe}$ ), which represents the minimum distance an animal must be at the start of piling, from the pile driving source to avoid experiencing cumulative sound exposure causing PTS throughout the piling sequence. Animals that are located at distances greater than  $R_{safe}$  when piling commences will remain below the PTS threshold; those starting closer to the pile than  $R_{safe}$  will accumulate enough threshold shift to exceed the auditory injury (PTS) criteria.

## 2.2. Summary comparison of RaDIN1 and RaDIN2 Movement Tools

A comparison of different model components (features) between the versions of the movement tool is provided in Table 3. The model is now fully implemented in R (R Core Team, 2026).

**Table 3. Comparison of movement tools implemented in RaDIN1 and RaDIN2 (grey cells denote features that have not changed).**

| Feature                    | RaDIN1 tool                                                                                                     | RaDIN2 tool                                                                                                                                                                                           |
|----------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Movement</b>            | Animals move with a fixed speed away from the source                                                            | Animals move with a variable speed with three avoidance triggers (distance-, duration-, or noise-based); stochastic speed draws (see section 2.1.3)                                                   |
| <b>Source level</b>        | Fixed per strike                                                                                                | Calculated from hammer energies (see section 2.1.4).                                                                                                                                                  |
| <b>Sound propagation</b>   | Simple sound propagation including propagation loss. No sound accumulation in between strikes (effective quiet) | Simple sound propagation including propagation loss. No sound accumulation in between strikes (effective quiet)                                                                                       |
| <b>Frequency weighting</b> | Single fixed correction (frequency-independent)                                                                 | Distance-specific correction using 9 distance bins (0–249 m to $\geq 9,000$ m); accounts for frequency-dependent sound attenuation; separate weightings for monopile vs. pin-pile (see section 2.1.5) |
| <b>SEL calculation</b>     | Frequency-weighted cumulative SEL; fixed TTS/PTS thresholds                                                     | Frequency-weighted cumulative SEL; fixed TTS/PTS thresholds                                                                                                                                           |

|                        |                                                                                                                                |                                      |
|------------------------|--------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|
| <b>PTS growth rate</b> | The growth rate in $SEL_{cum}$ from TTS to PTS threshold differs whether animal is exposed to impulsive or non-impulsive sound | Same for impulsive and non-impulsive |
| <b>Recovery</b>        | Not included                                                                                                                   | Not included                         |
| <b>Implementation</b>  | Simulations in NetLogo; analysis in R                                                                                          | All simulations in R                 |

## 3. Task 2: Census of real-world piling profiles

The purpose of this task was to collate real piling logs from a wide range of representative wind farm construction activities (all using impact piling). With this information, the intent was to calculate summary statistics that capture real-world piling installation operations across nine OWFs.

### 3.1. Data collation

Piling log records were collated for nine OWF constructed in UK waters in the last nine years. This resulted in piling log data for 1,448 piles in total (764 of these for monopiles, 684 of these were pin piles) (Table 4). The piling logs collated included both WTG and offshore platform piles, therefore, in some instances, an OWF may have both monopiles and pin piles included where wind turbine generator (WTGs) were installed on monopile foundations while offshore platforms were installed on pin pile jacket foundations. All OWF data has been anonymised in this report. None of the OWF used NMS, apart from one, which used vibropiling before impact piling.

**Table 4. Summary of the piling log information provided. \* vibropiling before impact piling**

| OWF          | # Monopiles | # Pin piles | Noise Mitigation Systems?         | Approximate water depth (m) |
|--------------|-------------|-------------|-----------------------------------|-----------------------------|
| 1            | 174         | 0           | no                                | 20-40                       |
| 2            | 158         | 12          | no                                | 30-40                       |
| 3            | 0           | 344         | no                                | 35-55                       |
| 4            | 87          | 4           | no                                | 18-63 (average 23)          |
| 5            | 0           | 308         | no                                | 38-54                       |
| 6            | 99          | 8           | no                                | 20-35                       |
| 7            | 58          | 0           | vibro piling before impact piling | 35-54                       |
| 8            | 94          | 4           | no                                | 18-63                       |
| 9            | 94          | 4           | no                                | 19-37                       |
| <b>TOTAL</b> | <b>764</b>  | <b>684</b>  | <b>na</b>                         | <b>na</b>                   |

### 3.2. Duration

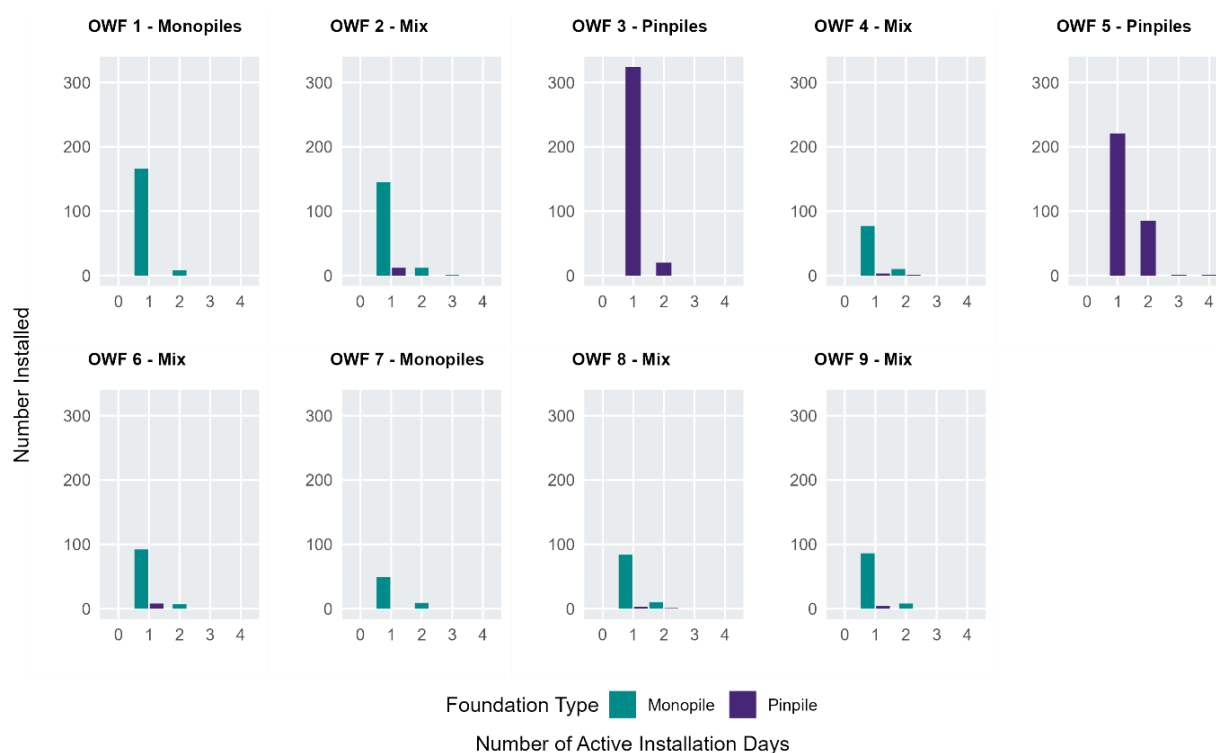
#### 3.2.1. Active piling days

Here, active piling days has been defined as “**the number of calendar days on which piling occurred for the installation of a single pile**”. Across all monopiles (n=764), the average number of piling days was 1.09 days (minimum = 1 and maximum = 3 days). Across all pin piles (n=684), the average

number of piling days was 1.16 days (minimum = 1 and maximum = 4 days). Overall, for both monopiles and pin piles it took around 1 day of active piling for the installation of a single pile.

**Table 5. Summary of the number active piling days it took to install a single pile at each OWF. The table is split for monopiles and pin piles.**

| OWF | MONOPILE Active piling days |      |      |     | PIN PILE Active piling days |      |      |     |
|-----|-----------------------------|------|------|-----|-----------------------------|------|------|-----|
|     | # piles                     | Min. | Avg. | Max | # piles                     | Min. | Avg. | Max |
| 1   | 174                         | 1    | 1.05 | 2   | 0                           | N/A  |      |     |
| 2   | 158                         | 1    | 1.09 | 3   | 12                          | 1    | 1    | 1   |
| 3   | 0                           | N/A  |      |     | 344                         | 1    | 1.06 | 2   |
| 4   | 87                          | 1    | 1.11 | 2   | 4                           | 1    | 1.25 | 2   |
| 5   | 0                           | N/A  |      |     | 308                         | 1    | 1.29 | 4   |
| 6   | 99                          | 1    | 1.07 | 2   | 8                           | 1    | 1    | 1   |
| 7   | 58                          | 1    | 1.16 | 2   | 0                           | N/A  |      |     |
| 8   | 94                          | 1    | 1.11 | 2   | 4                           | 1    | 1.25 | 2   |
| 9   | 94                          | 1    | 1.09 | 2   | 4                           | 1    | 1    | 1   |



**Figure 2. Number of active piling days per pile across the 9 OWFs**

### 3.2.2. Total installation duration per pile

Here, total installation duration has been defined as **“the number of hours between the first and the last hammer strike for a single pile, including all hours of breaks”**. Across all monopiles (n=764), the median total installation duration per pile was 1.65 hours (m IQR=1.16 - 1.96 hours). Across all pin piles (n=684), the median total installation duration per pile was 1.36 hours (iQR = 1.12 - 2.4 hours).

The total installation duration for the vast majority of monopiles and pin piles was less than 2 hours. However, there were a limited number of cases (n=18) in which the maximum duration exceeded 24 hours. Of these 18 occurrences, only two were monopiles and the remaining 16 were pin piles isolated to one wind farm (OWF 5). On these occasions, the outliers in duration were a result of long breaks in piling rather than an extended active piling duration. So, while breaks increased the total duration to install one pile, active piling time remained relatively low. More information on gaps in active piling is provided in section 3.2.3.

**Table 6. Summary of the total duration installation for a single pile across each OWF. The table is split between monopiles and pin piles.**

| OWF | MONOPILE<br>Total Installation duration (hours) |      |      |                     |        | PIN PILE<br>Total Installation duration (hours) |      |      |                     |        |
|-----|-------------------------------------------------|------|------|---------------------|--------|-------------------------------------------------|------|------|---------------------|--------|
|     | # piles                                         | Min. | Avg. | Median (IQR)        | Max.   | # piles                                         | Min. | Avg. | Median (IQR)        | Max.   |
| 1   | 174                                             | 0.56 | 0.87 | 0.85<br>(0.77-0.93) | 1.55   | N/A                                             |      |      |                     |        |
| 2   | 158                                             | 0.93 | 4.53 | 1.74<br>(1.65-1.84) | 429.98 | 12                                              | 1.16 | 1.49 | 1.45<br>(1.36-1.70) | 1.80   |
| 3   | N/A                                             |      |      |                     |        | 344                                             | 0.64 | 1.84 | 1.27<br>(1.03-1.56) | 11.44  |
| 4   | 87                                              | 0.93 | 1.58 | 1.40<br>(1.25-1.64) | 7.94   | 4                                               | 2.23 | 4.47 | 2.86<br>(2.34-4.98) | 9.92   |
| 5   | N/A                                             |      |      |                     |        | 308                                             | 0.78 | 7.70 | 1.44<br>(1.20-7.36) | 236.96 |
| 6   | 99                                              | 1.51 | 2.18 | 2.13<br>(1.96-2.27) | 5.20   | 8                                               | 2.23 | 2.43 | 2.42<br>(2.30-2.51) | 2.79   |
| 7   | 58                                              | 1.25 | 4.67 | 2.09                | 118.93 | N/A                                             |      |      |                     |        |

|   |    |      |      |                     |       |   |      |      |                     |       |
|---|----|------|------|---------------------|-------|---|------|------|---------------------|-------|
|   |    |      |      | (1.74-2.79)         |       |   |      |      |                     |       |
| 8 | 94 | 0.55 | 2.3  | 1.81<br>(1.56-2.19) | 18.49 | 4 | 3.06 | 8.27 | 6.06<br>(3.33-11.0) | 17.90 |
| 9 | 94 | 1.09 | 1.73 | 1.60<br>(1.35-1.83) | 4.51  | 4 | 3.60 | 3.87 | 3.65<br>(3.63-3.89) | 4.56  |

### 3.2.3. Gaps in piling

Here, a gap in piling has been defined as **“a period of at least 10 minutes between pile strikes”**.

Across all recorded monopile blows (n=1,408,037), only 102 had gaps between them which exceeded or were equal to 10 minutes. In such instances, the median gap between strikes was 29.3 minutes (IQR = 16.1 – 65.5 minutes). Across all recorded pin pile blows (n=117,531), only 181 had gaps between them which exceeded or were equal to 10 minutes. Of these, the median gap between strikes was 6.08 hours (IQR= 4.18 – 11.15 hours). Overall, gaps in piling exceeding 10 minutes occurred infrequently within the entire dataset. There were limited occurrences where gaps in piling that lasted multiple days, this is likely as result of equipment malfunctions, technical issues, or weather delays during installation.

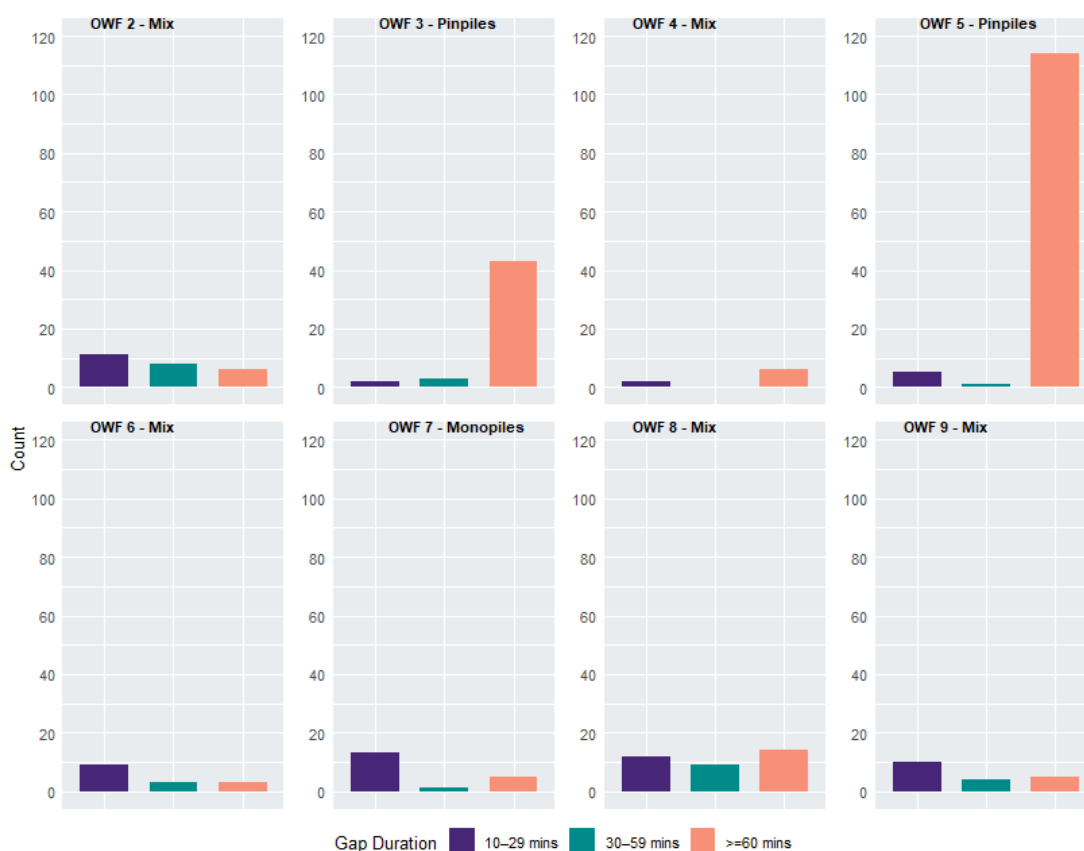


Figure 3. Frequency of gaps in piling when installing a single pile. N.B.: OWF1 was not included in this figure as exact piling log strike times were not provided. Hence, the exact length of gaps in piling could not be calculated.

### 3.3. Hammer energy

#### 3.3.1. Hammer energy during soft-start

Here the soft-start duration was defined as “the soft-start duration specified in the OWF specific MMMP”. Across the MMMPs for the 9 OWFs, the soft-starts were generally specified as lasting 20 minutes, though soft-start period ranged between a minimum of a 10 to 45 minutes.

Most soft-starts used hammer energies <500 kJ, although there was variation among the ranges of hammer energies used during soft-starts for different wind farms (Table 7). It was noteworthy that there were some challenges with adhering to the specified MMMP soft-start plan, with maximum hammer energies during the soft-start and the duration of the soft-start occasionally exceeding MMMP plans. Across wind farms, there was also variation between soft-start energies for pile types, with no consistent pile-type pattern driving this (Figure 4).

The mean of the average hammer energies used during soft-starts to install a monopile was 367 kJ, ranging from 115 to 1,586 kJ. The mean of the maximum hammer energies used during soft-starts to install a monopile was 525 kJ, ranging from 115 to 2717 kJ.

The mean of the average hammer energies used during soft-starts to install a pin pile was 334 kJ, ranging from 116 to 617 kJ. The mean of the maximum hammer energies used during soft-starts to install a pin pile was 493 kJ, ranging from 146 to 1234 kJ.

**Table 7. Summary of hammer energies used during the soft-start (using soft-start duration as defined by the MMMP) across all piles at each OWF. Across piles at each wind farm the minimum average and maximum are averaged, with the range also shown. Each cell shows the mean (min – max)**

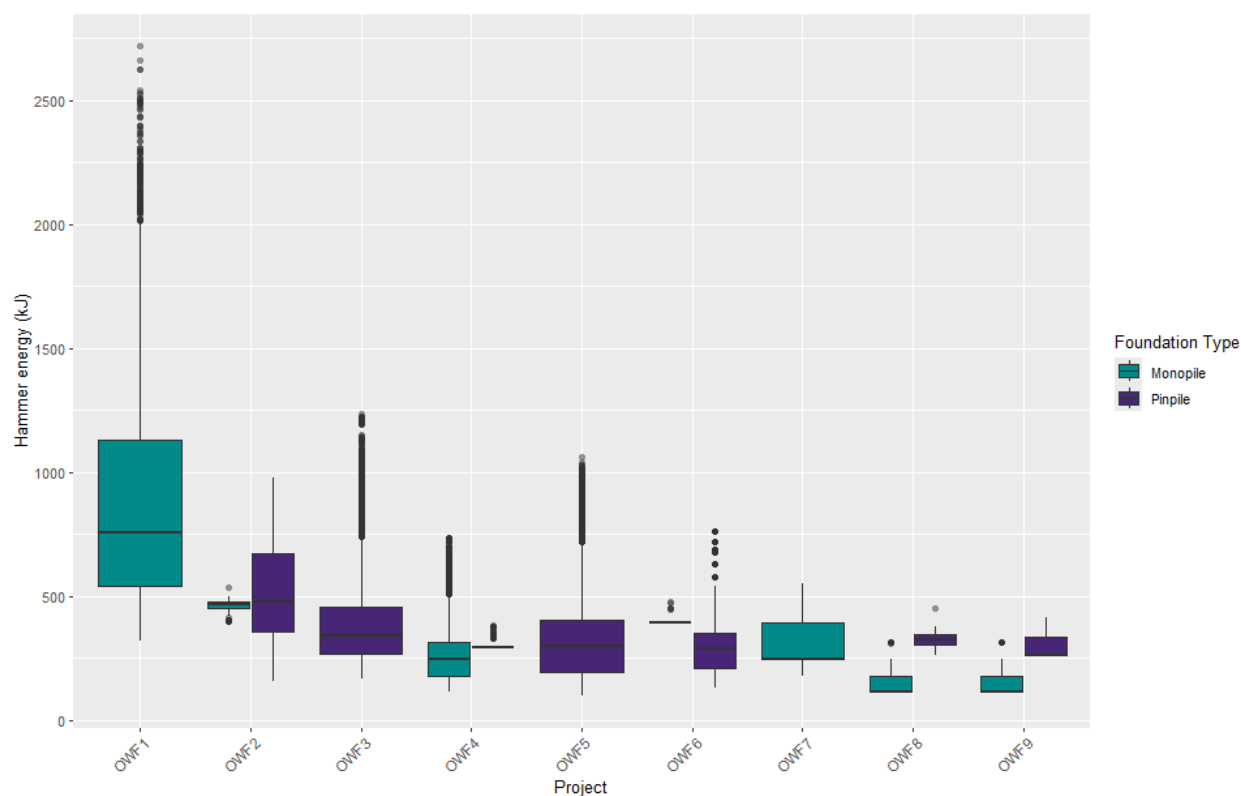
| OWF            | MONOPILE Hammer Energy |                    |                     |                      | PIN PILE Hammer Energy |                    |                    |                     |
|----------------|------------------------|--------------------|---------------------|----------------------|------------------------|--------------------|--------------------|---------------------|
|                | # piles                | Min.               | Avg.                | Max                  | # piles                | Min.               | Avg.               | Max                 |
| 1 <sup>1</sup> | 174                    | 496<br>(322 – 709) | 892<br>(458 – 1586) | 1451<br>(537 – 2717) | N/A                    |                    |                    |                     |
| 2              | 158                    | 402<br>(402 – 403) | 462<br>(454 – 470)  | 498<br>(496 – 534)   | 12                     | 237<br>(156 – 299) | 432<br>(172 – 617) | 582<br>(238 – 980)  |
| 3              | N/A                    |                    |                     |                      | 344                    | 231<br>(167 – 242) | 388<br>(265 – 553) | 750<br>(266 – 1234) |

<sup>1</sup> OWF1 did not follow the soft-start duration described in their MMMP. These values include significant ramp-up following an initial short soft-start

|                |           |                    |                    |                    |            |                    |                    |                     |
|----------------|-----------|--------------------|--------------------|--------------------|------------|--------------------|--------------------|---------------------|
| 4              | <b>87</b> | 115<br>(115 – 115) | 233<br>(115 – 403) | 416<br>(115 – 737) | <b>4</b>   | 293<br>(292 – 335) | 302<br>(292 – 364) | 316<br>(292 – 383)  |
| 5              | N/A       |                    |                    |                    | <b>308</b> | 146<br>(100 – 198) | 313<br>(116 – 476) | 705<br>(146 – 1064) |
| 6              | <b>99</b> | 397<br>(397 – 397) | 397<br>(397 – 398) | 398<br>(397 – 476) | <b>8</b>   | 226<br>(130 – 280) | 295<br>(144 – 460) | 416<br>(150 – 760)  |
| 7 <sup>2</sup> | <b>58</b> | 206<br>(181 – 247) | 309<br>(278 – 333) | 407<br>(397 – 553) | N/A        |                    |                    |                     |
| 8              | <b>94</b> | 115<br>(115 – 115) | 139<br>(116 – 170) | 264<br>(181 – 315) | <b>4</b>   | 300<br>(261 – 362) | 320<br>(261 – 398) | 344<br>(261 – 453)  |
| 9              | <b>94</b> | 115<br>(115 – 115) | 137<br>(115 – 182) | 242<br>(115 – 313) | <b>4</b>   | 261<br>(261 – 261) | 285<br>(261 – 348) | 341<br>(261 – 416)  |

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<sup>2</sup> OWF7 used vibro-piling prior to impact piling across many of the WTGs. This means that once they started impact piling after vibro-piling, their soft-start was at higher-than-normal hammer energies



**Figure 4. Hammer energy used during the soft-start period (with soft-start duration as defined by the MMMP). N.B.1: OWF1 did not follow the soft start duration described in their MMMP. These values include significant ramp-up following an initial short soft start. N.B.2: OWF7 used vibro-piling prior to impact piling across many of the WTGs. This means that once they started impact piling after vibro-piling, their soft start was at higher-than-normal hammer energies.**

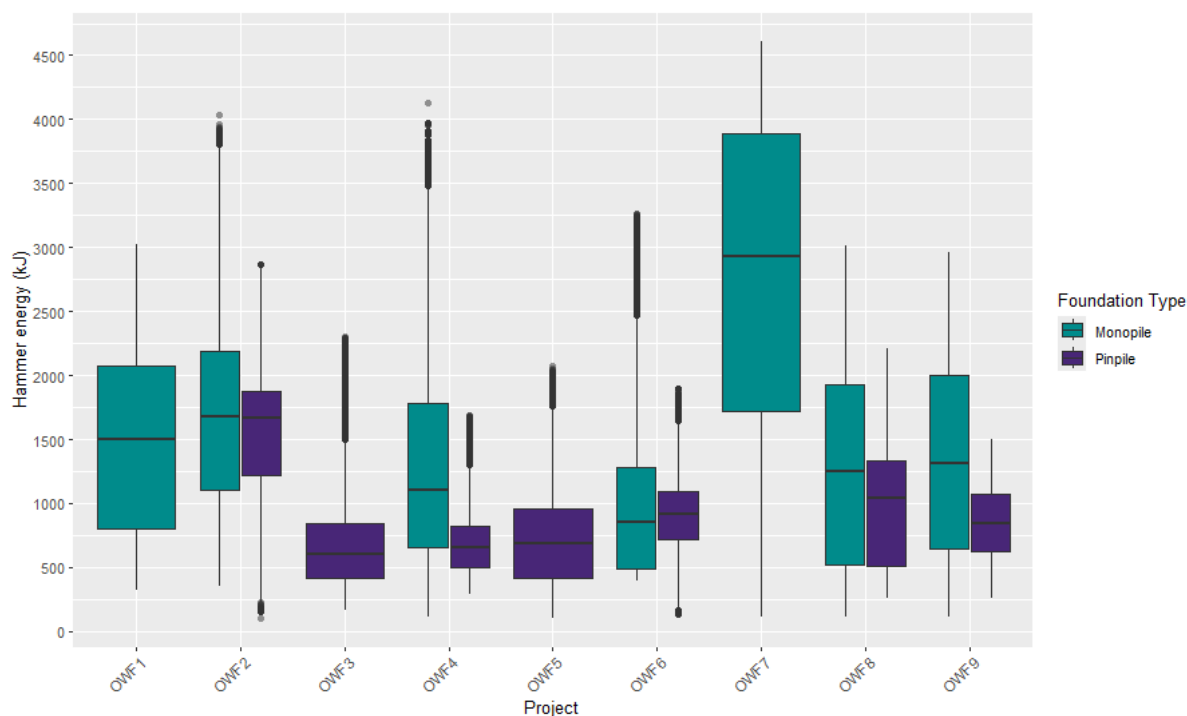
### 3.3.2. Hammer energy throughout all piling

Here hammer energy throughout piling includes full soft-starts as well as all operational piling.

The mean of the average hammer energies for monopiles was higher than that for pin piles, and hammer energies for monopiles also showed more variability than that for pin piles (Figure 5). Overall, however, distributions of hammer energies for both pile types across wind farms showed that the majority of blows tended to be concentrated at lower energies than the maximum recorded (Figure 6). This also demonstrated that real-world hammer energies were rarely at the maximum allowed in the MMMP or EIA for a given project (Figure 7).

The mean of the average hammer energies used to install a monopile was 1,493 kJ, ranging from 115 kJ to 3,848 kJ. The mean of the maximum hammer energies used to install a monopile was 2,563 kJ, ranging from 115 to 4,608 kJ.

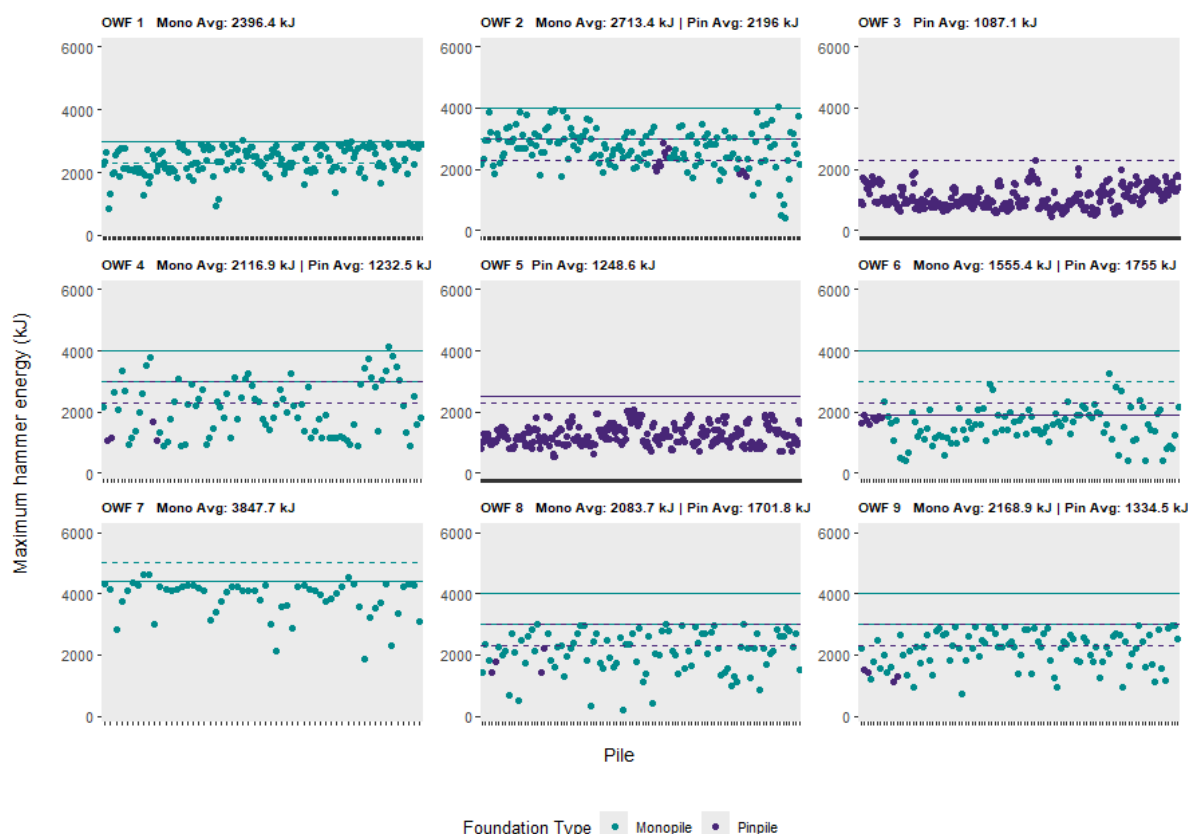
The mean of the average hammer energies used to install a pin pile was 898 kJ, ranging from 116 to 2,196 kJ. The mean of the maximum hammer energies used to install a pin pile was 2,078 kJ, ranging from 146 to 2,869 kJ.



**Figure 5. Box plots of the hammer energies used during piling (including the soft-start) across OWF 1-9.**



**Figure 6. The distribution of hammer energy across all piles installation on OWF 1-9. Green bars indicate monopiles. Blue bars indicate pin piles.**



**Figure 7. Maximum real-world hammer energy per pile (solid dots) for each foundation type at each OWF site. The solid line indicates the maximum hammer energy specified in the MMMP, while the dashed line indicates the maximum hammer energy assessed in the EIA.**

## 3.4. Blow rates

### 3.4.1. Blow rate during soft-start (MMMP)

Here the soft-start duration was defined as “[the soft-start duration specified in the OWF specific MMMP](#)”. Across the MMMPs for the 9 OWFs, the soft-starts were generally specified as lasting 20 minutes, though soft-start periods ranged between a minimum of 10 to 45 minutes.

Figure 8 and Table 8 show the blow rates used during the soft-start phase as outlined in the project-specific MMMPs. Soft-start blow rates varied considerably among projects and foundation types, reflecting differences in installation practices and site-specific conditions. Across all sites, monopile soft-start blow rates ranged from 1 to 52 blows min<sup>-1</sup>, while pin pile blow rates ranged from 1 to 62 blows min<sup>-1</sup>.

The mean of the average blow rates used during soft-starts to install a monopile across all projects was 7 blows min<sup>-1</sup>, where average blow rates ranged from 1 to 29 blows min<sup>-1</sup>. The mean of the maximum blow rates used during soft-starts to install a monopile was 11 blows min<sup>-1</sup>, where maximum blow rates ranged from 1 to 52 blows min<sup>-1</sup> across all projects.

In contrast, the mean of the average blow rates used during soft-starts to install a pin pile was 16 blows min<sup>-1</sup>, where average blow rates ranged from 1 to 45 blows min<sup>-1</sup>. The mean of the maximum

blow rates used during soft-starts to install a pin pile was 24 blows min<sup>-1</sup>, where maximum blow rates ranged from 1 to 62 blows min<sup>-1</sup>.

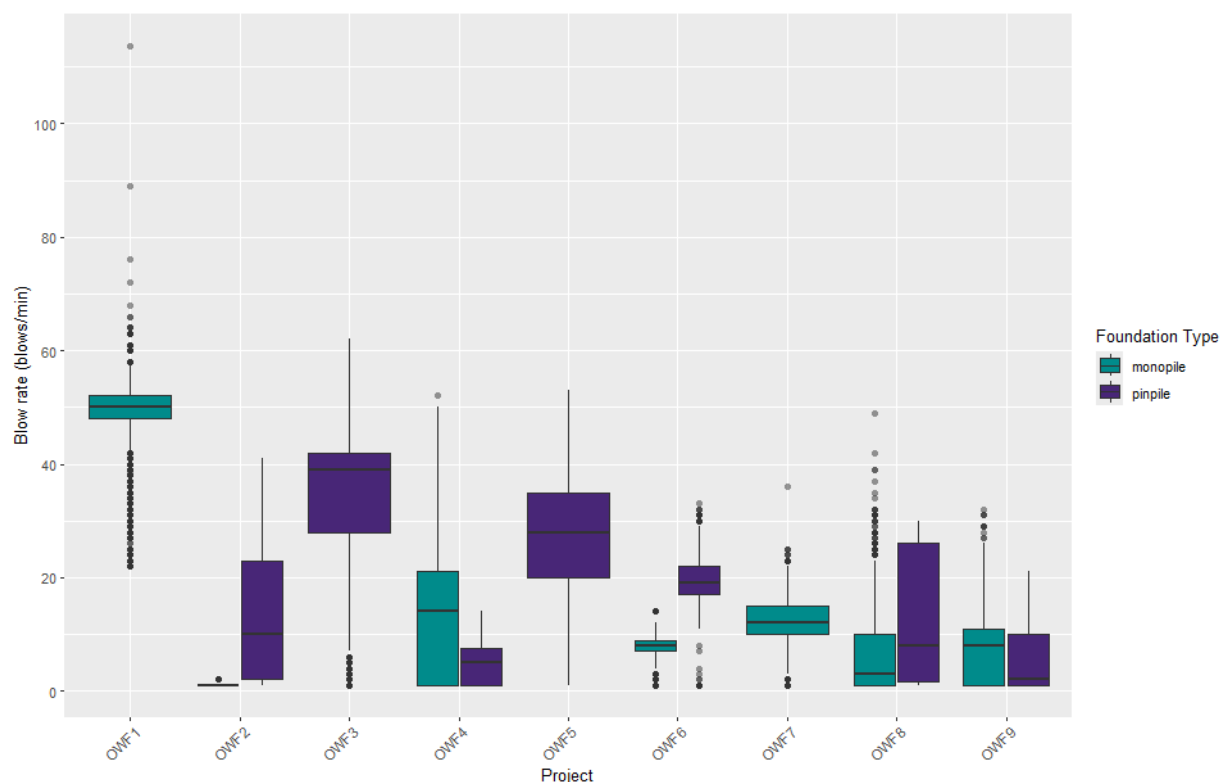
Variation was evident both among and within projects. For example, OWF 6 implemented higher blow rates during pin pile installation, whereas OWF 4 used higher blow rates for monopile installation than for pin piles.

**Table 8. Summary of blow rates used during the soft-start across all piles at each OWF. Values provided are: mean (min – max) (with soft-start duration as defined by the MMMP).**

| OWF            | MONOPILE<br>Blow Rate (blows/min) |               |               |                | PIN PILE<br>Blow Rate (/min) |             |               |               |
|----------------|-----------------------------------|---------------|---------------|----------------|------------------------------|-------------|---------------|---------------|
|                | # piles                           | Min.          | Avg.          | Max            | # piles                      | Min.        | Avg.          | Max           |
| 1 <sup>1</sup> | 174                               | 38<br>(22-50) | 49<br>(35-57) | 56<br>(48-114) | N/A                          |             |               |               |
| 2              | 158                               | 1<br>(1-2)    | 1<br>(1-2)    | 1<br>(1-2)     | 12                           | 1<br>(1-3)  | 13<br>(3-25)  | 25<br>(8-41)  |
| 3              | N/A                               |               |               |                | 344                          | 2<br>(1-5)  | 32<br>(1-45)  | 44<br>(1-62)  |
| 4              | 87                                | 1<br>(1-2)    | 12<br>(1-29)  | 22<br>(1-52)   | 4                            | 1<br>(1-1)  | 4<br>(3-8)    | 10<br>(6-14)  |
| 5              | N/A                               |               |               |                | 308                          | 3<br>(1-31) | 26<br>(4-37)  | 35<br>(9-53)  |
| 6              | 99                                | 1<br>(1-7)    | 7<br>(1-11)   | 8<br>(1-14)    | 8                            | 3<br>(1-11) | 20<br>(16-24) | 27<br>(21-33) |
| 7 <sup>2</sup> | 58                                | 3<br>(1-16)   | 11<br>(4-22)  | 15<br>(6-36)   | N/A                          |             |               |               |
| 8              | 94                                | 1<br>(1-4)    | 6<br>(1-23)   | 12<br>(1-49)   | 4                            | 2<br>(1-5)  | 12<br>(1-24)  | 17<br>(3-30)  |
| 9              | 94                                | 1<br>(1-3)    | 7<br>(1-16)   | 13<br>(1-32)   | 4                            | 1<br>(1-1)  | 6<br>(4-10)   | 15<br>(10-21) |

<sup>1</sup> Data for OWF 1 are not fully representative of the actual piling schedule, as blow rates were averaged over time, resulting in an overestimation of the true blow rates. Thus, these values are not included in the OWF comparison.

<sup>2</sup> Note, OWF7 used vibropiling before impact pile driving commenced



**Figure 8. Blow rates during soft-starts (with soft-start duration as defined by the MMMP).**

### 3.4.2. Blow rate throughout all piling

Blow rates throughout piling included the full soft-start as well as all operational piling periods. Table 9 and Figure 9 show blow rates throughout piling. Across most sites, monopiles were installed via more variable blow rates compared with pin pile installations. Blow rates ranged from 1 to 102 blows  $\text{min}^{-1}$  for monopiles and from 1 to 62 blows  $\text{min}^{-1}$  for pin piles.

The mean of the average blow rates used to install a monopile was 28 blows  $\text{min}^{-1}$ , where average blow rates ranged from 2.8 to 72.1 blows  $\text{min}^{-1}$ . The mean of the maximum blow rates used to install a monopile was 39.8 blows  $\text{min}^{-1}$ , where maximum blow rates ranged from 9 to 102 blows  $\text{min}^{-1}$ .

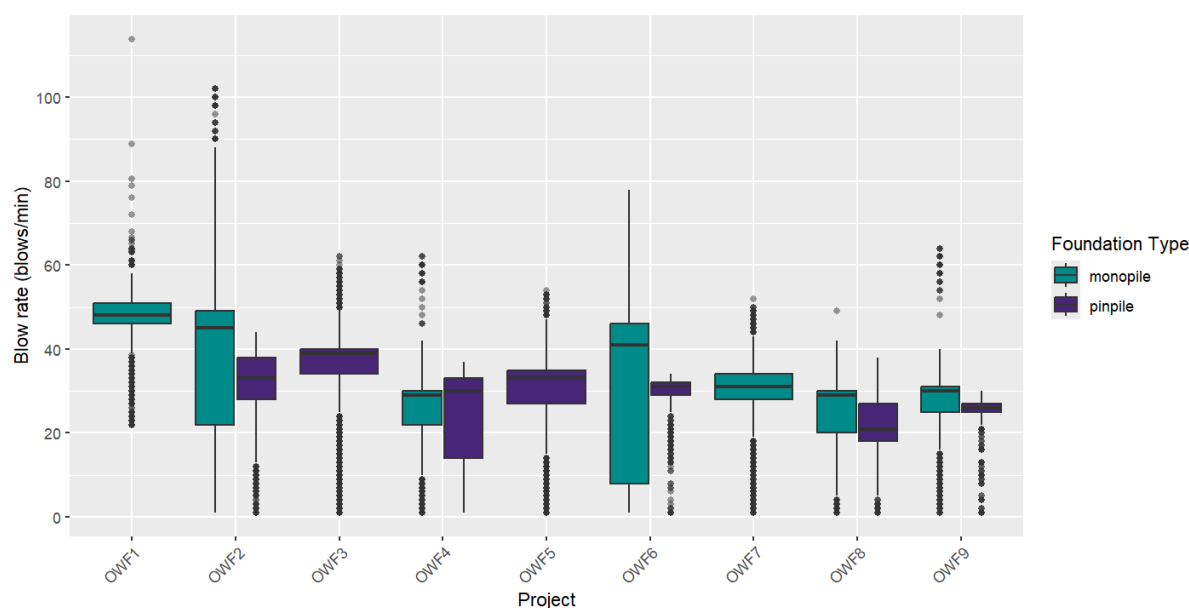
The mean of the average blow rates used to install a pin pile was 27.7 blows  $\text{min}^{-1}$ , where average blow rates ranged from 15.5 to 41.7 blows  $\text{min}^{-1}$ . The mean of the maximum blow rates used to install a pin pile was 36.1 blows  $\text{min}^{-1}$ , where maximum blow rates ranged from 22 to 62 blows  $\text{min}^{-1}$ .

Differences between foundation types were evident within some projects. For example, OWF 2 exhibited a substantially wider range of blow rates for monopiles (1 to 102 blows  $\text{min}^{-1}$ ) than for pin piles (1 to 44 blows  $\text{min}^{-1}$ ), while a similar pattern was observed at OWF 9 (1 to 64 blows  $\text{min}^{-1}$  for monopiles compared with 1 to 30 blows  $\text{min}^{-1}$  for pin piles).

**Table 9. Summary of blow rates used throughout the entire piling duration across all piles at each OWF. Values provided are: mean (min – max) (with soft-start duration as defined by the MMMP).**

| OWF                  | MONOPILE<br>Blow rate (blows/min) |                     |                       |                        | PIN PILE<br>Blow rate (blows/min) |                     |                       |                       |
|----------------------|-----------------------------------|---------------------|-----------------------|------------------------|-----------------------------------|---------------------|-----------------------|-----------------------|
|                      | # piles                           | Min.                | Avg.                  | Max                    | # piles                           | Min.                | Avg.                  | Max                   |
| <b>1<sup>1</sup></b> | <b>174</b>                        | 37.4<br>(21.9 – 48) | 48.4<br>(38.9 – 54.2) | 56.3<br>(48 – 113.8)   | N/A                               |                     |                       |                       |
| <b>2</b>             | <b>158</b>                        | 1.0<br>(1.0 – 2.0)  | 36.5<br>(7.9 – 72.1)  | 51.9<br>(11.0 – 102.0) | <b>12</b>                         | 1.3<br>(1.0 – 2.0)  | 30.0<br>(25.0 – 35.4) | 40.7<br>(34.0 – 44.0) |
| <b>3</b>             | N/A                               |                     |                       |                        | <b>344</b>                        | 1.5<br>(1.0 – 5.0)  | 34.2<br>(22.7 – 41.7) | 44.9<br>(38.0 – 62.0) |
| <b>4</b>             | <b>87</b>                         | 1.0<br>(1.0 – 2.0)  | 25.1<br>(19.7 – 49.4) | 33.0<br>(29.0 – 62.0)  | <b>4</b>                          | 1.0<br>(1.0 – 1.0)  | 24.4<br>(23.5 – 26.9) | 36.5<br>(35.0 – 37.0) |
| <b>5</b>             | N/A                               |                     |                       |                        | <b>308</b>                        | 1.9<br>(1.0 – 7.0)  | 29.8<br>(21.8 – 38.8) | 38.3<br>(32.0 – 54.0) |
| <b>6</b>             | <b>99</b>                         | 1.0<br>(1.0 – 3.0)  | 29.2<br>(15.3 – 52.8) | 48.7<br>(41.0 – 78.0)  | <b>8</b>                          | 3.1<br>(1.0 – 11.0) | 29.0<br>(26.6 – 30.4) | 33.0<br>(32.0 – 34.0) |
| <b>7</b>             | <b>58</b>                         | 1.8<br>(1.0 – 8.0)  | 29.5<br>(21.9 – 38.8) | 39.7<br>(31 – 52)      | N/A                               |                     |                       |                       |
| <b>8</b>             | <b>94</b>                         | 1.1<br>(1.0 – 2.0)  | 23.7<br>(2.8 – 28.2)  | 32.3<br>(9.0 – 49.0)   | <b>4</b>                          | 1.0<br>(1.0 – 1.0)  | 22.2<br>(15.5 – 27.8) | 30.5<br>(22.0 – 38.0) |
| <b>9</b>             | <b>94</b>                         | 1.1<br>(1.0 – 2.0)  | 26.1<br>(20.4 – 52.9) | 33.4<br>(30.0 – 64.0)  | <b>4</b>                          | 1.0<br>(1.0 – 1.0)  | 24.4<br>(23.5 – 25.2) | 29.0<br>(28.0 – 30.0) |

<sup>1</sup> Data for OWF 1 are not fully representative of the actual piling schedule, as blow rates were averaged over time, resulting in an overestimation of the true blow rates. Thus, these values are not included in the OWF comparison.



**Figure 9. Blow rates over the course of the entire pile installation (including soft-start).**

### 3.5. Summary

Maximum real-world hammer energies both during the soft-start and throughout piling varied both within and between OWF projects, demonstrating the level of variability in piling operations across the OWFs analysed (Figure 7). In most cases, real-world hammer energies remained below the maximum values assessed in the EIA and specified in the MMMP. Across all nine of the OWFs analysed, only 181 out of 1,448 piles (12.5%) reached or exceeded the maximum hammer energy defined in the EIA. Across eight of the nine OWFs analysed, only 8 out of 1,104 piles (0.55%) reached or exceeded the maximum hammer energy defined in the MMMP. These findings suggest that worst-case hammer energies used in environmental assessments are highly conservative and may overestimate the spatial extent of piling-related impacts under typical installation conditions.

Blow rates varied substantially among projects and foundation types, demonstrating considerable variation in soft-start and piling practices across OWFs. During soft-starts, pin piles generally used higher blow rates than monopiles, with mean maximum blow rates of 24 and 11 blows min<sup>-1</sup>, respectively. Across the full piling process, mean blow rates were similar between foundation types; however, monopiles exhibited greater variability and higher maximum blow rates, reaching up to 102 blows min<sup>-1</sup> compared with 62 blows min<sup>-1</sup> for pin piles.

The vast majority of piles were installed in under 2 hours across all OWFs, though piling profiles also varied considerably within and between OWFs, with no consistent installation pattern observed across projects. On average, pin pile installations took longer to complete than monopile installations (Table 6), although substantial variation was evident among projects. Large breaks in piling activity occurred on occasion and, in some cases, occurred multiple times during the installation of a single foundation (Figure 3). While breaks did occur, active piling days throughout installation remained fairly low with most piles being installed within 1 or 2 calendar days (Figure 2).

Collectively, these findings highlight the considerable variability in real-world piling schedules and indicate that a conservative single worst-case piling profile is unlikely to capture the full range of installation conditions encountered across offshore wind farm projects.

## 4. Task 3: Comparison of real vs EIA piling profiles

The cumulative PTS impact range is defined as “the minimum safe starting distance from the pile an individual must be at the start of the pile driving event”. This means that if the cumulative PTS range is 7 km, any animal that is located between 0-7 km from the pile at the start of the pile driving event will accumulate sufficient energy to result in a hearing threshold shift that meets the PTS-onset threshold. Any animal that is located >7 km from the pile at the start of the pile driving event will not accumulate sufficient energy to result in a hearing threshold shift that meets the PTS-onset threshold.

The piling profile presented in the EIA for each of the nine OWFs were run through the RaDIN2 simulation tool to obtain cumulative PTS impact ranges. Following this, each real piling log for each of the nine OWF was run through the RaDIN2 simulation tool to enable a comparison on the cumulative PTS impact ranges predicted by the EIA piling profile to real world piling logs.

### 4.1. RaDIN 2 tool settings for real vs EIA piling profiles comparison

#### 4.1.1. Movement and Behavioural Response Mechanisms

For all the simulations aiming at comparing real vs EIA piling profiles, the normal speed of the animats was set as in Table 10. No behavioural response was modelled.

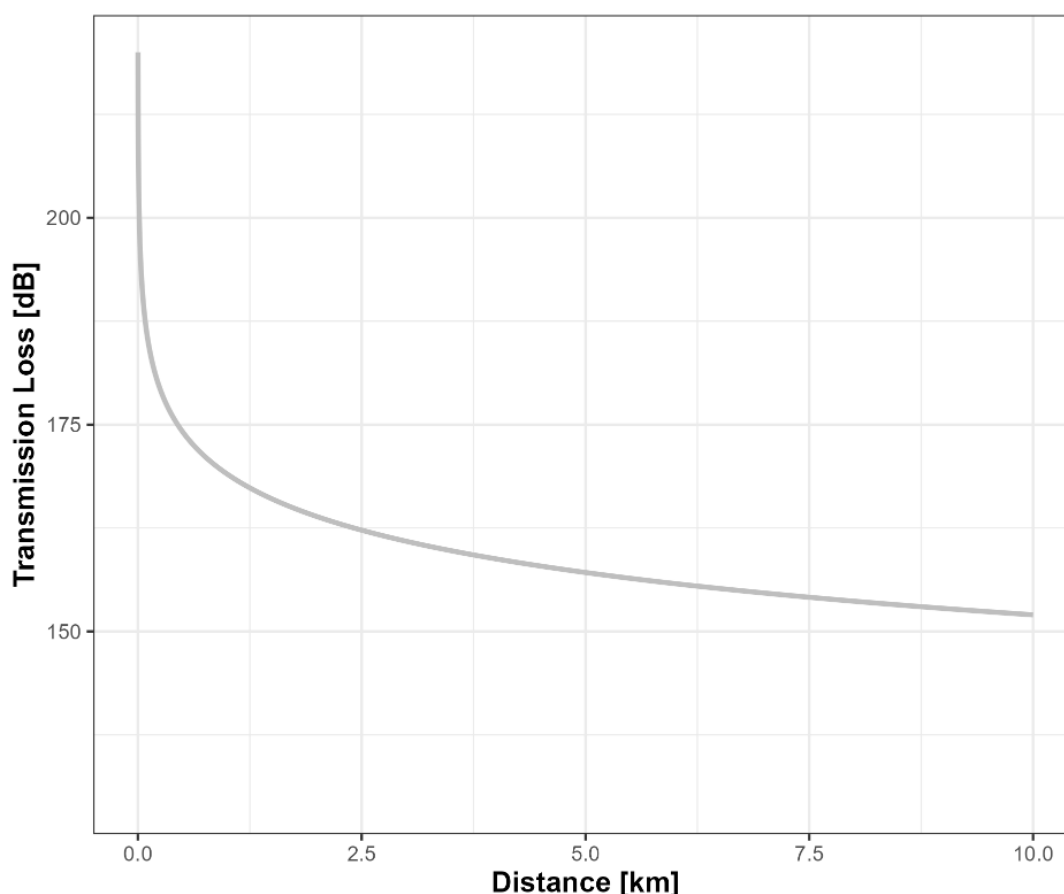
**Table 10. Summary of speeds for the two modelled species. SD – standard deviation.**

| Species         | Type   | Speed – mean (m/s) | Speed – SD (m/s) |
|-----------------|--------|--------------------|------------------|
| Harbor porpoise | normal | 1.5                | 0                |
| Minke whale     | normal | 3.25               | 0                |

#### 4.1.2. Acoustic Model

Transmission loss calculations incorporated spreading loss (geometric spreading coefficient  $x = 17$ ) without frequency-dependent attenuation ( $\alpha = 0$ ) (Equation 2). These parameters were chosen after reviewing past propagation loss curves from underwater noise modelling reports and plotting various combinations of coefficients against them. For this study, the frequency-dependent attenuation coefficient was set to zero because of the incorporation of frequency weighting corrections at a subsequent analysis stage (see section 4.1.3). Nonetheless, the tool would allow the user to change these parameters to better reflect the bathymetric and oceanographic at a given site.

That resulting transmission loss for this study, with a source level equal to 220 dB as an example, is shown in Figure 10.



**Figure 10. Sound transmission loss over distance assuming a source level of 220 dB, geometric spreading coefficient of 17, and frequency-dependent attenuation ( $\alpha$ ) set to zero.**

#### 4.1.3. Thresholds and frequency weighting corrections

For this study, auditory weighting corrections to broadband single-strike sound exposure level ( $SEL_{ss}$ ) were derived from Southall et al. (2019) auditory weighting functions for different marine mammal functional hearing groups (LF cetaceans, HF cetaceans, VHF cetaceans, and pinnipeds in water). Corrections were derived assuming a representative low-frequency-dominated impact pile-driving source spectrum for a large-diameter ( $\sim 11$  m) monopile, and a representative impact pile-driving source spectrum for a 2.5 m diameter pin pile, characterised by broader mid-frequency content than large-diameter monopiles (Verfuss et al., 2023, Bellmann et al., 2023, Robinson et al., 2012, Bailey et al., 2010).

For monopiles foundations driven by impact hammers, the underwater acoustic source spectrum is characteristically strongly dominated by low-frequency energy, with the majority of acoustic energy concentrated below  $\sim 300$ – $500$  Hz and spectral levels decreasing rapidly at higher frequencies. These spectral characteristics underpin the range-dependent auditory weighting corrections applied here (Table 11), particularly the large negative adjustments required for VHF cetaceans, and the comparatively small corrections for LF cetaceans. Compared to large monopiles, pin piles retain marginally greater mid-frequency energy at long range, although by  $\sim 7$ – $9$  km, the received spectrum is still sufficiently low-frequency dominated that auditory weighting corrections vary only weakly with additional range (Table 11).

Sound energy in seawater is attenuated by absorption processes that increase with frequency, leading to more rapid loss of mid and high frequency components relative to low frequencies over propagation distance. Progressive loss of mid- and high-frequency energy with range was therefore assumed when generating auditory weighting corrections due frequency-dependent absorption. Moreover, in shallow water, the sound field is constrained vertically, which leads to the acoustic energy in mid- and high-frequency ranges to attenuate faster as a result of modal stripping. The correction values presented in Table 11 account for these processes and are split into distance bins to appropriately capture the variability in spectral content received by an animal at various distances from a piling location.

**Table 11. Range-dependent auditory weighting corrections applied to broadband SEL<sub>ss</sub> for low-frequency (LF) and very high-frequency (VHF) cetaceans during simulations of animals exposed to impact pile driving. These values assume a water depth of 33 m, a monopile foundation diameter of 11 m and a pin pile foundation diameter of 2.5 m.**

| Distance from piling (m) | Range over which to apply corrections (m) | Monopile |       | Pin Piles |       |
|--------------------------|-------------------------------------------|----------|-------|-----------|-------|
|                          |                                           | LF       | VHF   | LF        | VHF   |
| 1                        | 1-249                                     | -1.5     | -18   | 0         | -11   |
| 250                      | 250-499                                   | -1.5     | -22   | 0         | -15   |
| 500                      | 500-749                                   | -1.5     | -24   | 0         | -17   |
| 750                      | 750-1,499                                 | -1.6     | -25.5 | 0         | -18.5 |
| 1,500                    | 1,500-2999                                | -1.6     | -28.5 | 0         | -21   |
| 3,000                    | 3,000-4,499                               | -1.7     | -32   | -0.1      | -24   |
| 4,500                    | 4,500-5,999                               | -1.7     | -34.5 | -0.1      | -26   |
| 6,000                    | 6,000-7,499                               | -1.8     | -36   | -0.1      | -27.5 |
| 7,500                    | 7,500-8,999                               | -1.9     | -37.5 | -0.2      | -28.5 |
| 9,000                    | >9,000                                    | -2       | -38.5 | -0.2      | -29.5 |

#### 4.1.4. Model outputs

All results are presented as percentage change in PTS distance (R<sub>Safe</sub>) between the predictions from piling schedules reported in the EIA and actual field logs. Because identical transmission loss and frequency weighting parameters were applied to both scenarios, the relative comparison is robust to uncertainty in these parameter values; differences in R<sub>Safe</sub> reflect true differences in exposure, not differences in model parameterization.

#### 4.1.5. MMMP vs piling logs

An assessment was carried out using a subset of piling logs from OWF with MMMP documents available to the project team. This was done to consider whether the MMMP, which is completed

after more detailed geophysical surveys are completed (leading to more accurate assessments of ground conditions for pile installation), would lead to more realistic estimates of impact. The MMMP or Piling Strategy documents are typically finalised around six months prior to construction. Therefore, comparisons undertaken between MMMP and real piling logs for a subset of four OWFs (374 piling logs, all monopiles).

## 4.2. Harbour porpoise

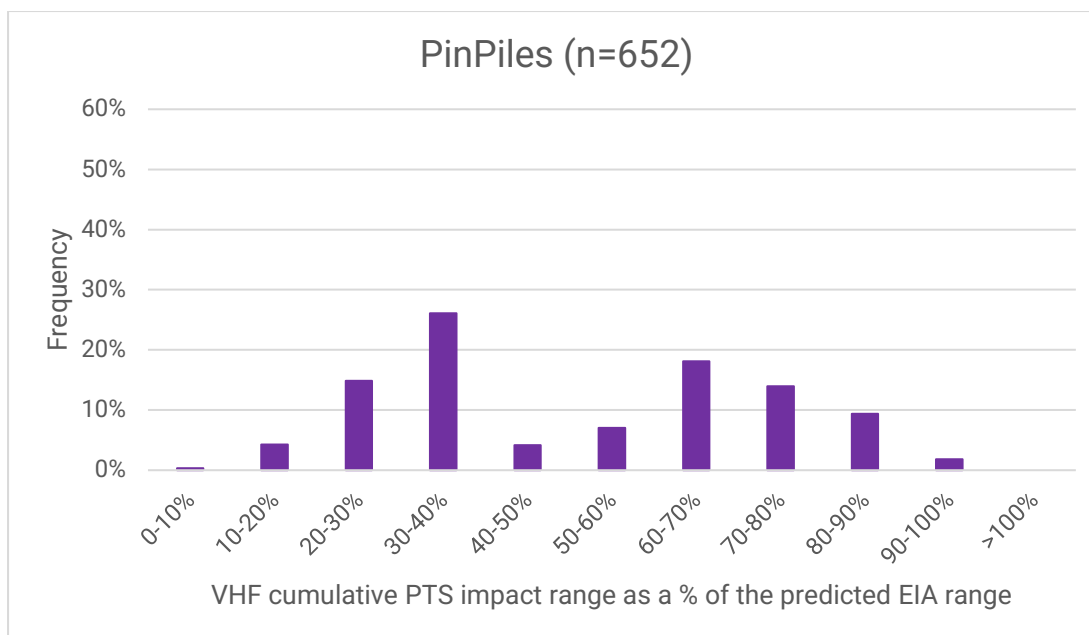
### 4.2.1. EIA piling profile vs real piling logs

The comparison of cumulative PTS impact ranges predicted by the EIA piling profile with the real piling logs has shown that the real cumulative PTS ranges are substantially smaller than those predicted by the EIA piling profile (Table 12, Figure 11, Figure 12). This shows that what is assessed in EIA looks likely to double (at least) the impact compared to reality:

- 50% of the real pin pile piling logs had cumulative PTS impact ranges that were <50% of the cumulative PTS range predicted using the EIA piling profile
- 96% of the real monopile piling logs had cumulative PTS impact ranges that were <50% of the cumulative PTS range predicted using the EIA piling profile.

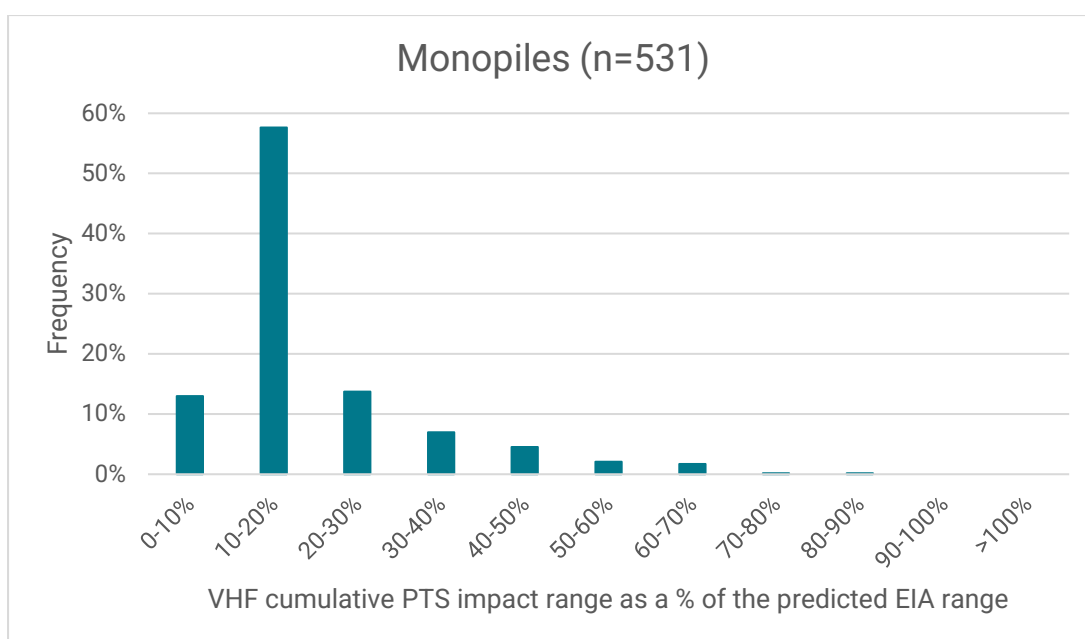
**Table 12. Piling log PTS range as a % of the EIA PTS range for harbour porpoise across all OWFs combined.**

| Piling log PTS range as a % of the EIA PTS range | Pin piles  | Monopiles  |
|--------------------------------------------------|------------|------------|
| 0-10%                                            | 0%         | 13%        |
| 0-20%                                            | 5%         | 71%        |
| 0-30%                                            | 19%        | 84%        |
| 0-40%                                            | 46%        | 91%        |
| <b>0-50%</b>                                     | <b>50%</b> | <b>96%</b> |
| 0-60%                                            | 57%        | 98%        |
| 0-70%                                            | 75%        | 100%       |
| 0-80%                                            | 89%        | 100%       |
| 0-90%                                            | 98%        | 100%       |
| 0-100%                                           | 100%       | 100%       |



**Figure 11. Harbour porpoise cumulative PTS impact range using real piling logs as a percentage of the predicted cumulative PTS impact range using the EIA piling schedule for pin piles.**

*100% means agreement in impact range between EIA and real piling logs, <100% means impact ranges from piling logs were less than predicted by the EIA piling schedule.*



**Figure 12. Harbour porpoise cumulative PTS impact range using real piling logs as a percentage of the predicted cumulative PTS impact range using the EIA piling schedule for monopiles.**

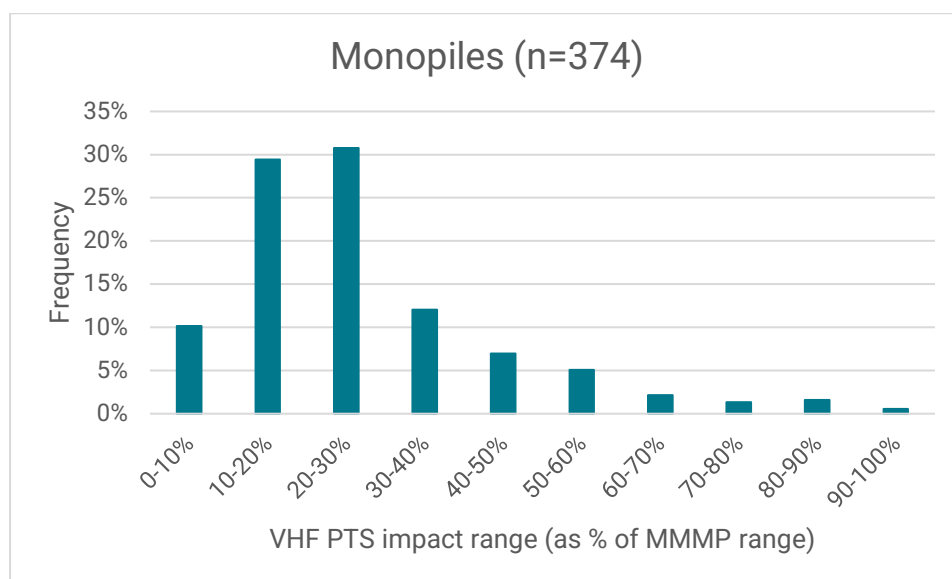
#### 4.2.2. MMMP piling profile vs real piling logs

The comparison of cumulative PTS impact ranges predicted by the MMMP piling profile with the real piling logs has shown that the real cumulative VHF cetacean PTS ranges are substantially smaller

than those predicted by the MMMP piling profile (Figure 13). This shows that what is assessed in MMMP looks likely to double (at least) the impact compared to reality:

- 89% of the real monopile piling logs had PTS-onset impact ranges that were <50% of the predicted range using the MMMP piling profile.

This means that overall, between the EIA and MMMP phases, the risk has moved from 96% chance of an overestimate by a factor of 2, to 89% chance of 2x overestimation. This suggests the detailed geophysical data and refined piling parameters has had only a minor effect on the precaution in the assessment. This is likely due to the fact that the MMMP is still required to provide the worse-case scenario.



**Figure 13. Harbour porpoise cumulative PTS impact range using real piling logs as a percentage of the predicted cumulative PTS impact range using the MMMP piling schedule for monopiles.**

## 4.3. Minke whales

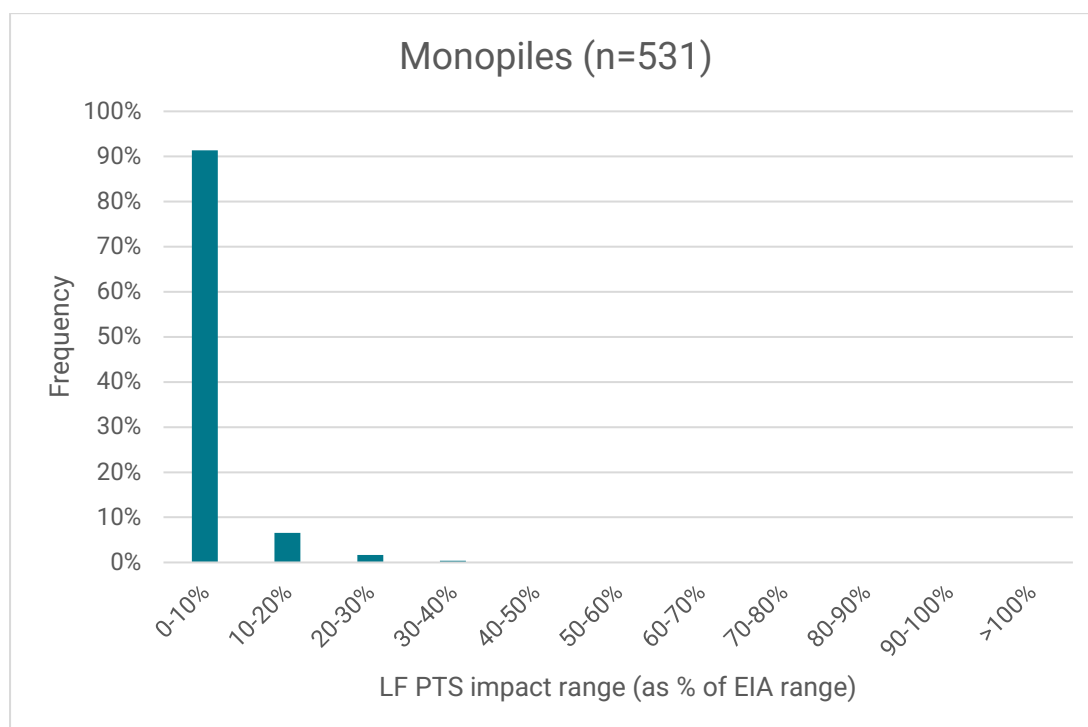
### 4.3.1. EIA piling profile vs real piling logs

The same approach, as above, for high frequency cetaceans like harbour porpoises, was taken for LF cetaceans, such as the minke whale. Similarly to VHF cetaceans, large overestimations in impact were apparent when comparing results from EIA piling profile and real piling logs (Table 13, Figure 14, Figure 15). These are summarised as:

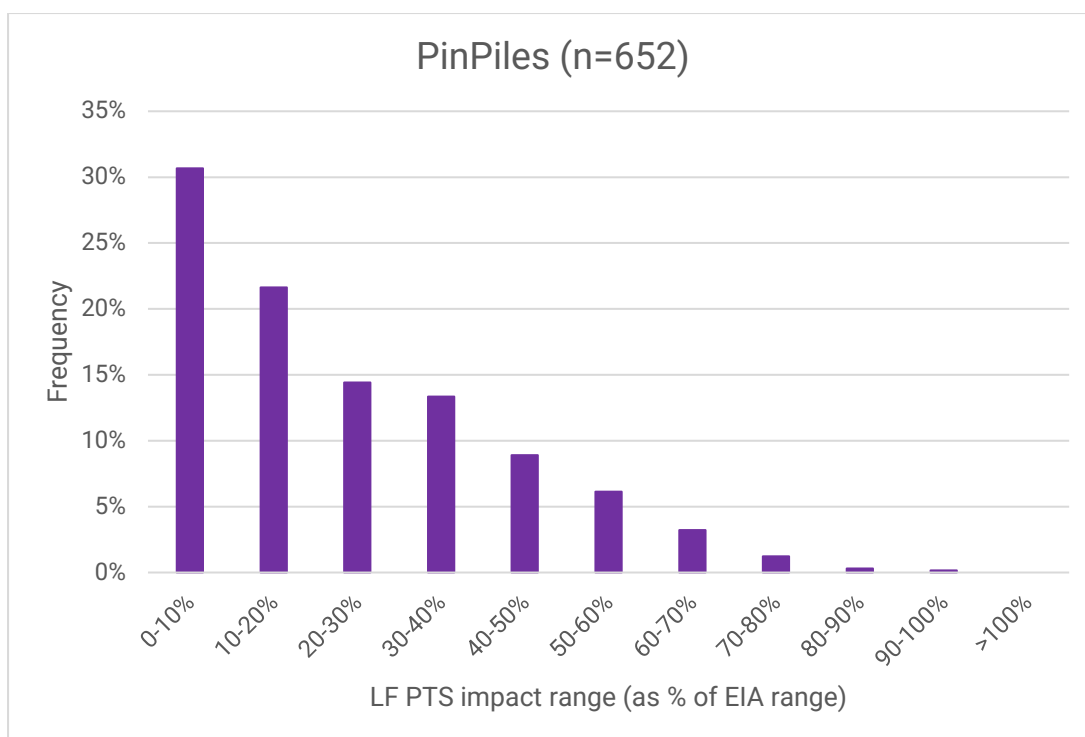
- 89% of the real pin pile piling logs had PTS-onset impact ranges that were <50% of the predicted range using the EIA piling profile
- 100% of the real monopile piling logs had PTS-onset impact ranges that were <30% of the predicted range using the EIA piling profile.

**Table 13. Piling log PTS range as a % of the EIA PTS range for minke whales across all OWFs combined.**

| Piling log PTS range as a % of the EIA PTS range | Pin piles  | Monopiles   |
|--------------------------------------------------|------------|-------------|
| 0-10%                                            | 31%        | 91%         |
| 0-20%                                            | 52%        | 98%         |
| 0-30%                                            | 67%        | 100%        |
| 0-40%                                            | 80%        | 100%        |
| <b>0-50%</b>                                     | <b>89%</b> | <b>100%</b> |
| 0-60%                                            | 95%        | 100%        |
| 0-70%                                            | 98%        | 100%        |
| 0-80%                                            | 100%       | 100%        |
| 0-90%                                            | 100%       | 100%        |
| 0-100%                                           | 100%       | 100%        |



**Figure 14. Minke whale cumulative PTS impact range using real piling logs as a percentage of the predicted cumulative PTS impact range using the EIA piling schedule for monopiles.**



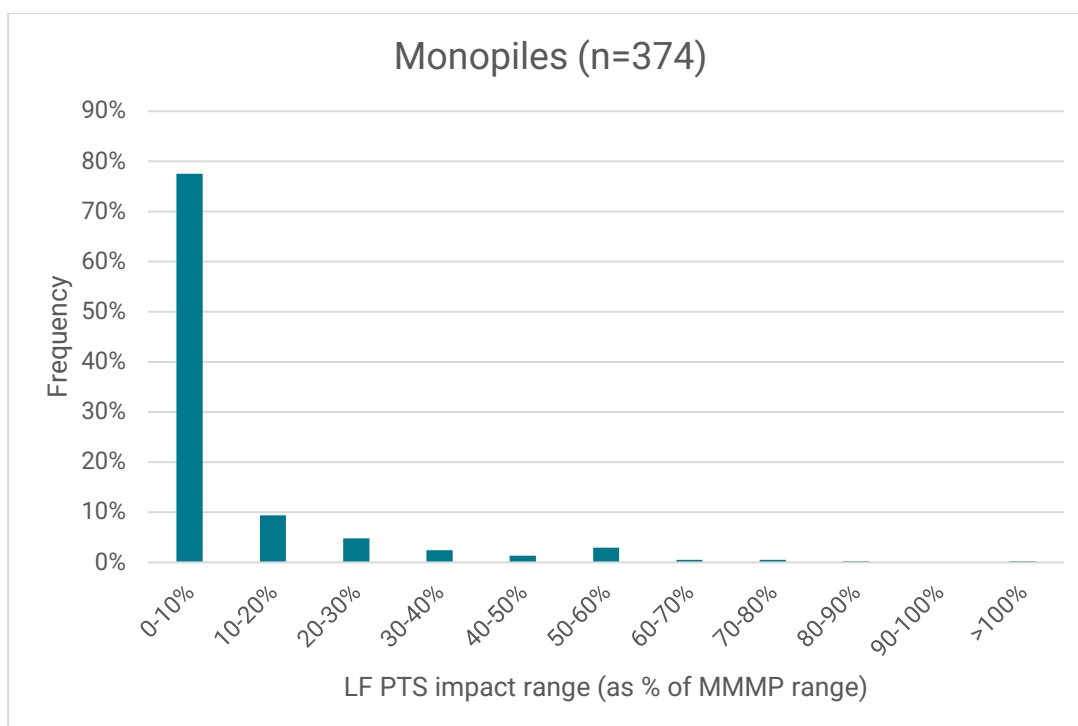
**Figure 15. Minke whale cumulative PTS impact range using real piling logs as a percentage of the predicted cumulative PTS impact range using the EIA piling schedule for pin piles.**

#### 4.3.2. MMMP piling profile vs real piling logs

The comparison of cumulative PTS impact ranges predicted by the MMMP piling profile with the real piling logs has shown that the real cumulative PTS ranges for LF cetacean are substantially smaller than those predicted by the MMMP piling profile (Figure 16). This shows that what is assessed in the MMMP looks likely to double (at least) the impact compared to reality:

- 95% of the real monopile logs had PTS-onset impact ranges that were <30% of the predicted range using the MMMP piling profile.

This means that overall, between the EIA and MMMP phases, the risk has moved from 100% chance of being an overestimate by a factor of 2, to 95% chance of a 2x overestimation. 78% of estimates were within 10% of the EIA ranges, suggesting a high chance of 10x overestimation. This suggests the detailed geophysical data and refined piling parameters that are available at the MMMP stage had only a minor effect on the precaution in the assessment.



**Figure 16. Minke whale cumulative PTS impact range using real piling logs as a percentage of the predicted cumulative PTS impact range using the MMMP piling schedule for monopiles.**

## 4.4. Summary

The EIA and MMMP piling profiles both substantially over-estimate cumulative PTS ranges compared to predictions using the real piling logs. There is no single reason for the large difference between EIA/MMMP and real piling logs, but is a combination of:

- higher blow rates during the soft-start and during the ramp-up for modelling compared to real piling logs
- higher hammer energies during the soft-start and during the ramp-up for modelling compared to real piling logs
- shorter soft-starts and ramp-up durations for modelling compared to real piling logs
- the requirement to model the worst-case scenario at both EIA and MMMP.

## 4.5. Assessing the effect of speed and response behaviour

### 4.5.1. Method

To systematically evaluate how swimming speed and avoidance behaviour mechanisms influence the minimum safe distance (R<sub>Safe</sub>), we designed a comprehensive scenario matrix encompassing 89 model runs using harbour porpoise as an example. All scenarios modelled a population of 1,500 harbour porpoise exposed to pile driving from a pin-pile foundation in accordance with the piling schedule outlined in the EIA.

Swimming speeds were drawn stochastically from normal distributions updated at each 1-second time step, with three mean normal swimming speeds tested: 1.19 m/s, 1.50 m/s and 1.97 m/s. These values represent realistic range of movement speeds for harbour porpoise (Table 1). Speed variability was incorporated by specifying standard deviations (SD = 0.17–0.19 m/s when included, or SD = 0 for deterministic scenarios) to capture population heterogeneity. Fleeing speeds were set to 1.97 m/s (mean observed speed when exposed to piling, Table 1) when avoidance behaviour was triggered, with animals reverting to normal speed upon behaviour cessation.

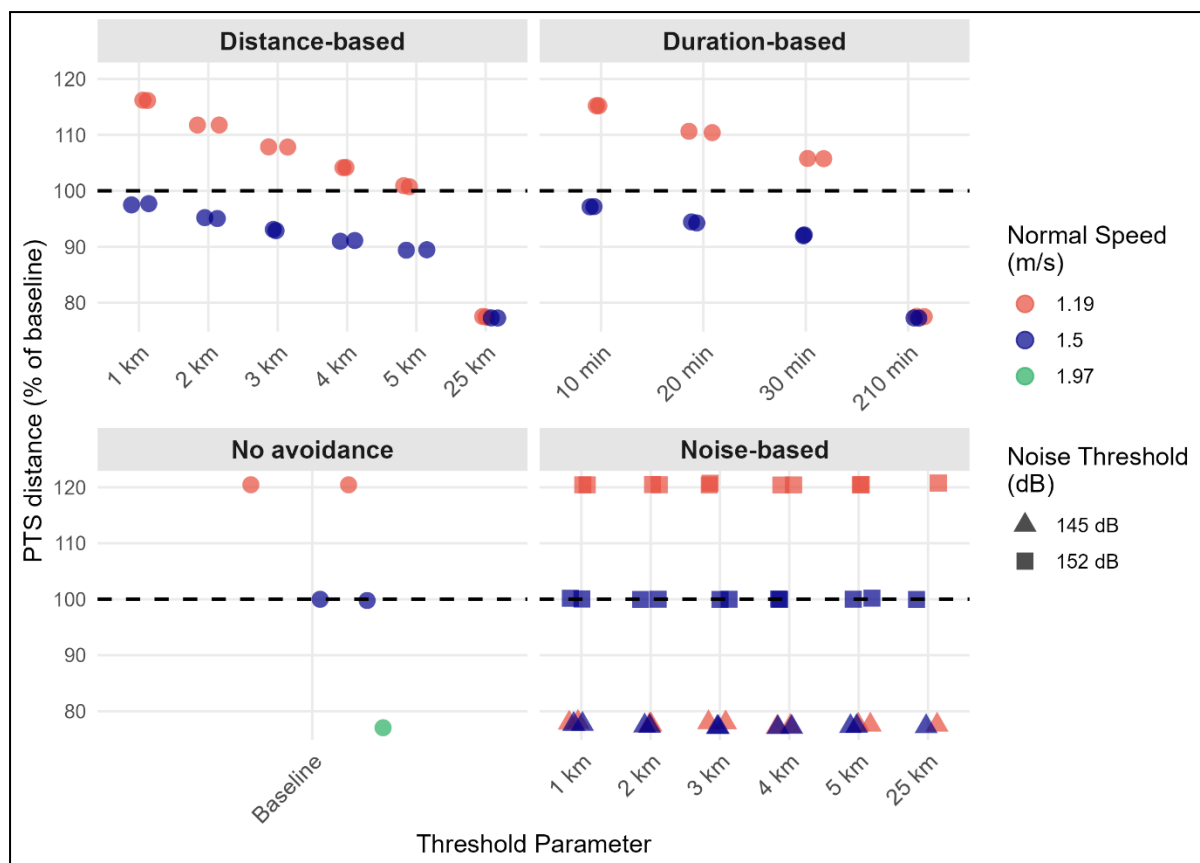
Three independent avoidance triggers were tested:

- Distance-based avoidance: Animals flee when distance from source drops below a specified threshold (tested thresholds: 1, 2, 3, 4, 5, or 25 km).
- Duration-based avoidance: Animals flee after cumulative exposure duration exceeds a specified threshold (tested thresholds: 10, 20, 30, or 210 minutes).
- Noise-based avoidance: Animals flee when received sound level exceeds a specified dB threshold (tested at 145 dB or 152 dB), with behaviour triggered across distance ranges of 1, 2, 3, 4, 5, or 25 km. The 145 dB threshold represents a biologically-informed behavioural response criterion, based on Lucke et al. (2009) observations of aversive behavioural reactions at received sound levels above SEL of 145 dB. The 152 dB threshold corresponds to empirical behavioural response used in DEPONS (Nabe-Nielsen et al., 2018).
- A scenario at 1.50 m/s, no speed SD and no behavioural response served as the baseline for calculating relative effects of behaviour and speed changes.

All scenarios used the same spherical spreading loss and frequency weighting as described in section 4.1.

#### 4.5.2. Results

Normal swimming speed had a substantially larger effect on the PTS-onset impact range (safe starting distance,  $R_{safe}$ ) than avoidance behaviour type (Figure 17). At the slowest normal speed (1.19 m/s), all avoidance scenarios required animals to initiate exposure at distances 5–17% greater than the baseline to avoid PTS, whereas the fastest speed (1.97 m/s with no avoidance) allowed animals to start 22% closer to the source while remaining protected. In contrast, avoidance behaviour mechanisms showed more modest effects, with  $R_{Safe}$  varying by 5–15% depending on trigger threshold. Noise-based avoidance showed the most constrained outcomes out of the three behavioural mechanisms, with 145 dB triggering distances requiring ~25% reduction in  $R_{Safe}$  compared to baseline, while 152 dB thresholds produced minimal change (within  $\pm 5\%$  of baseline). These results indicate that avoidance effectiveness is dominated by the chosen swimming speed rather than the specific mechanism triggering the behavioural response, likely because animals spend the majority of exposure time at normal swimming speeds rather than engaged in active fleeing. Only when avoidance is extended to unrealistic extremes—fleeing for 210 minutes or 25 km—do behavioural reductions in PTS distance approach the magnitude of speed-related effects.



**Figure 17. Effect of behavioural response and animal speed on the PTS distances.**

## 5. Task 4: Piling schedule workshop summary

The full workshop report is provided in Task 4 workshop report.

A key need identified from the RaDIN project, was the engagement of multiple stakeholders relevant to the issue of auditory injury impacts from pile driving. To achieve this, we delivered a 3 hour workshop to update stakeholders on the RaDIN2 project outcomes and to provide facilitated engagement between engineers, regulatory advisors, EIA and Consenting experts, acousticians, and marine mammal specialists to develop practical solutions to streamline EIA processes. The goal was that we would also gather feedback and stimulate discussion on how to collaboratively improve consenting processes, highlight limitations of the project's proposed approach and suggest next steps for follow-up analyses.

The workshop took place on the 19<sup>th</sup> May 2026, hosted by SMRU Consulting and the Carbon Trust. It was carried out over Microsoft Teams and used canva.com as an interactive whiteboard. Approximately 40 participants from a range of different stakeholder groups (including regulators, engineers, acousticians, and marine mammal specialists) were present throughout the session.

The workshop participants identified a shared need to move toward more realistic, flexible, and proportionate piling mitigation for impact pile driving. The outcomes of the workshop indicated that environmental protection and installation risk could not be treated separately: overly rigid mitigation could increase refusal risk, equipment stress, and operational downtime, while not necessarily improving environmental outcomes. The key priorities identified were to refine soft-start and break definitions, improve realism in hammer-energy and piling-profile assumptions, reduce reliance on blanket ADD use, and strengthen cross-disciplinary collaboration so that consenting requirements better reflected what could actually be delivered offshore.

Below we summarise key areas of potential advancement areas (see **Task 4 workshop report** for full details).

### 5.1. Definition of a practical design envelope

The workshop participants identified a need to create a framework that tolerated uncertainty while still reflecting actual offshore practice, balancing technical and consenting risks. The discussion indicated that this meant defining a realistic range for hammer energy, blow rate, and ramp-up behaviour, while allowing contractors to adapt within agreed limits when pile refusal, seabed conditions, or equipment behaviour required it. The outcomes of the workshop suggested that this would reduce the risk of mitigation becoming disconnected from what could actually be delivered offshore.

### 5.2. Clarify soft-start and break rules

Substantial uncertainty around the purpose of soft-start and how it interacted with breaks, ADDs, and ramp-up was identified. The discussion indicated that future guidance should clarify whether soft-start was defined by duration, energy level, number of blows, or some combination of those factors. It was highlighted that more data is required to understand if/when marine mammals return within piling breaks, and that this should inform the need for a type of post-break mitigations. The outcomes

of the workshop suggested that clearer break rules would reduce non-compliance risks over minor operational deviations that may not have had meaningful environmental consequences.

### **5.3. Improve the quality of input data**

The workshop participants identified a need for better pile-specific drivability, pile logs, geotechnical insight, and measured installation data to inform marine mammal impact assessment. The discussion indicated that these inputs would materially improve modelling and reduce uncertainty. The outcomes of the workshop suggested that the value lay not just in having more data, but in having the right data at the right project stage so that EIA and MMMP assumptions could be refined meaningfully, with co-developed solutions to narrow uncertainty and concern around each assessment.

### **5.4. Rebalance source control and downstream mitigation**

The session identified a desire for PTS impact mitigation to be tailored to the residual risk rather than applied as a blanket requirement. The outcomes of the workshop suggested that this approach would be more proportionate and could reduce disturbance created by the mitigation itself.

### **5.5. Build cross-discipline decision making**

The workshop participants highlighted the value of bringing consultants, consents managers, engineers, contractors, vessel crews, and environmental specialists into one room more often. The discussion indicated that this was the clearest route to using collective expertise to reach a workable path forward. The outcomes of the workshop suggested that the real advance would come not only from technical refinement, but also from shared understanding of trade-offs, thresholds, and practical constraints.

### **5.6. Effectiveness of soft-start as a mitigation measure**

The workshop participants queried whether prolonged soft-starts achieve their intended mitigation purpose, noting the lack of evidence of marine mammal response, and the lack of data on the type of response when it occurs (fleeing speed, fleeing duration, directionality etc).

## 6. Summary and recommendations

### 6.1. Summary

#### Task 1: RaDIN tool improvements

- The RaDIN2 tool allows for animals to move with a variable speed with three avoidance triggers (distance, duration, or noise-based) to improve realism in fleeing behaviour.
- The source level parameter is now calculated from hammer energies rather than being fixed per strike.
- Frequency-dependent sound attenuation has been added for specific distance bins, available for both monopiles and pin piles.
- Given the lack of a threshold to apply where sound characteristics transition from impulsive to non-impulsive (see RaDIN1), the same PTS growth rate was used assuming all sound was impulsive in character.
- Simulations were moved from Netlogo to R.

#### Task 2: Census of real-world piling profiles

- Piling log data was collated for 1,448 piles from nine OWF in the UK (764 monopiles, 684 pin piles).
- Overall, for both monopiles and pin piles it took around 1 day of active piling for the installation of a single pile.
- The total installation duration for the vast majority of monopiles and pin piles was less than 2 hours.
- There were a limited number of cases (n=18) in which the maximum duration exceeded 24 hours, the long duration was as a result of long breaks in piling rather than an extended active piling duration.
- Overall, gaps in piling exceeding 10 minutes occurred infrequently within the entire dataset.
- Most soft-starts used hammer energies <500 kJ, although there was variation among the ranges of hammer energies used during soft-starts for different wind farms.
- There appeared to have been some challenges with adhering to the specified MMMP soft-start plan, with maximum hammer energies during the soft-start and the duration of the soft-start occasionally exceeding the parameters specified in the MMMP.
- Across wind farms, there was also variation between soft-start energies for pile types, with no consistent pile-type pattern driving this.
- The mean of the average hammer energies for monopiles was higher than that for pin piles, and hammer energies for monopiles also showed more variability than that for pin piles.

- Overall, distributions of hammer energies for both pile types across wind farms showed that the majority of blows tended to be concentrated at lower energies than the maximum recorded. This demonstrated that real-world hammer energies were rarely at the maximum allowed in the MMMP or EIA for a given project.
- Soft-start blow rates varied considerably among projects and foundation types, reflecting differences in installation practices and site-specific conditions. Across all sites, monopile soft-start blow rates ranged from 1 to 52 blows/min, while pin pile blow rates ranged from 1 to 62 blows/min.
- Across most sites, monopile were installed via more variable blow rates compared with pin pile installations. Blow rates ranged from 1 to 102 blows/min for monopiles and from 1 to 62 blows/min for pin piles.

**Collectively, these findings highlight the considerable variability in real-world piling schedules and indicate that a conservative single worst-case piling profile at EIA/MMMP is unlikely to capture the full range of installation conditions encountered across offshore wind farm projects.**

### **Task 3: Comparison of real vs EIA**

- The comparison of cumulative PTS impact ranges predicted by the EIA or MMMP piling profile with the real piling logs has shown that in all but a very limited number of cases the real cumulative PTS ranges are substantially smaller than those predicted by the EIA or MMMP piling profile (for both monopiles and pin piles).
- What is assessed in EIA looks likely to double (at least) the impact compared to reality.
- What is assessed in MMMP looks likely to double (at least) the impact compared to reality.
- This means that even when detailed geophysical data and refined piling parameters were included in the MMMP modelling, this had only a minor effect on the precaution in the assessment.

**Collectively, these findings highlight the that piling profiles at both the EIA phase and the MMMP Phase substantially over-predicted cumulative PTS ranges compared to real piling logs.**

### **Task 4: Piling schedule workshop**

- Soft-start procedures can be difficult to implement in practice for engineers. It is often difficult to perfectly control hammer energy and blow rate in high precision.
- Regulatory guidance may need to better reflect operational realities and distinguish between technically feasibility and idealised procedures.
- Need to clearly specify what constitutes a break in piling in the MMMP and what procedures to follow when breaks occur
- Desire to move beyond strictly worst-case impact assessments towards incorporating a more proportionate approach to mitigation.

- Very low blow rates, such as single blows, were generally viewed unfavourably because they increase installation time and may place additional stress on equipment. A gradual increase to piling is preferred.
- Concerns that current modelling approaches can compound multiple worst-case assumptions, potentially resulting in unrealistic PTS ranges that may overstate environmental risk. EIA and MMMP piling profiles often differ from actual installation practices because they are based on conservative, worst-case assumptions designed to support consenting and regulatory compliance
- Suggestions included approaches based on overall project-level impact budgets, like methods used elsewhere in Europe, and increased opportunities for adaptive management during construction.
- Clearer guidance is needed on what constitutes a technical infringement when ramp-up procedures are not followed precisely.
- Clearer distinction between soft-start and ramp-up phases, alongside greater standardisation and stakeholder-led guidance to ensure requirements are consistent and practically achievable.
- A key theme was the importance of continued dialogue between developers, engineers, regulators, advisors, and contractors throughout EIA and MMMP process.
- Participants identified a need for improved communication and collaboration before formal approval of mitigation plans, particularly regarding soft-starts, pile refusals, and realistic installation scenarios.

## 6.2. Recommendations

There remains a lack of data on the fleeing speed and behaviour of marine mammals to pile driving noise. At present, underwater noise modelling to inform EIAs and MMMPs use relatively slow swimming speeds, more aligned with “normal” swimming speeds rather than “fleeing” speeds, and there is inconsistency as to the recommended approach used between countries in the UK. Likewise, underwater noise modelling to inform EIAs and MMMPs assumes the animals swim in a straight line away from the piling source. To obtain better data on the fleeing speed and behaviour of marine mammals to pile driving noise, behavioural response studies would be required, consisting of controlled exposure experiments and either focal follows or tagging of individuals to document their responses.

It is recommended that EIAs and MMMPs present not only the required “maximum/worst case” piling scenario but also an “average/most likely” piling scenario and to provide context as to the likelihood of the maximum/worst case scenario occurring. Where possible, identify the number of locations within an array that might require the “maximum/worst case” piling parameters.

It is recommended that better guidance and definitions on what constitutes a soft-start is developed, to update the current definition provided by JNCC (2010). This should, as far as possible, take into consideration the real-world practicalities of hammer energies and blow rates achievable during a soft-start.

To make cumulative PTS impact assessments more realistic, underwater noise modelling should incorporate recovery of the hearing threshold shift between pile strikes and in breaks in piling. There is evidence that intermittent sounds elicit lower threshold shifts than continuous sounds of the same cumulative SEL in harbour porpoise (Kastelein et al., 2015, Kastelein et al., 2014, Kastelein et al., 2026), bottlenose dolphins (Mulsow et al., 2023) and California sea lions (Kastelein et al., 2021, Kastelein et al., 2022); however, current underwater noise models do not incorporate any recovery between strikes. As stated in Kastelein et al. (2026), it is recommended that 1) more data is required to inform our understanding of the mechanisms' underlying threshold shift after exposure to intermittent sounds, 2) studies of short exposures (<1 seconds) would help us to understand the mechanisms for recovery and 3) studies on effective quiet thresholds would help understand to what extent hearing recovery can occur in real-world intermittent exposures. It is recommended that ways in which to incorporate duty cycle (inter-pulse-interval) and recovery in threshold shift into existing models is explored in order to reduce conservatism in the result impact ranges.

The issue of predicting and mitigating auditory injury is a significant issue in many jurisdictions, but the approaches taken to assess and manage risks differ significantly. Within the UK, different regulators require different levels of mitigation for PTS. Some require cumulative PTS to be fully mitigated, while others acknowledge the conservatisms and precaution in the current modelling methods and require that only instantaneous PTS is mitigated, though they encourage methods to at least partially mitigate cumulative PTS risk. It is understood that regulatory advice changes as new evidence becomes available, however, it would be beneficial for regulators to formally provide their position regarding mitigating PTS, acknowledging that any such position would be subject to change as new data becomes available.

It is recommended that the results of this RaDIN2 study are incorporated into new guidance for soft-starts and piling profiles, and EIA methodologies. This could, for example, be included within updated JNCC guidance for minimising the risk of injury to marine mammals from piling noise.

### **6.3. Next steps towards Best Practice Guidance**

Following the piling schedule workshop, it was clear that a longer dedicated workshop is required to help refine practical and agreed Best Practice Guidance (e.g. within updated JNCC guidance for minimising the risk of injury to marine mammals from piling noise) for soft-starts and piling profiles that balances both technical and consenting risks. This builds on the original goal of the RaDIN2 project, to co-develop solutions that can streamline offshore wind consenting.

The following themes emerged as possible follow-up steps:

#### **6.3.1. A review of piling noise monitoring reports**

The RaDIN2 project provided a comprehensive assessment of estimated cumulative PTS-onset impact ranges based on predicted and real-world piling schedules, highlighting a high degree of conservatism in predictions. A complementary follow-on exercise would be to also undertake a review of piling noise monitoring reports (i.e. from the monitoring of initial piles to discharge consent conditions) to compare estimated PTS-onset impact ranges from predictive modelling with equivalent estimated impact ranges derived from noise measurement data. This will enhance the current

assessment of conservatism in EIA and MMMPs by considering differences in predicted vs realised noise levels in addition to piling schedules.

While such a review would be of value as a stand-alone exercise, the findings could also be used to enhance the RaDIN Movement Tool by updating transmission loss assumptions based on the observed noise levels presented in noise monitoring reports and data. Scenarios can then be re-run to ensure robust assessments of real-world impacts. This would allow the integration of the latest evidence and would deliver a more realistic and compelling prediction tool.

### **6.3.2. Best Practice Guidance Workshop**

It is recommended that the workshop includes a live scenario testing component, to align piling engineers and regulators/SNCBs on a soft-start/piling profile approach that balances technical and consenting risks. This would involve the RaDIN2 modelling team attending the workshop to iteratively run co-developed piling scenarios live at the workshop (each scenario takes only minutes to run). This would allow the workshop participants to test a variety of scenarios spanning the relevant receptor range, from porpoises to baleen whales, such that the best practice guidance discussion reflects the full mitigation challenge. This would enable co-development of soft-start/piling profile best practice. It is anticipated that this would be a 1.5 day workshop with piling engineers and regulators/SNCBs.

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## APPENDIX

# Appendix 1: Task 2 further details

## 1.1. Hammer energy

Table 14. Summary of hammer energies used across all piles at each OWF. Values provided are: mean (min – max).

| OWF | MONOPILE Hammer Energy |                     |                        |                        | PIN PILE Hammer Energy |                      |                      |                       |
|-----|------------------------|---------------------|------------------------|------------------------|------------------------|----------------------|----------------------|-----------------------|
|     | # piles                | Minimum             | Average                | Max                    | # piles                | Minimum              | Average              | Max                   |
| 1   | 174                    | 558<br>(322 – 856)  | 1508<br>(458 – 2396)   | 2248<br>(537 – 3024)   | N/A                    |                      |                      |                       |
| 2   | 185                    | 403<br>(402 – 403)  | 1660<br>(454 – 2713)   | 2899<br>(496 – 4034)   | 12                     | 1293<br>(156 – 1746) | 1503<br>(172 – 2196) | 1763<br>(238 – 2869)  |
| 3   | N/A                    |                     |                        |                        | 344                    | 332<br>(167 – 435)   | 666<br>(265 – 1087)  | 1,460<br>(266 – 2299) |
| 4   | 87                     | 442<br>(115 – 887)  | 1,242<br>(115 – 2117)  | 2,483<br>(115 – 4132)  | 4                      | 626<br>(292 – 1049)  | 676<br>(292 – 1233)  | 720<br>(292 – 1688)   |
| 5   | N/A                    |                     |                        |                        | 308                    | 295<br>(100 – 527)   | 714<br>(116 – 1249)  | 1488<br>(146 – 2071)  |
| 6   | 99                     | 397<br>(397 – 397)  | 912<br>(397 – 1555)    | 2185<br>(397 – 3263)   | 8                      | 843<br>(130 – 1590)  | 925<br>(144 – 1755)  | 1030<br>(150 – 1900)  |
| 7   | 58                     | 693<br>(181 – 1882) | 2,617<br>(278 – 3,848) | 3,742<br>(397 – 4,608) | N/A                    |                      |                      |                       |
| 8   | 94                     | 119<br>(115 – 181)  | 1209<br>(116 – 2084)   | 2091<br>(181 – 3012)   | 4                      | 832<br>(261 – 1415)  | 962<br>(261 – 1702)  | 1043<br>(261 – 2207)  |
| 9   | 94                     | 351<br>(115 – 731)  | 1306<br>(115 – 2169)   | 2293<br>(115 – 2966)   | 4                      | 771<br>(261 – 1129)  | 841<br>(261 – 1335)  | 927<br>(261 – 1495)   |



### 1.1.1. Hammer energy: minimum during soft-start



Figure 18. Minimum hammer energy per pile during the soft-start (with soft-start duration as defined by the MMMP).

### 1.1.2. Hammer energy: Average



Figure 19. Average hammer energy per pile across the entire pile installation.

## 1.2. Blow rate

### 1.2.1. Blow rate: minimum during soft-start

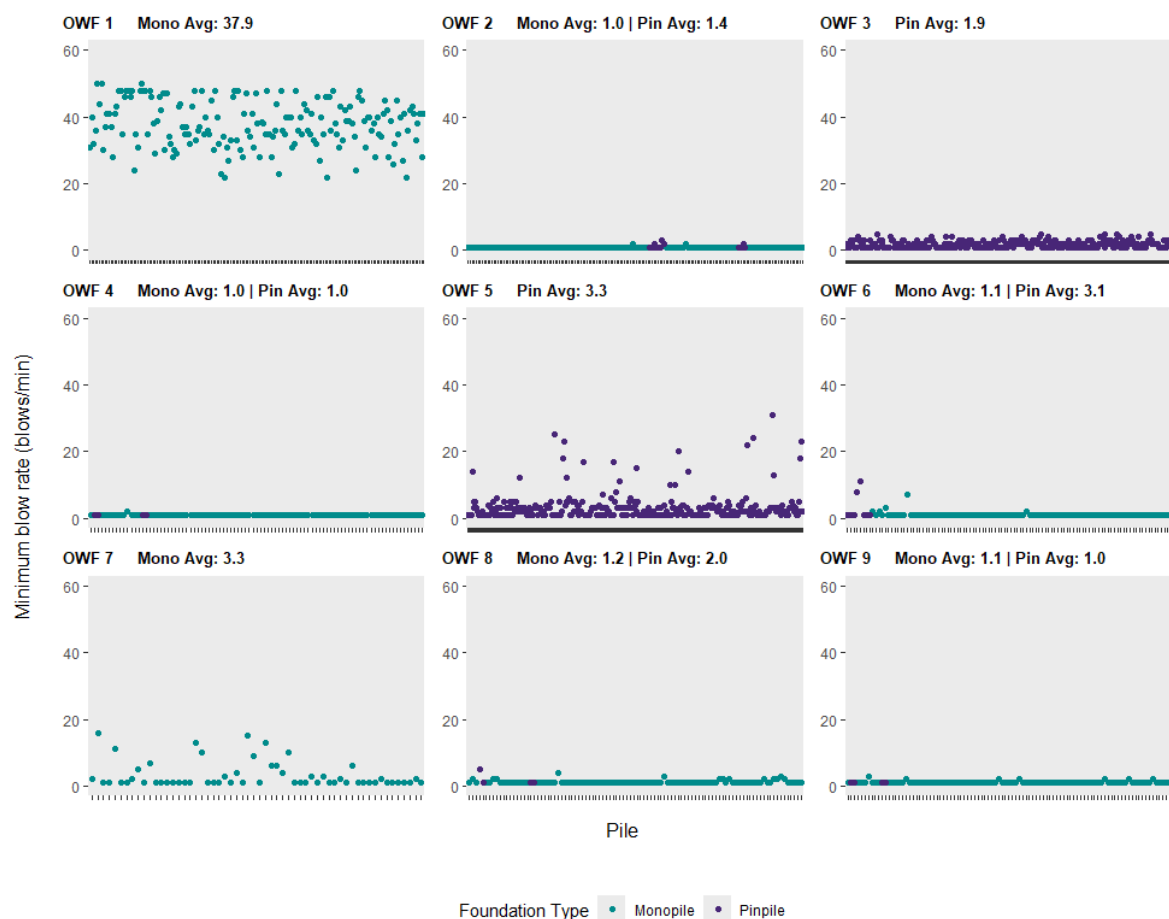
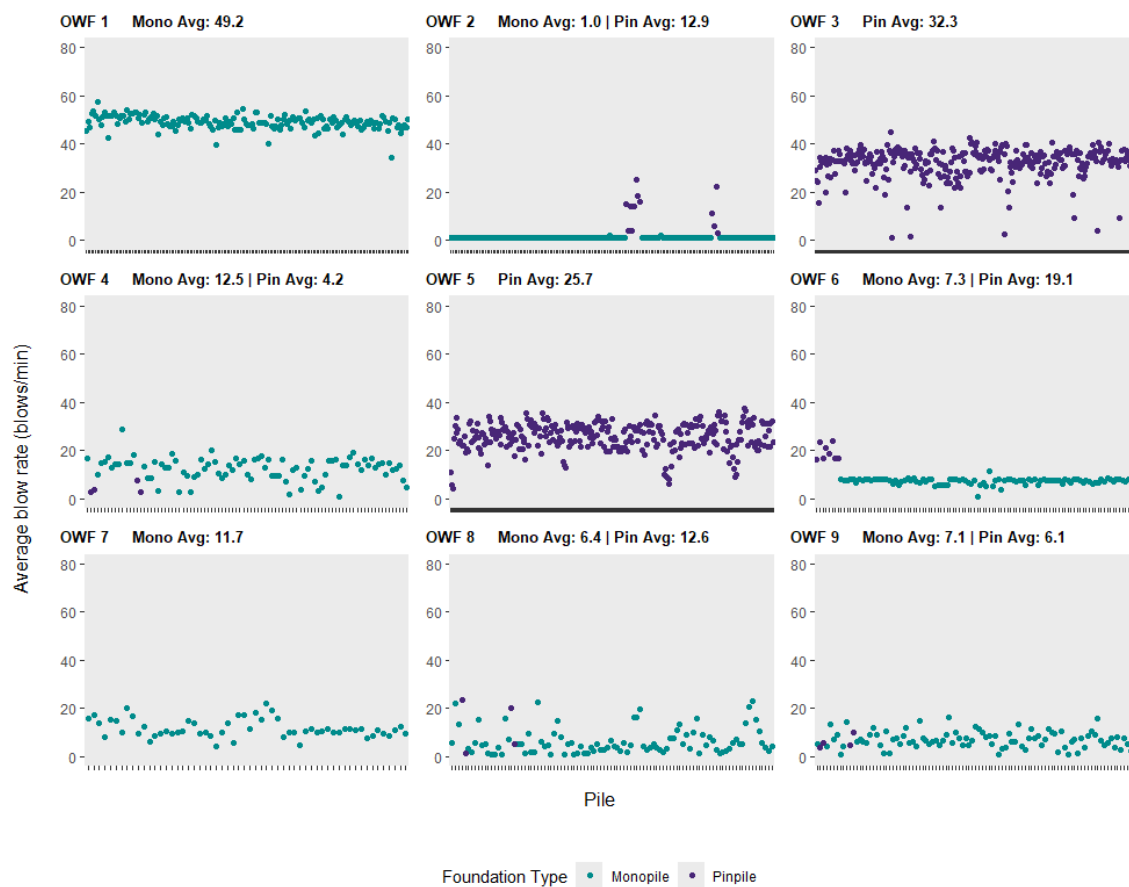


Figure 20. Minimum blow rate during the soft-start for each pile (with soft-start duration as defined by the MMMP).

### 1.2.2. Blow rate: Average during soft-start



**Figure 21. Average blow rate during the soft-start for each pile (with soft-start duration as defined by the MMMP).**

### 1.2.3. Blow rate: Maximum during soft-start



Figure 22. Maximum blow rate during the soft-start for each pile (with soft-start duration as defined by the MMMP).

### 1.2.4. Blow rate: Maximum throughout piling duration

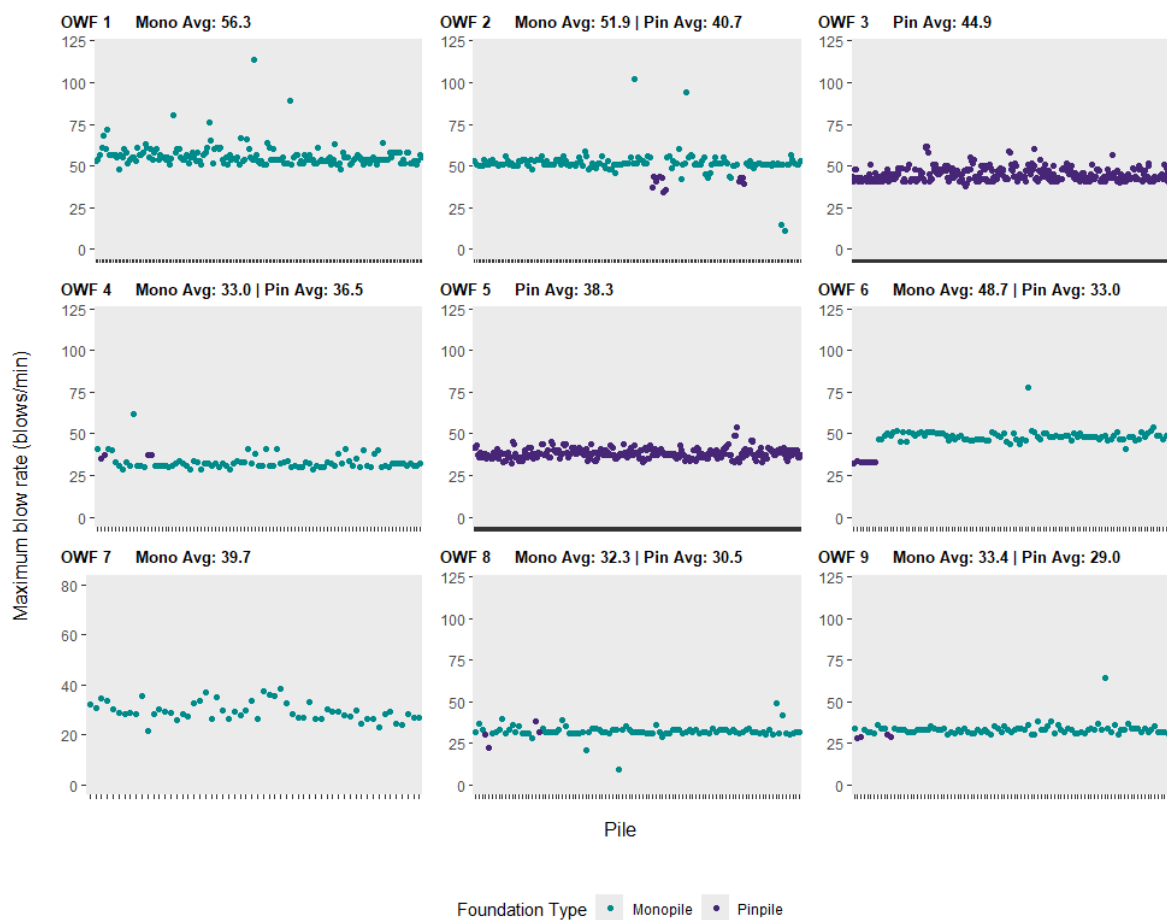
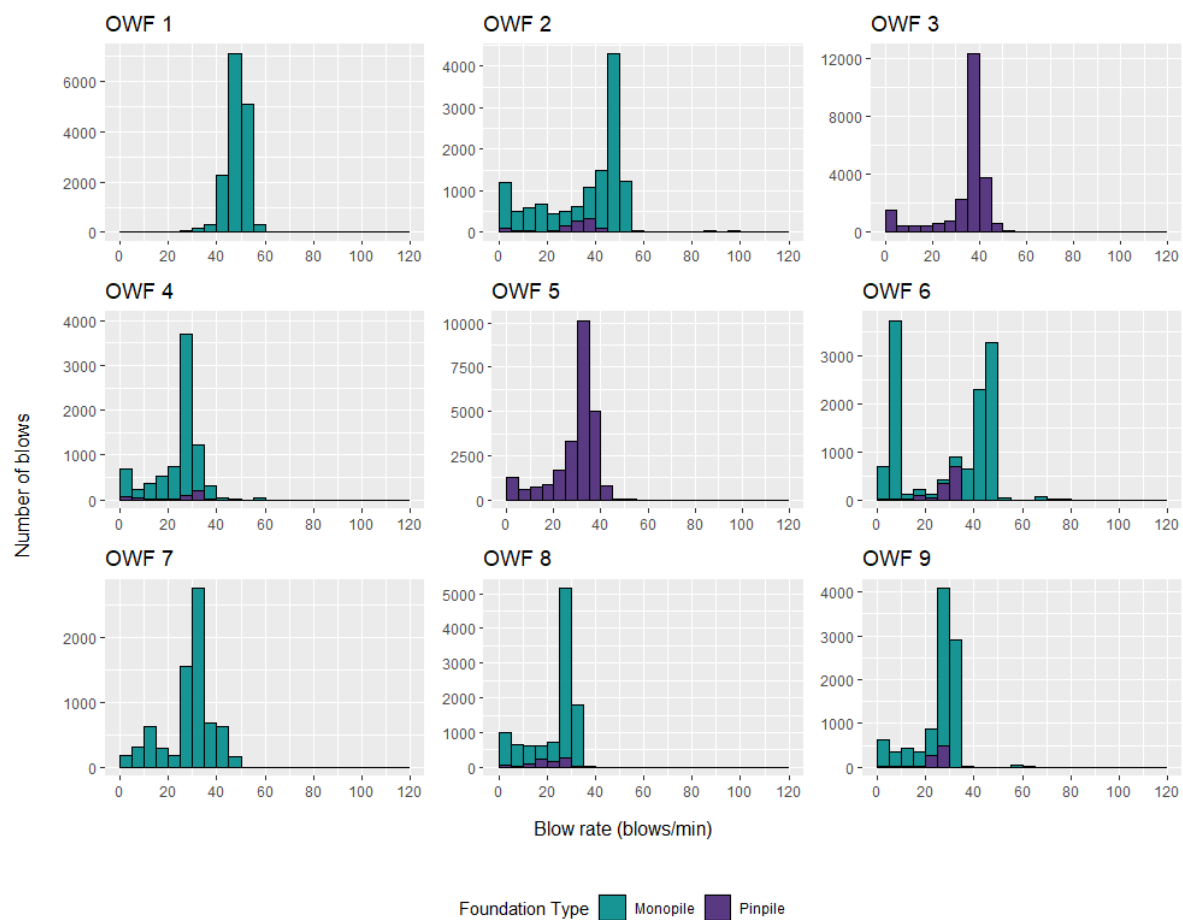


Figure 23. Maximum blow rate per pile.

### 1.2.5. Blow rate: Throughout piling duration



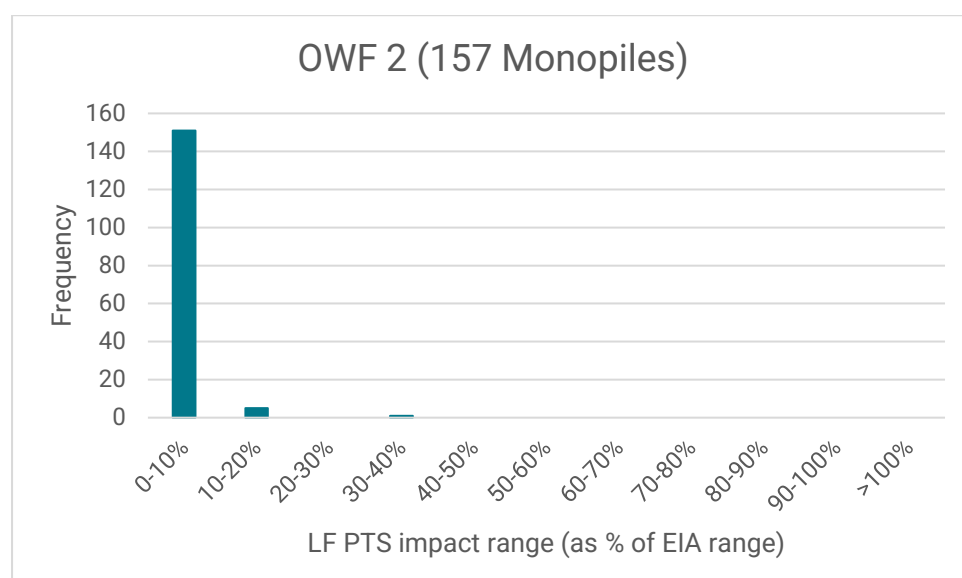
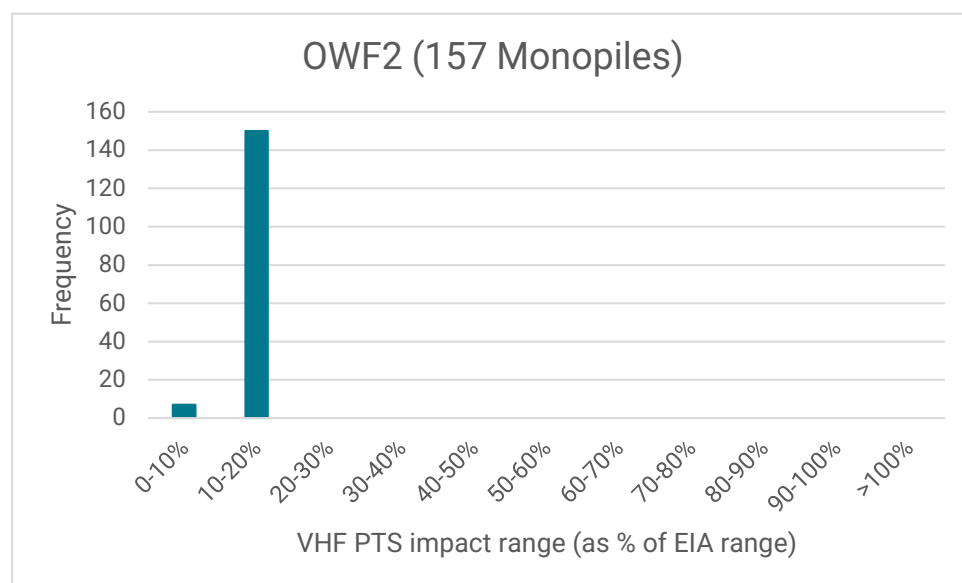
**Figure 24. Frequency of blows at varying blow rates.**

## Appendix 2: Task 3 further details

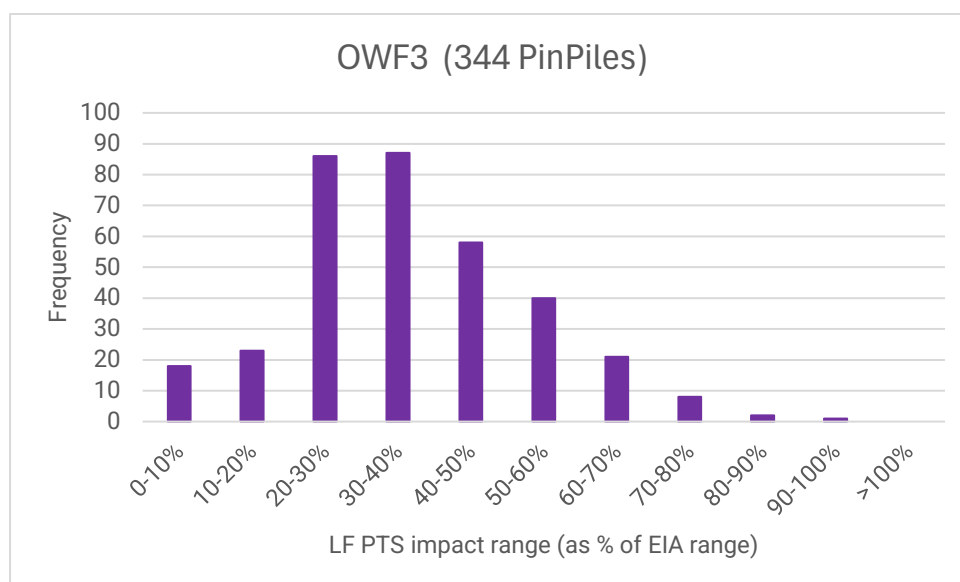
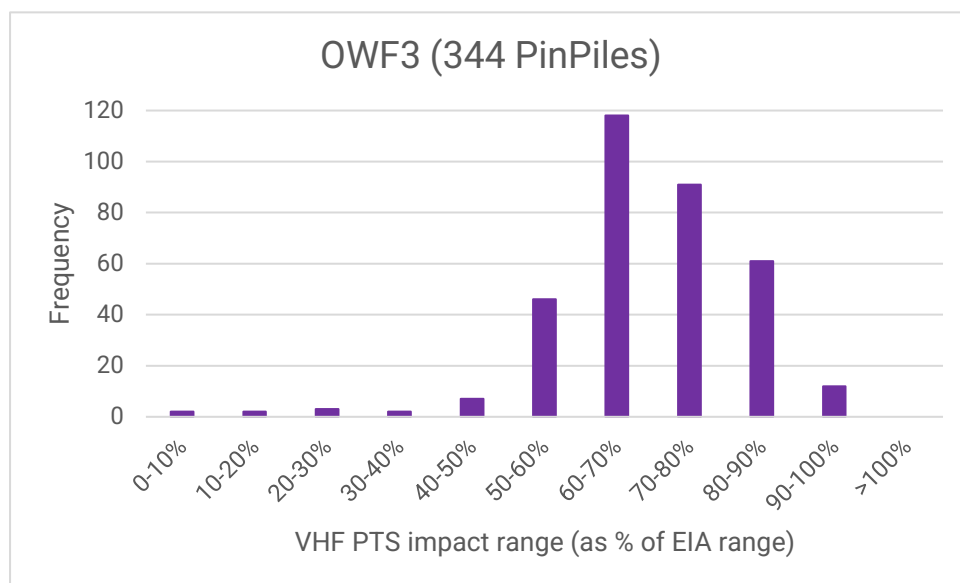
### 1.1. OWF1

Unfortunately, a comparison of EIA PTS impact ranges vs real piling log PTS impact ranges was not possible due to the fact that the EIA assessed pin pile foundations as the worst-case scenario, whereas OWF1 installed monopile foundations. Therefore, the real piling logs for monopiles were not directly comparable to the EIA pin pile piling profile.

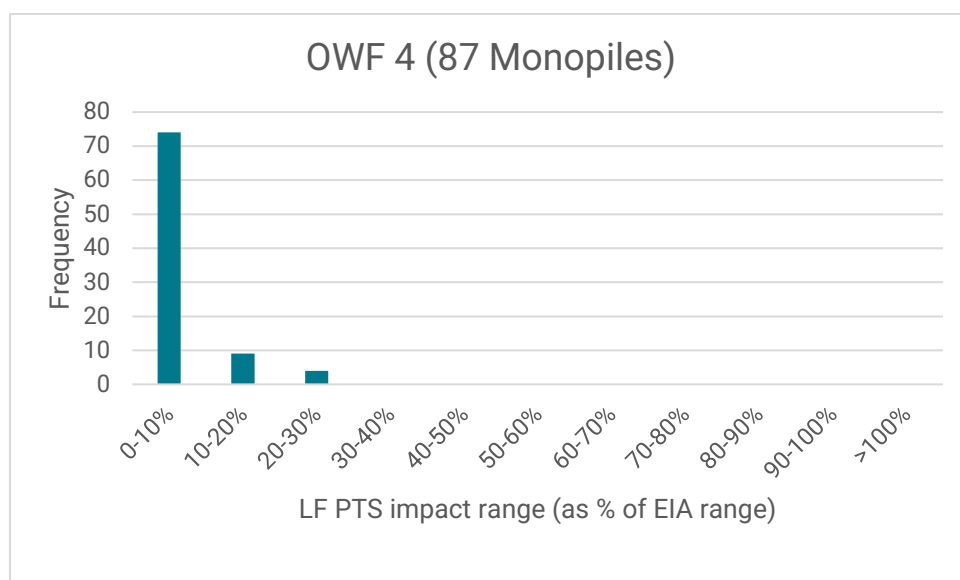
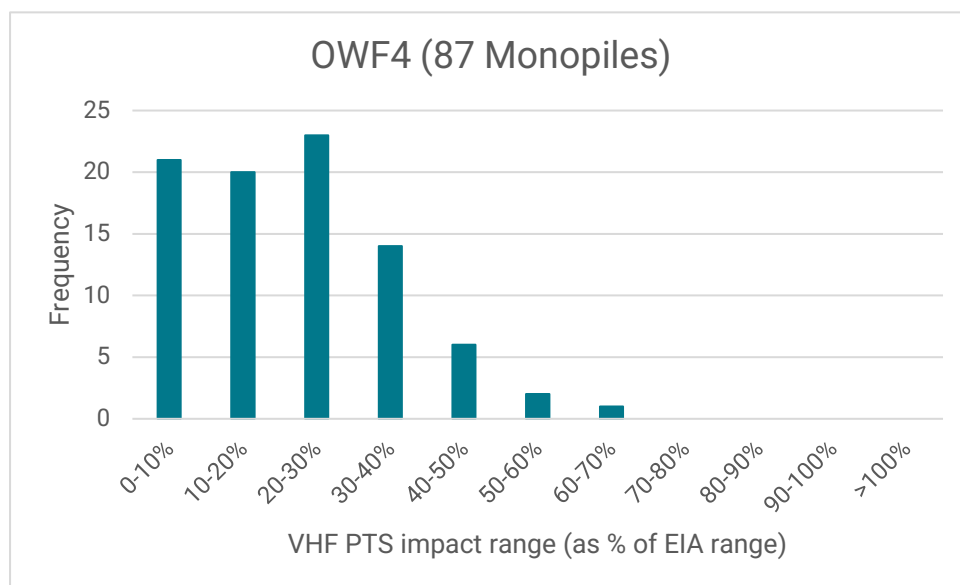
### 1.2. OWF2



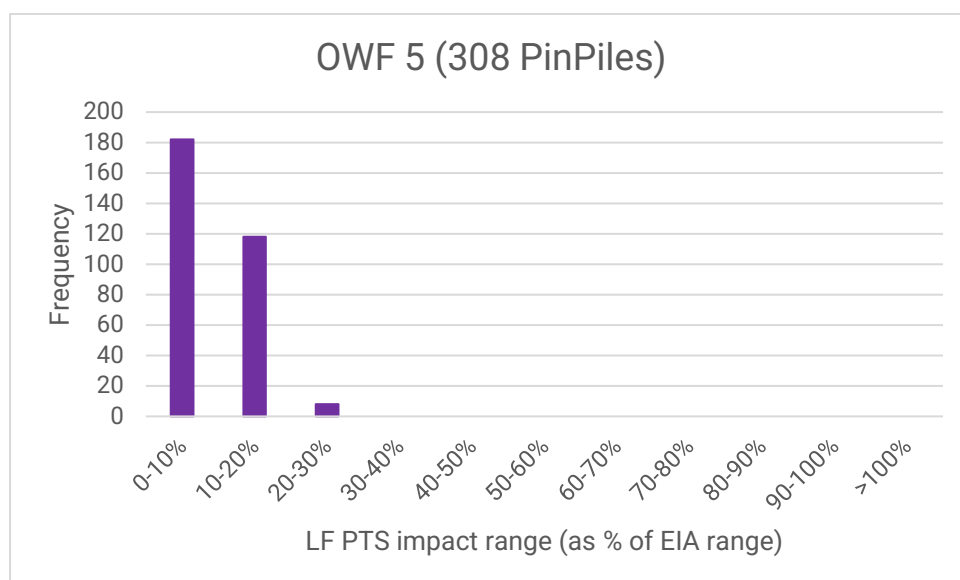
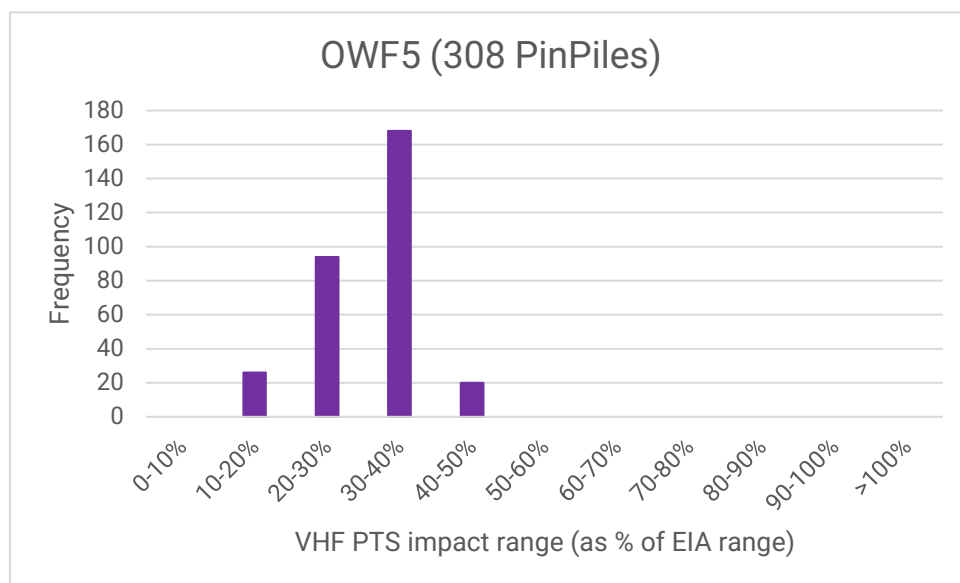
### 1.3. OWF3



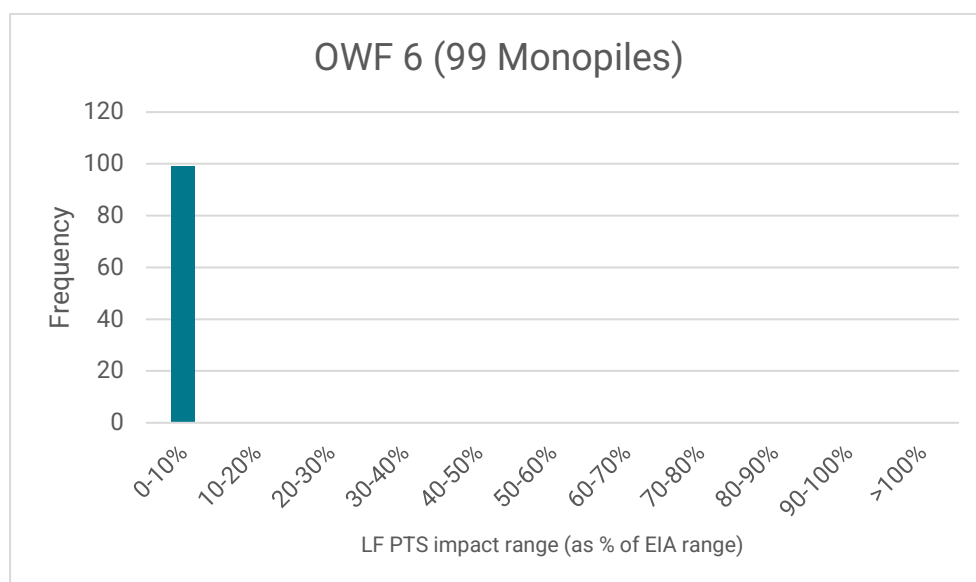
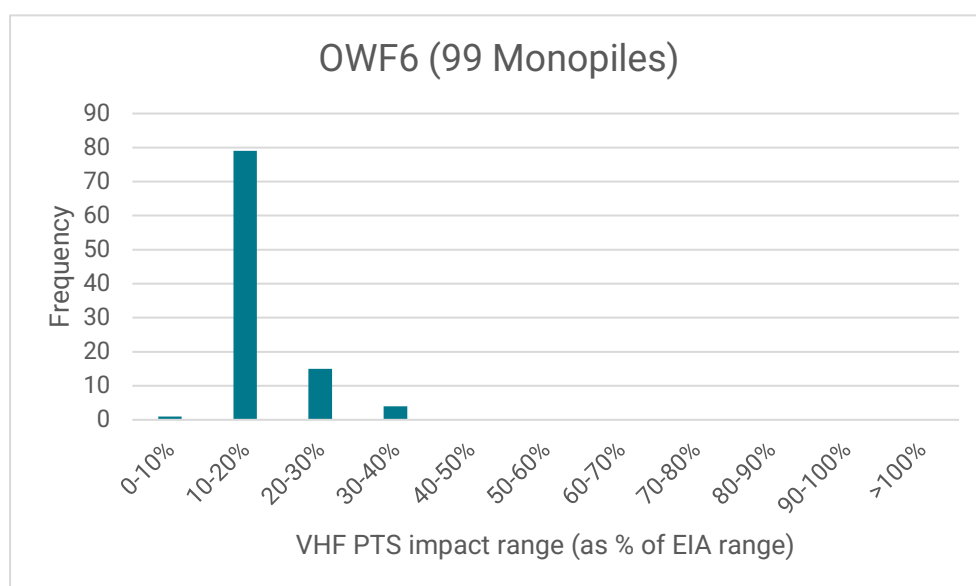
## 1.4. OWF4



## 1.5. OWF5



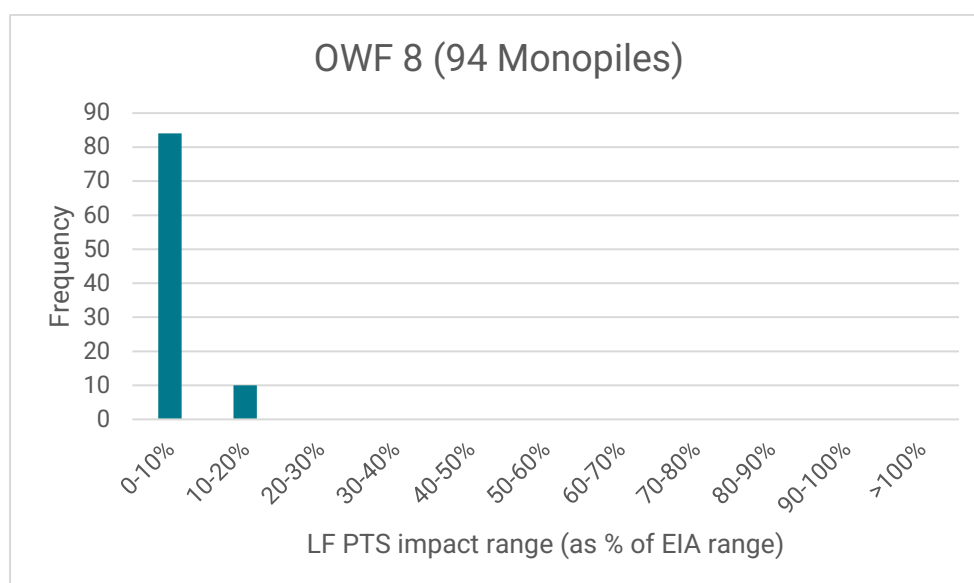
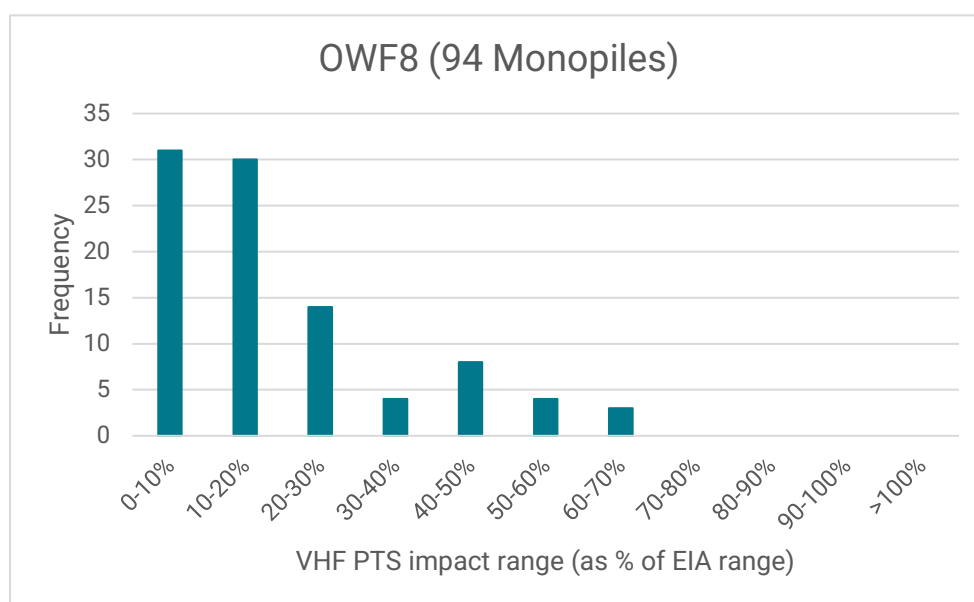
## 1.6. OWF6



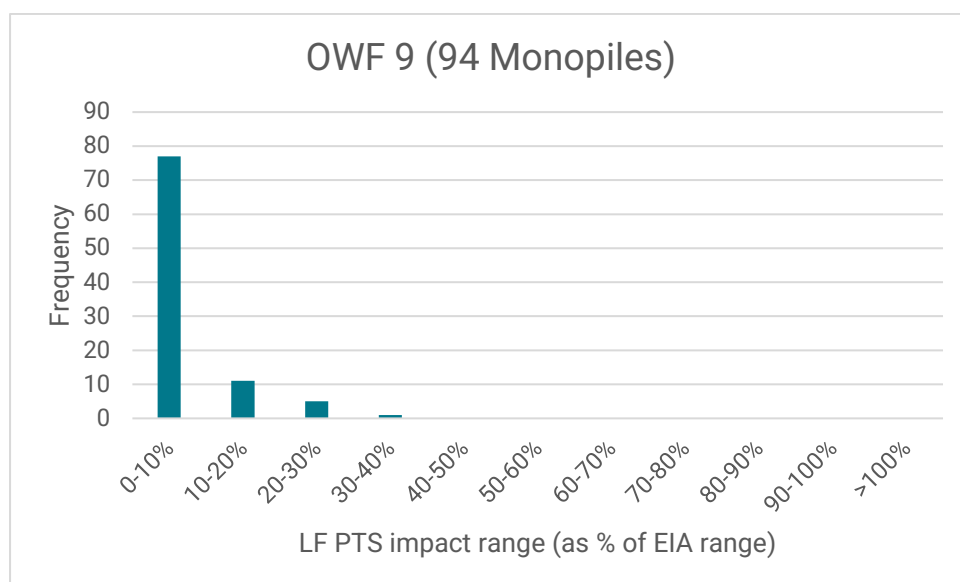
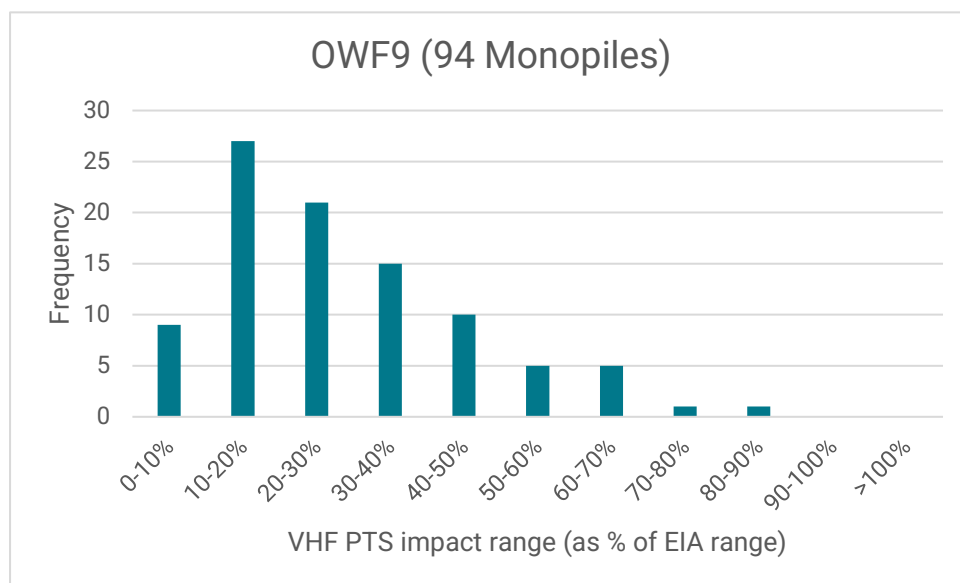
## 1.7. OWF7

Unfortunately, a comparison of EIA PTS impact ranges vs real piling log PTS impact ranges was not possible due to the fact that the real piling used vibro-piling before impact piling. Therefore, the real piling logs were not directly comparable to the EIA piling profile.

## 1.8. OWF8



## 1.9. OWF9



## Appendix 3: Task 4 workshop report

### 1.1. Background

A key need identified from the RaDIN project, was the engagement of multiple stakeholders relevant to the issue of auditory injury impacts from pile driving.

The RaDIN project identified that it was theoretically possible to reduce PTS impacts by only changing the temporal pattern of pile strikes during offshore wind construction, especially at the beginning of piling operation. Tasks 1-3 of RaDIN2 sought to determine what other conservatisms exist in these assessments – to help streamline the consenting process. For a compelling roadmap to this streamlining, it was deemed critical to integrate industry knowledge of what is practically achievable during construction (to ensure this is viable and beneficial).

To achieve this, we proposed further discussion on PTS assessments and their implications was needed between developers, their engineers and transport and installation specialists (along with the engagement of regulators and their advisors). The drivers for this are multi-faceted; it is important that developers consider the consequences of decisions in formulating the design envelope for the project (e.g., the potential for NMS to be a condition, coupled with the associated costs of implementing such solutions) and that regulators and their advisors have the information available to help assess the likelihood of impacts (and not only the worst case to consider). It is also important for the scientific community to understand the decision-making process related to the temporal patterns of pile strikes and whether they can be adapted to reduce PTS impact ranges. This likely requires a facilitated discussion to help better understand perspectives and to allow for improved processes to help conservation, management, and investment decisions.

Therefore, we delivered a 3-hour workshop to update stakeholders on the RaDIN2 project outcomes and to provide facilitated engagement between engineers, regulatory advisors, EIA and Consenting experts, acousticians, and marine mammal specialists to develop practical solutions to streamline EIA processes. The goal was that we would also gather feedback and stimulate discussion on how to collaboratively improve consenting processes, highlight limitations of the project's proposed approach and suggest next steps for follow-up analyses.

### 1.2. Workshop

The workshop took place on the 19<sup>th</sup> May 2026, hosted by SMRU Consulting and the Carbon Trust. It was carried out over Microsoft Teams and approximately 40 participants from a range of different stakeholder groups (including engineers, regulatory advisors, EIA and Consenting experts, acousticians, and marine mammal specialists) were present throughout the session. During the workshop, the SMRU Consulting project team presented the findings of the RaDIN2. The project team aimed to gather feedback and facilitate discussion among participants to explore the balance between technical feasibility of installing piles and consenting requirements.

At the start of the workshop, the SMRU Consulting team provided background information on the impact assessment process, what PTS is, how it can accumulate over time and why it is an important part of the consenting process. A key element was that cumulative PTS impact ranges are important to consider because they influence mitigation requirements, affect requirements for NMS, determine

specifications for ADD operations, and drive consenting decisions. While cumulative PTS is an important metric, there are potential conservatisms associated with it that may lead to overly precautionary results. Presenting this to a range of stakeholders with different background and expertise, helped establish a common foundation for discussions.

The project team presented outcomes from the original RaDIN project and RaDIN2 project Tasks 1-3 (described above). The main foci were on the improvements to the RaDIN Movement Tool to get a more accurate estimation of cumulative PTS. The results of Task 2 and 3 were presented to highlight to the participants the current state of the knowledge regarding pile installation and predicted impacts on animals. It was highlighted that soft-start blow rates varied considerably among projects, with monopiles generally exhibiting lower soft-start blow rates than pin-piles – but also that there was no clear industry-wide standard was observed regarding soft-starts. A key point highlighted was the limited occurrences of reaching maximum hammer energy. It was noted by a workshop participant that some of the monopiles exceed EIA assumptions for maximum hammer energy but remained below MMMP values. This was determined to be a result of both the fact that EIAs may be prepared many years before installation, leading to revisions in the MMMP and that increases in hammer energy are frequently requested later in project development once better information on ground conditions and pile design becomes available. Ultimately, there was broad alignment that there is no single standard offshore wind piling profile and considerable variability exists across projects, pile types, and installation campaigns.

The SMRU Consulting team presented the results from Task 3 indicating that that real-world cumulative PTS ranges were substantially smaller than EIA or final MMMP predictions. This facilitated discussion that while MMMPs are developed much closer to construction than EIAs, significant conservatism remained and actual piling activity still produced substantially smaller PTS ranges than predicted (i.e. the design envelope remaining broad to maintain design flexibility for construction program). There was discussion in the workshop around the potential risk of non-compliance being so high with current imposed piling profiles and a desire for greater discussions around more flexibility in piling programs and how this could be afforded.

### **1.3. Workshop discussions**

Following this portion of the workshop, a discussion amongst participants ensued. One participant asked if, in the future, EIAs might become more accurate as project knowledge improves. Responses agreed that uncertainty will likely remain because detailed geotechnical investigations cannot be undertaken everywhere during early development stages. However, the project finding was highlighted - that there was still substantial conservatism even in more recent MMMPs (which are supported by the outcomes of geotechnical investigation). The SMRU Consulting team also asked workshop participants whether the degree of conservatism was surprising. Participants agreed that they were not surprised by the finding, citing explanations such as worst-case assumptions in strike rates and hammer energy are to be expected, practical challenges often occur during soft-start and ramp-up implementation, and increasingly complex project envelopes makes modelling multiple full scenarios impractical which results in EIAs typically focusing on two worst case scenarios. To help address this gap between EIAs and real-world scenarios, participants suggested that future assessments should consider more realistic scenarios alongside worst-case ones however, others questioned what practical regulatory benefit such analyses would provide while worst-case assessment remains mandatory. Other attendees suggested that the gap may also be a result of

disagreements between modelled hammer capabilities and actual installation constraints and highlighted the need for clearer guidance regarding compliance and technical feasibility to improve the transition from modelling assumptions to MMMP implementation and practical offshore installation constraints. This gap between EIA and real-world piling scenarios also emphasized the importance of post consent work. One participant spoke about how post-consent studies become increasingly important once better project-specific information is available and the final MMMP development offers opportunities to improve predictions and refine mitigation measures. There was broad agreement among participants that existing UK soft-start guidance requires updating. A recurring theme throughout the workshop discussion was the need to balance technical feasibility offshore with regulatory expectations and consenting requirements, while ensuring that mitigation remains proportionate to actual risk. Future guidance should be jointly informed by engineers, regulators, developers, noise specialists, and marine mammal scientists.

## 1.4. Collaborative working session

Following the presentation, workshop attendees participated in a knowledge gathering and prioritisation exercise via Canva.com in which they were asked to write their most important evidence-based insight, experience, concern, or practical solution about various topics. The topics were: hammer energy, blow rate, breaks in piling, predicting piling profiles, defining soft-starts, ADD use, making mitigation more proportionate, and other. The team provided general questions to stakeholders in advance of the workshop. These were designed to help consider when working through the exercise. All of the questions were shared with all participants but had different foci for the different stakeholder groups.

Developers were asked to consider:

- Where is current conservatism adding cost without adding protection?
- What operational data can you share to reduce uncertainty?
- What would you accept as a monitoring or adaptive-management backstop?

T&I contractors, specialists, and engineers were asked to consider:

- What is technically necessary for safe and reliable installation?
- Where does mitigation create avoidable operational risk?

Regulators and Advisors were asked to consider:

- What evidence could provide comfort that reduced conservatism is still legally defensible?
- Which uncertainties are material to your decision, and which are not?

Scientists were asked to consider:

- Which uncertainties are genuinely decision-critical?
- How can uncertainty be communicated without defaulting to worst-case assumptions?
- What monitoring design would best test the key unknowns?

Following a dedicated quiet session in which participants individually responded to the prompts, they were then asked to identify which responses they thought were the most important and which areas should be prioritized.

#### 1.4.1. Hammer energy

The guiding questions for hammer energy were:

- What is the minimum desired hammer energy for T&I contractors (kJ or % of max)
- What limits are there to soft-start hammer energy?
- Can 10% hammer energy be used for 20 minutes? if not why not?
- If max hammer energy is rarely reached, are there solutions to develop more proportionate piling profiles

One main theme of the discussion was balancing minimising hammer energies with mitigating the risks of rebounds and refusal during piling. Participants highlighted two comments of this nature as important, as insufficient hammer energy increases the risk of pile rebounds and damage to the hammer which can lead to operational downtime, decreasing efficiency and prolonging environmental disturbance. Participants also noted that there is inherent uncertainty in pile driveability predictions, meaning that contractors may be prone to overprediction to minimise the risk of refusal.

Participants also provided several considerations for soft-starts and minimum hammer energies. Responses indicated that minimum hammer energy during soft-start is typically around 5–10% of the hammer's maximum energy, with 10% sometimes used throughout the full 20-minute soft-start period. However, these low energies can restrict penetration for large monopiles, also resulting in extending piling activities. In addition, participants noted that noise reduction technologies are sometimes only available for large hammers, potentially influencing hammer selection. Hammer energy increases are generally driven by penetration performance, with gradual ramp-up to maximum energy commonly observed in practice, despite assessments often assuming the fastest possible ramp-up.

The final theme for responses for hammer energy was uncertainty in maximum hammer energies and the need for realistic piling profiles as opposed to those for maximum, worst case scenarios. There was also interest in developing estimated maximum hammer energies for individual piles based on local soil and ground conditions, although concerns were raised about the practicality and prescriptiveness of this approach. It was also noted that whilst predicted hammer energies can be conservative, sometimes higher hammer energies than predicted are required for pile installation, and that this may not be identified by modelling.

#### 1.4.2. Blow rate

The guiding questions for blow rate were:

- What is the minimum desired blow rate for T&I in the soft-start?
- For how long can the minimum be safely maintained without increasing technical risks?
- How would you design a soft-start blow rate pattern?

The first theme of the responses for blow rate were comments from a developer's perspective. Participants emphasised the need to balance environmental mitigation measures with practical installation requirements. Very low blow rates, such as single blows, were generally viewed unfavourably because they increase installation time and may place additional stress on equipment. A gradual increase to piling is preferred. There was also interest in understanding whether blow rates can realistically be maintained at a precise value or whether specifying an upper limit would be more practical.

The second theme of responses were from an engineer's perspective and referred to technical feasibility in terms of blow rates. Several responses noted that exact blow rates cannot be directly selected because they are influenced by factors such as oil flow, hammer performance, and operational adjustments made to protect equipment and optimise installation. These therefore highlighted that, in response to the previous theme, although very low blow rates are possible, a specified maximum rather than a fixed blow rate can be favourable.

### 1.4.3. Breaks in piling

The guiding questions for breaks in piling were

- MMMP usually says soft-start will be redone if practicable. Are there principles that can be stated in soft-start guidance?
- What are the practical implications of reverting to soft-start after a break in piling?
- What kinds of breaks or interruptions should reset the soft-start, and which should not?

Responses to the topic varied but many of them highlighted the need to clearly specify what constitutes a break in piling in the MMMP and what procedures to follow when breaks occur. Participants seemed to agree that it is often unclear what defines a break and whether it is based on duration of no piling periods, technical breaks during the installation of piles, or breaks between multiple pin pile installations. Moreover, there is clarity needed around what machinery is still running during a break in piling. Responses emphasized that clear specification is important, especially around soft-starts, as it often dictates the next steps during installation. For example, one participant highlighted a situation in which during some projects, the ramp up is part of the soft-start and not separate which can cause issues because if there was a break in piling during ramp up it was unclear if this would trigger a 'break in piling during soft-start' procedure or not. Other participants noted this particular response as a priority. Another example provided was the lack of guidance on what the breaks between two ADD activations should be, more specifically there was no guidance on how soon after turning off the ADD that a new ADD stage could be restarted should breaks occur in sequence. This was reflected in another response that stated that there are frequently questions about when ADDs and BBCs should be switched on and off during breaks.

Another major theme within the participant responses surrounded the technical and engineering limits associated with breaks in piling. Multiple comments reiterated a similar point that when restarting after breaks, soft-starts and ramp-ups may not be technically possible. This point was highlighted as a priority by multiple participants. Reasons provided as to why restarting soft-starts and ramps ups were: mitigating pile fatigue, a risk of pile refusal, and requiring higher energies to overcome friction. The participants emphasized that instead of restarting a soft-start or ramp-up, commencing installation at the same energy level when piling stopped is the preferred methodology.

The final theme within the responses to breaks in piling surrounded potential solutions and areas of future work. While suggestions varied, two of the comments highlighted the need for better modelling of breaks in piling. One of the comments highlighted that, while breaks occur frequently in the real world, they are rarely modelled prior to installation. The second comment suggested that more work could be done to consider if or when marine mammals return and if breaks are a significant issue. One participant suggested that creating a new name for a phase in piling, for example slow start, in which a few warning blows occur prior to restarting may help address the previously mentioned issue of restarting soft-starts after a break. There were two solutions that many participants marked as a priority. The first was a suggestion that there should be more pragmatism when it comes to declaring non-compliance, given the technical challenges associated with breaks in piling. The final and most prioritized solution was that there needs to be more discussion amongst all stakeholder groups about practical MMMP requirements, to better align with what is realistically achievable offshore, rather than imposing theoretical limits.

#### 1.4.4. Predicting piling profiles

The guiding questions for predicting piling profiles were:

- Why are EIA & MMMP piling profiles so different to reality?
- Are drivability analysis studies used to refine piling profiles?
- Do engineers and T&I contractors input into EIA /MMMP piling profiles? If not why not?
- What do we need to make EIA/MMMP profiles more realistic? When can these data be available?

The first major theme in responses was creating a more realistic scenario versus using a worst-case approach. Participants generally agreed that EIA and MMMP piling profiles often differ from actual installation practices because they are based on conservative, worst-case assumptions designed to support consenting and regulatory compliance. The use of maximum design scenarios, combined with uncertainty around final designs, ground conditions, and installation methods at the EIA stage, can result in piling profiles that are more precautionary than realistic. Several respondents noted that multiple worst-case assumptions are often combined within a single assessment, potentially leading to scenarios that are unlikely to be realised in actual piling.

Another main theme was the level of contractor contributions to MMMPs and EIAs. Responses indicated that drivability assessments, engineers, and T&I contractors do contribute to refining piling profiles, particularly during later consenting stages. However, there is a tendency to rely on conservative drivability scenarios to minimise consenting risk, and contractors are often not engaged during the EIA phase when key project details remain unknown and therefore maximum design scenarios are used as default. Participants also highlighted that while contractor input increases during MMMP development, differences can still emerge between predicted piling requirements and what is actually needed during construction.

Participants suggested several alternative approaches to reduce potentially unnecessary conservatism. These included applying metrics for measuring marine mammal responses at the offshore wind farm level rather than individual pile level, allowing variations across the project to balance out, and adopting assessment frameworks that consider both realistic and worst-case

scenarios. Examples included using project-wide disturbance metrics, similar to the Dutch approach of number of harbour porpoise disturbance days across the entire OWF, or adopting a methodology comparable to UXO management where realistic operating conditions are assumed but defined exceedances are also captured in assessments and are allowable. One response also recommended focussing on representative piling locations for pile driveability assessments instead of “worst case” locations, acknowledging that exceedances may occur in specific locations.

Finally, several responses were focussed on technical limitations and data gaps. Participants highlighted that safe and reliable pile installation requires mitigation measures that reflect operational realities, including realistic soft-start durations, flexible ramp-up procedures, and that clearer guidance is also needed on when soft-starts should be repeated following pauses in piling. Noting comments regarding issues of longer soft-starts, it was also highlighted that more information is needed as to whether the use of NMS means soft-start durations can be reduced whilst still minimising the impact on marine mammals. However, responses also emphasised that drivability assessments are predictions and are not exact, meaning highly prescriptive requirements specifying exact hammer energies, blow counts, or ramp-up sequences may not be achievable.

#### 1.4.5. Defining soft-starts

The guiding questions for defining soft-starts were:

- What evidence would help refine definitions of soft-start to find balance of technical and ecological risk?
- What technical risks does a shorter or more adaptive soft-start create?
- What are the principles of a low (tech & consent) risk soft-start?
- Would updated guidance on soft-starts be beneficial?
- Should guidance differentiate between a soft-start and ramp up?

A key theme in responses for defining soft-starts was considerations around the efficacy of soft-starts for mitigation versus operational practicality. Several responses questioned whether prolonged soft-starts always achieve their intended purpose, noting that not all species respond or show avoidance behaviours to soft-start blows, and highlighted that importantly, the first few blows can sometimes generate higher noise levels than fully operational piling. This balanced with the fact that soft-starts have no benefit for piling equipment, efficiency and are technically challenging emphasises the need to resolve these concerns. Respondents suggested that additional modelling, monitoring, and evidence on animal responses could help determine the most effective combination of soft-start duration, blow rate, hammer energy, ramp-up procedures, and alternative mitigation measures such as ADDs.

A second theme amongst responses was the definition and monitoring of soft-starts and ramp-ups. Participants emphasised the need for updated guidance on both procedures to help hammer operators balance safe and efficient installation with environmental compliance. Clearer guidance is also needed on what constitutes a technical infringement when ramp-up procedures are not followed precisely. Respondents highlighted considerable uncertainty around how soft-starts are defined and applied in practice, particularly following breaks in piling. It is often unclear whether a soft-start is defined by its duration, energy level, or a combination of both, creating challenges when different

mitigation actions are triggered depending on whether piling is considered to still be in the soft-start phase or has transitioned to operational piling. Participants also noted significant variability in soft-start and ramp-up requirements between projects. Several respondents supported a clearer distinction between soft-start and ramp-up phases, alongside greater standardisation and stakeholder-led guidance to ensure requirements are consistent and practically achievable.

Several responses also proposed changes to defining soft-starts and alternative approaches. Suggestions included greater use of ADDs instead of prolonged soft-starts, reducing installation duration and associated operational impacts while still providing some mitigation benefits. Modelling a series of example soft-starts was also suggested to help identify protocols that avoid PTS onset within a reasonable distance of piling to reduce the need for large mitigation zones.

#### **1.4.6. ADD use**

The guiding questions for ADD use were:

- How to balance ADD usage and impacts of disturbance vs PTS?
- Can we reduce conservatism at MMMP phase - to reduce unnecessary ADD usage?
- If we don't need to disturb animal so far away, can we change ADD so it doesn't need to result in large scale disturbance?

The first theme for responses for ADD use were comments including context specific ADD usage. Participants suggested that ADD use should be dynamic, context specific and customised to each project. This would depend on the range and target species being mitigated for, for example by keeping activation durations to a minimum or using startle response cued ADDs to provide mitigation whilst reducing contributions to noise disturbance. One response also emphasised the importance of minimising the use of ADDs by mentioning that if used more than necessary there is a risk of the ADD causing more disturbance than the noise source being mitigated for.

The second theme for responses for ADDs was the identification of knowledge gaps and ADD effectiveness. Participants highlighted a need for additional evidence on how animals respond to prolonged ADD exposure (for example, >30mins), whether avoidance responses are maintained over time, and how effectiveness may vary between sites, species, and environmental conditions. The importance of evaluating whether ADDs are needed in some contexts where other mitigation measures such as NMS and soft-starts are used was also mentioned, as well as the suitability of ADDs from different manufacturers (Lofitech and FaunaGuard). Overall, participants identified a need for further research and monitoring to better understand when ADDs provide a clear mitigation benefit and how their use can be optimised to reduce unnecessary disturbance.

#### **1.4.7. Making mitigation proportionate**

The guiding questions for making mitigation proportionate were

- If worst case piling profiles represent only a fraction of those as built, can we make mitigation measures (e.g. ADD durations) more proportional to the risk?
- How might this be achieved?
- What would be the logistical and consenting barriers to this?

Many of the responses to the making mitigation proportionate focused on aspect of changing ADD usage during installation. Two comments favoured making changes to ADD usage. The first comment highlighted that if EIAs and MMMPs predicted reduced impacts different ADD systems could be used or ADD durations could be changed. Another comment suggested ADD usage should be tailored to allow flexibility, perhaps by a flowchart system, providing ADD procedure options depending on different hammer energies. However, a flowchart system would be difficult to implement because required hammer energies are difficult to predict. Other comments highlighted challenges presented by altering ADD usage. One participant highlighted that there may be consenting barriers as well as a risk of non-compliance with adaptive ADD procedures, largely because predicting hammer energies is so challenging. They emphasized that regulators would not be comfortable with the level of uncertainty presented by adaptive ADD mitigation. Two comments, which were highlighted as a priority by participants, argued that instead of altering ADDs, focus should be placed on trying to reduce noise levels. Reducing noise levels would reduce the need for ADDs which actually introduce additional noise to the installation process.

Another theme within the responses to the topic centred around making changes to the MMMP process. One of the suggestions was to use more realistic modelling scenarios rather than conservative ones so that the resulting MMMPs are more realistic while still capturing risk adequately. One of the participants asked whether it is possible to link together better mitigation measures with site characteristics at the MMMP stage once ground conditions are clear. Another participant emphasized that, by the time the MMMP occurs there should be more knowledge about which piles are likely to require max hammer energy. This would allow the MMMP to be more flexible and include different protocols for different piles. When considering this approach though, it would be important to not limit contractors in case issues arise during installation.

The last point is closely tied to the final theme within the topic responses, which is making protocols more flexible generally. One suggestion was to have flexibility built into mitigation strategies so that decision could be made in the field on a per pile basis. Another participant stressed that it would be best to have a toolkit that balances costs and risks of different NMS and mitigation options, but this is dependent on an understanding of NMS; this point was marked a priority by participants.

#### 1.4.8. Other

The guiding questions under other were:

- Does cumulative PTS need to be fully mitigated (i.e. aim to exclude all animals from impact range)? (expectations differ across jurisdictions within the UK)?
- Reporting and data sharing Would a repository of piling logs in the public domain be a useful asset?
- Piling Implementation Reports in the public domain?
- Can these provide a better evidence base to better inform future piling profiles?

The first theme of responses included considerations around the transferability of results between projects. This refers to results from RaDIN2, and whether they are transferable to piles of different sizes and for OWF construction on softer sediments than those in the North Sea. Participants suggested that to provide context it could be helpful to aggregate piling data encompassing a range of pile sizes and seabed characteristics. Whilst the results from RaDIN2 could be useful for mitigating

and refining project specific piling strategies, more research is needed for to get results which can be used to inform piling strategies on a wider range of projects.

Responses also contained considerations for applying mitigation techniques, as it is important to evaluate where mitigation could pose increased operational risk or disturbance. Participants noted that mitigation technologies such as noise abatement systems and bubble curtains can increase the complexity, duration, number of vessels, personnel and cost of offshore operations, impacting their overall environmental benefit. One response also highlighted differences in mitigation requirements between jurisdictions (UK and Germany), and that it is difficult to confirm which is under- or over-precautionary.

Several responses also consisted of calls for more realistic animal movement data. This is required to improve prediction tools, which could benefit from improved knowledge of the variability in animal speed and movement patterns when performing different behaviours (travelling, feeding, diving). This was emphasised by one participant pointing out that speeds of 1.5 m/s and 3.25 m/s have been assumed for very high frequency and low frequency cetaceans for some time, however the references for these values are from over 20 years ago.

Disturbance from noise and cumulative effects were also mentioned in the responses. Participants highlighted the need to consider a broader range of ecological impacts beyond PTS when assessing and mitigating underwater noise. For example, one response noted that noise can affect behaviours such as feeding and habitat use, with some species such as harbour porpoise potentially experiencing impacts even where injury thresholds are not exceeded. Another participant also emphasised the importance of considering impacts across multiple projects, suggesting that it may be beneficial for future work to use this information to assess cumulative project impacts on PTS and disturbance.

Another major theme throughout responses was model conservatism and noise measurements. Participants highlighted concerns that current modelling approaches can compound multiple worst-case assumptions, potentially resulting in unrealistic PTS and TTS ranges that may overstate environmental risk. It was suggested that while maximum hammer energies may remain appropriate for assessing instantaneous injury, more representative metrics such as average hammer energy could instead be used to predict  $SEL_{cum}$  to avoid compounding worst case scenarios. It is also important to consider which piles are measured, as one response mentioned it is often the first four, which are probably most likely to be those with “teething issues” but simultaneously, piles requiring higher hammer energies are likely to be later in the piling campaign. There was also discussion around whether mitigation should focus on reducing injury risk to a negligible level rather than requiring the exclusion of all animals from predicted impact ranges, particularly given the layers of conservatism already built into assessments. Participants supported further work through expert elicitation to refine cumulative SEL measurement methods (such as modified power law or kurtosis corrected SEL) to aid in reducing some conservatism, whilst acknowledging that data gaps still exist which could make this more difficult.

The final theme throughout responses was surrounding operational procedure and regulation. Participants outlined a typical piling procedure involving initial low-energy blows followed by gradual increases in blow rate and hammer energy to achieve target penetration rates, with settings continually adjusted throughout installation. Responses also highlighted concerns around how non-compliances are governed and assessed, particularly where minor deviations from soft-start or ramp-

up procedures can trigger discussions around compliance. There was support from one participant for piling logs and noise monitoring being made public once accepted.

## 1.5. Final workshop discussions

Following the Canva.com exercise, the workshop came back together for a final discussion. The discussion aimed to highlight some of the identified priorities and focused on the practical challenges of implementing soft-start procedures and developing more proportionate approaches to underwater noise mitigation during pile installation.

Participants highlighted that soft-start procedures can be difficult to implement in practice for engineers. From an installation perspective, operators typically increase energy and blow rate progressively until the required performance is reached without worrying about time. Moreover, it is often difficult to perfectly control hammer energy and blow rate in high precision due to the mechanistic means by which this is controlled (i.e. they are emergent properties determined after the pile is struck). These insights suggest that regulatory guidance may need to better reflect operational realities and distinguish between technically feasibility and idealised procedures.

The discussion also explored the possibility of moving beyond strictly worst-case impact assessments towards incorporating a more proportionate approach to mitigation. While participants agreed that worst-case assumptions are often highly conservative, there was broad recognition that individual pile behaviour, hammer energy requirements, and ground conditions remain inherently difficult to predict accurately before installation. As a result, specifying which piles will require higher-energy installation or mitigation measures is often unreliable. In response, several attendees noted that greater flexibility within the consenting and mitigation process may be beneficial, if uncertainty is acknowledged and managed appropriately. Suggestions included approaches based on overall project-level impact budgets, like methods used elsewhere in Europe, and increased opportunities for adaptive management during construction. However, participants also recognised that greater flexibility could create compliance and regulatory challenges if not carefully designed.

A key theme emerging from the discussion was the importance of continued dialogue between developers, engineers, regulators, advisors, and contractors throughout EIA and MMMP process. Participants identified a need for improved communication and collaboration before formal approval of mitigation plans, particularly regarding soft-starts, pile refusals, and realistic installation scenarios. The workshop concluded with thanks to participants and an outline of next steps.

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