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Predicted and observed responses of harbour porpoises to pile driving noise at Moray West Offshore Wind Farm

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Summary

- Offshore wind farm construction requires regulatory assessment of the numbers of protected marine mammals that may experience auditory injury or disturbance from impulsive piling noise. However, there is high uncertainty within available assessment frameworks, and limited opportunities to validate outputs.
- We present data on underwater noise levels and porpoise behavioural responses during construction at Ocean Winds' Moray West wind farm in 2023. Specifically, we compare measurements of 1) underwater noise and 2) harbour porpoise behavioural responses with predictions made during regulatory assessments.
- Broadband acoustic recorders were used to measure noise levels at 750 m and 2,000 m during impact piling of thirteen 9.5 -10 m monopiles, with additional opportunist recordings at up to 15 km. Harbour porpoise responses were assessed between 1 km and 33.4 km from each monopile using an array of 60 echolocation detectors (CPODs) as reported in Benhemma-Le Gall et al. (2024). Analysis of changes in echolocation click detections provided a proxy for behavioural responses during the installation of seven monopiles, where detections during 24 hours after piling were compared with matched periods two days before piling started.
- Measured maximum received noise levels were typically within 1 dB (range -2.4 dB to + 3 dB) of values predicted from acoustic modelling at two focal sites used in earlier regulatory assessments. INSPIRE v5.2, an acoustic modelling tool used in many current UK assessments, was used to conduct blind retrospective modelling of spatial variation in received noise levels from all piling locations where field measurements were available. There was a strong correlation between measured and INSPIRE modelled received noise levels, but with a tendency to over-predict received levels within ~7 km of source and under-predict at greater distances. Overall, 68% of the measurements were lower than model predictions. Where measured values exceeded INSPIRE predictions, all were within 3 dB.
- Using recommended dose-response curves from Graham et al. (2017), modelled predictions of porpoise responses within the areas covered by our PAM array suggested that there would be a > 75% chance of disturbance throughout its 35 km range. In contrast, observed changes in echolocation detections indicated that the probability of disturbance was < 50% at distances beyond 5 km from piling. Monitoring data indicated that <100 porpoises would be disturbed by each piling event, compared to worst-case predictions of > 4,500 in regulatory assessments.
- These results provide confidence in current approaches to acoustic modelling but suggest that existing approaches to estimating disturbance to harbour porpoise from impact piling in UK waters are likely to be unrealistically conservative. This could constrain efforts both to assess impacts on protected populations and to identify mitigation measures that are proportionate to realistic levels of risk.

1. Introduction

The rapid growth in offshore renewables in European shelf seas raises concerns over potential impacts on protected marine mammals, particularly in relation to auditory injury or disturbance resulting from impulsive piling noise (Bailey et al. 2014, Galparsoro et al. 2022).

Regulatory requirements have driven the development of frameworks for assessing how many individual marine mammals may experience noise-related auditory injury or disturbance (Thompson et al. 2013, Faulkner et al. 2018). This requires noise propagation models to predict how received levels of noise vary around pile driving, and information on the distribution of individual marine mammals, of different species, across that landscape. The aim is then to use these data to assess the likelihood that individuals in different areas may be injured or disturbed, and the potential population consequences of these effects (King et al. 2015, Nabe-Nielsen et al. 2018). Critically, this requires an understanding of thresholds, or response functions, for assessing the likelihood of auditory injury or disturbance (Southall et al. 2021, Southall 2024).

Whilst there are a growing number of tools available to support the regulation and management of marine noise, there is high uncertainty over many of the key parameters within these assessment frameworks. Particularly at early stages of planning, these include uncertainties over engineering design, for example over the exact number or dimensions of turbine foundation piles and the hammer energies required to install these. Despite a growing evidence base, there also remains uncertainty over the resulting source levels of piling noise, especially given that new phases of development typically involve extending engineering design and the introduction of new technology (ORJIP 2023). Finally, there are biological uncertainties, for example over baseline distribution of marine mammals, and how individual animals may respond to received levels of noise (Southall et al. 2021). Validating assumptions about key biological responses is especially challenging, and many aspects of these assessment frameworks have not been tested in real world scenarios.

A key aim of the PrePARED project has been to conduct analyses that support future consenting by increasing confidence and consensus in predicted impacts of planned offshore wind farm developments. In this report, we present data on underwater noise levels and porpoise behavioural responses during construction of the Moray West offshore wind farm. By comparing these observations with predictions that had previously been submitted to regulators during the consenting process, we aim to provide a case study that can be used to evaluate methodologies currently being used within Environmental Impact Assessments (EIA) for other offshore wind projects. Specifically, this report compares: (1) underwater noise measurements made during Moray West construction with predictions from noise propagation modelling; (2) measured responses of harbour porpoises to piling noise with behavioural response levels predicted in regulatory assessments.

2. Case study background

The Moray West offshore wind farm is located on the Smith Bank in the Outer Moray Firth, 22 km offshore and adjacent to Moray East offshore wind farm (operational since 2020) and Beatrice offshore wind farm (operational since 2019) (Figure 1).

Moray West's development site covers an area of 225 km^2 over water depths ranging from 35 m to 55 m. The application phase commenced in 2016, and the project was consented by Scottish Government in June 2019. The installation of Moray West's 62 monopile foundations started on 4 October 2023 and finished on 13 April 2024.

Monopiles of 9.5 -10.0 m diameter and 74 - 92 m in length were installed through pre-installed scour pads using a 4,400 kJ hydraulic impact hammer (MENCK MHU 4400) deployed from a dynamically positioned (DP) heavy lift vessel (Bokalift 2, IMO: 9190705). Agreed mitigation measures during monopile installation required the use of Acoustic Deterrence Devices (ADD) for 10 mins, followed by a 15-min soft start procedure with a maximum hammer energy of 432 kJ. Hammer energy was then ramped up gradually to maintain a steady pile penetration rate (Moray Offshore Wind Farm (West) Ltd. 2023). If any breaks in piling exceeded 6 hours, an ADD was again deployed for 10 mins before resuming impact piling. At those sites where there was a period of vibro-piling prior to impact piling, no ADD was required. No noise abatement systems (see Verfuss et al. 2019) were used in this piling campaign.

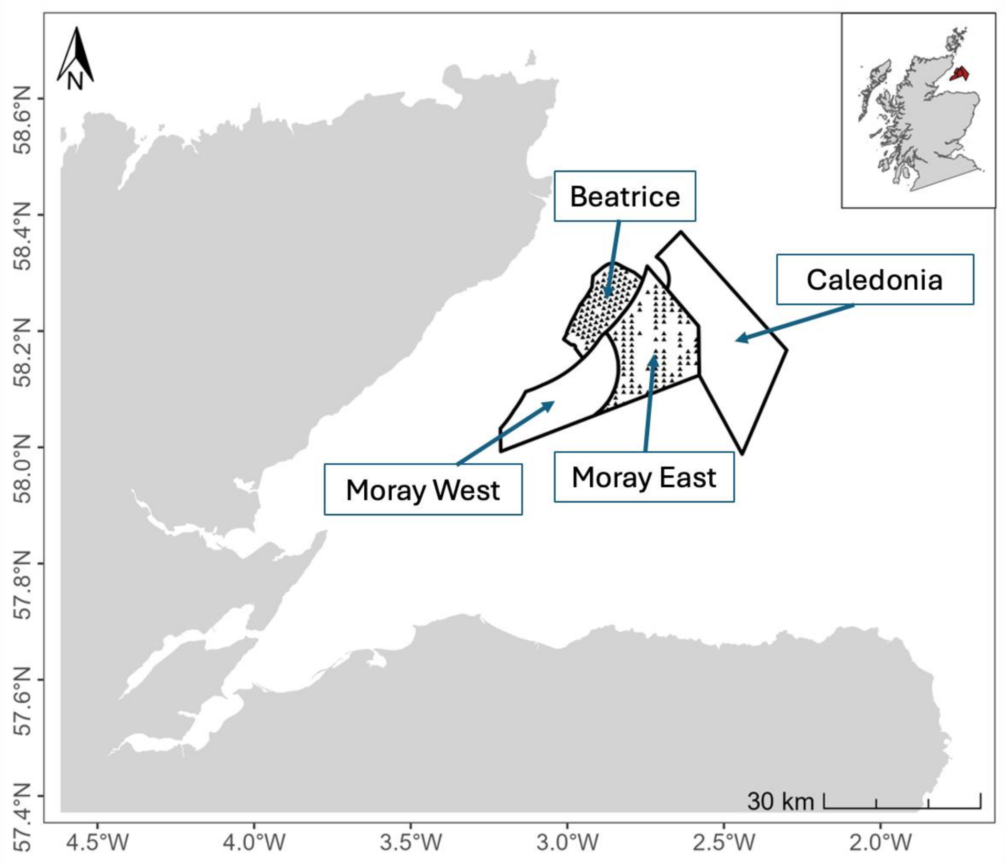

Figure 1. A map of the Moray Firth showing the location of Moray West and other offshore wind farms mentioned in the text.

2.1 Regulatory assessments

Assessments of construction noise impacts on protected marine mammals were required at two stages in the regulation of each of the Moray Firth developments. First, assessments were included within EIA reports to support project applications (e.g., Moray Offshore Wind Farm (West) Ltd 2018). Second, impacts were re-assessed within the Piling Strategy Reports which developers were subsequently required to produce as a consent condition prior to the start of construction. These Piling Strategy Reports provided detail on the final engineering design and procedures, potential impacts on marine mammals, and appropriate measures to mitigate those impacts (e.g., Moray Offshore Wind Farm (West) Ltd 2023)

To support these regulatory assessments, Moray Firth developers used two approaches to model the propagation of piling noise. Noise modelling as part of the EIAs at Beatrice and Moray East was conducted by Subacoustech Ltd, who used their semi-empirical underwater noise model INSPIRE (e.g., Technical Annex 7A in Beatrice Offshore Wind Farm Ltd 2012). At the time, some stakeholders called for more transparency in the underwater noise modelling methods used in the EIA process. In response, assessments in Moray West's EIA (e.g., Moray Offshore Wind Farm (West) Ltd 2018) were conducted by the Centre for Environment Fisheries and Aquaculture Science (CEFAS) using a more open approach for estimating source levels (see Farcas et al. 2016). This was based upon an energy conversion factor (ECF) model, which predicts the level of noise in the water via a direct conversion from the hammer energy applied to the pile (De Jong and Ainslie 2008). CEFAS then used a published Parabolic Equation model (Collins 1993) to predict spatial variation in received noise levels at different distances from the noise source. Nevertheless, this approach also involved uncertainties over appropriate conversion factors for the energy conversion model. In the Moray West EIA, a 1% ECF was used based upon Dahl et al. (2015), but subsequent modelling within the Moray West Piling Strategy used more conservative values of 4% and 10%. For further discussion on the use of ECF to model piling noise, see Wood et al. (2023). Assessments for the latest round of ScotWind projects continue to be based on a variety of noise propagation models, with more recent versions of Subacoustech's INSPIRE model being used in EIAs for several developments in NE Scotland (eg, Caledonia Offshore Wind Farm 2024, Muir Mhòr Offshore Wind Farm 2024).

Predictions of spatio-temporal variation in received levels of piling noise were subsequently used in assessments to estimate the likelihood that marine mammals present around the construction sites were subject to auditory injury or disturbance. Southall et al. (2007, 2019) developed noise exposure thresholds for assessing auditory injury. These underpin the more recent US National Marine Fisheries Service guidance (NMFS 2024) and have been accepted widely by other regulators globally. However, there is greater uncertainty over thresholds likely to elicit behavioural responses, not least because it is recognised that responses vary in different behavioural contexts (Ellison et al. 2018, Booth et al. 2022, Southall et al. 2023). As a consequence, there is less consistency in regulatory approaches to assessing behavioural responses, and guidance is evolving to use a more probabilistic and context specific response (Southall et al. 2021, Southall 2024). Currently, EIAs in UK waters have generally used a dose-response approach when assessing the probability of disturbance to cetaceans to different received levels of piling noise (NRW 2023, Sinclair et al. 2023). In many of these cases, including at Moray West, developers have used dose-response curves based upon harbour porpoise response data that were collected by Graham et al. (2017) during early phases of construction of the Beatrice offshore wind farm. Although subsequent analyses of data from the entire construction period suggested a reduction in response later in the development (Graham et al. 2019), response data from Graham et al. (2017) have generally been used to provide a more conservative estimate of disturbance.

Final regulatory approval for the pile driving required to construct Moray West was based on the assessment in the Moray Offshore Wind Farm (West) Ltd (2023) Revised Piling Strategy. Based upon geophysical site characteristics and local porpoise densities, it was agreed that this worst-case scenario for potential impacts upon harbour porpoises should be based upon piling location L13, in the northeast of the Moray West site (see Figure 2). It is this assessment of potential behavioural disturbance to harbour porpoises that we focus upon in this report.

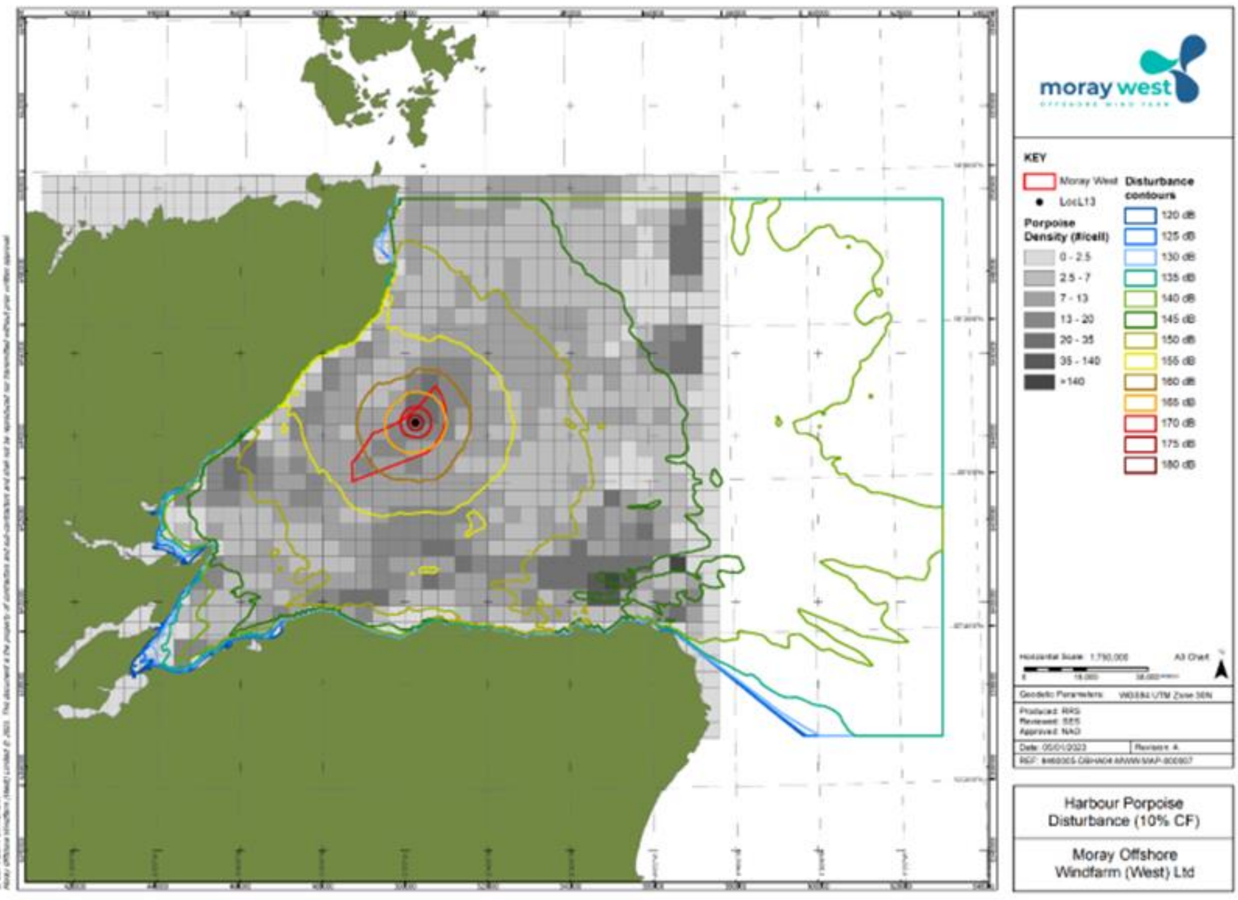

Figure 2. Reproduction of Figure 3.6 from the Revised Moray West Piling Strategy showing the predicted variation in received noise levels for piling location L13. SEL_{ss} isopleths between 120 and 180 dB re 1 μPa^{2}s are shown in relation to the underlying porpoise density surface. Source levels were estimated using an estimated hammer energy of 4,400 kJ and an energy conversion factor of 10%.

Figure 2 and Table 1 present key outputs from this assessment as included in the Revised Moray West Piling Strategy (Moray Offshore Wind Farm (West) Ltd 2023). Figure 2 illustrates the baseline density of harbour porpoises across the region with contours for received noise levels (unweighted SEL_{ss} in 5 dB increments), as predicted by the Parabolic Equation Model and a source level estimated using a 10% energy conversion factor. Based upon these data, the relationship of Graham et al. (2017) between the probability of a behavioural response and received noise levels was used to estimate how many individual porpoises would be disturbed in a worst-case situation (Table 1). Data from the 2018 EIA assessment (Moray Offshore Wind Farm (West) Ltd 2018) are included in Table 1 for comparison, where the assessment was based upon a higher hammer energy and a literature value for a conversion factor of 1% (Dahl et al. 2015). The predicted number of porpoises disturbed in the final assessment, the Revised Moray West Piling Strategy, are presented using more conservative alternatives for conversion factors (4% and 10%) as requested at the time by statutory advisors.

Table 1. Reproduction of Table 3-10 of the Revised Moray West Piling Strategy, showing predictions of the numbers of harbour porpoises that could be disturbed using different values for the Energy Conversion Factor (CF). Data are presented both for the worst-case scenario used in the piling strategy and the earlier estimates produced in the 2018 EIA.

Assessment (Location)	Hammer Energy (kJ)	1% CF			4% CF			10% CF		
		# Porpoise	% entire MU	% UK portion	# Porpoise	% entire MU	% UK portion	# Porpoise	% entire MU	% UK portion
2018 EIA – concurrent piling events	5,000	2,207	0.64%	....	....	....	....	....	....	....
Revised PS single piling event (L13)	4,400	....	....	....	3,533	1.02%	2.21%	4,681	1.35%	2.93%

2.2 *Construction Monitoring*

As part of their consents approval, Moray West undertook monitoring of underwater noise and harbour porpoise behavioural responses during pile installation to validate assumptions made within earlier impact assessments.

In line with Moray West's offshore consent conditions, the methodology for monitoring underwater noise and marine mammals was approved following discussion and agreement within the Moray Firth Regional Advisory Group – Marine Mammals (MFRAG-MM) subgroup (https://marine.gov.scot/ml/moray-firth-regional-advisory-group-mfrag).

3. Methods

3.1 Measurement of piling noise

Noise monitoring was conducted by Seiche Ltd. between 5 October and 2 December 2023, during installation of 13 monopiles (Figure 3, Appendix 1).

At each of these locations, two Acoustic Recorder Units (ARUs) were deployed approximately 8 m above the seabed at nominal distances of 750 m and 2,000 m from the centre of the monopile. In practice, recorders were deployed for sufficiently long periods to record multiple piling events, which provided additional data at a range of other distances from source. 24-bit recordings with a 128 kHz sample rate were made using RT-SYS Sylence-LP 440 ARUs with an HT-96-MIN-210 dB hydrophone. Internal clocks were synchronised to GPS time prior to deployment and ARUs were given a one-minute 250 Hz pistonphone calibration test before and after recovery.

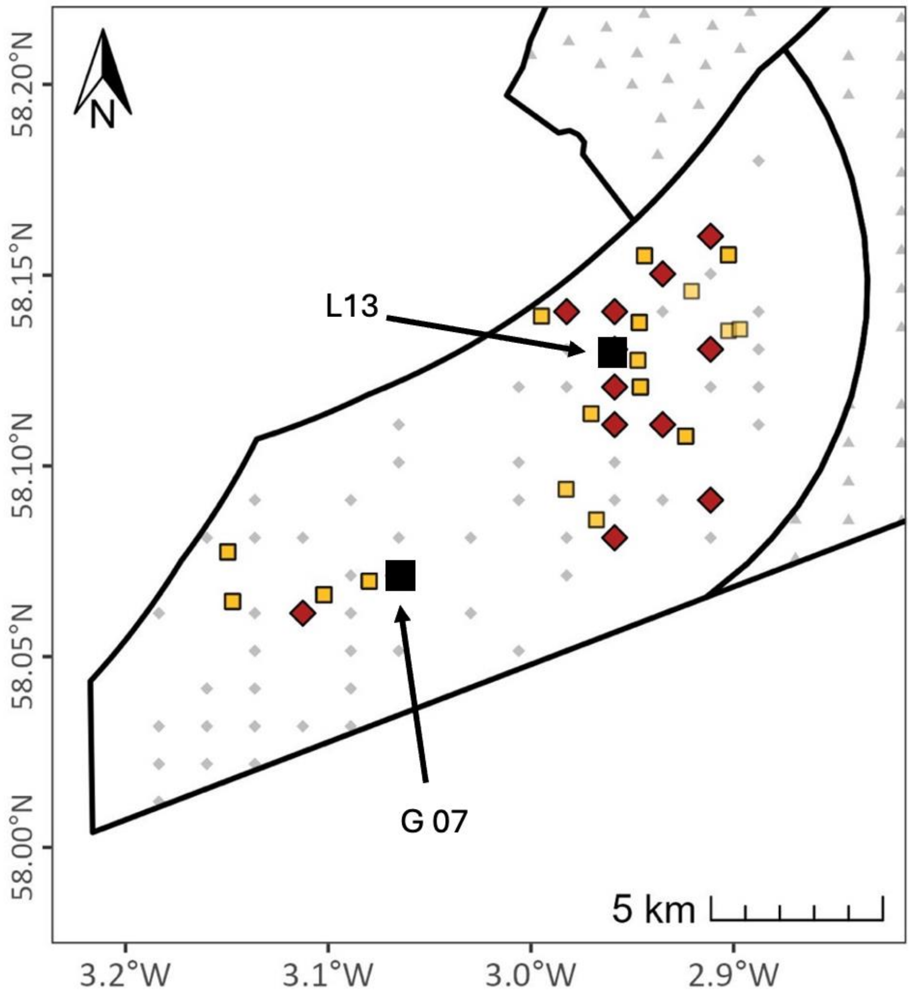

Figure 3. A map of the Moray West site showing the location of moorings used for underwater noise measurements (yellow squares) and the locations of L13 and G07 (black squares) and the other 11 monitored monopile foundations (red diamonds). Grey diamonds represent the remaining Moray West monopile locations (not included in the analyses) and grey triangles represent the turbine layout at Beatrice and Moray East offshore windfarms.

Recordings were subsequently analysed using purpose written software to provide a standard set of measurements using metrics recommended in Robinson et al. (2014). In this report, we focus on comparisons using unweighted sound exposure level (SEL) for a single strike (SEL_{ss}) as used within the assessments of behavioural disturbance for cetaceans.

3.2 Monitoring porpoise behavioural responses

To monitor responses of harbour porpoises to piling noise, an array of 60 echolocation detectors (CPODs) was deployed between 1 September and 31 December 2023 (Figure 4). Eighteen monopiles were piled during this period, each taking 1.8 - 4.3 hrs (mean = 2.8 hrs) to install. Following methods used in Graham et al.'s (2019) study at the Beatrice offshore wind farm, resulting data were used to assess responses to the sub-set of seven piling events where gaps in piling activity allowed comparison of response and baseline periods. Further details of the field methodology and data analysis can be found in Benhemma-Le Gall et al. (2024), where analyses of these data were used to model responses of porpoises along a gradient of distances from the piling vessel. As in Benhemma-Le Gall et al. (2024), we focus our comparison with EIA predictions on responses during the first two piling events as the response was stronger than that predicted from the full dataset of seven events, and therefore represents the worst-case scenario.

3.3 Comparison of construction monitoring data and predictions from regulatory assessments

3.3.1 EIA and Piling Strategy Predictions using Parabolic Equation modelling

There were two piling locations where modelled received noise levels within the Revised Moray West Piling Strategy could be compared with measurements made by Seiche during the 2023 piling campaign. Outputs from the Parabolic Equation modelling at pile location L13 (Figure 2) and G07 (see Figure 3.13 in Moray Offshore Wind Farm (West) Ltd. 2023) were provided as GIS shapefiles and then used to derive predictions of received noise levels at each of the broadband recorder and CPOD moorings (see Figure 3). Modelled isopleths were provided in 5 dB increments, and linear interpolation was used to estimate received noise levels at each point location by rounding up to the nearest decibel. These predictions were then compared with measurements of received noise levels available from seven monitored locations during the installation of L13 and six monitored locations during the installation of G07.

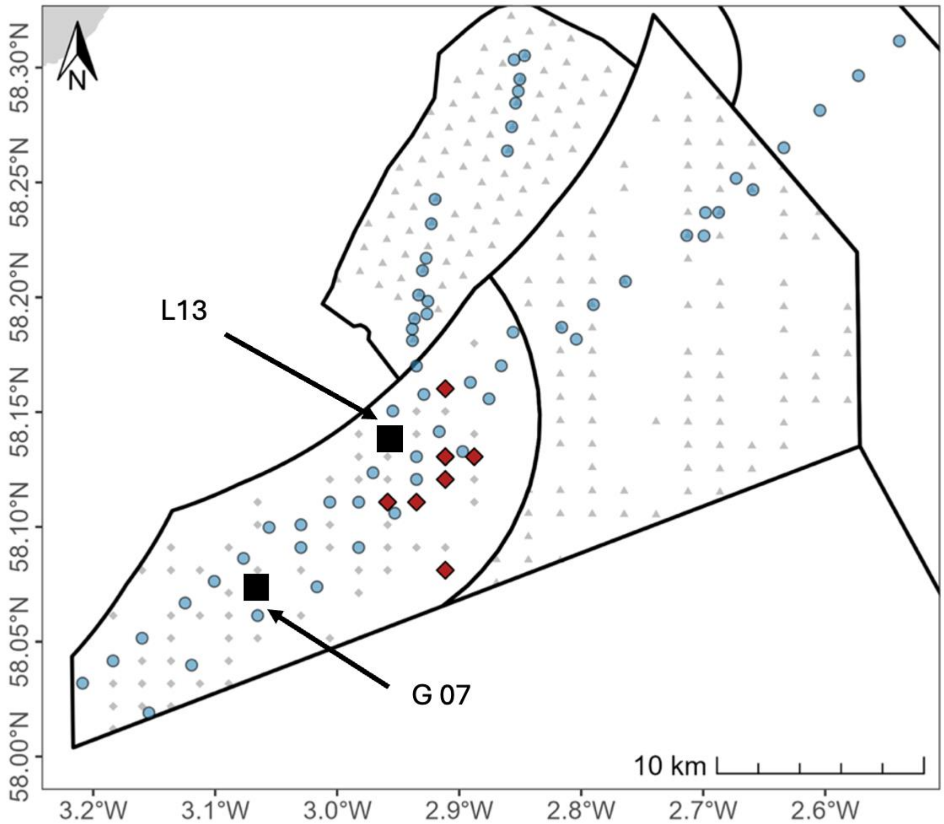

Figure 4. A map of the Moray Firth showing the location of moorings used for passive acoustic monitoring (PAM) of porpoises (blue circles) and the locations of seven pile foundations used in the response study (red diamonds). Grey diamonds represent the remaining Moray West monopile locations (not included in the analyses) and grey triangles represent the turbine layout at Beatrice and Moray East offshore wind farms. Locations G07 and L13 that were selected for modelling within the Revised Piling Strategy are marked as Black Squares.

3.3.2 Retrospective analysis using INSPIRE

To extend comparisons of model predictions and measurements of received levels, we also conducted blind retrospective modelling for all 18 pile foundations installed during the study period. Firstly, this allowed us to extend the comparison across a wider range of piling locations. Second, it provides an illustration of how this extensive archive of piling noise measurements from Moray West can be used to validate other acoustic modelling frameworks. Here, we conducted a retrospective analysis using Subacoustech's INSPIRE V5.2. This was primarily due to regional interest in the validation of this model given its use by several ScotWind developers, including the Ocean Winds Caledonia project within the Moray Firth (Figure 1).

In September 2024, PrePARED researchers at the University of Aberdeen (PMT & ABLG) collated engineering data and provided Subacoustech with a) the location of each monopile foundation and b) the maximum hammer energy recorded during installation. This largely mirrors the process used when conducting acoustic modelling for regulatory assessments, the difference being that maximum hammer energies would normally be predictions from design engineers rather than realised values. Critically, all prior information about noise measurements was kept confidential, so that the acoustic modelling by Subacoustech was conducted blind to the construction monitoring measurements.

Subacoustech subsequently provided PrePARED researchers (PMT & ABLG) with model outputs as GIS shapefiles with isopleths in 1 dB increments, and these were used to obtain predictions of received levels (rounded up to the nearest 1 dB isopleth) at each of the broadband noise recorder and CPOD moorings (see Figure 3). Analyses comparing measured and modelled noise levels, and porpoise behavioural responses, were carried out independently by PrePARED researchers.

As for the Parabolic Equation modelling used in the Revised Piling Strategy, INSPIRE predictions were first compared with measurements of received noise levels at seven locations during the installation of L13 and six locations during the installation of G07. In addition, INSPIRE predictions could be compared with measurements made during the installation of another eleven monopiles (Figure 3).

To maximise potential for future semi-blind comparison with other modelling tools, we avoid presenting detailed measurements at the additional eleven locations. Instead, we compared predicted and measured noise levels using a simple correlation and the frequency distribution of differences in measured and modelled SEL_{ss}, which could in future be used to compare the performance of different models.

3.3.3 Responses of marine mammals in relation to distance and received noise levels

Following the same method used in Graham et al (2017, 2019), Benhemma-Le Gall et al. (2024) used changes in acoustic detections of porpoises to explore how the probability of response in the 24 hours following the end of each piling event varied with distance from the piling vessel. We refer to this relationship with distance as a deterrence function. Where changes in the probability of response in the 24 hours following the end of each piling event are related to measured or predicted received levels of noise (e.g. in Graham 2017), we refer to this as a dose-response function. Further details of the methodology used can be found in Graham et al. (2017, 2019) and Benhemma-Le Gall et al. (2024).

In the Moray West Revised Piling Strategy, the Graham et al. (2017) dose-response function was related to noise modelling outputs (see Figure 2) to predict how many individuals would be disturbed given an average local density of 0.31 porpoises per km^2 (see Table 1). In this report, we use Benhemma-le Gall et al.'s (2024) deterrence function, which was based upon observations during the first two piling events at Moray West, to provide a comparable estimate of the numbers of individuals disturbed during one piling event. This was achieved by assuming the same local density of 0.31 porpoises per km^2, and estimating the cumulative number of individuals disturbed given the observed deterrence function (Figure 3 in Benhemma-Le Gall et al. 2024), which provides estimates of the probability of disturbance at different distances from piling.

In this report, INSPIRE-predictions of received noise levels at each of PAM location were also used to estimate average SEL_{ss} at different distances from piling at Moray West. These predictions of received noise levels at different distances from source permit more direct comparison between the Graham et al. (2017) dose-response function (which underpinned predictions in the EIA and Revised Piling Strategy) and the Benhemma-Le Gall et al. (2024) deterrence function (which was based on monitoring data collected during construction at Moray West). We use these values to visualise how predicted levels of disturbance in the Revised Piling Strategy (that were based upon the Graham et al. (2017) dose-response function) would be expected to vary in relation to distance from source; thus providing a more direct comparison with the monitoring data that were used to produce the Benhemma-Le Gall (2024) deterrence function.

4. Results

4.1 Comparison of measured and modelled noise levels at key sites used in the Revised Moray West Piling Strategy

Table 2 presents measurements of piling noise at G07 and L13 in comparison to the Parabolic Equation model predictions presented in the Revised Moray West Piling Strategy. All predictions in the Revised Moray West Piling Strategy were based on an assumed maximum hammer energy of 4,400 kJ, whereas realised maximum hammer energies were slightly lower than this (4,249 kJ at G07 and 4,016 kJ at L13). Measurements at 750 m were similar to predicted noise levels but, at greater ranges, modelling in the Revised Moray West Piling Strategy underestimated received levels by up to 2.7 dB re 1 $\mu Pa^2 s$ at one site (G07).

4.2 Comparison of measured and retrospective noise modelling using INSPIRE

Table 3 presents comparable data to those in Table 2, but here using predicted noise levels from the retrospective modelling using INSPIRE, which used realised maximum hammer energies. At one site (G07), measured received levels generally fell within the predicted 1 dB band, while those at the second site (L13) were typically 1 - 3 dB lower than the predicted received levels.

For the INSPIRE modelling, predicted received levels could also be compared with measurements at a total of 79 locations that were between 750 m and 14,210 m from thirteen monopile foundations installed at Moray West (Figure 3).

There was a strong correlation between measured and modelled received noise levels (Figure 5; $r = 0.97$, $p < 0.001$), but with a tendency for INSPIRE to over-predict at closer distances to the source (less than ~ 7km) and under-predict at greater distances (Figure 6). Overall, 54 (68%) measurements were lower than the model predictions. Where measured values exceeded INSPIRE predictions, only 11% were > 1 dB of the predicted value and all were within 3 dB (Figure 7).

Table 2. A comparison of measured and Parabolic Equation modelled received noise levels at different distances from focal piling locations (G07 & L13) used in the Revised Moray West Piling Strategy. Modelled levels are presented both for the 5 dB isopleth in which recorders were located, and interpolated point estimates.

Turbine	Range (m)	Measured Max SEL_{ss} (dB re 1 μPa²s)	Modelled Max SEL_{ss} 5 dB isopleth (dB re 1 μPa²s)	Modelled Max SEL_{ss} interpolated (dB re 1 μPa²s)
G07	1047	179.9	175 - 180	180
G07	2533	175.9	170 - 175	174
G07	5187	171.5	165 - 170	169
G07	5356	170.5	165 - 170	170
G07	11776	164.0	160 - 165	162
G07	12089	163.7	160 - 165	161
L13	748	178.8	180 - 185	181
L13	1060	178.9	175 - 180	179
L13	1328	177.5	175 - 180	178
L13	1994	172.7	170 - 175	175
L13	2862	172.6	170 - 175	173
L13	3266	170.5	170 - 175	172
L13	4303	169.4	165 - 170	169

Table 3. A comparison of measured and INSPIRE retrospectively modelled received noise levels at different distances from focal piling locations (G07 & L13). Modelled levels are presented for the 1 dB isopleth in which

recorders were located. In contrast to the Parabolic Equation modelled predictions in the Revised Moray West Piling Strategy (see Tabel 2) INSPIRE modelled predictions were based upon realised maximum hammer energies of 4,249 kJ at G07 and 4,016 kJ at L13.

Turbine	Range (m)	Measured Max SEL_{ss} (dB re 1 μPa^2s)	Modelled Max SEL_{ss} (dB re 1 μPa^2s)
G07	1047	179.9	180 - 181
G07	2533	175.9	176 - 177
G07	5187	171.5	170 - 171
G07	5356	170.5	170 - 171
G07	11776	164.0	163 - 164
G07	12089	163.7	163 - 164
L13	748	178.8	180 - 181
L13	1060	178.9	180 - 181
L13	1328	177.5	179 - 180
L13	1994	172.7	176 - 177
L13	2862	172.6	173 - 174
L13	3266	170.5	173 - 174
L13	4303	169.4	170 - 171

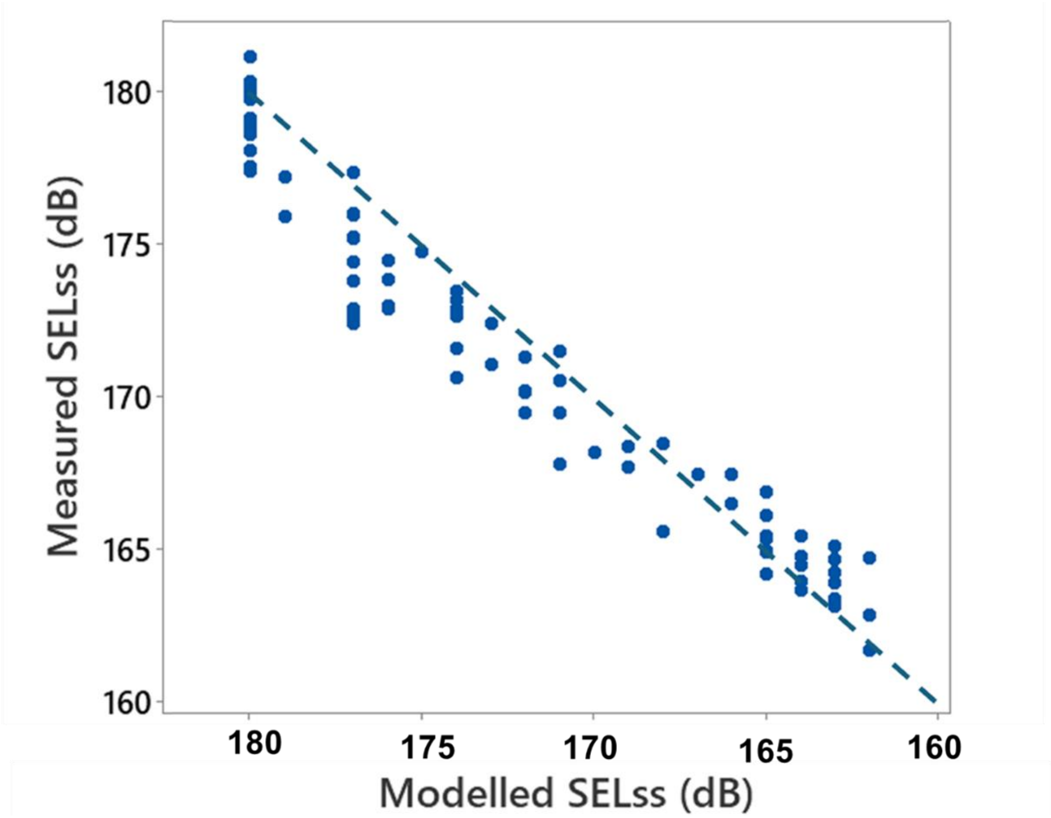

Figure 5. Comparison of measured and INSPIRE modelled SEL_{ss} received noise levels (dB re 1 μPa^2s) from monopile installation at thirteen locations at Moray West. The dashed line represents the line of equality.

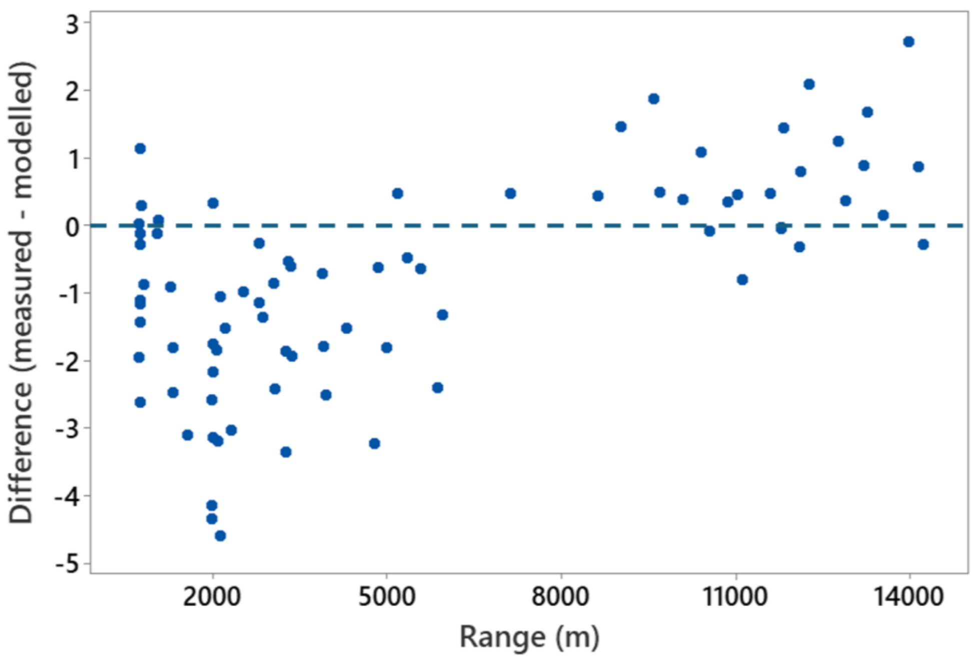

Figure 6. Scatter plot showing the relationship between range from source and the absolute difference (in dB) between measured and INSPIRE modelled SEL_{ss} received noise levels at Moray West. As for Figure 5, data are from a total of 79 locations, at ranges of 750 m to 14,210 m from piling, during the installation of thirteen monopile foundations. The dashed line represents a difference of zero.

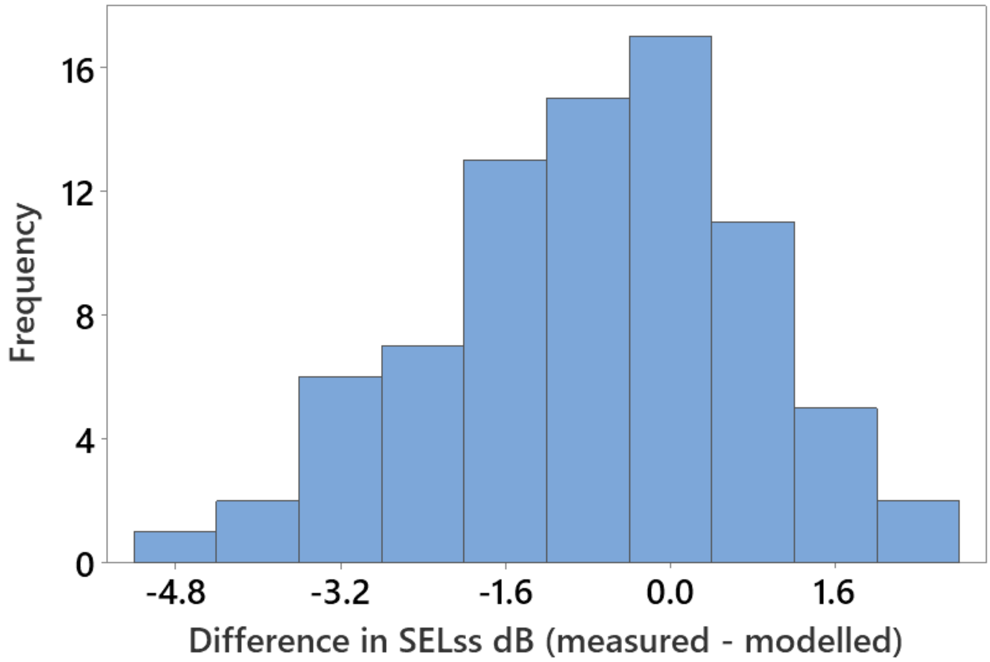

Figure 7. Frequency distribution of the absolute difference (in dB) between measured and INSPIRE modelled SEL_{ss} received noise levels at Moray West. Data are from a total of 79 locations, at ranges of 750 m to 14,210 m from piling, during the installation of thirteen monopile foundations.

4.3 Responses of marine mammals to different received levels of noise

In the Revised Moray West Piling Strategy, worst-case estimates of disturbance to porpoises were based upon modelling at location L13 (Table 1). Although noise measurements were obtained during pile driving at this location (Table 2), the monopile-installation sequence meant that there was insufficient baseline to directly estimate changes in porpoise occurrence in response to this piling event. Instead, we compare predicted and measured responses using data from the installation of the first two monopiles (N13 & L11) which occurred immediately before the installation of L13. Piling durations and maximum received noise levels at 750m were similar at all three of these sites (Appendix 1).

Figure 8 presents the porpoise deterrence function reported in Benhemma-Le Gall et al. (2024), which is based upon changes in echolocation detections in the 24 hours following the installation of these first two monopiles. This is presented as the red line in Figure 8, and shows that there was a 50% chance of a response at around 5 km from the piling event, reducing to a 25% chance of response at around 7.5 km.

INSPIRE predictions of received noise levels at each of the PAM locations (see Figure 4) were applied to the Graham et al. (2017) dose response curve to compare this "observed" deterrence function with responses predicted using approaches used in the Revised Moray West Piling Strategy (Moray Offshore Wind Farm (West) Ltd. 2023). In the Graham et al. (2017) dose-response, a 50% probability of disturbance is predicted to occur at a received SEL_{ss} of approximately 145 dB re 1 μPa^2s. These data demonstrate that the predicted responses, illustrated as the blue line in Figure 8, were extremely conservative compared to observed data. For example, at 5 km the predicted response was > 98% compared to the *observed* value of 50%. Beyond 30 km, the level of conservatism was more extreme, and predicted responses remained >75% even though *observed* responses had dropped to close to zero.

Finally, these relationships can be compared with the deterrence function that was also reported in Graham et al. (2017), but which has not subsequently been considered within regulatory assessments given the preferred use of a dose-response function (Sinclair et al. 2023). This is presented as the black line in Figure 8. It should be highlighted that the blue line and the black line in Figure 8 are derived from a dose-response function and a deterrence function that were modelled using the same dataset from the first phase of piling at Beatrice Offshore Wind Farm. As such, they can be considered as alternative hypotheses for predictions of responses at Moray West. First, the blue line illustrates predicted responses assuming that received noise levels are the main driver of disturbance (as currently used within regulatory assessments in Scottish waters). Second, the black line shows the predicted response assuming that distance from source is the main driver of disturbance.

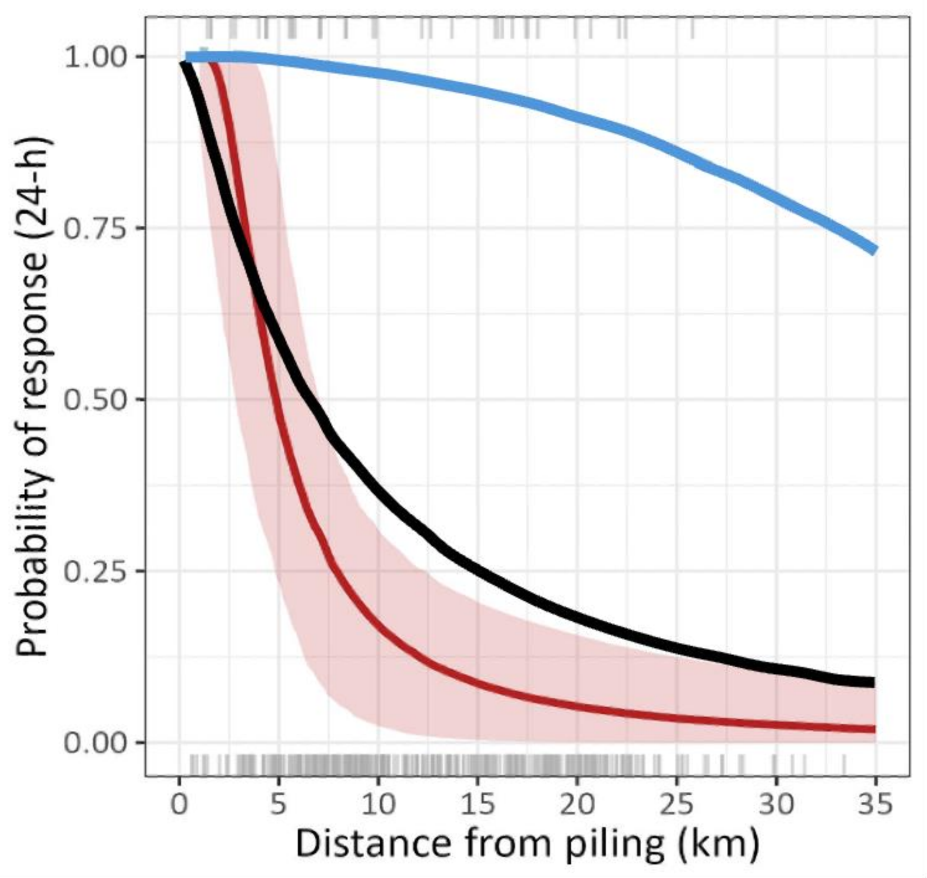

Figure 8. The probability of 24-h harbour porpoise response in relation to the partial contribution of distance from piling at the first two piling events (N13 & L11) (solid red line) at Moray West offshore wind farm, assuming a 3h piling duration. Confidence intervals (shaded areas) estimated for uncertainty in fixed effects only. Rug plots show actual response data for the first two piling events (grey). The blue line represents the predicted disturbance based upon the dose response function in Graham et al. (2017) based upon INSPIRE predictions of received noise levels. The black line represents the predicted disturbance based upon the deterrence function in Graham et al. (2017).

Given the observed deterrence function (the red line in Figure 8) and an average porpoise density of 0.31 animals per km^2, it is estimated that approximately 90 individuals were disturbed during each of these piling events. In comparison, using the dose-response function in Graham et al (2017) and the same average porpoise density, the Revised Moray West Piling Strategy predicted that > 4,500 individuals could be disturbed during a single piling event (see Table 1).

5. Discussion

There are a growing number of modelling frameworks available to support regulatory assessments of potential disturbance to protected marine mammals. However, there are uncertainties over the parameterisation of these models which risk reducing stakeholder confidence in the outcomes of these assessments.

Although the approach used in these frameworks varies in detail, assessments of potential impacts of offshore wind farm construction are generally underpinned by two key components. First, noise propagation models provide estimates of spatial variation in received noise levels around pile-driving events (Farcas et al. 2016). Second, behavioural thresholds or response functions are used to assess spatial variation in the probability that animals will be disturbed given the received noise levels they experience (Southall 2024). Although widely used during consenting, opportunities to validate the predictions used in regulatory assessments are rare.

Here, we used data from a regional strategic research and monitoring programme to compare field measurements made during construction of the Moray West offshore wind farm to model predictions presented in earlier regulatory assessments. Our results demonstrate that predictions of maximum SEL_{ss} from two different noise propagation models used during consenting were in broad agreement with measurements made at ranges of 750 m to 15 km (Tables 2 & 3, Figure 6). However, measured behavioural responses of harbour porpoises were much lower than those predicted from the Graham et al. (2017) dose-response function that is currently recommended for regulatory assessments in Scottish waters (Figure 8). In combination, this suggests that current assessments of disturbance impacts are overly conservative. In the sections below, we explore these comparisons in more detail and discuss how frameworks could be adapted to provide more realistic estimates of the number of animals disturbed in future construction scenarios.

5.1 Comparison of measured and modelled levels of pile-driving noise

Despite their fundamental role in regulatory assessments, validation of models estimating propagation of piling noise are rare (Vigness-Raposa et al. 2025), and the details are not always publicly available due to the proprietary nature of many acoustic modelling tools (ORJIP 2023). Uncertainties over predicted noise levels has therefore been a key issue during the consenting of many wind farms. This has often been exacerbated by the diversity of approaches used both to estimate source levels and model acoustic propagation, which have made it difficult for regulators and their advisors to draw comparison across projects.

Here, we focussed on comparison of the maximum unweighted SEL_{ss} values within each piling event, as these currently underpin many assessments of marine mammal behaviour responses in UK waters. We refer readers to Lucke et al. (2024) and the ORJIP funded RECON (ORJIP 2023) and RADIN (ORJIP 2024) project outputs for more detailed discussion of other acoustic metrics and issues related to the estimation of auditory injury through cumulative sound exposure throughout entire piling events.

During the consenting process for the Moray West wind farm, one of the key issues raised by stakeholders was uncertainty over the approach used to predict source levels during the installation of large monopiles. In the EIA, an energy conversion factor model was used to estimate the pile-driving source levels that form the basis of the acoustic propagation models. However, there was concern that the original estimates based on a 1% energy conversion factor could underestimate noise exposure. As a result, subsequent modelling in the Revised Moray West Piling Strategy was based upon 4% and 10% conversion factors, with 10% being used for all worst-case scenarios (Moray West Offshore Wind Farm Ltd 2023).

In this study, we were able to compare field measurements with these modelled predictions at two of the focal sites used in the Revised Moray West Piling Strategy. This comparison suggests that predictions using Parabolic Equation modelling were close to measured values at the locations within 750 – 1050 m (Table 2). However, even when using the higher 10% conversion factors, predictions slightly underestimated maximum measured levels at greater ranges, occasionally by up to 3 dB. It is possible that the accuracy of these predictions could be improved by using alternative models, such as directional line source energy flux models, instead of a point source model (see Wood et al. 2023). Nevertheless, greater conservatism in other components of these regulatory assessments (see below) mean that this underestimation of noise levels beyond 7 km seems unlikely to have had a major impact on the outcome of these assessments.

A key aim of this comparison was to build confidence in future regulatory assessments. We therefore also undertook blind retrospective analyses using predictions from INSPIRE, an acoustic modelling framework that is currently being used for similar developments in UK waters. This allowed us to compare modelled and measured SEL_{ss} across a broader suite of pile-driving events. Furthermore, this illustrates how the exercise could be repeated should regulators or other stakeholders wish to use existing noise measurements to validate these or other relevant noise metrics (see Lucke et al. 2024) using alternative acoustic modelling tools.

Comparison of predictions with measurements made at the two focal sites in the Revised Moray West Piling Strategy indicated that there was broad agreement between modelled and measured maximum SEL_{ss} for both the Parabolic Equation modelling (Table 2) and INSPIRE (Table 3). There was also good agreement between predicted and measured maximum SEL_{ss} across the broader range of sites available for the INSPIRE modelling (Figure 5), but with a tendency to overestimate noise levels within 7 km, and underestimate them beyond this distance.

Overall, however, these results suggest that uncertainties over noise modelling predictions have a relatively small influence on predictions of the number of animals disturbed. Instead, as discussed below, it is the dose-response function applied to these predicted noise levels that has a much greater impact on predictions of the numbers of porpoises disturbed.

5.2 Responses of harbour porpoises to pile driving

In UK waters, environmental impact assessments typically use dose-response functions to estimate spatial variation in the probability of disturbance in relation to locally predicted unweighted SEL_{ss} (NRW 2023, Sinclair et al. 2023). In the absence of empirical data from other species, current guidance within Scottish waters is to use the dose-response function from Graham et al. (2017) based upon responses of porpoises to the first phase of piling at the Beatrice offshore wind farm for all species of cetaceans.

In an earlier PrePARED report (Benhemma-Le Gall et al. 2024), we explored how harbour porpoise responses to construction at Moray West varied with distance from piling events, focussing on the implication of these findings for the management of disturbance in harbour porpoise Special Areas of Conservation using EDRs (see JNCC 2020). In the present study, we were able to extend these findings and estimate received SEL_{ss} at different distances from piling events using the retrospective INSPIRE modelling that had been based upon realised piling parameters. This allowed us to relate observed changes in porpoise behaviour to predicted received levels of piling noise, for comparison with predictions made using the Graham et al. (2017) dose-response function.

In the Revised Moray West Piling Strategy, modelling was conducted for one site (L13) which was considered a worst-case scenario for behavioural impacts on porpoises (Figure 2 & Table 1). Unfortunately, porpoise responses to this specific piling event at L13 could not be monitored directly. This is because the design used to quantify behavioural responses compares echolocation detections during the 24 hours after piling with matched periods starting two days before piling (see Graham et al. 2017, 2019). In practice, piling schedules at both Beatrice and Moray West meant that only a sub-set of pile installations could be included in these analyses, for example where weather downtime provided sufficient baseline and impact windows. Instead, we focus our comparison of modelled and measured responses using response data for the previous two piling events at Moray West, which occurred twelve and seven days before the installation of L13. As in Benhemma-Le Gall et al. (2024), we focus our comparison on these first two piling locations to provide a conservative measure of observed responses, given that a weaker response to piling was observed when the analysis was repeated for all seven locations (see Figure S1 in Benhemma-Le Gall et al. 2024). We recognise that our two key monitoring sites did not include the site used for modelling responses within the Revised Moray West Piling Strategy. However, pile dimensions, maximum hammer energies and measured noise levels at 750 m were similar at all three sites (Appendix 1) and we suggest that this provides a reasonable comparison of modelled and observed data. In future, it would be possible to conduct additional retrospective modelling for a more direct comparison, but we suggest that piling parameters are similar enough for this not to be a priority.

Observed responses of harbour porpoises to these first two piling events at Moray West were dramatically lower than those predicted from the Graham et al. (2017) dose-response function which underpinned the predictions in the Revised Moray West Pilling Strategy (Figure 8). Recommended use of this initial dose-response from Beatrice was intentionally precautionary, as subsequent analysis of the full dataset from Beatrice showed that responses weakened through construction, either due to habituation or other seasonal effects (Graham et al. 2019). Nevertheless, given that measured responses were substantially lower than predicted values (Figure 8), it seems likely that other contributing factors are involved. We suggest three key issues deserve further investigation.

First, it must be remembered that neither in this study, nor previous PAM-based studies of piling noise (e.g., Dähne et al. 2013, Dähne et al. 2017, Brandt et al. 2018, Graham et al. 2019) has it been possible to disentangle the impact of piling noise from other disturbance factors. In particular, variation in the types of installation and support vessels (Benhemma-Le Gall et al. 2023, Pigeault et al. 2024), and use of ADD for mitigating injury impacts (Brandt et al. 2013, Thompson et al. 2020), will also affect responses. ADD use and vessel activity during the construction of the Beatrice offshore wind farm was high relative to more recent developments (Benhemma-Le Gall et al. 2021). Nevertheless, current regulatory guidance to use the Graham et al (2017) dose-response function assumes observed responses at Beatrice were primarily driven by maximum received levels of pile driving noise rather than any of these other contributing factors. Disturbance responses may also depend on the duration of the pile-driving events as well as maximum noise levels. The Beatrice dose-response curve was derived from data collected during the relative long periods (mean piling duration = 5 hrs) required to install pin-pile foundations for quadruped jackets (Benhemma-Le Gall et al. 2021). Thus, weaker than expected responses to the installation of Moray West monopiles (which took a mean of 2.8 hrs) may be because greater disturbance from louder piling was offset by shorter installation times.

Second, the Graham et al. (2017) dose response function relates behavioural responses to unweighted SEL_{ss}. Subsequent analyses of the entire Beatrice dataset found slightly stronger support for the relationship with auditory weighted SEL_{ss} (Graham et al. 2019) which is in line with results of a more recent meta-analysis of other data on porpoise responses to pile driving noise (Tougaard 2025). This difference is especially important where behavioural response relationships are used to predict impacts from the installation of piles that are much larger, and louder than those used in the original studies. For example, application of the Graham et al. (2017) dose-response curve to acoustic modelling of noise installation of 15 m piles has led to predictions of significant levels of disturbance at distances of >50 km (e.g. Caledonia offshore wind farm 2024, Muir Mhòr offshore wind farm 2024). However, most of the energy reaching these distances will be in low frequencies that are outside the hearing range of porpoises (Tougaard 2025).

Finally, there is increasing recognition that behavioural response may vary in relation to both received noise levels and proximity to source (Dunlop et al. 2017; Southall et al. 2021, Wensveen et al. 2025). It can be difficult to disentangle these different drivers because distance from source and received levels are highly correlated. Studies at Beatrice Offshore wind farm found that relationships between behavioural responses and distance were slightly stronger than those between behavioural responses and received levels. Data from Moray

West, where piling noise levels were greater, now add weight to this finding, given that observed responses were more similar to predictions based on the Beatrice deterrence function than the Beatrice dose-response function (Figure 8). Further work within the PrePARED project aims to conduct an integrated analysis using PAM data collected during the construction of all three Moray Firth wind farms to explore this question further.

5.3 Implications for future regulatory assessments

Overall, our results provide confidence in the outputs from acoustic modelling tools that are being used to underpin current regulatory assessments. Although there were slight differences in predicted maximum received noise levels, these were all within 3 dB. We suggest that uncertainty over other components of frameworks for assessing auditory injury and behavioural impacts will be more important than variation in the performance of these physical models (see ORJIP 2024). Nevertheless, we recognise that stakeholders may still have concerns over, for example, outputs from new acoustic modelling tools. In these cases, archive data from this and other projects could be used to conduct similar blind retrospective comparison of model outputs. We recommend that regulators consider gathering an archive of standardised noise monitoring and engineering data so that similar blind retrospective exercises can be conducted in future to provide confidence in other modelling tools.

In contrast, observed levels of disturbance at Moray West indicate that current approaches to assessing disturbance require re-assessing. It is recognised that regulators and their advisors need to assess a realistic worst case scenario. However, the unrealistic ranges at which high levels of disturbance have been predicted risks making assessments unfit for purpose, particularly when considering assessments of cumulative impacts (see Sinclair 2025). As the Graham et al. (2017) dose-response function is related to predicted exposure using the metric of unweighted SEL_{ss}, this problem will scale with future increases in pile diameter and hammer energies. We suggest that recent assessments for larger 15 m piles predicting a 50% chance of disturbing porpoises at distance of 65 – 75 km are biologically implausible, as animals at this range are unlikely to detect, let alone react to, piling noise.

There is strong support for using probabilistic response functions to assess behavioural disturbance (Southall 2024). However, it is critical to recognise that received noise levels are not the only, or necessarily even the main, driver of disturbance responses. It is unlikely to be practical to develop predictive models that capture all the intrinsic and extrinsic contextual factors that may influence responses (see Booth et al. 2022). Instead, there is an urgent need to develop tools and/or guidance that uses best available science to incorporate key factors such as proximity to source and received signal to noise ratios into predictions of how animals detect and respond to distant sources. Planned integration of comparative data from other wind farms will provide more robust generic response functions for use in future assessments. In the meantime, we recommend that extrapolations of disturbance developed under current guidance be treated with appropriate levels of caution. Furthermore, we highlight that earlier recommendations to use distance rather than dose to predict disturbance (see Graham et al. 2019) would have resulted in predictions that were closer to observed responses at Moray West (Figure 8). Our findings add further weight to this recommendation and suggest that the use of distance-based response functions may be more appropriate in future assessments.

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Appendix 1. Information on the piling locations selected for noise monitoring, and the locations at which there was a sufficient baseline period between piling events to assess behavioural responses of porpoises. Data are also provided on the pile size and hammer energy at each site, and the maximum received noise levels at 750 m at monitored piling events.

Pile	Date	Noise Monitoring	Porpoise Monitoring	Active Piling Duration (mins)	Pile Diameter (m)	Max Hammer Energy (kJ)	Max SEL_{ss} (dB re 1μ Pa^2s)
N13	4/10/23	Y	Y	258	9.5	3,700	179
L11	9/10/23	Y	Y	172	9.5	3,768	178
L13	16/10/23	Y	N	170	9.5	4,016	179
M15	17/10/23	Y	N	170	9.5	3,562	180
N16	23/10/23	Y	Y	142	9.5	2,280	177
M11	31/10/23	Y	Y	207	9.5	4,526	178
N09	9/11/23	Y	N	123	9.5	3,210	No Data
L12	10/11/23	Y	N	101	10	3,820	181
L08	15/11/23	Y	N	126	10	4,155	180
E06	16/11/23	Y	N	89	9.5	4,257	179
K14	17/11/23	Y	N	152	9.5	4,277	180
P13	26/11/23	N	Y	127	9.5	4,295	No Data
N12	30/11/23	N	Y	111	9.5	3,521	No Data
L14	1/12/23	Y	N	151	9.5	4,228	180
G07	2/12/23	Y	N	97	10	4,249	179
P11	5/12/23	N	N	116	9.5	3,334	No Data
P14	6/12/23	N	N	163	9.5	4,265	No Data
N08	18/12/23	N	Y	154	10	1,882	No Data