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Underwater Noise Modelling

Seagreen Offshore Windfarm

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Executive Summary

This report presents the results of underwater noise modelling carried out by Cefas in support of the Environmental Impact Assessment (EIA) for the optimised Seagreen Offshore Wind Farm. Predictions were made of the sound exposure levels (SELs) and peak sound pressure levels (peak SPLs) arising from percussive pile driving for maximal hammer energies of 3,000 kJ (monopiles) and 1,710 kJ (pin piles) at several locations within the Seagreen Project Alpha and Project Bravo areas, including concurrent piling at two locations. Predictions were also made of peak sound pressure levels (peak SPLs) at the initial (soft start) hammer energies of 400 kJ (monopile) and 270 kJ (pin pile) to assess the risk of instantaneous auditory injury at the onset of piling activity. Based on these predictions, effect zones were computed for the risk of Permanent Threshold Shift (PTS) on harbour porpoise (*Phocoena phocoena*), bottlenose dolphin (*Tursiops truncatus*), white-beaked dolphin (*Lagenorhynchus albirostris*), minke whale (*Balaenoptera acutorostrata*), grey seal (*Halichoerus grypus*), and harbour seal (*Phoca vitulina*), using the Southall (Southall *et al*. 2007) and NOAA (National Marine Fisheries Service 2016) noise exposure criteria for marine mammals. The model included the assumption that marine mammals would flee from the pile foundation at the onset of an acoustic deterrent device (ADD) deployed 15 minutes prior to the commencement of a piling soft start. Furthermore, the risk of Temporary Threshold Shift (TTS), recoverable injury, and mortality was predicted for herring (*Clupea harengus*), using the Popper *et al.* (2014) criteria. No fleeing behaviour was assumed for fish.

Of the marine mammal species assessed, only harbour porpoises were predicted to incur PTS at distances greater than 50 m. The NOAA (2016) guidance consists of dual criteria, with thresholds for both cumulative SEL and peak SPL. Harbour porpoises were predicted to incur PTS to a distance of 170 m from the monopile foundation under the peak SPL criterion (PTS effect area was <0.01 km^2 under the cumulative SEL criterion). Given the planned deployment of an ADD prior to piling, the risk of PTS under the peak SPL criterion is considered negligible.

Under the cumulative SEL criterion, the largest effect zone predicted for mortality of herring was 2.83 km^2 under the concurrent piling of two jacket foundations scenario, which had the largest energy accumulation over 24 hours. The greatest effect zones for recoverable injury and TTS were 8.83 km^2 and 1275 km^2, respectively.

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1 Introduction

This report presents the results of underwater noise modelling carried out by Cefas in support of the environmental impact assessment for the optimised Seagreen Offshore Wind Farm. The consented Seagreen Project includes jacket foundation structures with pin pile foundations, the optimised Seagreen Project proposes monopiles or pin piled jackets. Predictions were made of the sound exposure levels (SELs) and peak sound pressure levels (peak SPLs) arising from percussive pile driving for maximal hammer energies of 3,000 kJ (monopiles) and 1,710 kJ (pin piles, representing 95% of the full hammer capacity of 1800 kJ[1]) at several locations around the perimeter of the Development site, including concurrent piling at two locations. Based on these predictions, effect zones were computed for the risk of permanent threshold shift (PTS) on harbour porpoise (*Phocoena phocoena*), bottlenose dolphin (*Tursiops truncatus*), white-beaked dolphin (*Lagenorhynchus albirostris*), minke whale (*Balaenoptera acutorostrata*), grey seal (*Halichoerus grypus*), and harbour seal (*Phoca vitulina*), using the Southall (Southall *et al.* 2007) and NOAA (National marine Fisheries Service, 2016) noise exposure criteria for marine mammals. Furthermore, the risk of temporary threshold shift (TTS), recoverable injury, and mortality was predicted for herring (*Clupea harengus*), based on the Popper *et al.* (2014) criteria.

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[1] This reflects the ramp up for jacket pin piles assumed for the 2012 Offshore ES.

2 Methodology

2.1 Source model

The source level estimate for pile driving was calculated using an energy conversion model (De Jong and Ainslie, 2008), whereby a proportion of the expected hammer energy is converted to acoustic energy:

$$\boldsymbol{SL_E = 120 + 10log_{10}\left(\frac{\beta E c_0 \rho}{4\pi}\right)} \quad (1)$$

where E is the hammer energy in joules, SL_E is the source level energy for a single strike at hammer energy E, $\boldsymbol{\beta}$ is the acoustic energy conversion efficiency, c_0 is the speed of sound in seawater in m s^{-1}, and ρ is the density of seawater in kg m^{-3}.

This yields an estimate of the source level in units of sound exposure level (dB re 1 μPa^2 s). This energy is then distributed across the frequency spectrum based on previous measurements of impact piling (Ainslie *et al.*, 2012).

Hammer energy profiles for the piling scenarios (see Section 0) formed the basis of the source level estimates. Equation 1 was used to compute the source level energies, using an acoustic energy conversion efficiency of 0.5%, which assumes that 0.5% of the hammer energy is converted into acoustic energy. This energy conversion factor is in keeping with current understanding of how much hammer energy is converted to noise (Dahl and Reinhall, 2013; Zampolli *et al.*, 2013; Dahl *et al.*, 2015). Equation (1) gives the source level energy for a single strike (single-strike SEL). The maximal single-pulse SEL, SEL_{ss}, as well as the cumulative SEL (the total SEL generated during a specified period), SEL_{cum}, were computed.

The peak SPL was calculated using the empirical linear equations linking peak sound pressure levels and sound exposure levels for pile driving sources found by Lippert et al. (2015).

2.2 Propagation model

The propagation of piling noise was modelled using the Cefas noise model (Farcas et al., 2016), which is based on a parabolic equation solution to the wave equation (RAM; Collins, 1993). Unlike many propagation models, this model takes into account the bathymetry, sediment properties, water column properties, and tidal cycle, leading to more detailed and reliable predictions of sound level. It is also widely used in peer-reviewed scientific studies which have benchmarked it against empirical data.

The Cefas model is a quasi-3D model consisting of 360 2D transects extending away from the source at intervals of one degree. Sound propagation is modelled at each discrete frequency in the source spectrum (10 frequencies per 1/3 octave band). These transects were then resampled and integrated over frequency (using the appropriate auditory weightings where needed). Finally, the resulting levels were averaged over depth to produce noise maps.

2.3 Input data

Aside from source levels of piling, the main model inputs were bathymetry, water temperature and salinity (used to compute sound speed), and the acoustic properties of the seabed sediments.

Bathymetric data in UTM30N projection was provided to Cefas, covering the area inside the Project Alpha and Project Bravo boundaries. This was supplemented by a more extensive dataset, with a 7.5" resolution and in WGS84 projection, which was downloaded from EMODNET database (http://www.emodnet-bathymetry.eu/data-products) and then converted to UTM30N projection. The bathymetric datasets were interpolated and used to define the model numerical grid with a resolution of 100 m, and a coverage of 500000-750000, 6100000-6500000 (eastings, northings UTM30N), or approximately 250 km by 400 km, which was more than adequate for the frequency ranges and the spatial scales used in the simulations.

The water temperature and salinity data, which are used by the model for calculating the water column sound speed profiles, were taken from a validated, multiyear hindcast model produced by Cefas, known as GETM-ERSEM-BFM. The model provides extensive daily coverage at 0.1 degree spatial resolution, and includes 25 depth layers. Typical November water properties were used for the acoustic propagation predictions, representing a midpoint between winter and summer sound propagating conditions. It was chosen to model water properties based on a typical November as this represents a mixture of most probable and worst-case scenarios which would form a conservative but probable scenario.

The noise model also includes the acoustic properties of the seabed sediments, namely speed of sound, density, and acoustic attenuation, which are used to construct a geoacoustic model of the seafloor. These properties were derived from the seabed core data by correlating the core sediment information with published acoustic properties of various sediment types (Hamilton, 1980).

2.4 Piling Locations

The piling locations that were modelled in the assessment and their coordinates are given in Table 2.1. These locations, and piling parameters summarised below, were provided to Cefas by NIRAS Consulting, the Project Lead EIA consultants, following consultation with Marine Scotland and Scottish Natural Heritage.

Table 2.1 Pile driving locations used for noise modelling with coordinates in decimal degrees

Location	Latitude	Longitude
Alpha 2012	56.5929	-1.9301
Bravo 2012	56.5897	-1.7328
Alpha NW	56.677553	-1.937101
Alpha SW	56.513386	-1.939632
Bravo SW	56.515385	-1.892356

Location	Latitude	Longitude
Bravo NE	56.665388	-1.577116

2.5 Piling Scenarios

Hammer energy profiles were estimated for driving monopiles of 10 m diameter for the worst-case ground conditions at the site, with a maximum hammer energy of 3000 kJ (Table 2.2), and for driving pin piles of 2 m diameter (Table 2.3), with a maximum hammer energy of 1710 kJ (representing 95% of the full hammer capacity of 1800 kJ).

Table 2.2: Monopile hammer energy profile

Pre-pile ADD deployment duration		15 min
A. Soft start initiation	Soft start A starting energy	400 kJ
	Soft start A energy ramp up	none
	Soft start A duration	1 min
	Soft start A strike rate	7 blows/min
	Soft start A end energy	400 kJ
B. Soft start	Soft start B starting energy	400 kJ
	Soft start B energy ramp up	even
	Soft start B duration	19 min
	Soft start B strike rate	31 blows/min
	Soft start B end energy	600 kJ
C. Progression to Full Power	Piling C starting energy	600 kJ
	Piling C energy ramp up	even
	Piling C duration	120 min
	Piling C strike rate	35 blows/min
	Piling C end energy	3000 kJ
D. Full Power Piling	Piling D starting energy	3000 kJ
	Piling D energy ramp up	none
	Piling D duration	100 min
	Piling D strike rate	35 blows/min
	Piling D end energy	3000 kJ
Total active piling duration (min)		240 min
Total blows		8296

Table 2.3: Hammer energy profile for one pin pile, based on the hammer capacity of 1800 kJ

Pre-pile ADD deployment	15 min (only for first pine pile of the jacket)		
Hammer capacity	Hammer energy	Duration (mins)	Strike rate
15 %	270 kJ	6	45
35 %	630 kJ	4	45
55 %	990 kJ	5	45
75 %	1350 kJ	30	45
95 %	1710 kJ	90	45
Active duration per pile	135 mins		
Total blows per pin pile	4725		

Based on piling location and foundation time, a total of seven scenarios were assessed (Table 2.4), including monopiles and jackets at a single location, combinations of a monopile and a jacket and combination of 2 jackets piled simultaneously at two locations. For the cumulative exposure assessments, it was assumed that a single pile is installed in 24 hours for monopiles, and 4 pin piles (one jacket) is installed in 24 hours for jackets, with a 90 minutes interval between the piling of each pin pile.

Table 2.4: Pilling location(s) and foundation type of each modelled scenario

Scenario	Hammer energy profile	Location(s)
Scenario 1	Monopile	Alpha 2012
Scenario 3	Monopile	Bravo 2012
Scenario 5	Jacket (4 pin piles)	Alpha 2012
Scenario 6	Jacket (4 pin piles)	Bravo 2012
Scenario 7	Monopile & Jacket	Alpha NW & Alpha SW
Scenario 8	Monopile & Jacket	Bravo SW & Bravo NE
Scenario 9	2 Jackets (2x4 pin piles)	Alpha NW & Bravo SW

The source levels for the starting and maximum energies of the hammer energy profiles, derived using the methodology described in Section 2.1, are shown in Table 2.5 in both the energy and the peak pressure metric.

Table 2.5: Single strike sound exposure source levels and peak pressure source levels, at 1 m, for the start and maximum hammer energies

Hammer energy (kJ)	Description	SL_{ss} [dB re 1µPa^2 s]	SL peak [dB re 1µPa]
270	Pin pile start	202.2	243.1
400	Monopile start	203.9	245.4
1710	Pin pile maximum	210.2	254.3
3000	Monopile maximum	212.6	257.7

2.6 Metrics modelled

Three model types were run for each foundation type:

(1) SEL_{ss} based on the maximum hammer energy (to inform assessment of risk of disturbance, see Section 3.1);
(2) Peak SPL based on initial and maximum hammer energies (to assess instantaneous PTS risk at piling onset and during piling, see Section 0); and
(3) SEL_{cum} over 24 hours based on the hammer energy profiles (to assess risk of cumulative PTS for marine mammals, see Section **Error! Reference source not found.** and for fish, see Section 0).

To assess the eventuality of two piling vessels being available concurrently, scenarios were also run for simultaneous piling at two locations for the above three model types. The model types and associated abbreviations and effects are listed in Table 2.6.

Table 2.6: Metrics and associated effects for each of the three model types

Metric	Abbreviation	Effect assessed	Criterion
Single-strike SEL	SEL_{ss}	Disturbance	Dose-response curve
Cumulative SEL	SEL_{cum}	PTS	NOAA criteria (all scenarios) Southall criteria (scenarios 1, 5 and 9) Popper criteria (fish only)
Peak SPL	Peak SPL	PTS	NOAA criteria Southall criteria

2.7 Noise Exposure Criteria

For marine mammals, the risk of PTS was assessed using the NOAA criteria (National Marine Fisheries Service, 2016) for all scenarios, and the Southall criteria (Southall et al. 2007) for selected scenarios, including the one with the highest cumulative hammer energy, namely Scenario 9. The NOAA and Southall criteria are based on both of the dual criteria: cumulative sound exposure level (SEL_{cum}) and peak sound pressure level (peak SPL). To assess the SEL_{cum} criterion, the predictions of received sound level are frequency weighted to reflect the hearing sensitivity of each functional hearing group (first column in Table 2.7 and Table 2.8). The peak SPL criterion is for unweighted received sound levels.

Table 2.7 NOAA criteria sound exposure thresholds for marine mammals (National Marine Fisheries Service, 2016)

Hearing group	TTS		PTS	
	SEL_{cum} [dB re 1 μPa² s]	Peak SPL [dB re 1 μPa]	SEL_{cum} [dB re 1 μPa² s]	Peak SPL [dB re 1 μPa]
Low-frequency cetaceans	168	213	183	219
Mid-frequency cetaceans	170	224	185	230
High-frequency cetaceans	140	196	155	202
Phocids	170	212	185	218

Table 2.8 Southall criteria sound exposure thresholds for marine mammals (Southall *et al.* 2007)

Hearing group	TTS		PTS	
	SEL_{cum} [dB re 1 μPa² s]	Peak SPL [dB re 1 μPa]	SEL_{cum} [dB re 1 μPa² s]	Peak SPL [dB re 1 μPa]
Low-frequency cetaceans	183	224	198	230
Mid-frequency cetaceans	183	224	198	230
High-frequency cetaceans	183	224	198	230
Phocids	171	212	186	218

For fish, the SEL_{cum} Popper criteria (Popper *et al.*, 2014) were applied (Table 2.9). These consist of thresholds for TTS, recoverable injury and mortality. None of these thresholds apply frequency weightings. Note that the fish species considered, namely herring (*Clupea harengus*) belong to the most sensitive group, Popper III (fish species with swim bladder involved in hearing).

Table 2.9 Sound exposure thresholds for fish (Popper *et al.*, 2014)

Hearing group	TTS	Recoverable injury	Mortality
	SEL_{cum} [dB re 1 μPa² s]	SEL_{cum} [dB re 1 μPa² s]	SEL_{cum} [dB re 1 μPa² s]
Popper III	186	203	207

2.8 Marine mammal fleeing behaviour for PTS estimation

To assess the risk of instantaneous and cumulative PTS, it is necessary to make assumptions of how animals may respond to noise exposure, since any displacement of the animal relative to the noise source will affect the noise exposure incurred.

For this assessment, it was assumed that animals would flee from the pile foundation at the onset of operation of an acoustic deterrent device (ADD) deployed 15 minutes prior to the commencement of a piling soft start. Animals were assumed to flee out to a maximum distance of 25 km (after which they were assumed to remain stationary at that distance).

Table 2.10 Fleeing speeds assumed for each marine mammal species/taxon

Species	Harbour Porpoise	Dolphin	Minke Whale	Phocid Seal
Swimming speed (m/s)	1.4	1.52	2.1	1.8
Minimum depth constraint (m)	5	5	10	0

The fleeing model simulates the animal displacement and their noise exposure for a given piling scenario by placing an animal agent in each grid cell of the domain (i.e. every 100 m by 100 m) and allowing them to move on the domain grid according to a set of pre-defined rules. The position of all agents and the cumulated exposure are re-evaluated at constant time intervals (e.g. 5 minutes) and at the end of the scenario piling activity the total cumulated exposure of all animal agents is mapped back to their starting positions on the grid.

In the case of single location pile driving, the model assumes that the animal agents are fleeing at constant speeds (Table 2.10), along straight lines away from the pile location, as long as the local water depth exceeds a minimum value (Table 2.10). If moving away along this line would take the animal agent into shallower water than the allowed minimum depth, then a change in direction is calculated and effected, with the allowed values, relative to current direction from the pile location to the present agent position and in order of preference, being +/- 45° (forwards left or right) , +/-90° (sideways left or right), +/-135° (backwards left or right) and, as a last option 180° (backward towards the piling location, but not to the previous position, unless the previous movement direction was 0°, i.e. straight forwards along the pile - agent line). It should be noted that, as indicated in Table 2.10, these rules do not apply to the seal agents, who are allowed to move in any depths of water and even move to the shore (within the 25 km maximum distance from the pile location), thus stopping their sound exposure.

In the case of dual location pile driving, the model still assumes that the animal agents are fleeing at the same constant speeds as in the case of single location pile driving, but their fleeing direction is re-evaluated at every time step according to their position relative to the location of the two piles. Specifically, at a given time, the fleeing direction is calculated by summing up the two vectors originating at the current animal agent position, pointing straight away from the two sources, and having their magnitude proportional with the specific dose responses of the animal for the current single strike SEL from the two sources, respectively. The same minimum depth constrains and shallow water avoidance rules as in the single location pile driving described above apply also in the case of dual location pile driving.

3 Results

3.1 Single-Strike Sound Exposure Levels for Behavioural Response Assessment

The scenario assessed for SEL_{ss} are listed in Table 3.1 and the results are shown in Figure 3-1 to Figure 3-7. Scenario numbering is non-sequential because Scenarios 2 and 4 (2,300 kJ monopile installation at Alpha and Bravo respectively) were not pursued following review of the results of higher energy piling (scenarios 1 and 3) at the same locations.

Table 3.1: Scenario list for SEL_{ss}

Scenario	Description	Figure number
Scenario 1	3000 kJ at Alpha 2012	Figure 3-1
Scenario 3	3000 kJ Bravo 2012	Figure 3-2
Scenario 5	1710 kJ at Alpha 2012	Figure 3-3
Scenario 6	1710 kJ at Bravo 2012	Figure 3-4
Scenario 7	3000 kJ at Alpha NW & 1710 kJ at Alpha SW	Figure 3-5
Scenario 8	3000 kJ at Bravo SW & 1710 kJ at Bravo NE	Figure 3-6
Scenario 9	1710 kJ at Alpha NW & 1710 kJ at Bravo SW	Figure 3-7

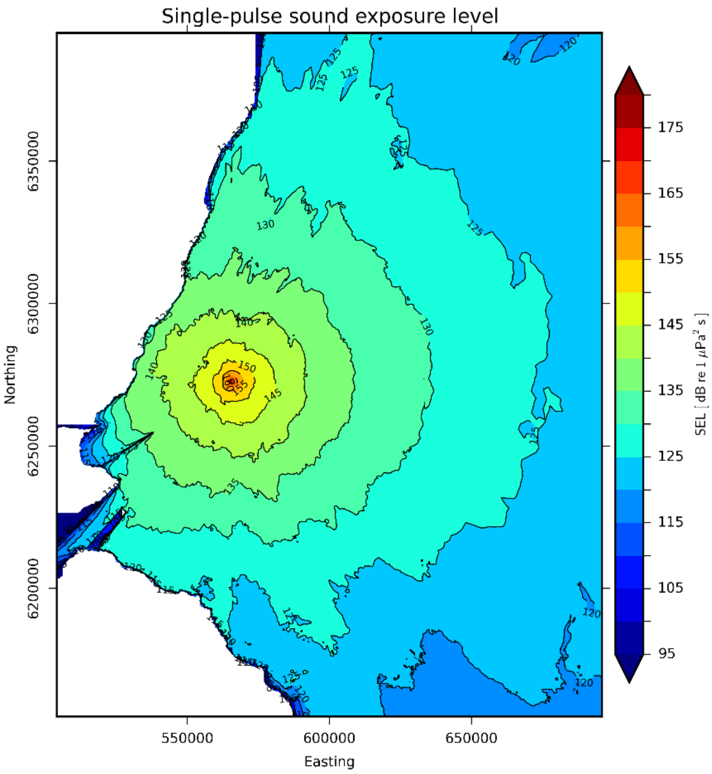

Figure 3-1: Single-strike SEL for a hammer energy of 3000 kJ (maximum monopile hammer energy) at location Alpha 2012 (Scenario 1)

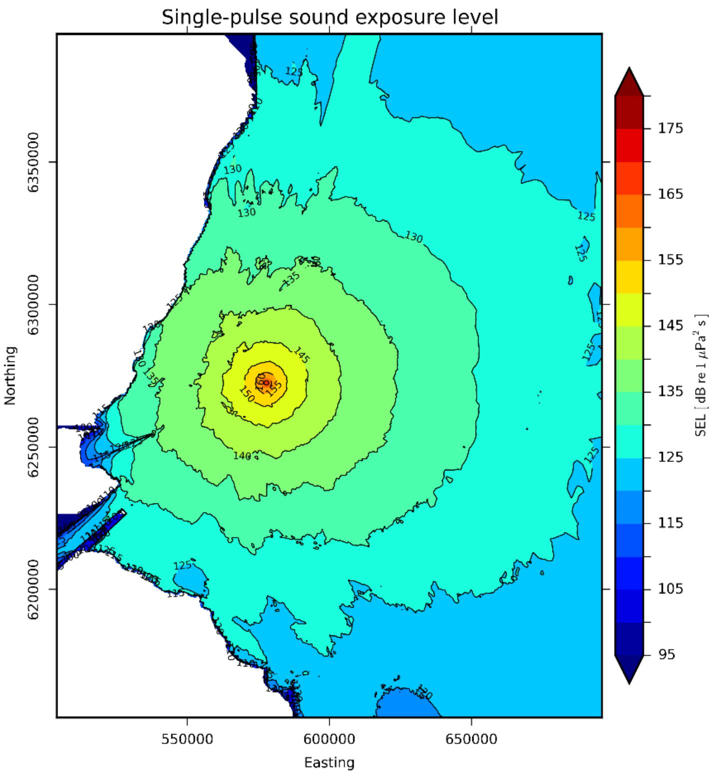

Figure 3-2: Single-strike SEL for a hammer energy of 3000 kJ (maximum monopile hammer energy) at location Bravo 2012 (Scenario 3)

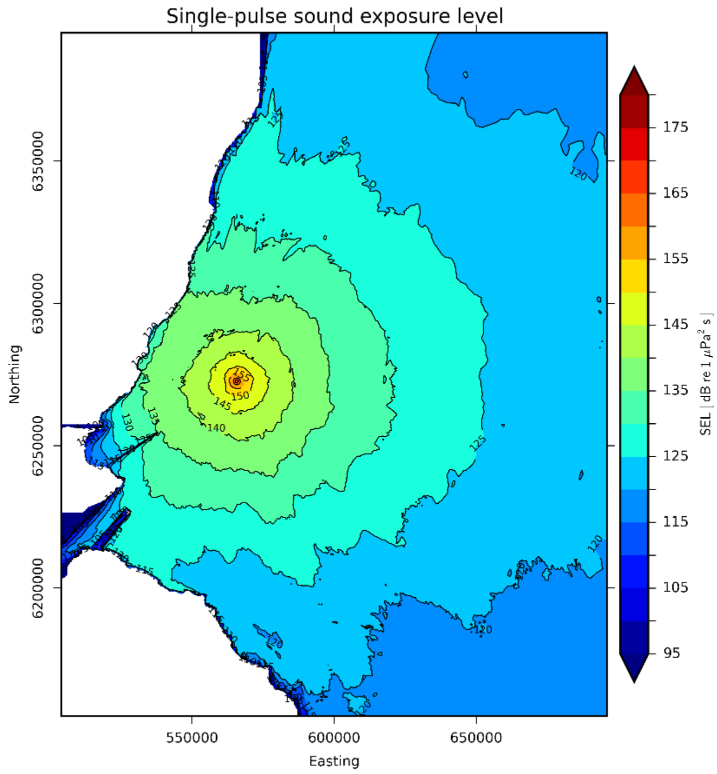

Figure 3-3: Single-strike SEL for a hammer energy of 1710 kJ (maximum pin pile hammer energy) at location Alpha 2012 (Scenario 5)

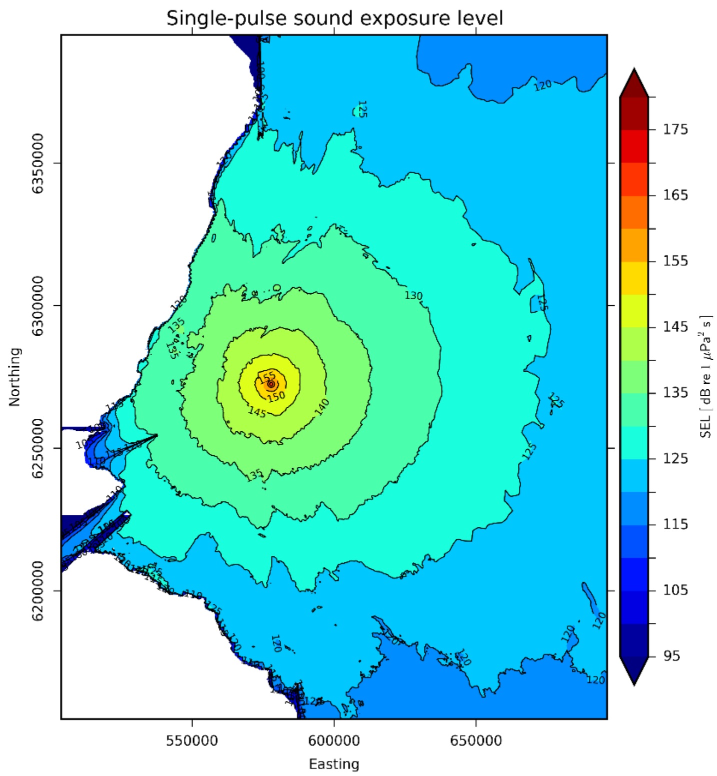

Figure 3-4: Single-strike SEL for a hammer energy of 1710 kJ (maximum pin pile hammer energy) at location Bravo 2012 (Scenario 6)

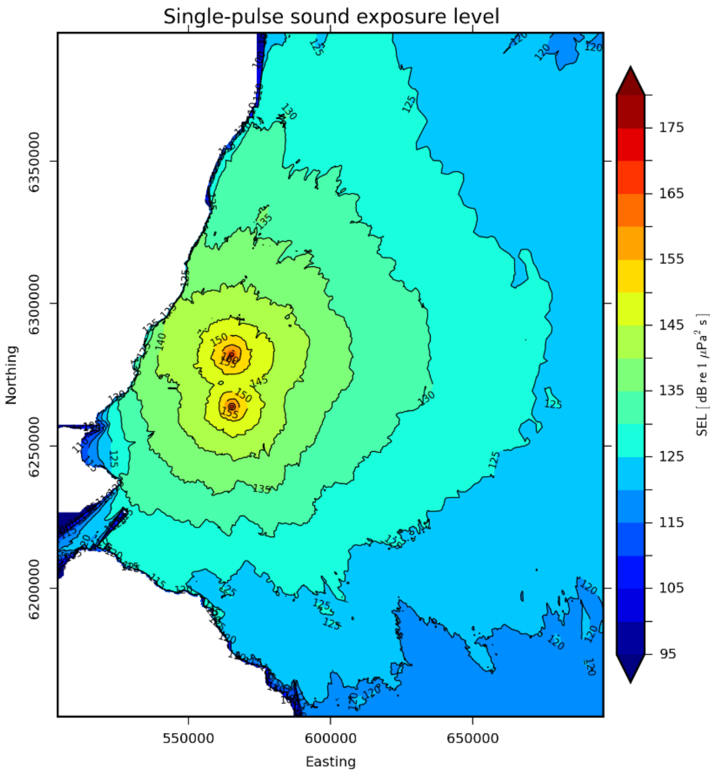

Figure 3-5: Combined single-strike SEL for a hammer energy of 3000 kJ (maximum monopile hammer energy) at location Alpha NW and a hammer energy of 1710 kJ (maximum pin pile hammer energy) at location Alpha SW (Scenario 7)

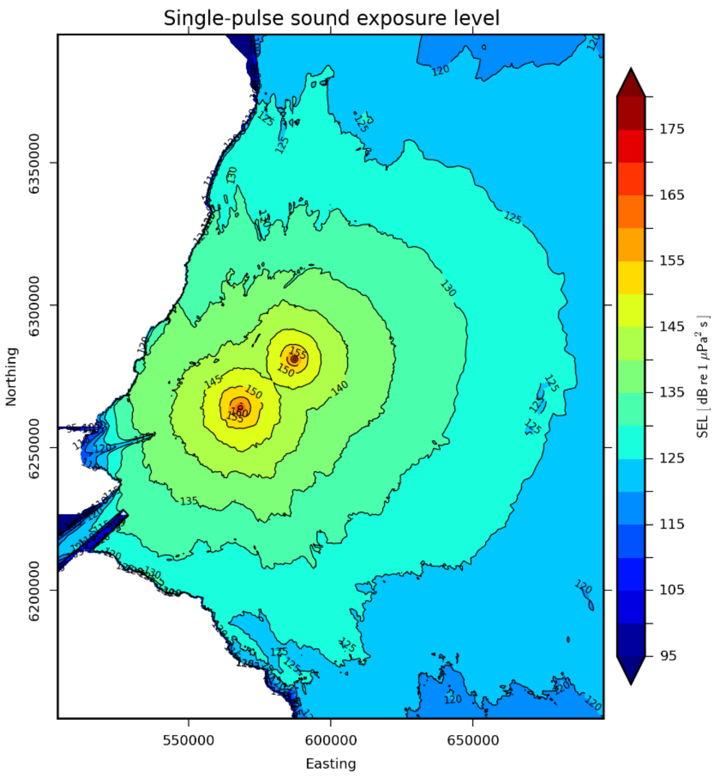

Figure 3-6: Combined single-strike SEL for a hammer energy of 3000 kJ (maximum monopile hammer energy) at location Bravo SW and a hammer energy of 1710 kJ (maximum pin pile hammer energy) at location Bravo NE (Scenario 8)

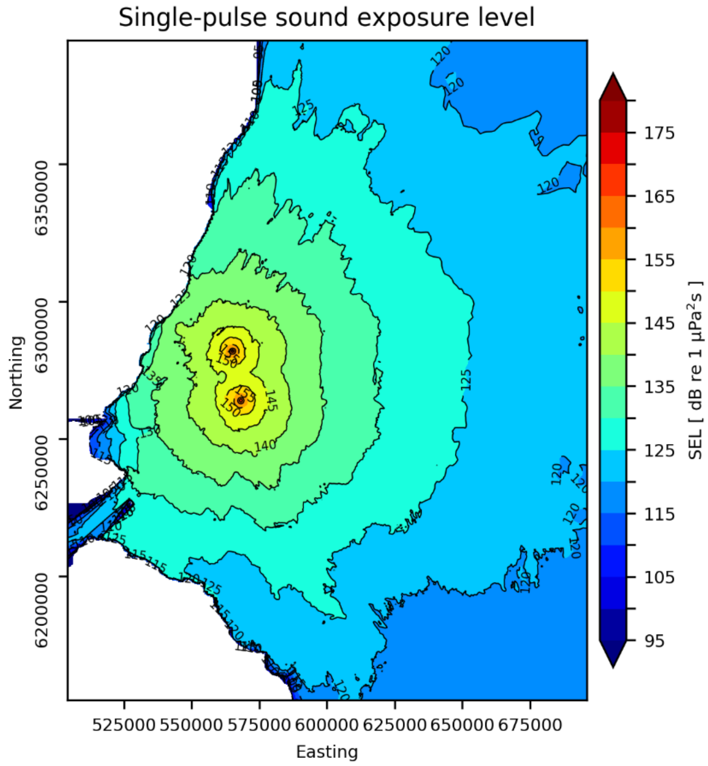

Figure 3-7: Combined Single-strike SEL for a hammer energy of 1710 kJ (maximum pin pile hammer energy) at locations Alpha NW and Bravo SW (Scenario 9)

3.2 Peak SPL Assessment of Instantaneous PTS Effect Zones for Marine Mammals

All the effect ranges for the peak SPL criterion for instantaneous PTS at the initial hammer energies of 400 kJ (monopiles) and 270 kJ (pin piles) were less than 50 m for all modelled scenarios (Table 3.2).

Table 3.2: Effect ranges for instantaneous PTS for marine mammals at the initial hammer energy (400 kJ for monopiles and 270 kJ for pin piles)

Scenario	Low-Frequency Cetaceans		Mid-Frequency Cetaceans		High-Frequency Cetaceans		Phocid	
	Southall	NOAA	Southall	NOAA	Southall	NOAA	Southall	NOAA
1	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m
3	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m
5	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m
6	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m
7	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m
8	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m
9	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m

All the scenarios modelled for the peak SPL criterion for instantaneous PTS at the maximum hammer energies of 3000 kJ (monopiles) and 1710 kJ (pin piles) had effect ranges of less than 200 m (maximum was 170 m for harbour porpoise for Scenario 1, namely the single monopile at location Alpha 2012, under the NOAA criteria). The full list of scenarios and corresponding impact ranges are provided in Table 3.3.

Table 3.3: Effect ranges for instantaneous PTS for marine mammals at the maximum hammer energy (3000 kJ for monopiles and 1710 kJ for pin piles)

Scenario	Low-Frequency Cetaceans		Mid-Frequency Cetaceans		High-Frequency Cetaceans		Phocid	
	Southall	NOAA	Southall	NOAA	Southall	NOAA	Southall	NOAA
1	<50 m	<50 m	<50 m	<50 m	<50 m	170 m	<50 m	<50 m
3	<50 m	<50 m	<50 m	<50 m	<50 m	165 m	<50 m	<50 m
5	<50 m	<50 m	<50 m	<50 m	<50 m	98 m	<50 m	<50 m
6	<50 m	<50 m	<50 m	<50 m	<50 m	95 m	<50 m	<50 m
7	<50 m	<50 m	<50 m	<50 m	<50 m	137 m & 92 m	<50 m	<50 m
8	<50 m	<50 m	<50 m	<50 m	<50 m	150 m & 89 m	<50 m	<50 m
9	<50 m	<50 m	<50 m	<50 m	<50 m	80 m & 90 m	<50 m	<50 m

3.3 Cumulative SEL Assessment of PTS Effect Zones for marine Mammals

For both NOAA and Southall criteria, all modelled scenarios for fleeing marine mammals predicted no PTS effect zones, i.e. the effect zones were less than the size of the model grid cell, namely 0.01 km^2 (Table 3.4). It should be noted that for the Southall criteria, only Scenario 1 (single monopile), Scenario 5 (single jacket) and Scenario 9 (concomitant monopile and jacket piling, which had the highest cumulative hammer energy of all scenarios) were assessed.

Table 3.4: Effect areas for cumulative PTS according to the Southall and NOAA SEL_{cum} criteria for each marine mammal functional hearing group and scenario

Scenario	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans	Phocid
	NOAA	NOAA	NOAA	NOAA
1-9	<0.01 km^2	<0.01 km^2	<0.01 km^2	<0.01 km^2
	Southall	Southall	Southall	Southall
1, 5 and 9	<0.01 km^2	<0.01 km^2	<0.01 km^2	<0.01 km^2

3.4 Cumulative SEL Assessment of TTS, Recoverable Injury, and Mortality Effect Zones for Fish

Mortality, recoverable injury, and TTS effect zones were predicted for all seven scenarios assessed for herring (i.e. Group III fish species) (Table 3.5). Maps of these effect zones are shown in Figure 3-8 to Figure 3-14. The largest effect zones (2.83 km^2 mortality, 8.83 km^2 for recoverable injury and 1275.45 km^2 for TTS) were predicted for concomitant piling of two jacket foundations (Scenario 9, Figure 3-14), which had the highest cumulative hammer energy from all the scenarios assessed.

Table 3.5: Effect areas for mortality, recoverable injury, and TTS according to the Popper SEL_{cum} criterion for herring

Scenario	TTS area (km^2); *range (m)*	Recoverable injury area (km^2); *range (m)*	Mortality area (km^2); *range (m)*	Figure number
Scenario 1	268.64; *10,638*	1.98; *804*	0.04; *141*	Figure 3-8
Scenario 3	297.01; *10,509*	1.95; *822*	0.01; *50*	Figure 3-9
Scenario 5	593.39; *15,863*	5.21; *1,354*	1.64; *726*	Figure 3-10
Scenario 6	665.42; *16,932*	4.96; *1,312*	1.58; *726*	Figure 3-11
Scenario 7	970.83	6.55	1.5	Figure 3-12
Scenario 8	1057.64	6.4	1.38	Figure 3-13
Scenario 9	1275.45	8.83	2.83	Figure 3-14

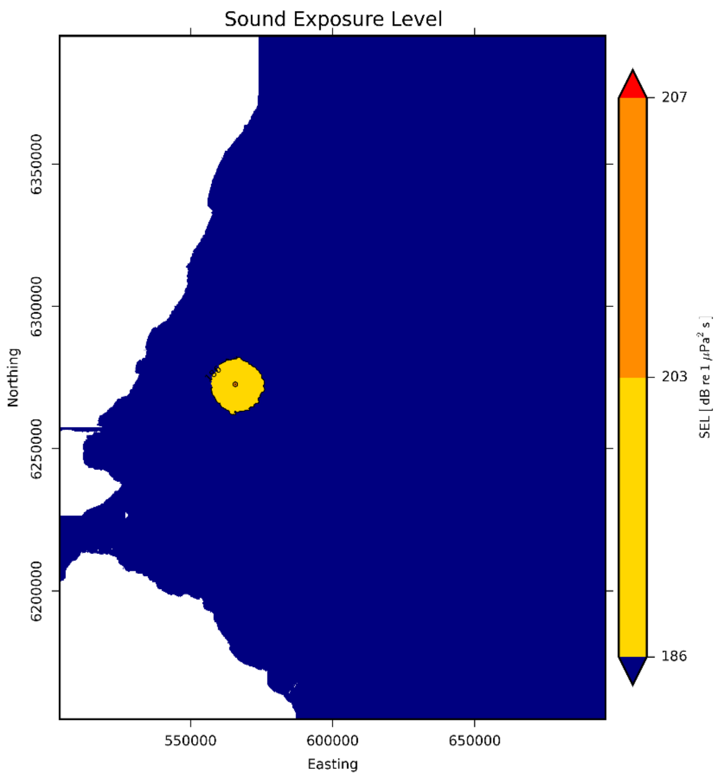

Figure 3-8: Cumulative exposure effect zones for herring exposed to piling of a single monopile foundation at location Alpha 2012 (Scenario 1)

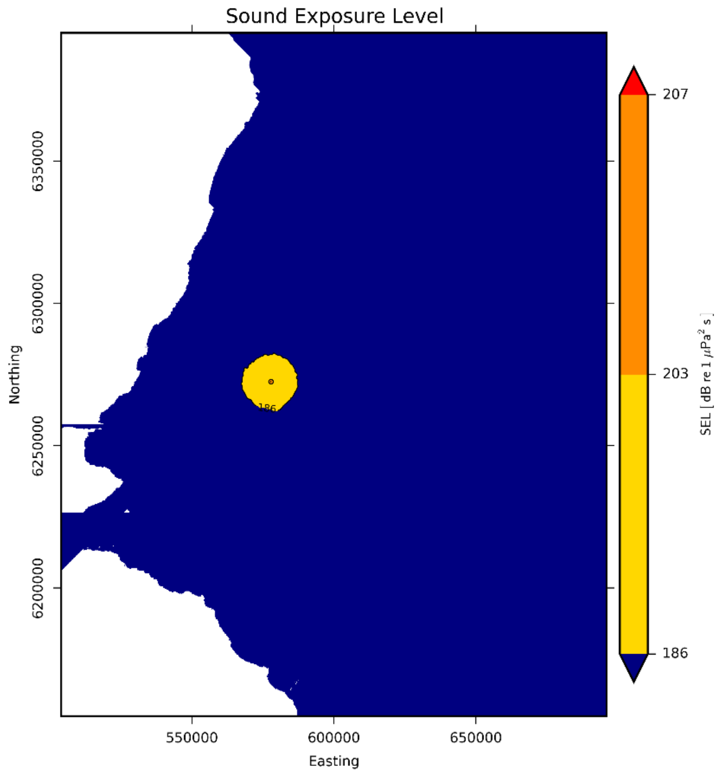

Figure 3-9: Cumulative exposure effect zones for herring exposed to piling of a single monopile foundation at location Bravo 2012 (Scenario 3)

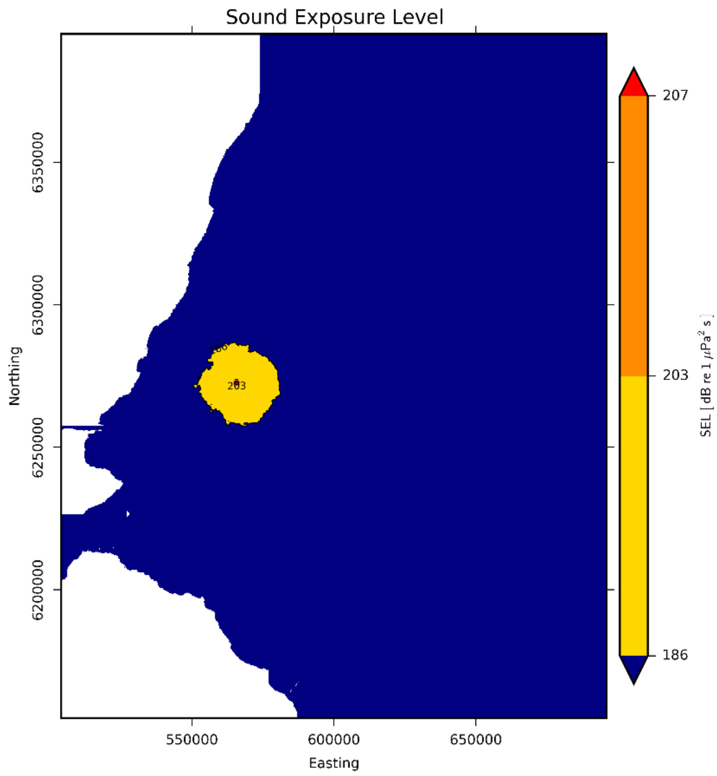

Figure 3-10: Cumulative exposure effect zones for herring exposed to piling of a single jacket foundation (4 pin piles) at location Alpha 2012 (Scenario 5)

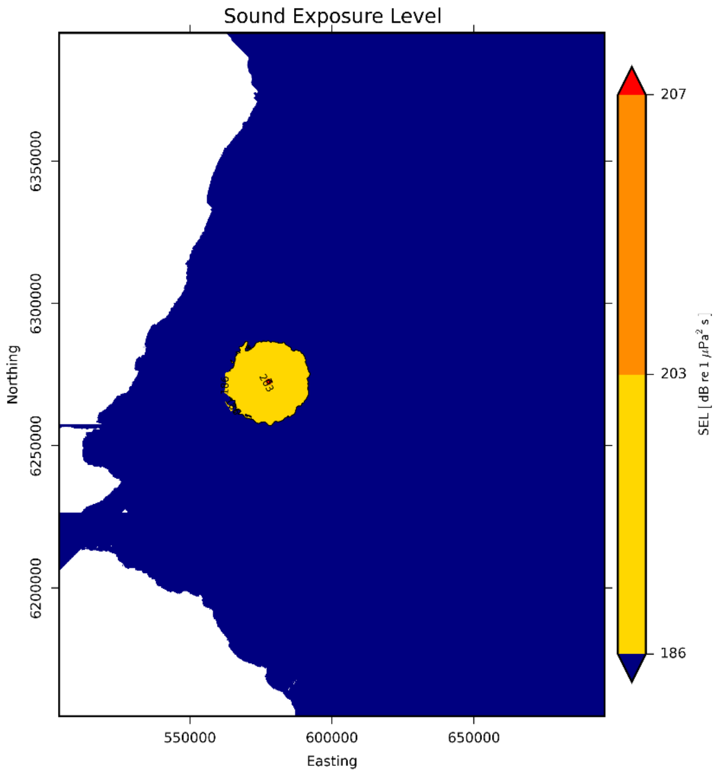

Figure 3-11: Cumulative exposure effect zones for herring exposed to piling of a single jacket foundation (4 pin piles) at location Bravo 2012 (Scenario 6)

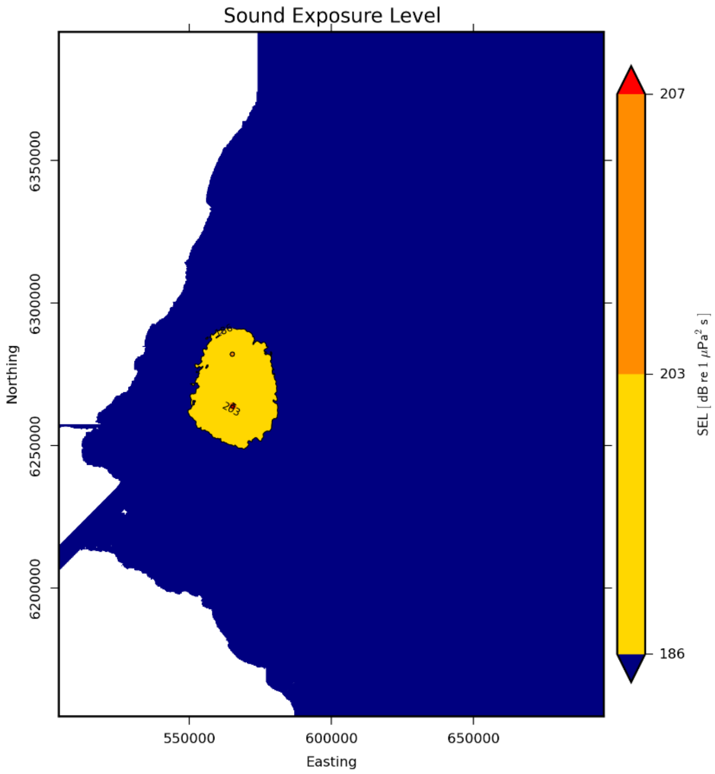

Figure 3-12: Cumulative exposure effect zones for herring exposed to concomitant piling of a monopile foundation at location Alpha NW and a jacket foundation (4 pin piles) at location Alpha SW (Scenario 7)

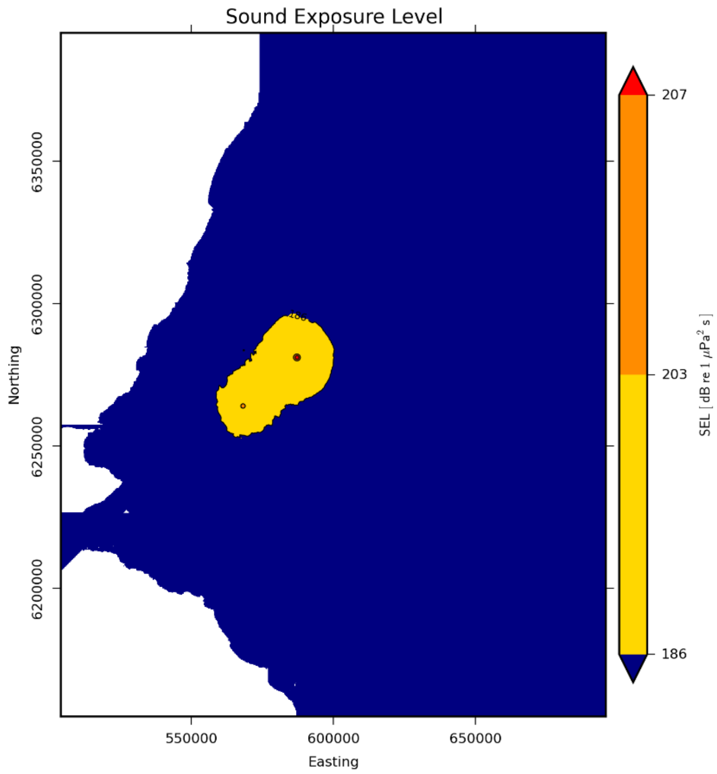

Figure 3-13: Cumulative exposure effect zones for herring exposed to concomitant piling of a monopile foundation at location Bravo SW and a jacket foundation (4 pin piles) at location Bravo NE (Scenario 8)

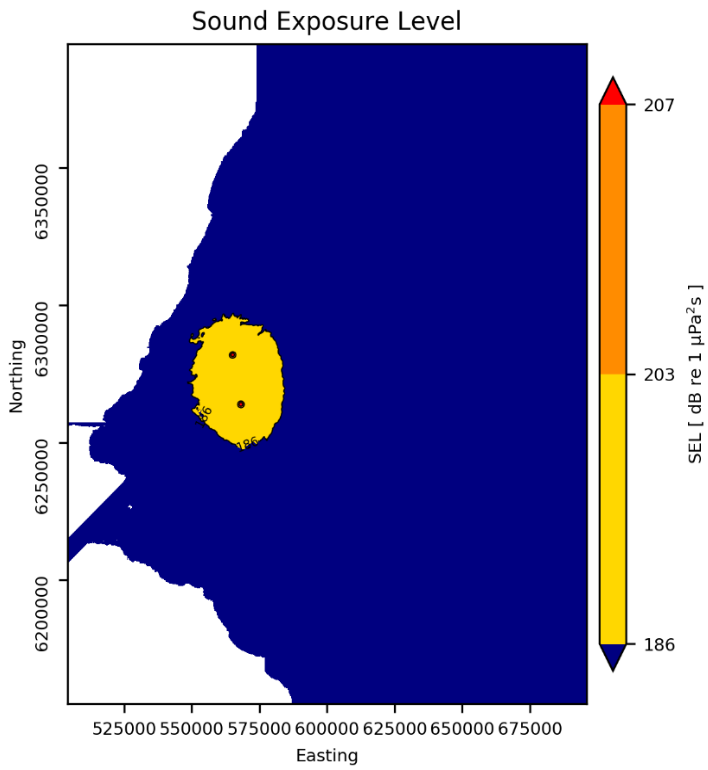

Figure 3-14: Cumulative exposure effect zones for herring exposed to concomitant piling of two jacket foundations (4 pin piles per jacket) at locations Alpha NW and Bravo SW, respectively (Scenario 9)

4 References

Ainslie, M.A., de Jong, C.A.F., Robinson, S.P. & Lepper, P.A. (2012). What is the source level of pile-driving noise in water? *In*: Eff. Noise Aquat. Life (eds. Popper, A.N. & Hawkins, A.D.). Springer, NY, pp. 445–448.

Collins, M.D. (1993). A split-step Padé solution for the parabolic equation method. J. Acoust. Soc. Am., 93, 1736–1742.

Dahl, P.H., de Jong, C.A.F. & Popper, A.N. (2015). The Underwater Sound Field from Impact Pile Driving and Its Potential Effects on Marine Life. Acoust. Today, 11.

Dahl, P.H. & Reinhall, P.G. (2013). Beam forming of the underwater sound field from impact pile driving. J. Acoust. Soc. Am., 134, EL1-6.

Etter, P.C. (2013). Underwater acoustic modeling and simulation. CRC Press, FL.

Farcas, A., Thompson, P.M. & Merchant, N.D. (2016). Underwater noise modelling for environmental impact assessment. Environ. Impact Assess. Rev., 57, 114–122.

Jensen, F.B., Kuperman, W.A., Porter, M.B. & Schmidt, H. (2011). Computational ocean acoustics. Springer, NY.

De Jong, C.A. f & Ainslie, M.A. (2008). Underwater radiated noise due to the piling for the Q7 Offshore Wind Park. J. Acoust. Soc. Am., 123, 2987.

Lippert, T., Galindo-Romero, M., Gavrilov, A.N. & von Estorff, O. (2015) Empirical estimation of peak pressure level from sound exposure level. Part II: Offshore impact pile driving noise. The Journal of the Acoustical Society of America, 138 (3), EL287-EL292.

National Marine Fisheries Service. (2016). Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-55, 178 p.

Popper, A.N., Hawkins, A.D., Fay, R.R., Mann, D.A., Bartol, S., Carlson, T.J., Coombs, S., Ellison, W.T., Gentry, R.L., Halvorsen, M.B., Løkkeborg, S., Rogers, P.H., Southall, B.L., Zeddies, D.G. & Tavolga, W.N. (2014). ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards committee S3/SC1 and registered with ANSI. American National Standards Institute.

Southall, B., Bowles, A., Ellison, W., Finneran, J.J., Gentry, R., Greene, C.R.J., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W.J., Thomas, J. & Tyack, P. (2007). Marine mammal noise-exposure criteria: initial scientific recommendations. Aquat. Mamm., 33, 411–521.

Zampolli, M., Nijhof, M.J.J., de Jong, C.A.F., Ainslie, M.A., Jansen, E.H.W. & Quesson, B.A.J. (2013). Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving. J. Acoust. Soc. Am., 133, 72–81.

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