Contents

List of Tables

List of Figures

Abbreviations and Acronyms

ADD	Acoustic deterrent device
Cefas	Centre for Environment Fisheries and Aquaculture Science
EIA	Environmental impact assessment
NnG	Neart na Gaoithe
NOAA	National Oceanic and Atmospheric Administration
PTS	Permanent threshold shift
RAM	Range-dependent Acoustic Model
SEL	Sound exposure level
SEL_{cum}	Cumulative sound exposure level
SEL_{ss}	Single-strike sound exposure level
SPL	Sound pressure level
TTS	Temporary threshold shift

9B Underwater Noise Modelling

9B.1 Executive Summary

1 This report presents the results of underwater noise modelling carried out by the Centre for Environment Fisheries and Aquaculture Science (Cefas) in support of the Environmental Impact Assessment (EIA) for the Inch Cape Wind Farm and Offshore Transmission Works (the Development). Predictions were made of the sound exposure levels (SELs) arising from percussive pile driving for maximal hammer energies of 4,500 kJ (monopiles) and 2,160 kJ (pin piles) at two locations on the perimeter of the Development Area including concurrent piling at these two locations. Predictions were also made of peak sound pressure levels (peak SPLs) at the initial (soft start) monopile hammer energy of 500 kJ 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*), 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 two fish hearing groups: fish with a swim bladder which is not involved in hearing [hereafter termed *Popper II;* this group includes Atlantic salmon *(Salmo salar*)], and fish with a swim bladder which is involved in hearing [hereafter termed *Popper III;* this group includes cod (*Gadus morhua*), herring (*Clupea harengus*) and sprat (*Sprattus sprattus*)] using the Popper *et al.* (2014) criteria. No fleeing behaviour was assumed for fish.

2 Of the marine mammal species assessed, those predicted to incur PTS at distances greater than 50 m were minke whale and harbour porpoise (under the NOAA criteria), and harbour and grey seals (under the Southall criteria). Both sets of noise exposure criteria are dual criteria, with PTS thresholds for both peak SPL (instantaneous exposure) and cumulative SEL (cumulative exposure). The maximum PTS effect range for peak SPL was for harbour porpoise at a distance of 50 m from the source under the NOAA criteria (all other species were <50 m for both sets of criteria). Given the planned deployment of an ADD prior to piling, the risk of PTS under this criterion is considered negligible. For cumulative SEL, the largest effect zones were 0.82 km^2 for harbour porpoise (for concurrent piling of twelve pin pile foundations in 24 hours; NOAA criteria), 133.58 km^2 for minke whale (concurrent piling of two monopile foundations in 24 hours; NOAA criteria), and 134.93 km^2 for grey and harbour seals (concurrent piling of two monopile foundations; Southall criteria). Single-strike SELs were also calculated for the maximal hammer energies to inform the assessment of marine mammal displacement.

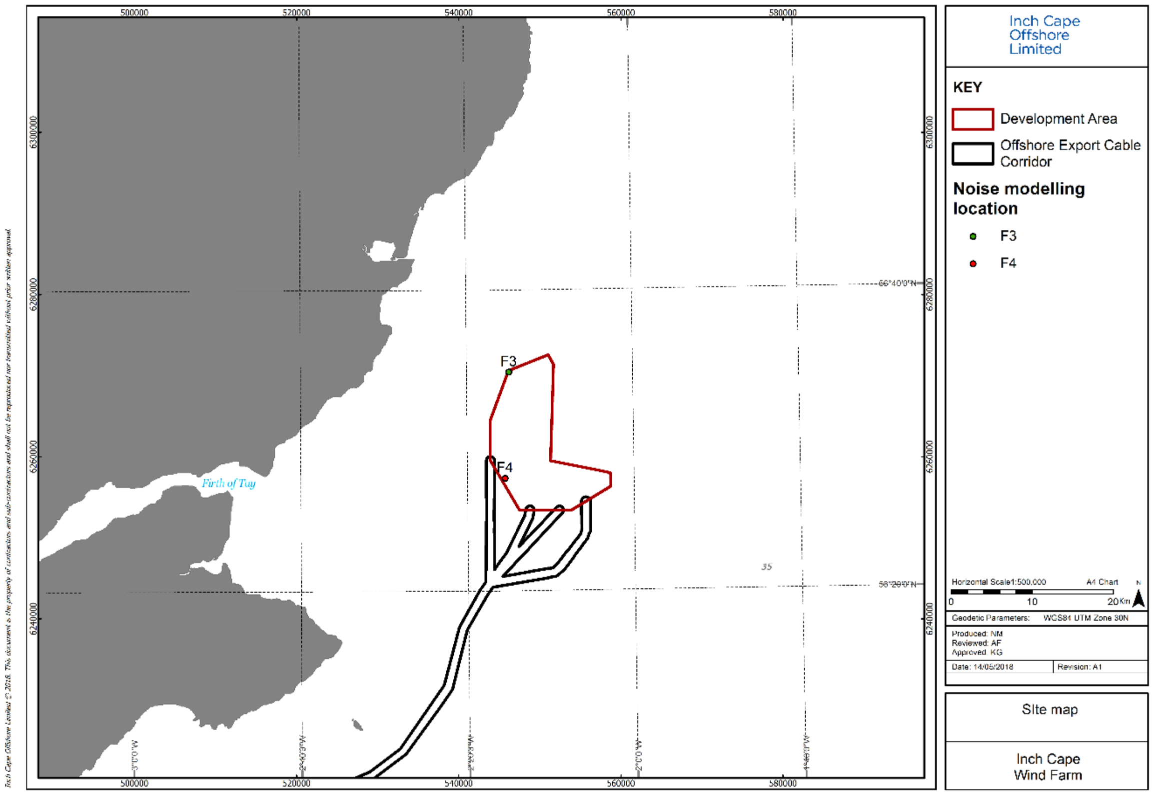
3 Effect zones for mortality and recoverable injury under the peak SPL criterion for fish did not exceed 50 m for either of the hearing groups at the initial hammer energy of 500 kJ. Under the cumulative SEL criterion, the largest effect zone predicted for mortality of fish was 4.66 km^2 for Popper III under the highest expected concurrent piling scenario for pin piles. The

greatest effect zones for recoverable injury and TTS were 16.95 km^2 and 1,738 km^2, respectively, for both hearing groups under the highest expected concurrent piling scenario for pin piles.

9B.2 Introduction

4 This report presents the results of underwater noise modelling carried out by Cefas in support of the EIA for the Inch Cape 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 4,500 kJ (monopiles) and 2,160 kJ (pin piles) at two locations on the perimeter of the Development Area (*see Figure 9-1*), including concurrent piling at these two locations (see section 9B.3.3 for other piling parameters used in the model). 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*), 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 as agreed during consultation (see *Chapter 10: Marine Mammals*). Furthermore, the risk of Temporary Threshold Shift (TTS), recoverable injury, and mortality was predicted for two fish hearing groups: fish with a swim bladder which is not involved in hearing [hereafter termed *Popper II;* this group includes Atlantic salmon *(Salmo salar*)], and fish with a swim bladder which is involved in hearing [hereafter termed *Popper III;* this group includes cod (*Gadus morhua*), herring (*Clupea harengus*) and sprat (*Sprattus sprattus*)] using the Popper *et al.* (2014) criteria.

Figure 9-1 Site map showing the noise modelling locations F3 (56.5759° N, -2.2483° E) and F4 (56.4583° N, -2.2579° E)



9B.3 Methodology

9B.3.1 Source model

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

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

where E is the hammer energy in joules, SL_E is the source level energy for a single strike at hammer energy E, β 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}.

6 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).

7 Hammer energy profiles for the piling scenarios (see Section 9B.3.4) 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 & 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}, for both a single pile, and for 2 piles being installed within 24-hours at the same location, were computed.

9B.3.2 Propagation model

8 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 (the Range-dependent Acoustic Model (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 (Jensen *et al*. 2011; Etter 2013).

9 The Cefas model is a quasi-3D model consisting of 360 2D transects extending away from the sound 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 are then resampled and integrated over frequency (using the appropriate auditory weightings where needed). Finally, the resulting levels are averaged over depth to produce modelled noise maps.

9B.3.3 Input data

10 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 were provided by Inch Cape Offshore Limited (ICOL, at 1” resolution in WGS84 projection, and were used to define the model numerical grid with a resolution of 6” (approximately 185 m by 100 m), which was more than adequate for the frequency ranges and spatial scales used in the simulations.

11 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.

12 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 (provided by ICOL) by correlating the core sediment information with published acoustic properties of various sediment types (Hamilton, 1980).

9B.3.4 Piling scenarios

13 Hammer energy profiles were estimated for two scenarios of ground conditions at the site: most probable (80% of turbine locations) and highest expected (20% of locations). The hammer energy profiles were based on a typical profile as a percentage of the maximum hammer capacity: 5,000 kJ for monopiles (Table 9B.1) and 2,400 kJ for pin piles (Table 9B.2).

Table 9B.1: Monopile hammer energy profiles

Scenario	Most probable blow energies (80% of locations)			Highest expected blow energy (20% of locations)		
Monopile diameter (mm)	12,000			12,000		
Hammer capacity (kJ)	5,000			5,000		
Max blow energy (kJ)	2,250 (45%)			4,500 (90%)		
Total piling duration (hours/monopile)	4			6		
Ramp-up details	**Time (min)**	**Efficiency (% of max blow energy)**	**Average strike rate (blows/sec)**	**Time (min)**	**Efficiency (% of max blow energy)**	**Average strike rate (blows/sec)**
	30	10% (500 kJ)	0.29	30	10% (500 kJ)	0.29
	20	20% (1,000 kJ)	0.58	20	20% (1,000 kJ)	0.58
	10	30% (1,500 kJ)	0.58	10	30% (1,500 kJ)	0.58
	180	45% (2,250 kJ)	0.58	300	90% (4,500 kJ)	0.58
Total number of monopiles	59			15		

Table 9B.2: Pin pile hammer energy profiles

Scenario	Most probable blow energies (80% of locations)	Highest expected blow energy (20% of locations)
Monopile diameter (mm)	2,438	2,438
Hammer capacity (kJ)	2,400	2,400
Max blow energy (kJ)	1,080 (i.e. 45%)	2,160 (i.e. 90%)

Total piling duration (hours/pile)	2.5			2.6		
Ramp-up details	**Time (min)**	**Efficiency (% of max blow energy)**	**Average strike rate (blows/sec)**	**Time (min)**	**Efficiency (% of max blow energy)**	**Average strike rate (blows/sec)**
	20	11% (264 kJ)	0.33	20	11% (264 kJ)	0.33
	20	20% (480 kJ)	0.58	20	20% (480 kJ)	0.58
	10	30% (720 kJ)	0.58	10	30% (720 kJ)	0.58
	100	45% (1080 kJ)	0.58	106	90% (2160 kJ)	0.58
Total number of pin piles	244			60		

14 In addition to the Development alone modelling for noise impacts on fish, a cumulative assessment was carried out which included the proposed Neart na Gaoithe (NnG) and Seagreen offshore wind farms. The piling parameters used in this assessment are shown in Table 9B.3.

Table 9B.3: Seagreen and NnG piling locations and hammer energy profiles used in the cumulative noise assessment for fish

Development	**Seagreen**			**NnG**		
Piling locations	56.5921 N, 1.73345 W 56.59565 N,1.9308 W			56.3157 N, 2.28155 W 56.24697 N, 2.30409 W		
Hammer capacity (kJ)	1,800			1,635		
Max blow energy (kJ)	1,710 (i.e. 95%)			1,383 (i.e. 84.6%)		
Total piling duration (minutes/pile)	55			216		
Ramp-up details	**Time (min)**	**Efficiency (% of max blow energy)**	**Average strike rate (blows/min)**	**Time (min)**	**Efficiency (% of max blow energy)**	**Average strike rate (blows/min)**
	6	15% (270 kJ)	45	114	19.45% (318 kJ)	30
	4	35% (630 kJ)	45	85	56.6% (925 kJ)	30

	5	55% (990 kJ)	45	17	84.6% (1383 kJ)	30
	10	75% (1350 kJ)	45	-	-	-
	30	95% (1710 kJ)	45	-	-	-

9B.3.5 Metrics modelled

15 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);
(2) Peak SPL based on initial hammer energy of 500 kJ (to assess instantaneous PTS risk at piling onset); and
(3) SEL_{cum} over 24 hours based on the hammer energy profiles (to assess risk of cumulative PTS).

16 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 9B.4.

Table 9B.4: 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	Southall and NOAA criteria
Peak SPL	Peak SPL	PTS	Southall and NOAA criteria

9B.3.6 Noise exposure criteria

17 For marine mammals, the risk of PTS was assessed using the Southall criteria (Southall *et al*. 2007) and the NOAA criteria (National Marine Fisheries Service 2016) 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. The peak SPL criterion is for unweighted received sound level. The sound level thresholds for each set of criteria are shown in Table 9B.5 and Table 9B.6.

Table 9B.5: Southall criteria sound exposure thresholds for marine mammals (Southall *et al*. 2007)

Hearing group	PTS	
	SEL$_{cum}$ [dB re 1 µPa^2 s]	**Peak SPL** [dB re 1 µPa]
Low-frequency cetaceans	198	230
Mid-frequency cetaceans	198	230
High-frequency cetaceans	198	230
Phocids	186	218

Table 9B.6: NOAA criteria sound exposure thresholds for marine mammals (National Marine Fisheries Service 2016)

Hearing group	PTS	
	SEL$_{cum}$ [dB re 1 µPa^2 s]	**Peak SPL** [dB re 1 µPa]
Low-frequency cetaceans	183	219
Mid-frequency cetaceans	185	230
High-frequency cetaceans	155	202
Phocids	185	218

18 For fish, the Popper criteria (Popper *et al*. 2014) were applied (Table 9B.7). These consist of dual criteria for recoverable injury and mortality, and an SEL$_{cum}$ criterion for TTS. None of these thresholds apply frequency weightings. The Popper criteria divide fish species into three categories: (i) no swim bladder; (ii) swim bladder not involved in hearing; and (iii) swim bladder involved in hearing. The second and third of these hearing groups were modelled in the assessment. The second group (Popper II), swim bladder not involved in hearing, includes Atlantic salmon *(Salmo salar*). The third group (Popper III), swim bladder involved in hearing, includes cod (*Gadus morhua*), herring (*Clupea harengus*), and sprat (*Sprattus sprattus*).

Table 9B.7: Sound exposure thresholds for fish (Popper *et al*. 2014)

Hearing group	TTS	Recoverable injury		Mortality	
	SEL$_{cum}$ [dB re 1 µPa^2 s]	**SEL$_{cum}$** [dB re 1 µPa^2 s]	**Peak SPL** [dB re 1 µPa]	**SEL$_{cum}$** [dB re 1 µPa^2 s]	**Peak SPL** [dB re 1 µPa]
Fish: no swim bladder (Popper I)	186	216	213	219	213

Hearing group	TTS	Recoverable injury		Mortality	
	SEL_{cum} [dB re 1 μPa^2 s]	SEL_{cum} [dB re 1 μPa^2 s]	Peak SPL [dB re 1 µPa]	SEL_{cum} [dB re 1 μPa^2 s]	Peak SPL [dB re 1 µPa]
Fish: swim bladder is not involved in hearing (Popper II)	186	203	207	210	207
Fish: swim bladder involved in hearing (Popper III)	186	203	207	207	207

9B.3.7 Piling locations assessed for each species

19 For each marine mammal species, noise from a single location which would best reflect the greatest risk to that species based on available data on estimated distributions (see *Chapter 10* for details) was modelled. Table 9B.8 provides the coordinates of these piling locations, and Table 9B.9 shows the locations assessed for each marine mammal species and can be seen in Figure 9-1. In addition to the single pile location (either F3 or F4[1]), both pile locations were modelled for all species in the assessments of concurrent piling (Scenarios 3 and 4; see Table 9B.9).

Table 9B.8: Pile driving locations used for noise modelling

Location name	Location position (decimal degrees)
F3	56.5759, -2.2483
F4	56.4583, -2.2579

Table 9B.9: Piling scenarios modelled for each marine mammal species

Scenario		Description	Location	Species modelled	Ground conditions[2]	Number of monopiles per 24 h period	Number of pin piles per 24 h period
Most Likely	1a	Piling at a single location (1 vessel)	F3	Minke whale Bottlenose dolphin Harbour porpoise	MP	1	4

[1] The nomenclature for the naming of the noise modelling locations for the Development was assigned during the assessment process for the 2013 Inch Cape Environmental Statement (ES; ICOL, 2013), and has been maintained for clarity during this assessment. F1 and F2 were located within the NNG Offshore Wind Farm, and are not referred to specifically within this assessment.

[2] The geophysical and geotechnical survey campaigns that have been conducted across the site have enabled the Inch Cape engineers to develop a ground model of the sediments present. This ground model has been utilised in a study into the blow energies that are likely to be required to drive pin piles into the sediment to the required depth to secure the foundations. The study has revealed that up to 20 per cent of the site (Highest Expected, HE, ground conditions) may require higher blow energies to drive the pin piles to the required depth than within the remaining 80 per cent (Most Probable, MP, ground conditions). Thus the most likely blow energy profile represents the soft start and ramp up to full power required to pile drive the pins into the sediment across 80 per cent of the site, while the worst case represents the increased blow energy required to pile drive the pins across the remaining 20 per cent of the site.

Scenario		Description	Location	Species modelled	Ground conditions[2]	Number of monopiles per 24 h period	Number of pin piles per 24 h period
	1b		F4	White-beaked dolphin Harbour seal Grey seal			
Worst Case	2a		F3	Minke whale Bottlenose dolphin Harbour porpoise	HE	1	6
	2b		F4	White-beaked dolphin Harbour seal Grey seal			
Most Likely	3	Piling at 2 locations (2 vessels)	F3 + F4	All	MP	2	8
Worst Case	4				HE	2	12

20 For fish, both hearing groups were assessed for concurrent piling at both locations (F3 and F4) using the highest expected piling scenarios for monopiles and pin piles (see Table 9B.1 and Table 9B.2, respectively).

9B.3.8 Scenarios of marine mammal fleeing behaviour for PTS estimation

21 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. Given the lack of scientific evidence to support fleeing behaviour from noise in the fish species considered, fish were assumed to remain stationary during piling.

22 For marine mammals, it was assumed that animals would flee from the pile foundation at the onset of pile driving. Animals were assumed to flee out to a maximum distance of 25 km (after which the model assumed them to remain stationary at that distance). Table 9B.10 below identifies the agreed fleeing speeds to be used in the model.

Table 9B.10: Fleeing speeds and minimum water depths assumed for each marine mammal species/taxon

Swim speeds (m/s):			Minimum depth constraint (m)
Minke whale	2.1	SNH (2016)	10
Bottlenose/white-beaked dolphin	1.52	Bailey (2006)	5

Harbour porpoise	1.4	SNH (2016)	5
Harbour seal	1.8	SNH (2016)	0
Grey seal	1.8	SNH (2016)	0

23 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 90 m by 90 m) and allowing them to move on the domain grid according to a set of pre-defined rules (see below). 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's piling activity the total cumulated exposure of all animal agents is mapped back to their starting positions on the grid.

24 In the case of single location pile driving, the model assumes that the animal agents are fleeing at constant speeds (Table 9B.10), along straight lines away from the pile location, as long as the local water depth exceeds a minimum value (Table 9B.10). When an animal agent would arrive into shallower water than the allowed minimum depth if moving along the straight line from the pile location, then a change in direction is calculated and effected, with the allowed values, in the 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° (backwards, but not necessarily to the previous position unless the previous move was straight forwards). It should be noted that, as indicated in Table 9B.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.

25 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 being 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 also apply in the case of dual location pile driving.

9B.4 Results

9B.4.1 Single-strike sound exposure levels for behavioural response assessment

26 The scenarios assessed for SEL_{ss} are listed in Table 9B.11, and examples are shown of the most probable and worst case for monopiles and pin piles at location F3, and the worst case for concurrent piling of monopiles and pin piles at both locations.

Table 9B.11: Scenario list for SELss

Pile type	Scenario	Hammer energy	Location(s)	Figure
Monopile	Most probable blow energies (80% of locations)	2,250 (45%)	F3	Figure 9-2
Monopile	Highest expected blow energy (20% of locations)	4,500 (90%)	F3	Figure 9-3
Monopile	Highest expected blow energy (20% of locations)	4,500 (90%)	F3 + F4	Figure 9-4
Pin pile	Most probable blow energies (80% of locations)	1,080 (45%)	F3	Figure 9-5
Pin pile	Highest expected blow energy (20% of locations)	2,160 (90%)	F3	Figure 9-6
Pin pile	Highest expected blow energy (20% of locations)	2,160 (90%)	F3 + F4	Figure 9-7

Figure 9-2 Single-strike SEL for a hammer energy of 2,250 kJ (most likely monopile hammer energy) at location F3

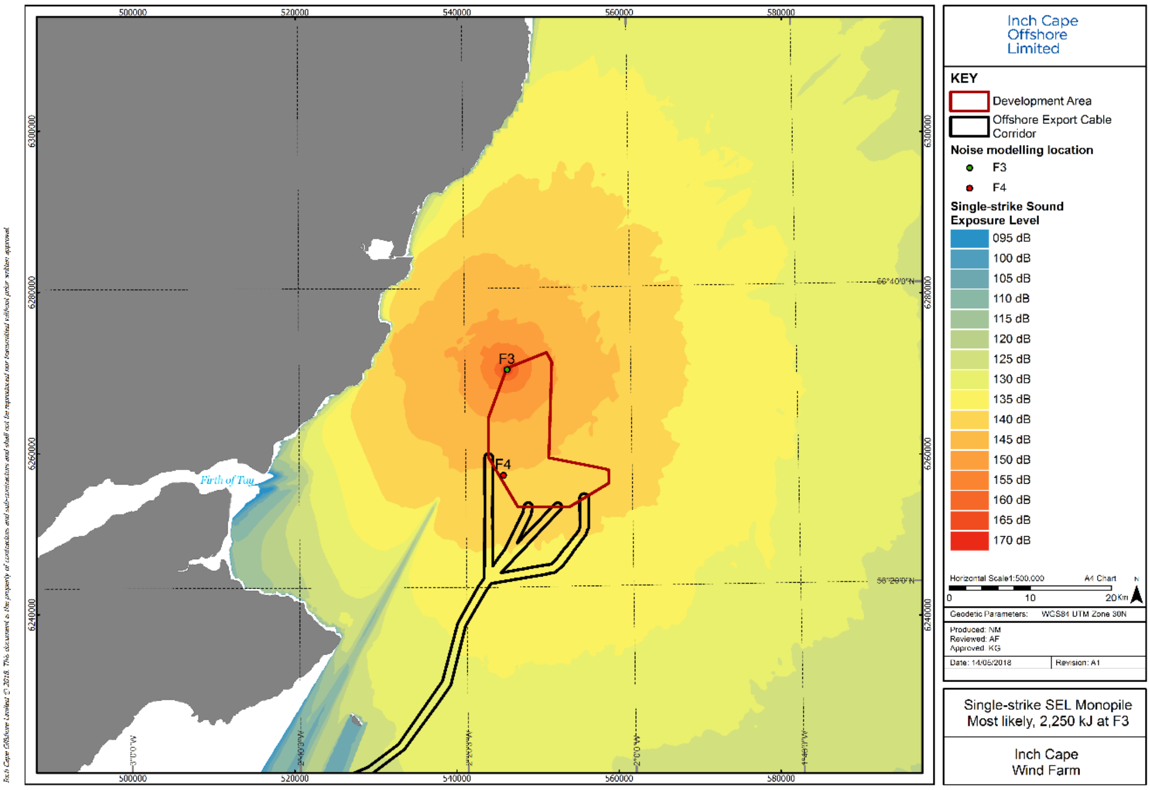


Figure 9-3 Single-strike SEL for a hammer energy of 4,500 kJ (highest expected monopile hammer energy) at location F3

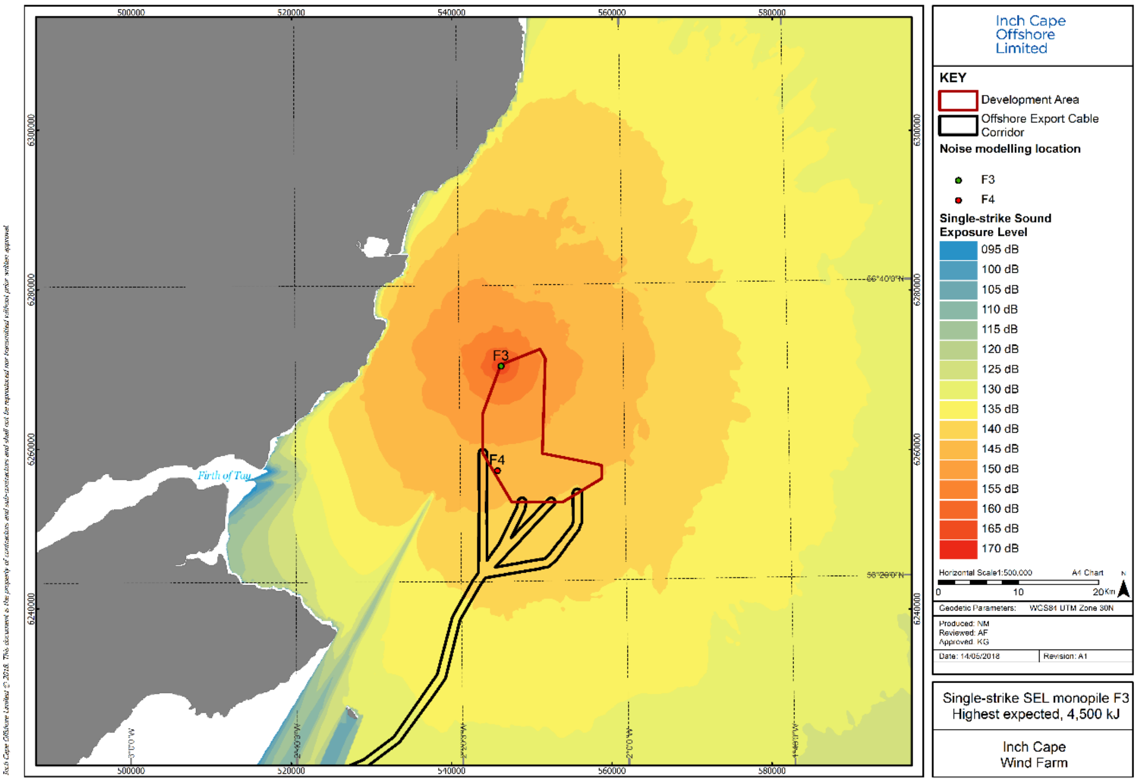


Figure 9-4 Single-strike SEL for a hammer energy of 4,500 kJ (highest expected monopile hammer energy) at locations F3 and F4

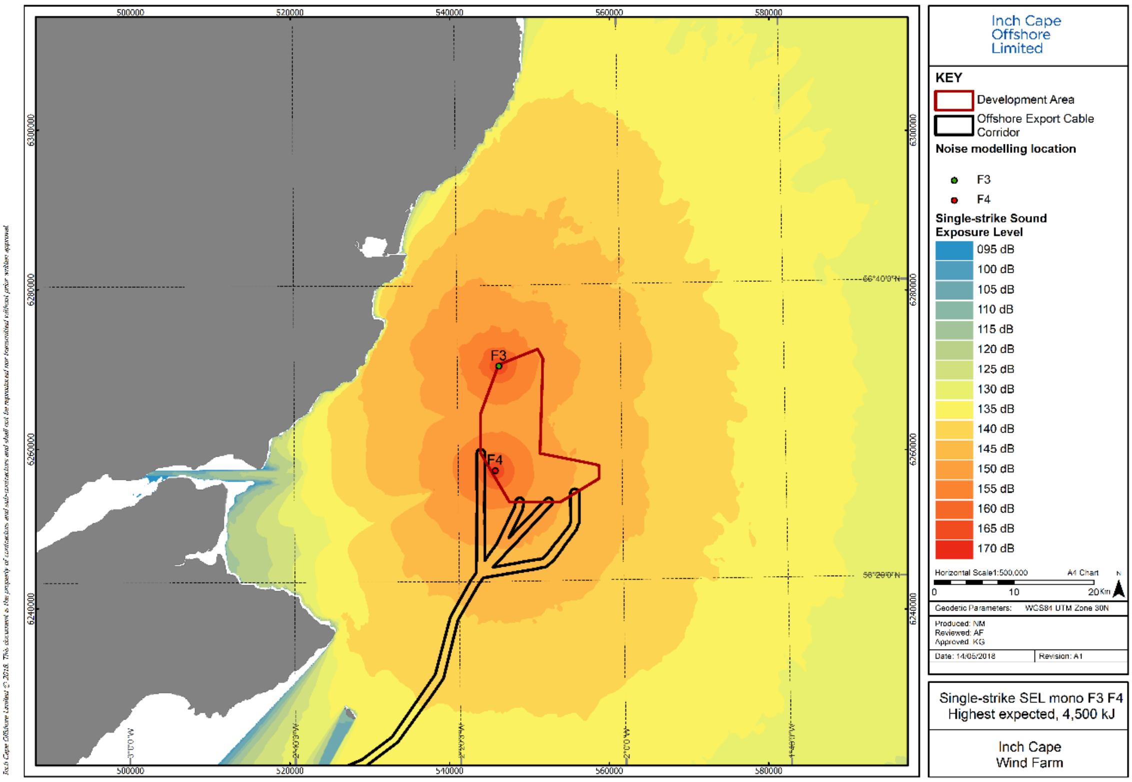


Figure 9-5 Single-strike SEL for a hammer energy of 1,080 kJ (most likely pin pile hammer energy) at location F3

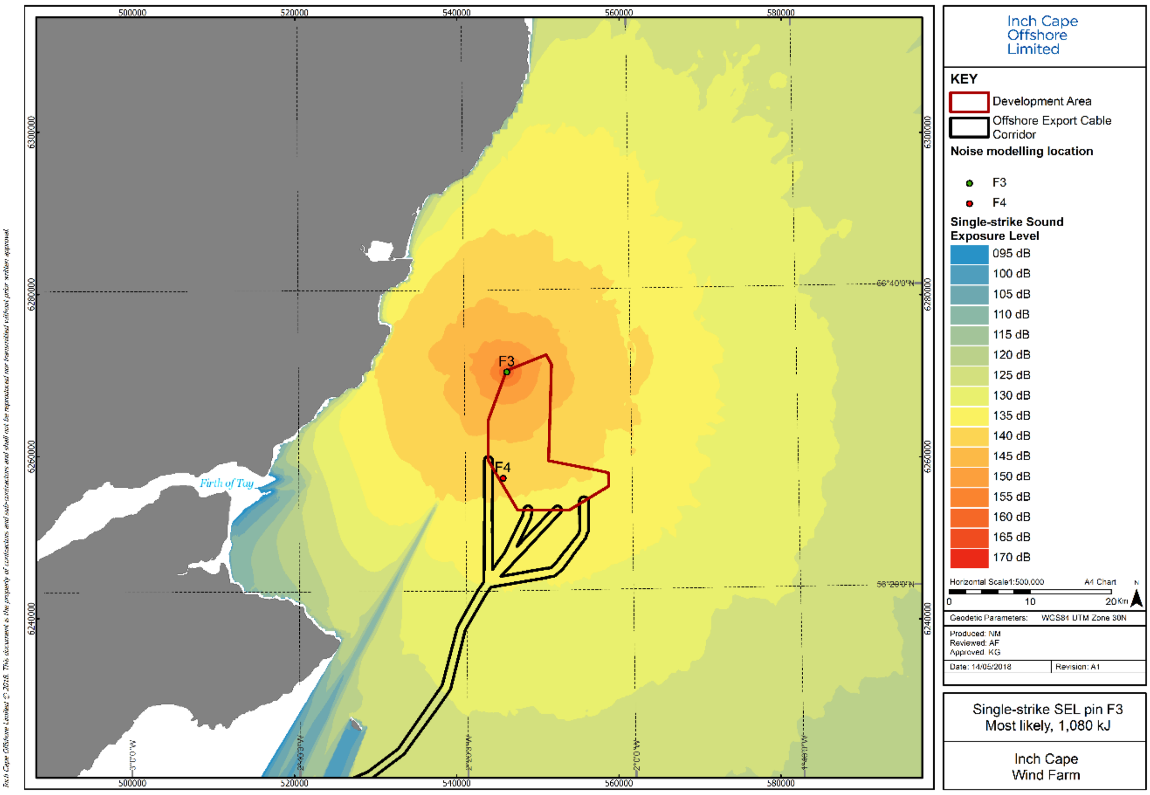


Figure 9-6 Single-strike SEL for a hammer energy of 2,160 kJ (highest expected pin pile hammer energy) at location F3

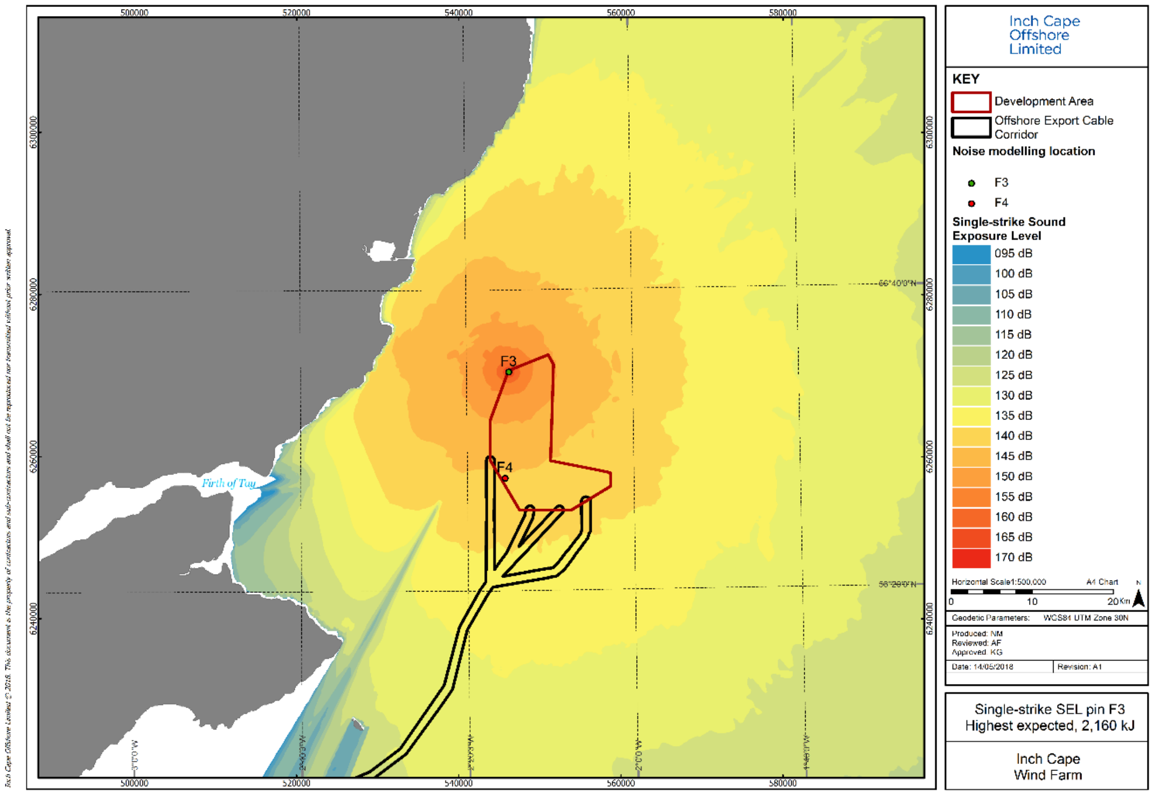
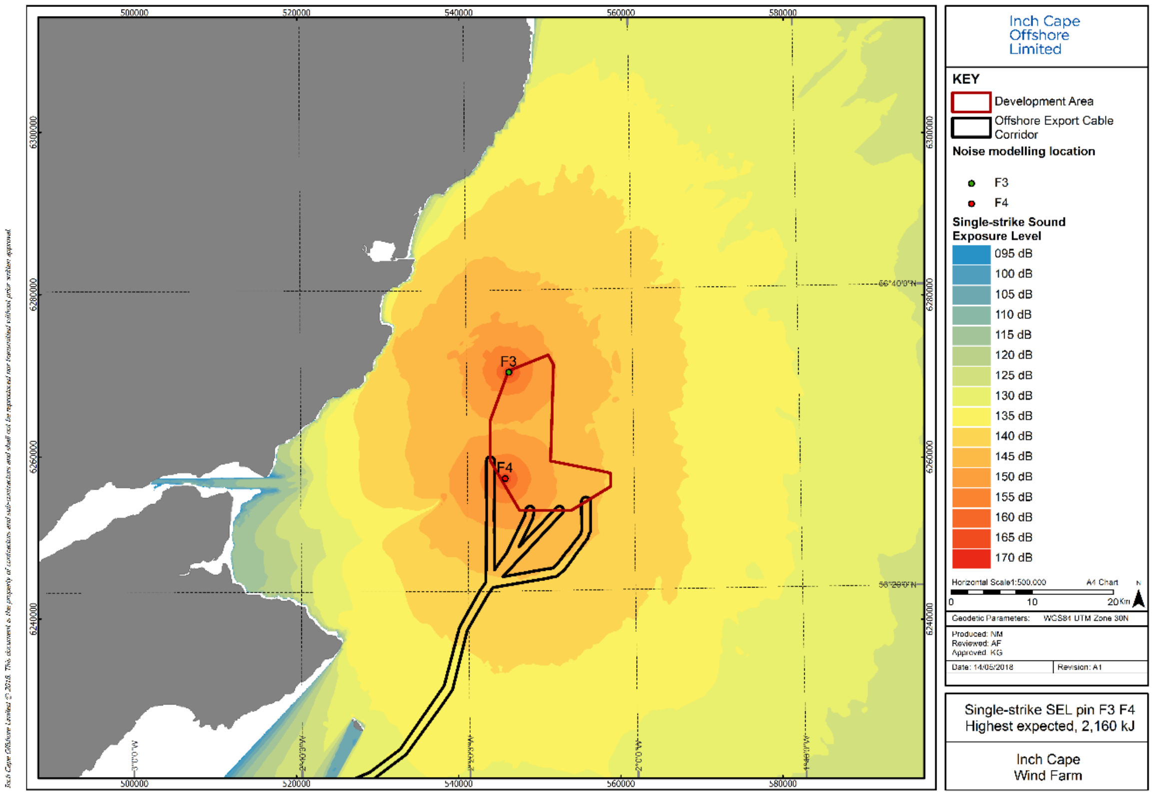


Figure 9-7 Single-strike SEL for a hammer energy of 2,160 kJ (highest expected pin pile hammer energy) at locations F3 and F4



9B.4.2 Peak SPL assessment of instantaneous PTS effect zones for marine mammals

27 All of the scenarios modelled for the peak SPL criterion for instantaneous PTS at an initial hammer energy of 500 kJ had effect ranges ≤ 50 m (maximum was 50 m for harbour porpoise). The full list of scenarios and corresponding impact ranges are provided in Table 9B.12.

Table 9B.12: Effect ranges for instantaneous PTS for marine mammals at an initial hammer energy of 500 kJ

Species (functional hearing group)	Predicted effect range, Southall criteria	Predicted effect range, NOAA criteria
Harbour porpoise (HF cet)	<50 m	50 m
Bottlenose and white-beaked dolphin (MF cet)	<50 m	<50 m
Minke whale (LF cet)	<50 m	<50 m
Harbour and grey seal (phocid)	<50 m	<50 m

9B.4.3 Peak SPL assessment of mortality and recoverable injury for fish

28 All of the scenarios modelled for the peak SPL criterion for instantaneous PTS at an initial hammer energy of 500 kJ had effect ranges below 50 m. The full list of scenarios and corresponding impact ranges are provided in Table 9B.13.

Table 9B.13: Effect ranges for mortality and recoverable injury for fish at initial hammer energy of 500 kJ

Hearing group	Predicted effect range, Popper criteria
Swim bladder not involved in hearing (Popper II)	<50 m
Swim bladder involved in hearing (Popper III)	<50 m

9B.4.4 Cumulative SEL assessment of PTS effect zones for marine mammals

29 For the NOAA criteria, minke whale had predicted PTS ranges > 50 m for both the monopile (Table 9B.14) and pin pile (Table 9B.15) foundations at both most likely and highest expected hammer energies for both single and two piling vessel scenarios. Harbour porpoise had predicted PTS ranges >50 m for both monopiles and pin piles at the highest expected concurrent scenario only.

30 For the Southall criteria, only grey and harbour seals had predicted PTS ranges >50 m. These were for the highest expected scenario for monopiles (single foundation), and for both monopile and pin pile concurrent piling scenarios (Table 9B.14, Table 9B.15).

Table 9B.14: Effect ranges for cumulative PTS according to the Southall and NOAA SEL_{cum} criteria for each marine mammal functional hearing group and monopile scenario

Scenario		Description	Location	Number of piles per 24 h period	Species modelled	Effect range or area, Southall	Effect range or area, NOAA
Most likely	1a	Piling at a single location (1 vessel)	F3	1	Minke whale	<50 m	0.25 km^2 Figure 9-8
					Bottlenose dolphin	<50 m	<50 m
					Harbour porpoise	<50 m	<50 m
	1b		F4		White-beaked dolphin	<50 m	<50 m
					Harbour seal Grey seal	<50 m	<50 m
Worst case	2a		F3	1	Minke whale	<50 m	4.52 km^2 Figure 9-9
					Bottlenose dolphin	<50 m	<50 m
					Harbour porpoise	<50 m	<50 m
	2b		F4		White-beaked dolphin	<50 m	<50 m
					Harbour seal Grey seal	1.74 km^2 Figure 9-18	<50 m
Most likely	3	Piling at 2 locations (2 vessels)	F3+F4	2	Minke	<50 m	31.04 km^2 Figure 9-10
					Bottlenose dolphin White-beaked dolphin	<50 m	<50 m
					Harbour porpoise	<50 m	<50 m
					Harbour seal Grey Seal	9.42 km^2 Figure 9-19	<50 m
Worst case	4			2	Minke	<50 m	133.58 km^2 Figure 9-11
					Bottlenose dolphin White-beaked dolphin	<50 m	<50 m

					Harbour porpoise	<50 m	0.69 km^2 Figure 9-16
					Harbour seal Grey Seal	134.93 km^2 Figure 9-20	<50 m

Table 9B.15: Effect ranges for cumulative PTS according to the Southall and NOAA SEL_{cum} criteria for each marine mammal functional hearing group and pin pile scenario

Scenario		Description	Location	Number of piles per 24 h period	Species modelled	Effect range or area Southall	Effect range or area NOAA
Most likely	1a	Piling at a single location (1 vessel)	F3	4	Minke whale	<50 m	0.15 km^2 Figure 9-12
					Bottlenose dolphin	<50 m	<50 m
					Harbour porpoise	<50 m	<50 m
	1b		F4		White-beaked dolphin	<50 m	<50 m
					Harbour seal Grey seal	<50 m	<50 m
Worst case	2a		F3	6	Minke whale	<50 m	0.27 km^2 Figure 9-13
					Bottlenose dolphin	<50 m	<50 m
					Harbour porpoise	<50 m	<50 m
	2b		F4		White-beaked dolphin	<50 m	<50 m
					Harbour seal Grey seal	<50 m	<50 m
Most likely	3	Piling at 2 locations (2 vessels)	F3+F4	8	Minke whale	<50 m	0.67 km^2 Figure 9-10
					Bottlenose dolphin White-beaked dolphin	<50 m	<50 m
					Harbour porpoise	<50 m	<50 m
					Harbour seal Grey Seal	2.19 km^2 Figure 9-21	<50 m
Worst case	4			12	Minke whale	<50 m	83.16 km^2 Figure 9-15
					Bottlenose dolphin White-beaked dolphin	<50 m	<50 m
					Harbour porpoise	<50 m	0.82 km^2 Figure 9-17
					Harbour seal Grey Seal	41.81 km^2 Figure 9-22	<50 m

Figure 9-8 Cumulative PTS effect zones for minke whale exposed to piling of a single monopile foundation with most likely hammer energy of 2,250 kJ at location F3, NOAA criteria

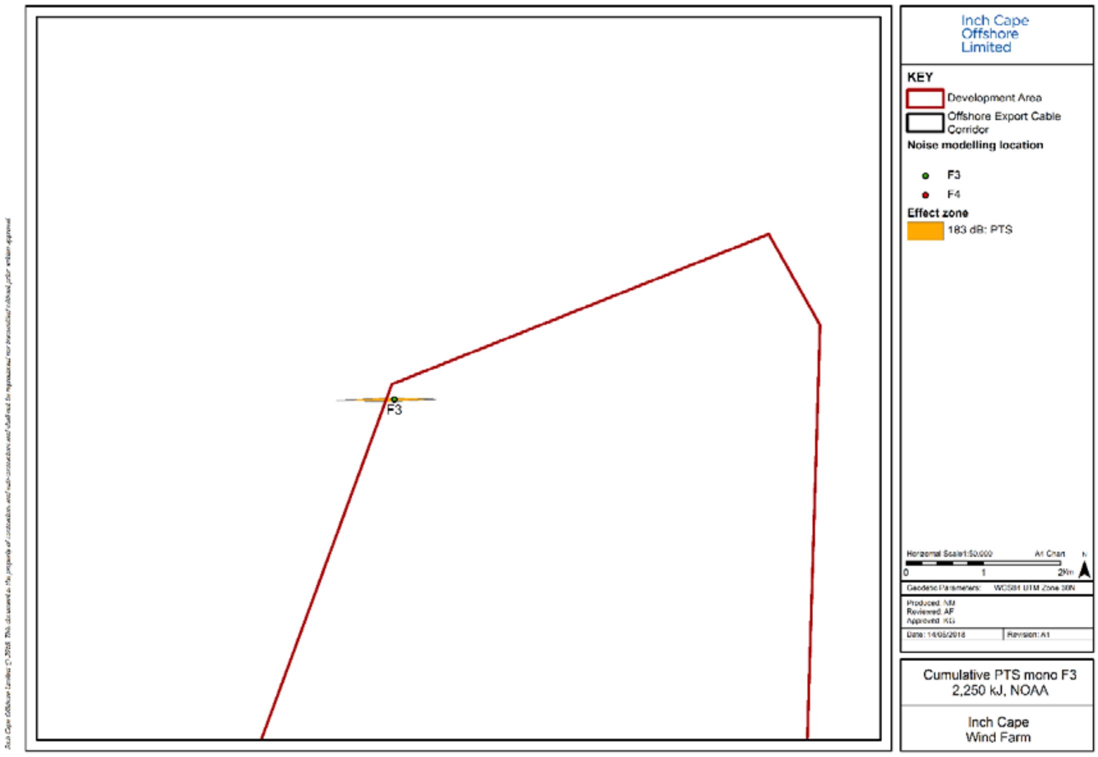


Figure 9-9 Cumulative PTS effect zones for minke whale exposed to piling of a single monopile foundation with maximum hammer energy of 4,500 kJ at location F3, NOAA criteria

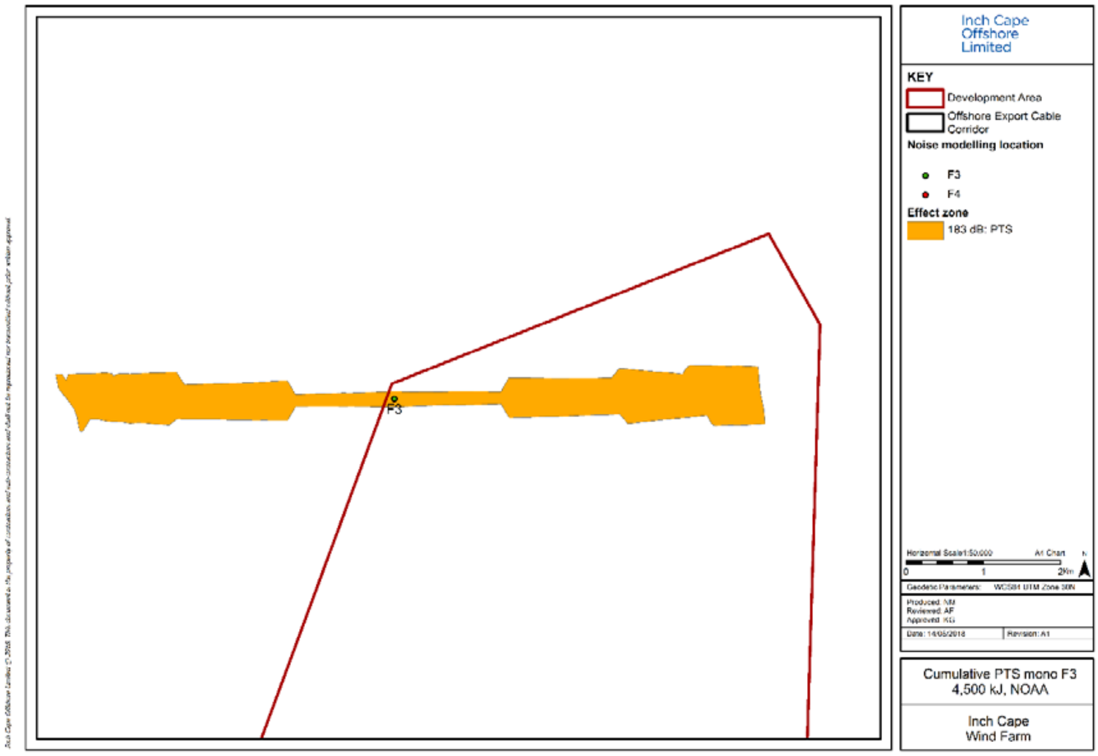


Figure 9-10 Cumulative PTS effect zones for minke whale exposed to concurrent piling of two monopile foundations with maximum hammer energy of 2,250 kJ at F3 and F4, NOAA criteria

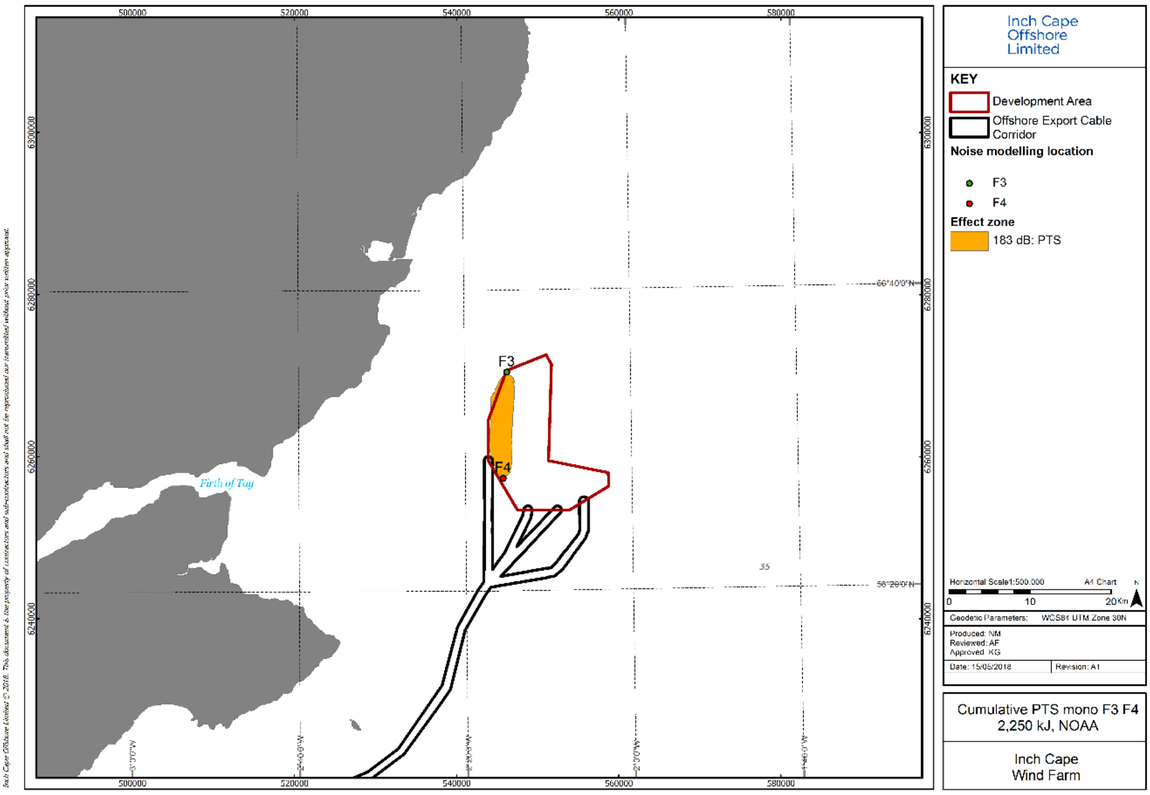


Figure 9-11 Cumulative PTS effect zones for minke whale exposed to concurrent piling of two monopile foundations with maximum hammer energy of 4,500 kJ at F3 and F4, NOAA criteria

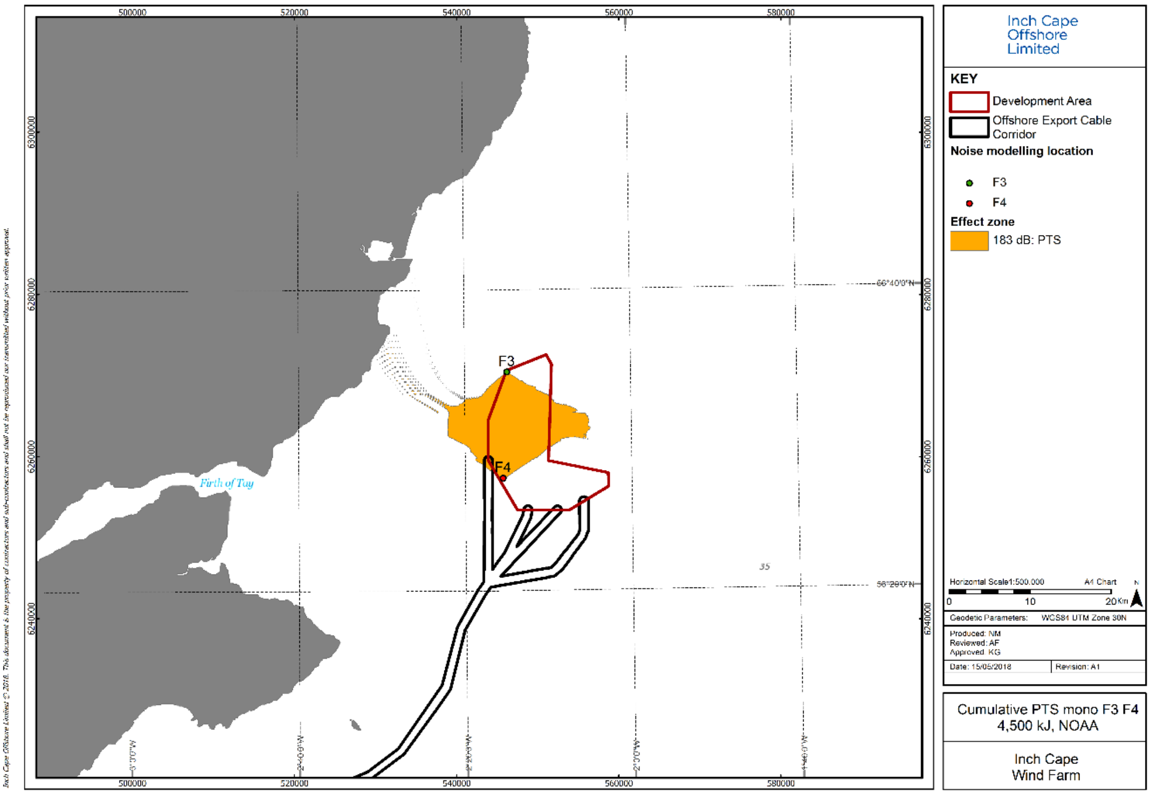


Figure 9-12 Cumulative PTS effect zones for minke whale exposed to piling of four pin pile foundations with a maximum hammer energy of 2,160 kJ at location F3, NOAA criteria

Figure 9-13 Cumulative PTS effect zones for minke whale exposed to piling of six pin pile foundations with a maximum hammer energy of 2,160 kJ at location F3, NOAA criteria

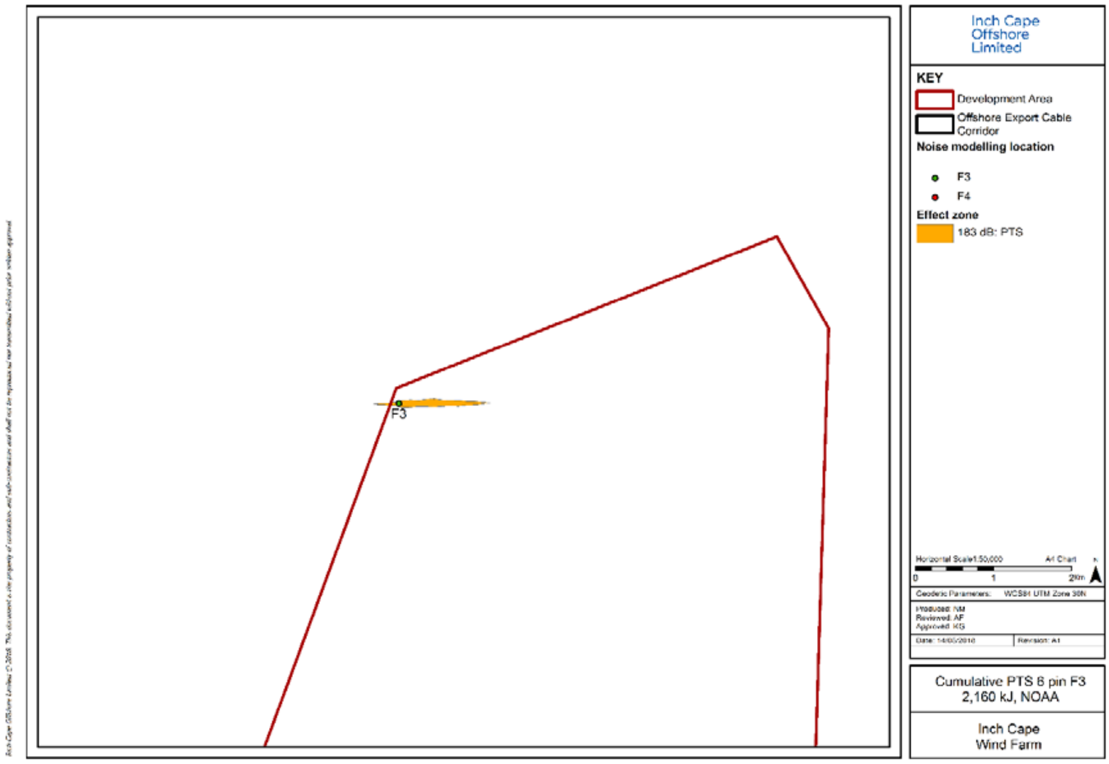


Figure 9-14 Cumulative PTS effect zones for minke whale exposed to concurrent piling of eight pin pile foundations with maximum hammer energy of 2,160 kJ at locations F3 and F4, NOAA criteria

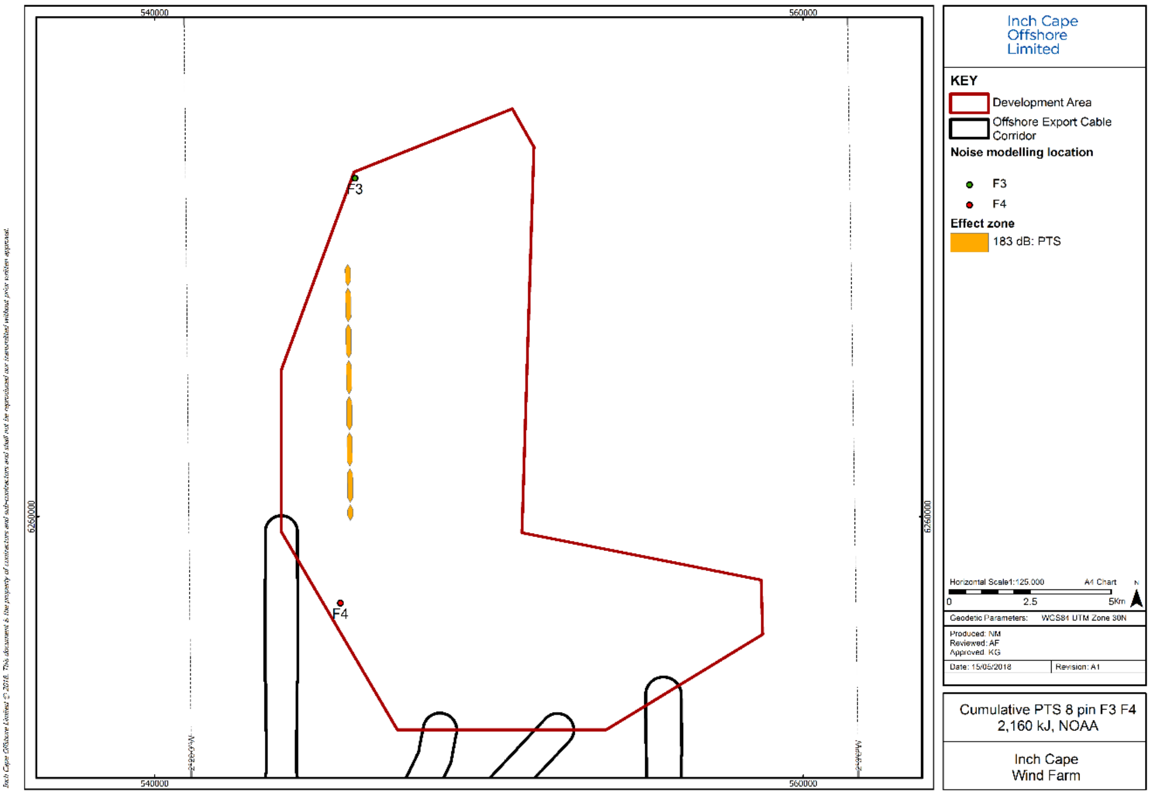


Figure 9-15 Cumulative PTS effect zones for minke whale exposed to concurrent piling of twelve pin pile foundations with maximum hammer energy of 2,160 kJ at F3 and F4, NOAA criteria

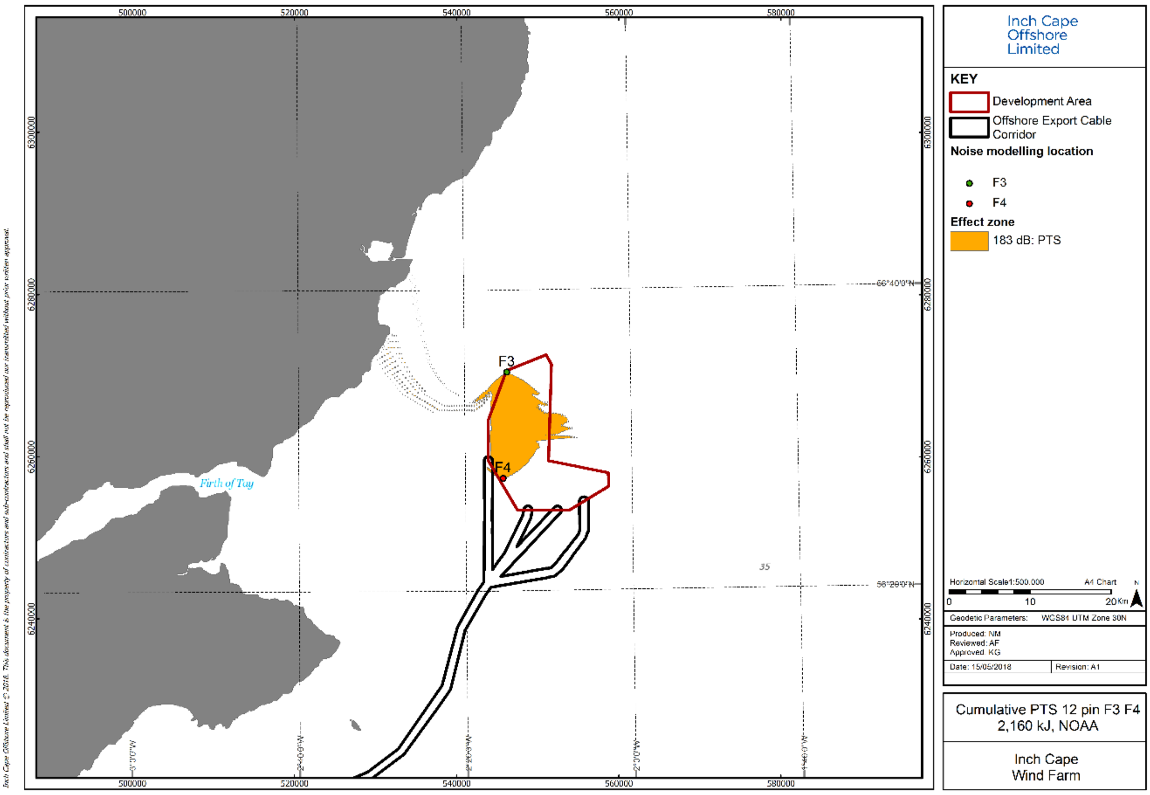


Figure 9-16 Cumulative PTS effect zones for harbour porpoise exposed to concurrent piling of two monopile foundations with maximum hammer energy of 4,500 kJ at F3 and F4, NOAA criteria

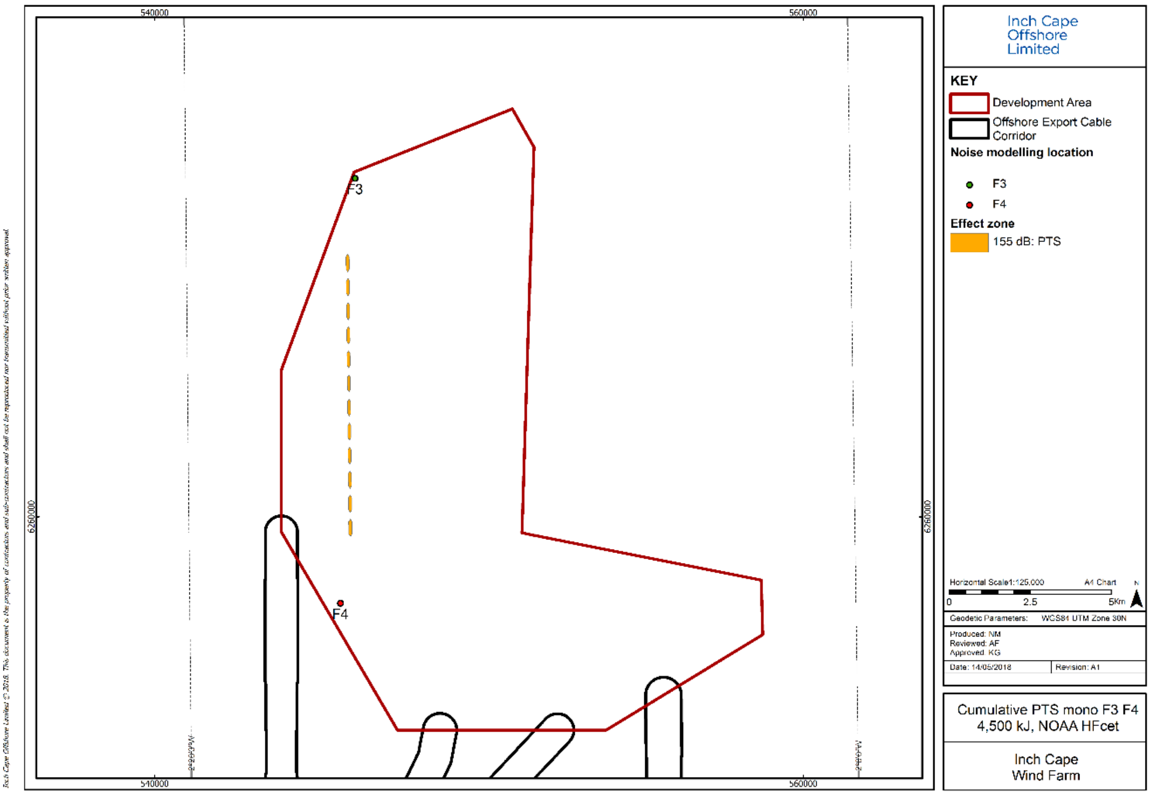


Figure 9-17 Cumulative PTS effect zones for harbour porpoise exposed to concurrent piling of twelve pin pile foundations with maximum hammer energy of 2,160 kJ at F3 and F4, NOAA criteria

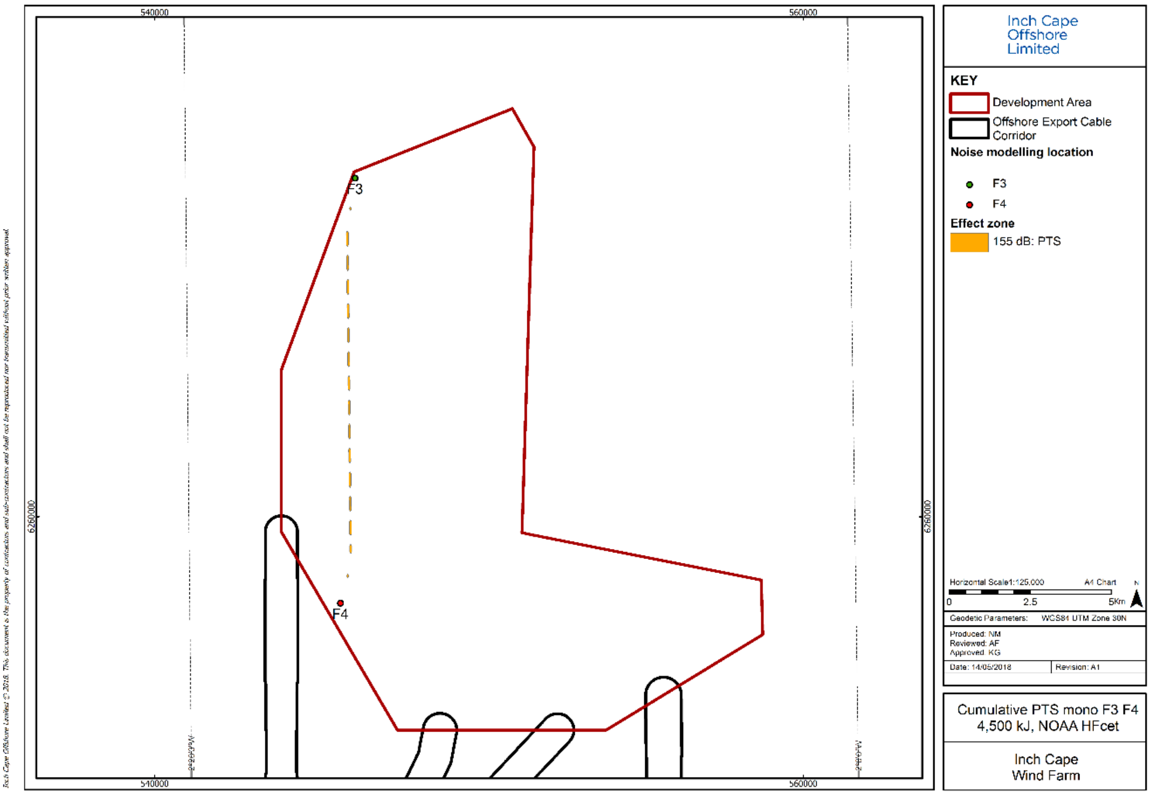


Figure 9-18 Cumulative PTS effect zones for grey and harbour seal exposed to piling of a single monopile foundation with a maximum hammer energy of 4,500 kJ at location F4, Southall criteria

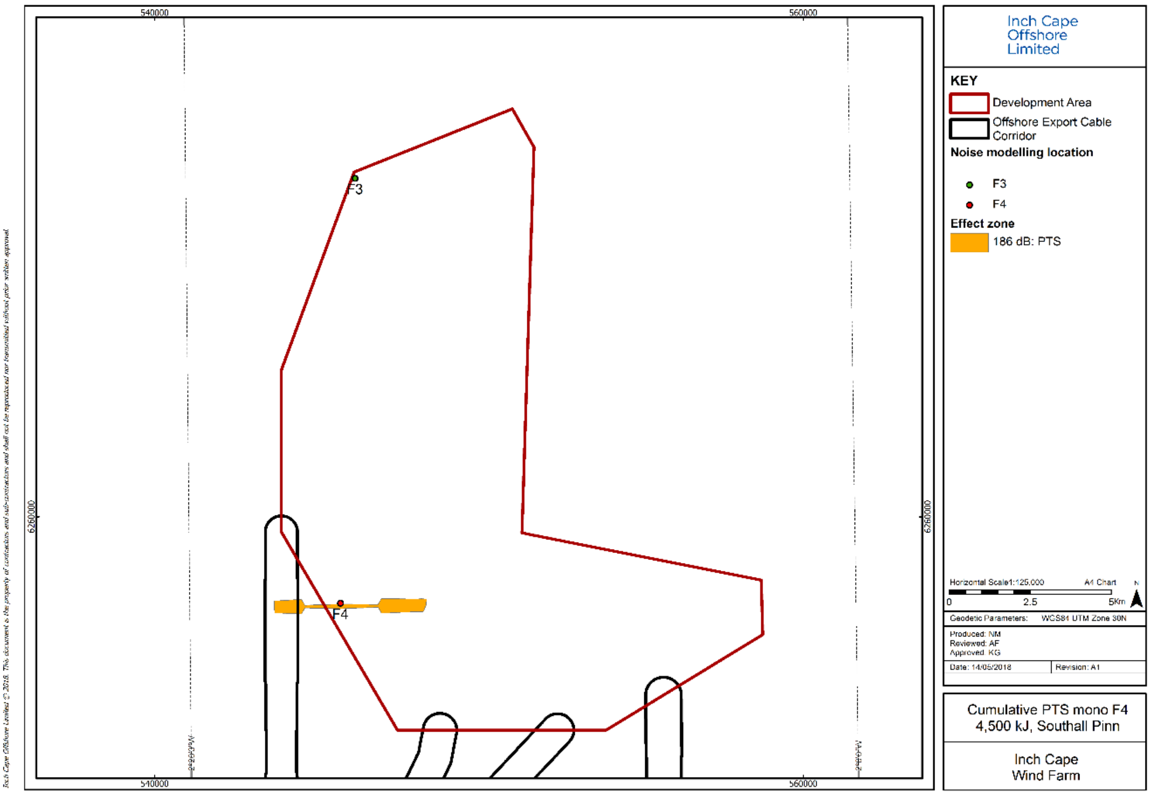


Figure 9-19 Cumulative PTS effect zones for grey and harbour seal exposed to concurrent piling of 2 monopile foundations with maximum hammer energy of 2,250 kJ at F3 and F4, Southall criteria

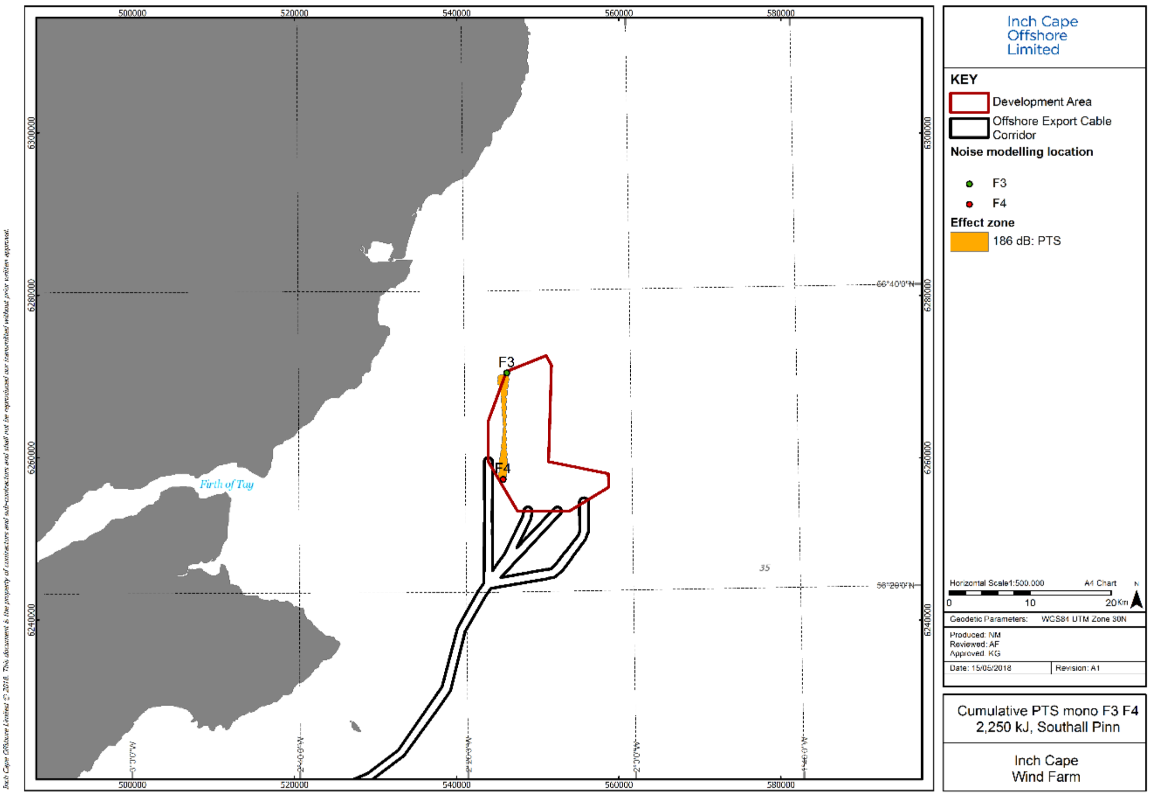


Figure 9-20 Cumulative PTS effect zones for grey and harbour seal exposed to concurrent piling of 2 monopile foundations with maximum hammer energy of 4,500 kJ at F3 and F4, Southall criteria

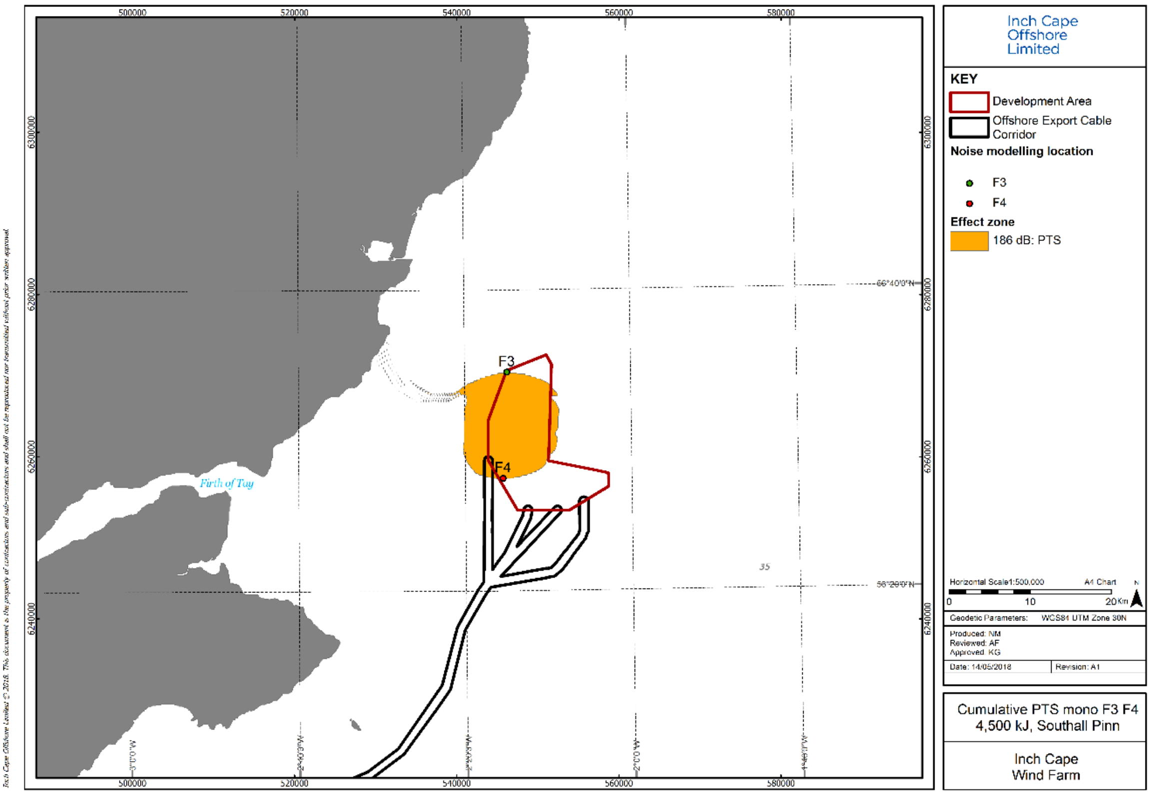
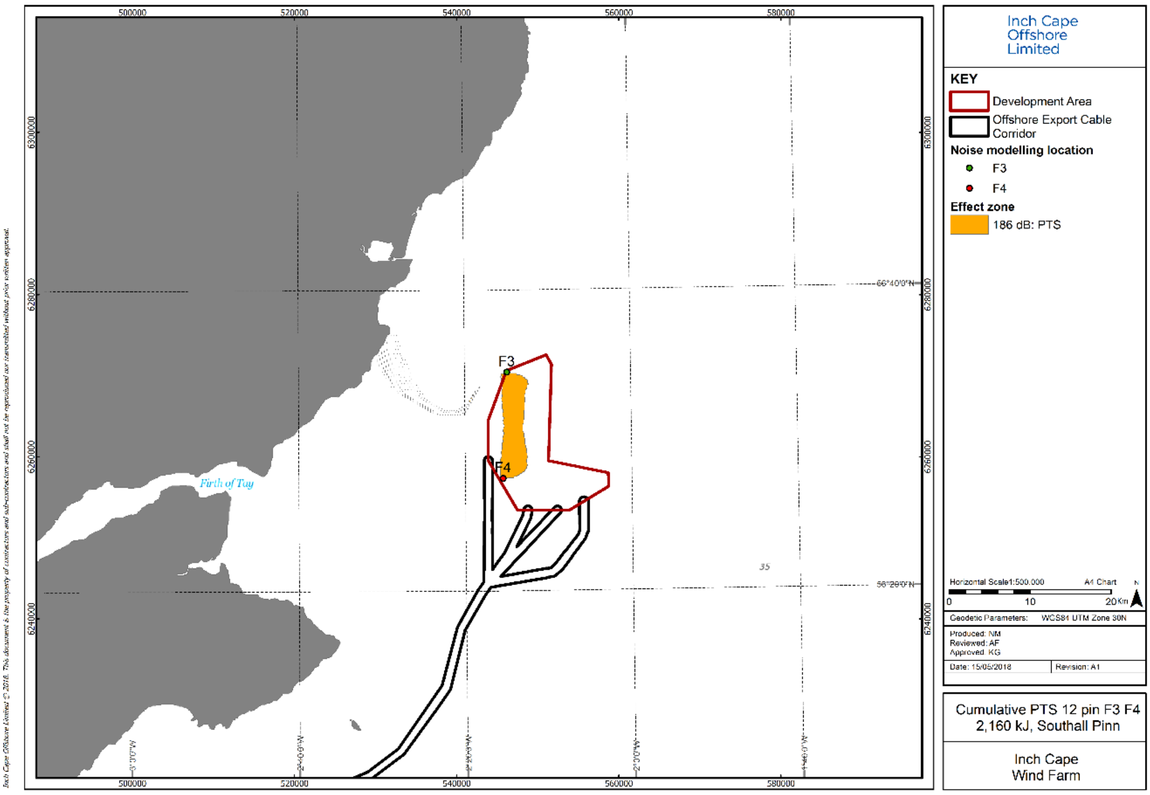


Figure 9-21 Cumulative PTS effect zones for grey and harbour seal exposed to concurrent piling of 8 pin pile foundations with maximum hammer energy of 2,160 kJ at F3 and F4, Southall criteria

Figure 9-22 Cumulative PTS effect zones for grey and harbour seal exposed to concurrent piling of 12 pin pile foundations with maximum hammer energy of 2,160 kJ at F3 and F4, Southall criteria



9B.4.5 Cumulative SEL assessment of TTS, recoverable injury, and mortality effect zones for fish

31 Effect zones for the highest expected concurrent piling scenarios are shown in Table 9B.16. Maps of these effect areas are shown in Figure 9-23 to Figure 9-26.

Table 9B.16. Monopile and pin pile effect areas for mortality, recoverable injury, and TTS according to the Popper SEL_{cum} criterion for both hearing groups

Scenario, location	Number of piles per 24 h	Hearing group	TTS area (km²)	Recoverable injury area (km²)	Mortality area (km²)	Figure number
Highest expected, monopile	2	Popper III	1,656	15.42	4.15	Figure 9-23
		Popper II	1,656	15.42	1.79	Figure 9-24
Highest expected, pin pile	12	Popper III	1,738	16.95	4.66	Figure 9-25
		Popper II	1,738	16.95	2.09	Figure 9-26

Figure 9-23 Cumulative exposure effect zones for Popper III hearing group exposed to piling of monopile foundations with maximum hammer energy of 4,500 kJ at locations F3 and F4

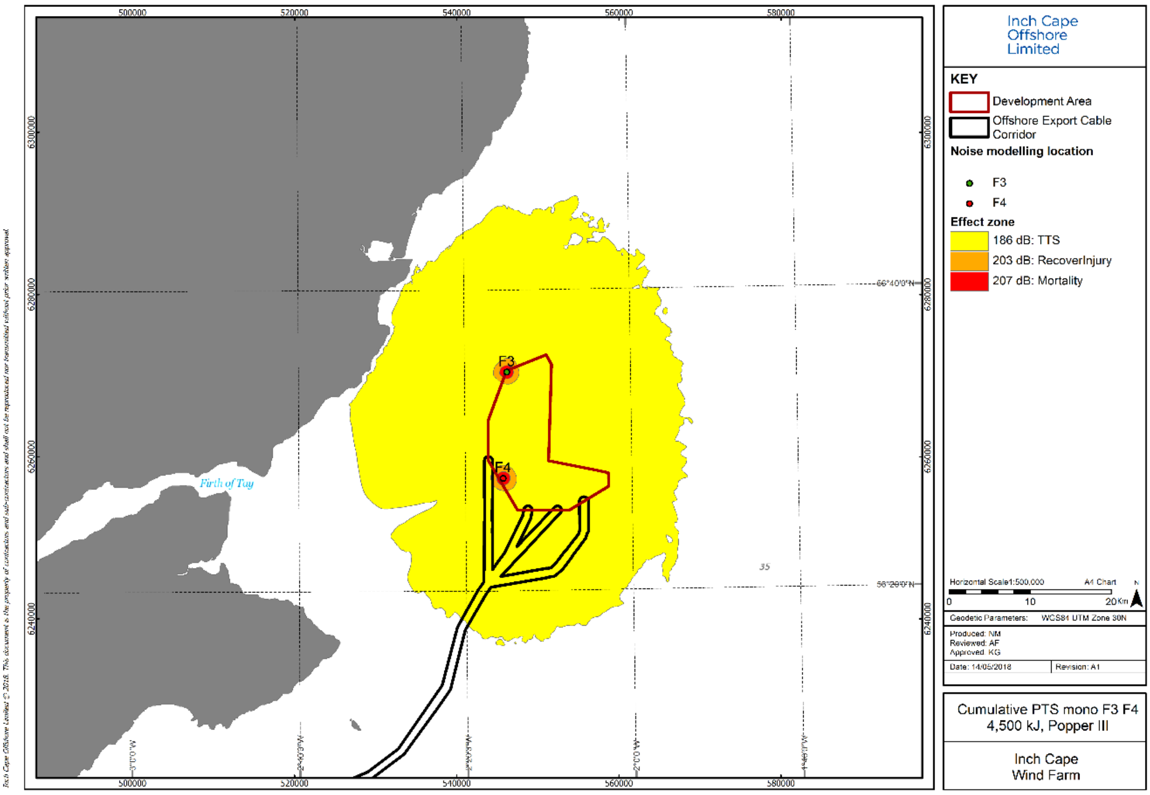


Figure 9-24 Cumulative exposure effect zones for Popper II hearing group exposed to piling of monopile foundations with maximum hammer energy of 4,500 kJ at locations F3 and F4

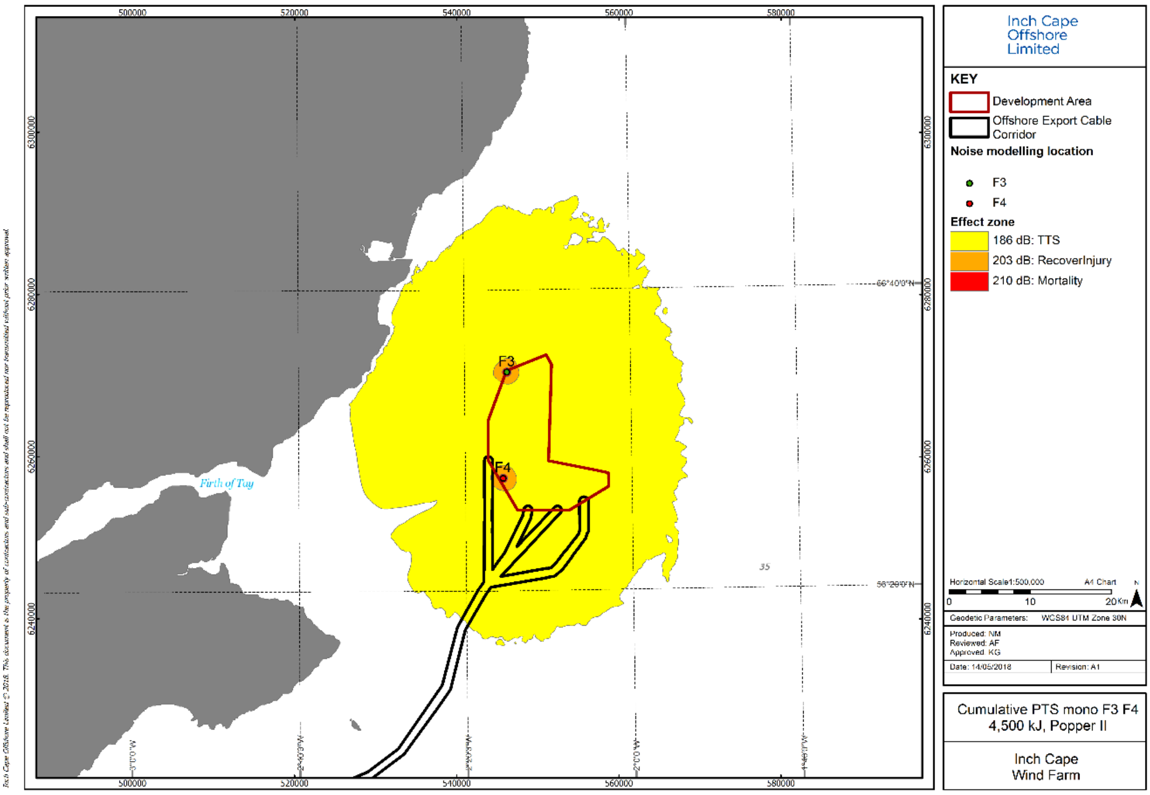


Figure 9-25 Cumulative exposure effect zones for Popper III hearing group exposed to concurrent piling of 12 pin piles (2 piles per location) with maximum hammer energy of 2,160 kJ at F3 and F4

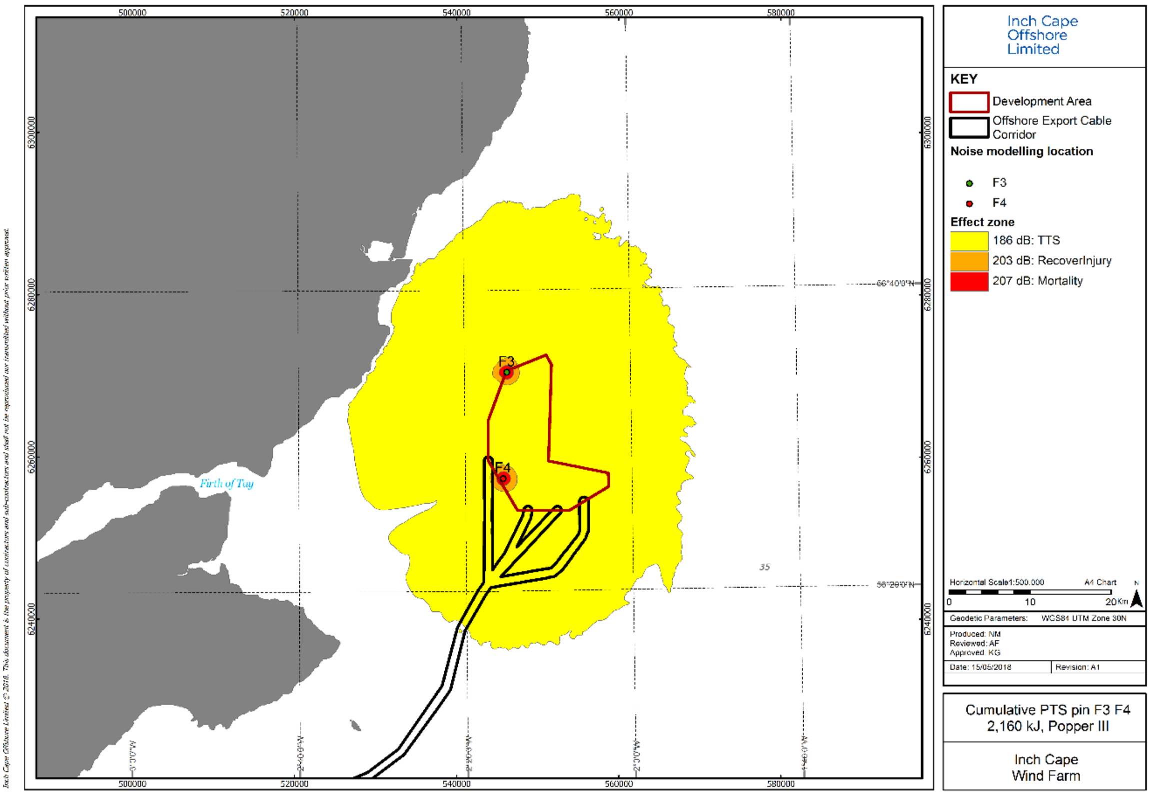
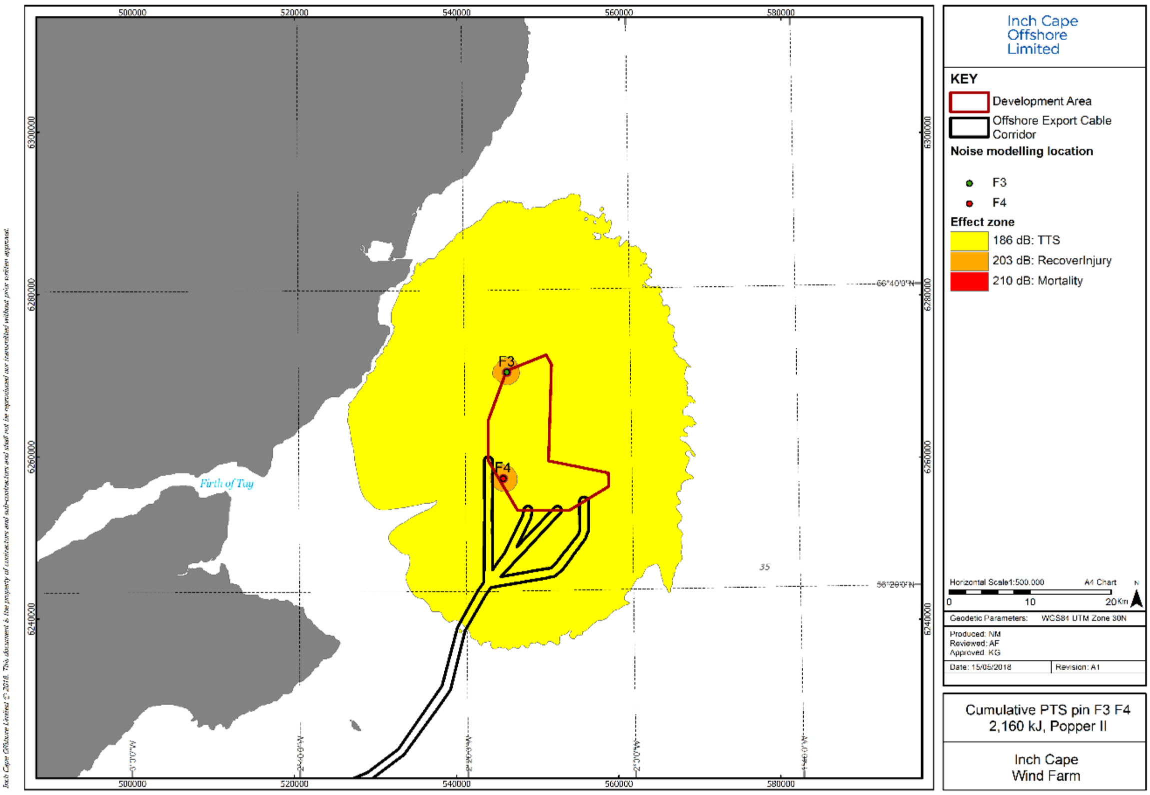


Figure 9-26 Cumulative exposure effect zones for Popper II hearing group exposed to concurrent piling of 12 pin piles (6 piles per location) with maximum hammer energy of 2,160 kJ at F3 and F4



9B.4.6 Combined assessment of cumulative SEL for fish for ICOL, NNG and Seagreen

Based on data provided for two adjacent offshore wind farm proposals (NNG and Seagreen), a combined assessment was conducted for the risk of effects on fish. Effect zones for the highest expected concurrent piling scenarios are shown in Table 9B.17. Maps of these effect areas are shown in Figure 9- 27 to Figure 9-30.

Table 9B.17: Combined assessment effect areas with monopile and pin pile scenarios at ICOL, for mortality, recoverable injury, and TTS according to the Popper SELcum criterion for both hearing groups

Scenario, location	Number of piles per 24 h at ICOL	Species modelled	TTS area (km^2)	Recoverable injury area (km^2)	Mortality area (km^2)	Figure number
Highest expected, monopile	2	Popper III	3,535	27.64	7.38	FIgure 9-27
		Popper II	3,535	27.64	1.79	Figure 9-28
Highest expected, pin pile	12	Popper III	3,588	29.22	7.89	Figure 9-29
		Popper II	3,588	29.22	2.09	Figure 9-30

Figure 9-27 Cumulative exposure effect zones for Popper III hearing group exposed to highest expected concurrent monopile piling at Inch Cape, NNG and Seagreen

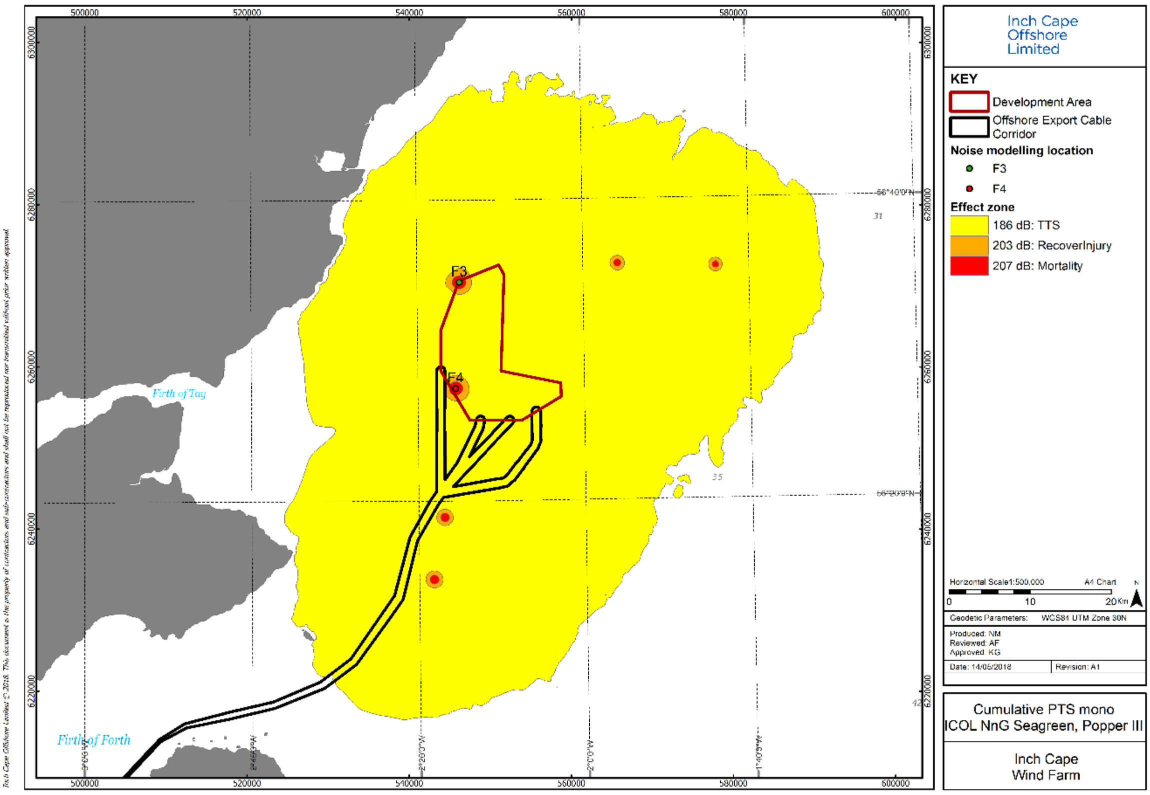


Figure 9-28 Cumulative exposure effect zones for Popper II hearing group exposed to highest expected concurrent monopile piling at Inch Cape, NNG and Seagreen

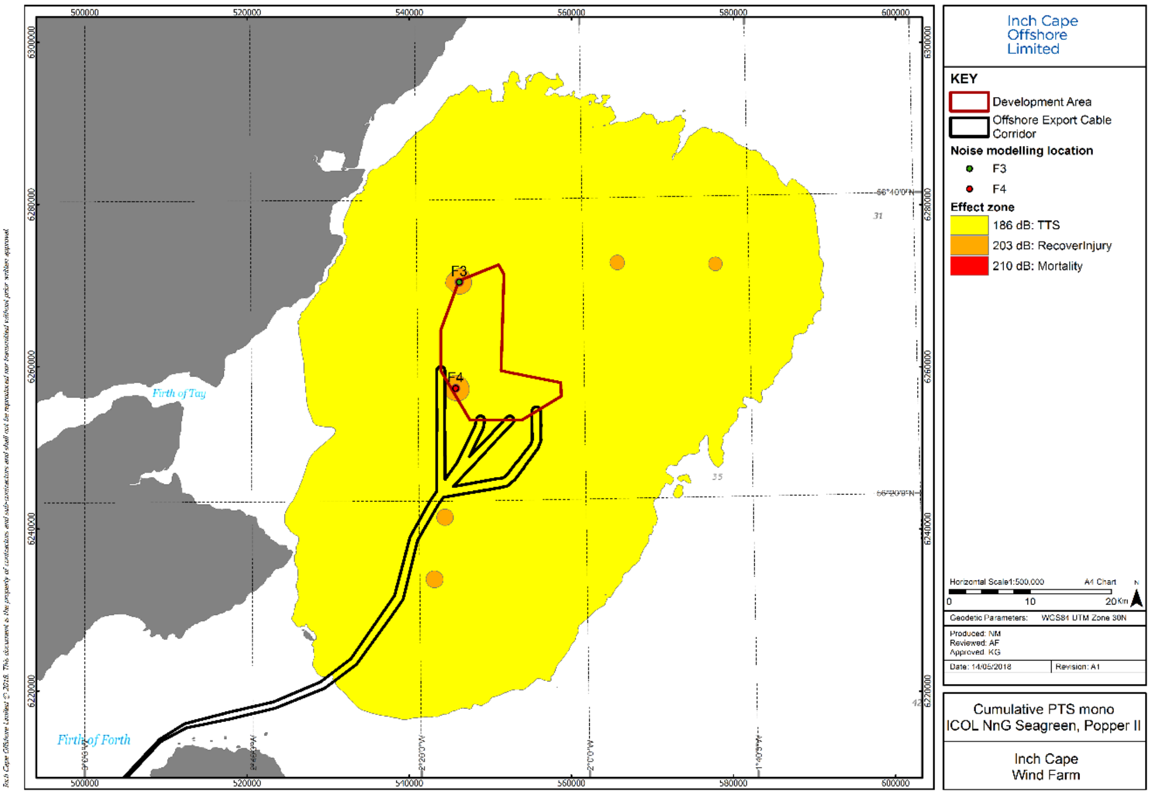


Figure 9-29 Cumulative exposure effect zones for Popper III hearing group exposed to highest expected concurrent pin pile piling at Inch Cape, NNG and Seagreen

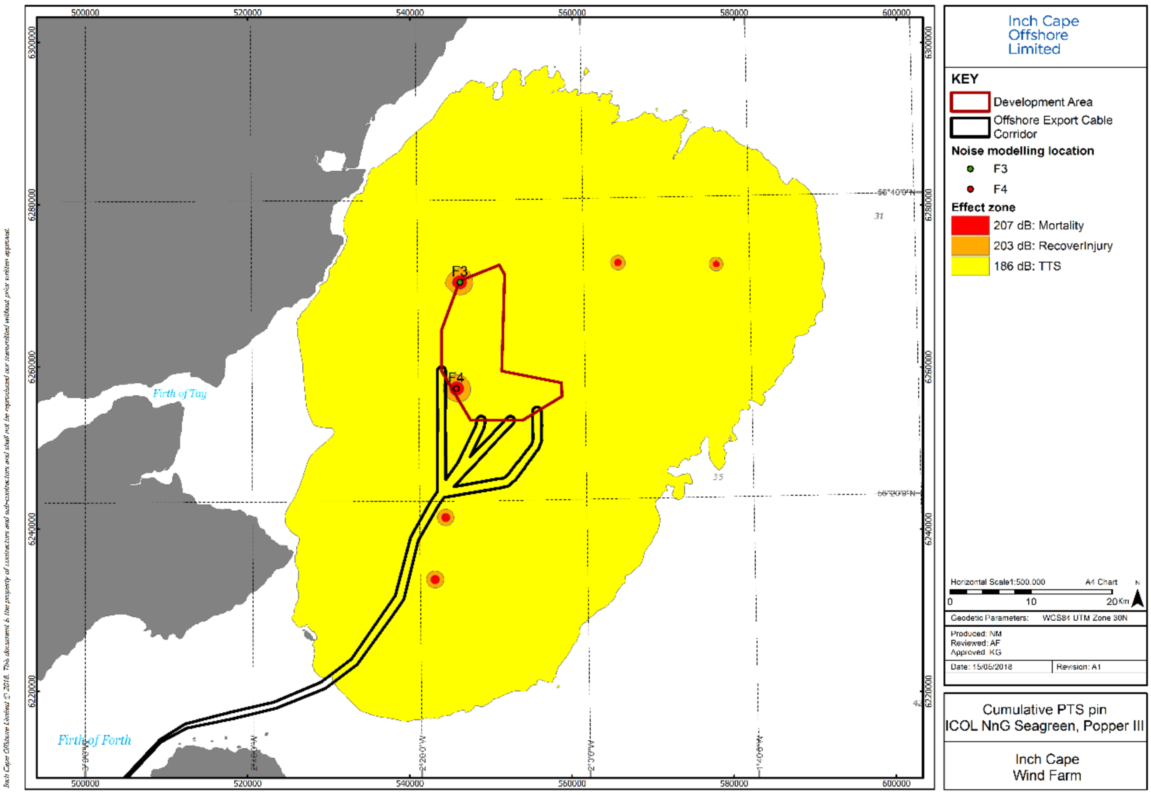
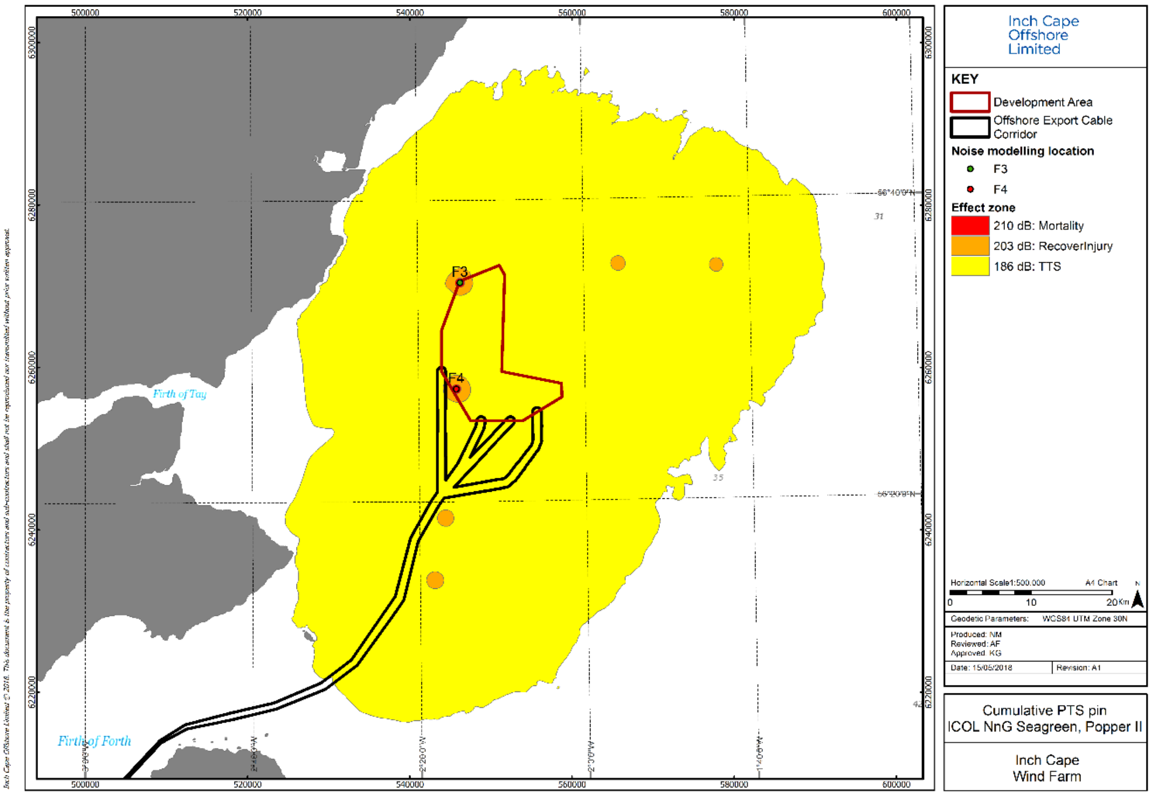


Figure 9-30 Cumulative exposure effect zones for Popper II hearing group exposed to highest expected concurrent pin pile piling at Inch Cape, NNG and Seagreen



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