Inch Cape Offshore Wind Farm

New Energy for Scotland

Offshore Environmental Statement:
VOLUME 2D
Appendix 11A: Underwater Noise

REPSOL

edp renewables

Contents

List of Tables

List of Figures

11A Underwater Noise

11A.1 Introduction

This Appendix presents in detail the results of modelling undertaken to inform a prediction of the likely extent of impacts on marine fauna associated with underwater noise that has the potential to be generated during the construction and operation of the Wind Farm and OfTW. It also provides a review of the literature relating to underwater noise and its impacts on marine fauna, the various metrics used in assessing impacts and additional details relating to the noise modelling methodology.

Underwater noise modelling was undertaken with a noise source at the Wind Farm, and in combination with noise sources potentially operating at the same time at the Firth of Forth (FoF) Phase 1 (Seagreen) and Neart na Gaoithe (NnG) offshore wind farms.

11A.2 Measurement of Underwater Noise

11A.2.1 Introduction

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium the pressures associated with underwater sound tend to be much higher than in air. As an example, background levels of sea noise of approximately 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al*, 2003 and 2007a). This level equates to about 100 dB re 20 µPa in the units that will be used to describe a sound level in air. Such levels in air would be considered to be hazardous. However, marine mammals and fish have evolved to live in this environment and are thus relatively insensitive to sound pressure compared with terrestrial mammals. The most sensitive thresholds are often not below 100 dB re 1 µPa and typically not below 70 dB re 1 µPa (44 dB re 20 µPa using the reference unit that would be used in air).

11A.2.2 Units of Measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. This is required to accommodate the large range between the minimum and maximum perceptible sound pressures.

Any quantity expressed in this scale is termed a “level”. If the unit is sound pressure, expressed on the dB scale it will be termed the “Sound Pressure Level”.

The fundamental definition of the dB scale is:

eqn. 11.1 $$Level = 10\ \log_{10}\left(Q/Q_{ref}\right)$$

where Q is the quantity being expressed on the scale, and Q_{ref} is the reference quantity.

The dB scale represents a ratio and is therefore used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, a reference quantity of 20 µPa is usually used for sound in air, since this is the threshold of human hearing.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than the pressure. If this was not the case, if the acoustic power level of a source rose by 10 dB the Sound Pressure Level (SPL) would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of RMS (Root Mean Squared) pressure squared. This is equivalent to expressing the sound as:

eqn. 11.2 $$Sound\ Pressure\ Level = 20\ \log_{10}\left(P_{RMS}/P_{ref}\right)$$

For underwater sound typically a unit of one micropascal (µPa) is used as the reference unit (a Pascal is equal to the pressure exerted by one Newton over one square metre. One micropascal equals one millionth of this). For the SPL, an increase in level of 6 dB means a doubling of pressure.

11A.2.3 Quantities of Measurement

Sound may be expressed in many different ways depending upon the particular type of noise, and it is the parameter of the noise that allows it to be evaluated in terms of a biological effect. These are described in more detail below.

Peak Level

The peak level is the maximum level of the acoustic pressure, usually a positive pressure. This form of measurement is often used to characterise underwater blasts where there is a clear positive peak following the detonation of explosives. Examples of this type of measurement used to define underwater blast waves can be found in Bebb and Wright (1953, 1955), Richmond *et al* (1973), Yelverton *et al* (1973 and 1981). The data from these studies have been widely interpreted in a number of reviews on the effect of high level underwater noise causing fatality and injury in human divers, marine mammals and fish (see for example Rawlins (1974); Hill (1978); Goertner (1982); Richardson *et al* (1995); Cudahy and Parvin (2001); Hastings and Popper (2005)). For offshore operations, such as well head severance, typical charge weights of 40 kg may be used giving a source peak pressure of 195 MPa or 285 dB re 1 µPa @ 1 m (Parvin *et al* (2007)).

Peak-to-peak Level

The peak-to-peak level is usually calculated using the maximum variation of the pressure from positive to negative within the wave. This represents the maximum change in pressure (differential pressure from positive to negative) as the transient pressure wave propagates. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, and hence 6 dB higher.

Peak-to-peak levels of noise are often used to characterise sound transients from impulsive sources such as percussive impact piling and seismic airgun sources. Measurements during offshore impact piling operations to secure tubular steel piles into the seabed have indicated peak-to-peak source level noise from 244 to 252 dB re 1µPa @ 1 m for piles from 4.0 to 4.7 m diameter (Parvin *et al* (2006), Nedwell *et al* (2007a)).

Sound Pressure Level

The Sound Pressure Level is normally used to characterise noise and vibration of a continuous nature such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific time period to determine the RMS level of the time varying sound. The SPL can therefore be considered to be a measure of the average unweighted level of the sound over the measurement period.

As an example, small sea going vessels typically produce broadband noise at source SPLs from 170 to 180 dB re 1 µPa @ 1 m (Richardson *et al* (1995)), whereas a supertanker generates source SPLs of typically 198 dB re 1 µPa @ 1 m (Hildebrand (2004)).

Where an SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or piling, it is critical that the time period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting say a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean taken over one second.

Sound Exposure Level

When assessing the noise from transient sources such as blast waves, impact piling or seismic airguns, the issue of the time duration of the pressure wave (highlighted above) is often addressed by measuring the energy flux density of the wave. This form of analysis was used by Bebb and Wright (1953 to 1955), and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long range blast waves on human divers. More recently this form of analysis has been used to develop an interim exposure criterion for assessing the injury range for fish from impact piling operations (Hastings and Popper, 2005; Popper *et al*, 2006) and marine mammals (Southall *et al*, 2007).

The Sound Exposure sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound and the length of time the sound is present in the acoustic environment.

Sound Exposure (SE) is defined by the equation:

eqn. 11.3 $$SE = \int_0^T p^2(t)\, dt$$

Sound Exposure is a proportional to the acoustic energy and has units of Pascal squared seconds (Pa^2s).

To express the Sound Exposure on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy $(P_{ref})^2 T_{ref}$, using 1 µPa for P_{ref} and 1 second for T_{ref}. The Sound Exposure Level (SEL) is then defined by:

eqn. 11.4 $$SEL = 10\ \log_{10}\left(\frac{\int_0^T p^2(t)\,dt}{P_{ref}^2 T_{ref}}\right)$$

By selecting a common reference pressure for the SPL and the SEL (i.e. 1 µPa) for assessments of underwater noise, the SEL and SPL can be compared using the expression:

eqn. 11.5 $$SEL = SPL + 10\ \log_{10} T$$

where the SPL is a measure of the average level of the broadband noise, and the SEL sums the cumulative broadband noise energy.

Therefore, for continuous sounds of duration less than one second, the SEL will be numerically lower than the SPL. For periods greater than one second the SEL will be numerically greater than the SPL. For example, for a sound of 10 seconds duration the SEL will be 10 dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL, and so on.

Impulse

The Impulse (I) is defined as the integral of pressure over time and is given by the equation:

eqn. 11.6 $$I = \int_0^\infty P(t)\,dt$$

where I is the impulse in Pascal-seconds (Pa.s) and P(t) is the acoustic pressure in Pa of the blast wave at time t. Impulse may be thought of as the average pressure of the wave multiplied by its duration. The importance of Impulse is that in many cases a wave acting for a given time will have the same effect as one of twice the pressure acting for half the time. The Impulse of both these waves would be the same.

11A.3 Overview of Hearing in Fish and Marine Mammals

11A.3.1 Introduction

The ways fish react following their exposure to underwater sound relate to the way in which they hear. Variation in the anatomy and physiology of the ears and associated structures in fish is extensive, indicating that different species detect sound in different ways (Popper and Fay (1993)). Furthermore, published data also indicate that, for fish which are sensitive to sound, there is a considerable variation in the hearing abilities both in terms of the minimum levels of sound perceptible and the frequency range over which they can hear (e.g. Hawkins (1981); Lovell *et al* (2005); Popper *et al* (2004); Hastings and Popper (2005); Thomsen *et al* (2006) and Madsen *et al* (2006)). Any assessment of potential impacts on a particular species must therefore take this into account.

This variation appears to be linked to particular physiological adaptations in the distance of the swim bladder to the inner ear. The herring (*Clupea harengus*), for example, has an extension of the swim bladder that terminates within the inner ear (Blaxter *et al* (1981); Popper *et al* (2004)). By comparison, the swim bladder in salmon (*Salmo salar*) is not in close proximity to the ear anatomy and, as such, this species has poorer hearing. Species such as dab (*Limanda limanda*) and plaice (*Pleuronectes platessa*) do not have a swim bladder and thus tend to have a lower hearing ability than many other species of fish.

In general, fish such as the herring (*Clupea harengus*) that are considered hearing specialists are able to perceive sounds in the frequency range 30 Hz to 4 kHz, though at the higher frequencies sensitivity is very low. Threshold levels, the minimum sound level at which a sound can be perceived, for these species are at approximately 75 dB re 1 µPa at frequencies between 30 Hz and 1 kHz.

In comparison, the less sensitive group, termed hearing generalists are only able to perceive sounds between 30 Hz and 400 Hz, with peak sensitivity at 118 dB re 1 µPa over this range. This group includes dab (*Limanda limanda*) and bass (*Dicentrarchus labrax*). The salmon (*Salmo salar*) representing one of the more sensitive hearing generalists and has a threshold level of 95 dB re 1 µPa at 160 Hz. In comparison the dab (*Limanda limanda*), has a threshold level of approximately 90 dB re 1 µPa at frequencies between 30 Hz and 200 Hz.

In contrast to fish, marine mammal species such as the bottlenose dolphin (*Tursiops truncatus*) and harbour porpoise (*Phocoena phocoena*) are sensitive to a very broad bandwidth of sound. Audiogram data for the porpoise indicate that they are responsive at frequencies from 100 Hz to 170 kHz. Peak hearing sensitivity occurs over the frequency range 20 kHz to 150 kHz where, for example, the audiogram for the harbour porpoise (Kastelein *et al* (2002)) indicates that it is able to hear sounds below 40 dB re 1 µPa. This typically corresponds to sea noise levels at these frequencies.

11A.3.2 Introduction to Audiograms

An audiogram is a means of showing a species' sensitivity to sound; it is the variation of hearing threshold level with frequency of sound stimulus. The principle of measuring an audiogram is that sound at a single frequency and a known level is presented to the test subject, typically in the form of a pulsed tone. A uniform, calibrated sound field is created, in air, by means of a loudspeaker or headphones, and in water by underwater projectors. A protocol is required to determine whether the subject has heard the sound stimulus. For humans this is normally in the form of the subject pressing a button if it has detected the sound (a behavioural response). The level of the stimulus is then reduced and the test repeated. This method is generally known as the 'staircase method'. Eventually a level is reached at which the subject can no longer detect the sound, which is therefore below the subject's threshold of hearing. The actual threshold is taken to be the last level that evoked a repeatable response. The measurement is typically repeated at a range of frequencies.

11A.3.3 Audiograms of Underwater Species

When measuring the audiogram of an animal it is necessary to determine the response to the sound by a technique that does not require cognitive compliance. Two principal techniques have been used to determine the audiograms of fish and marine mammal species. These involve either a behavioural response technique, or auditory evoked potential measurements (monitoring of the electrical activity of the animal's hearing mechanism; see, for example, Lovell *et al* (2005)).

Behavioural response techniques rely on training an animal to provide a specific response when an auditory stimulus is heard. This can take the form of a reward-based procedure, usually involving the feeding of an animal, or obtaining a conditioned response by some form of aversion response; for example electric shocks have been used. When the animal hears the sound it is usually required to move into or out of a predetermined area. The disadvantage of this type of technique is that it relies upon the compliance of the subject and can only be used with animals that can easily be trained.

An alternative approach involves direct measurement of the Auditory Evoked Potential (AEP), a bio-electric impulse in the auditory nerves that results from stimulation of the sensory hair cells within the ear. In this approach either subcutaneous or cutaneous electrodes are attached to the animal to measure the response to the sound directly. This latter technique is referred to as the Auditory Brainstem Response (ABR) method and has been used recently by SMRU on harbour seals in The Wash.

Audiograms for a number of species considered in this assessment are given in Figure 11A.1 to Figure 11A.3 below.

Figure 11A.1: Audiograms for Species of Marine Mammal

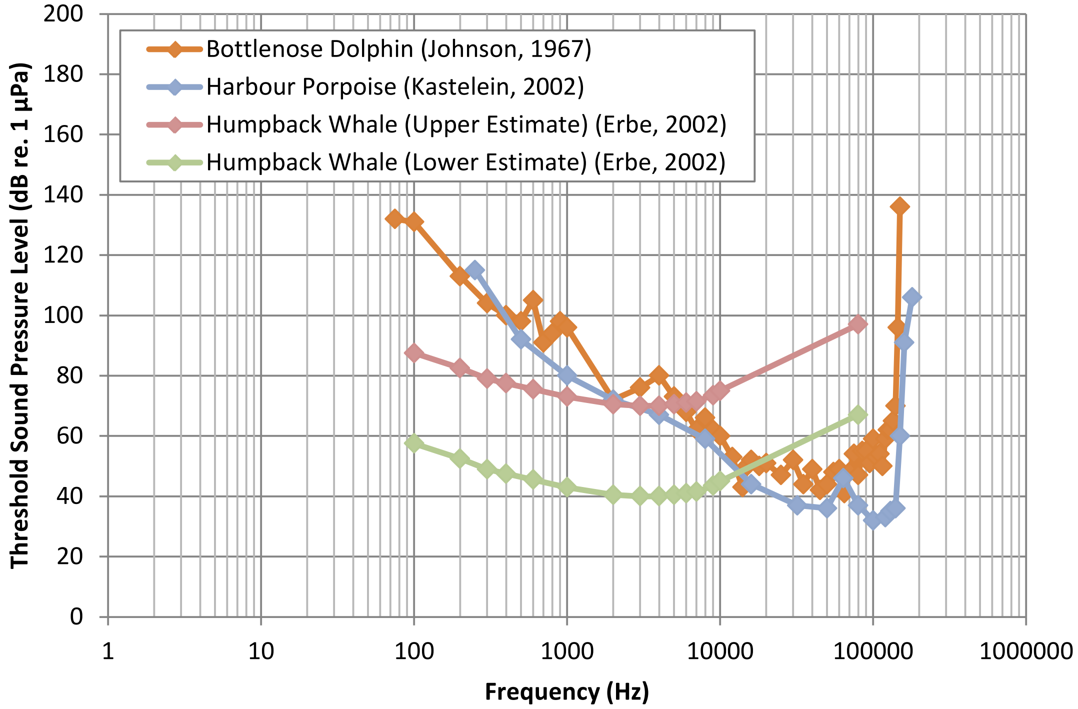


Figure 11A.2: Audiograms for Species of Seal

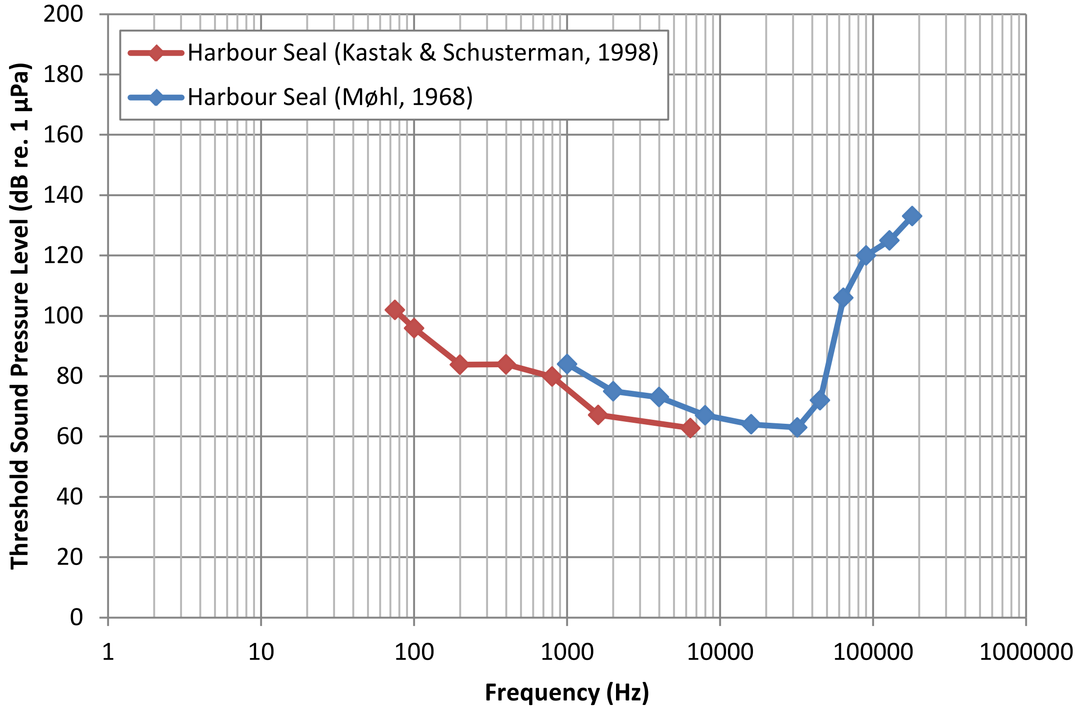
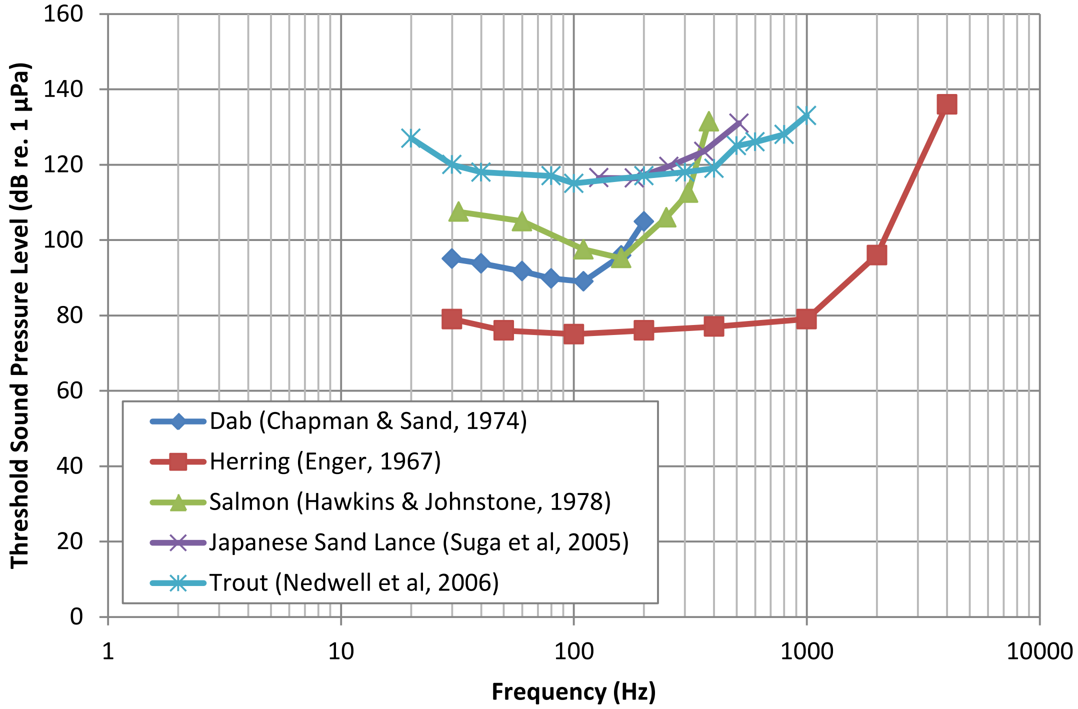


Figure 11A.3: Audiograms for Species of Fish



11A.3.4 A Metric which Takes into Account a Species' Hearing Sensitivity: the dB_{ht}(*Species*)

Measurements of noise are frequently made using an unweighted RMS level of that sound, or its peak pressure. This, however, does not provide an indication of the impact that the sound will have upon a particular fish or marine mammal species. This is of fundamental importance when considering the behavioural response of animals to activities generating underwater noise, as avoidance is associated with the perceived level of loudness and vibration of the sound by the animals. Therefore, the same underwater noise may have a different behavioural impact on different species with different hearing sensitivities.

Where the intention is to estimate these more subtle behavioural or audiological effects of noise, caused by "loudness", hearing ability has to be taken into account and simple metrics based on unweighted measures are inadequate. For instance, it has been determined that in humans a metric incorporating a frequency weighting that parallels the sensitivity of the human ear is required to accurately assess the behavioural effects of noise. The use of frequency weighted measures has been adopted by regulatory bodies worldwide, such as the Health and Safety Executive in the UK, as a method off assessing the impacts of noise in the workplace. The most widely used metric in this case is the dB(A), which incorporates a frequency weighting (the A-weighting), based on the 40-phon human hearing curve.

The dB_{ht}(*Species*) metric (Nedwell *et al* (2007b)) has been developed as a means for quantifying the potential for a behavioural impact of a sound on a species in the underwater environment. It is similar to the dB(A) in that it uses a species' audiogram in its calculation. The dB_{ht}(*Species*) metric can be understood as the level above the minimum audible sound (threshold of hearing) which a species can hear. A level of 0 dB_{ht}(*Species*) represents the minimum audible sound, hence levels below this will not be perceived by the species.

As any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level using this metric. For instance, the same construction event might have a level of 70 dB_{ht}(*Salmo salar*) for a salmon, and 110 dB_{ht}(*Tursiops truncatus*) for a bottlenose dolphin.

The perceived noise levels of sounds measured in dB_{ht}(*Species*) are usually much lower than the unweighted levels, both because the sound will contain frequency components that the species cannot detect, and also because most species that live in the underwater environment have high thresholds of perception (i.e. are relatively insensitive) of sound.

11A.3.5 The M-Weighting Curves for Marine Mammals

Based on the evidence from numerous studies of auditory damage Southall *et al* (2007) proposed a procedure for assessing the possible effects of sound on marine mammals when using the Sound Exposure metric. They proposed that the sound should be filtered into 'generic' frequency ranges or passbands for four groups of mammals; low, mid and high frequency cetaceans, and pinnipeds in water. The four passbands are shown in Figure 11A.4 and Figure 11A.5 below and the bandwidths are tabulated in Table 11A.1. The levels resulting from employing these are termed by the authors 'M-weighted Sound Exposure Levels', and are given in dB re 1 $\mu Pa^2/s$ (M_{lf}) for the low frequency hearers. The 'M_{lf}' is replaced by 'M_{mf}' and 'M_{hf}' for the other cetaceans as appropriate, and 'M_{pw}' for the pinnipeds. The nomenclature is not strictly accurate as the sound is not weighted but rather filtered to remove low and high frequencies. Between these frequencies the sound is unweighted. The distinction is important as most marine animals have highly sloped audiograms, and an unweighted measure may tend to overestimate the effects of sound at low frequencies and underestimate it at high frequencies.

Table 11A.1: Estimated Auditory Bandwidth of Marine Mammals

Marine Mammals	Bandwidth
Low Frequency Cetaceans (e.g. Minke Whale)	7 Hz – 22 kHz
Mid Frequency Cetaceans (e.g. Bottlenose Dolphin)	150 Hz – 160 kHz
High Frequency Cetaceans (e.g. Harbour Porpoise)	200 Hz – 180 kHz
Pinnipeds (in water) (e.g. Harbour Seal)	75 Hz – 75 kHz

Figure 11A.4: The M-Weighting Curves for Cetaceans

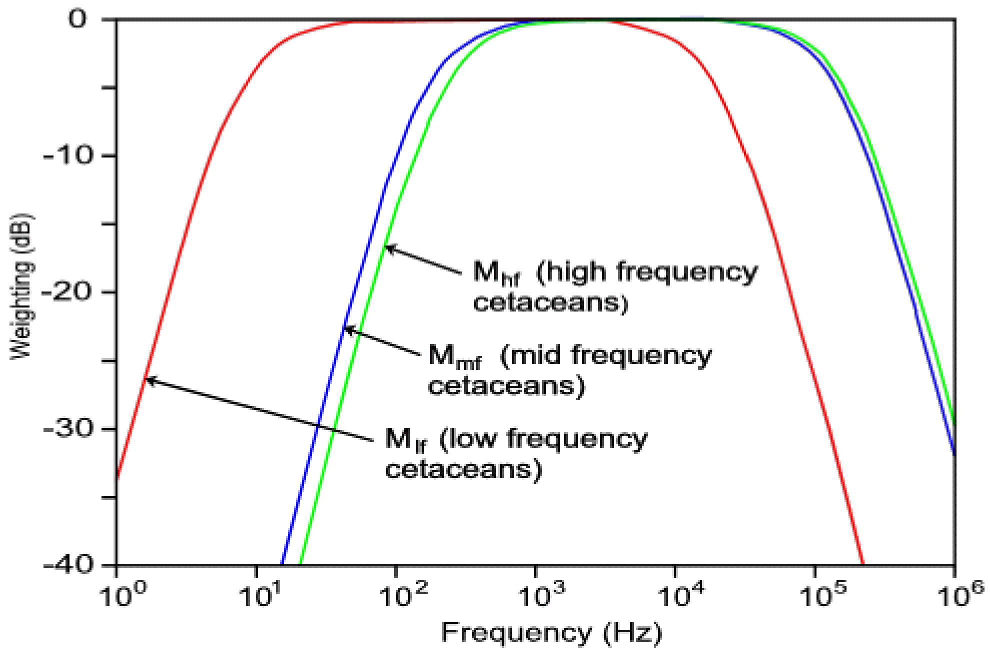
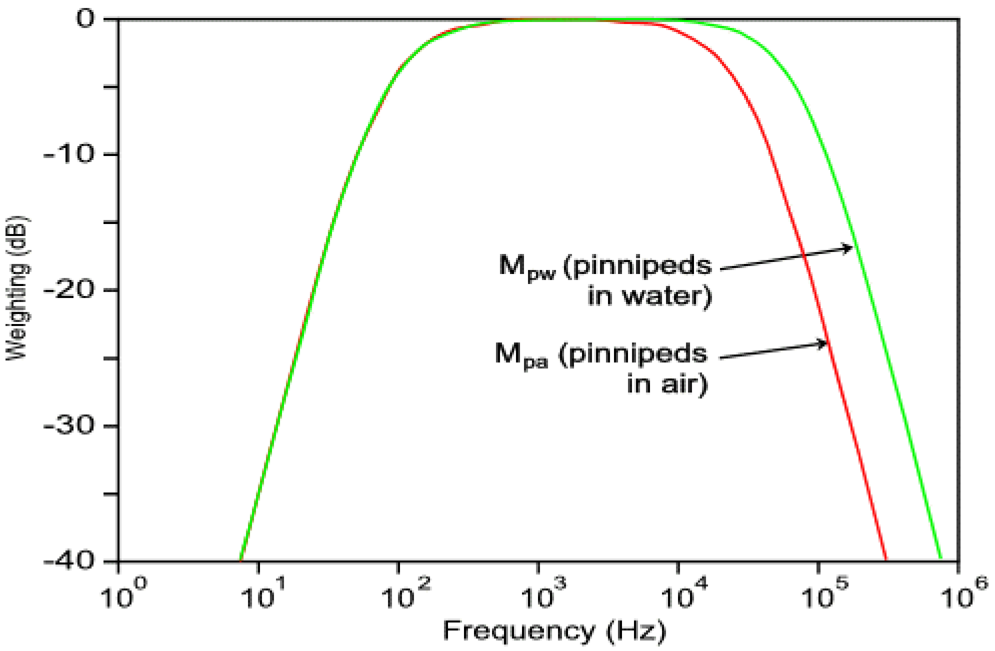


Figure 11A.5: The M-Weighting Curves for Pinnipeds



11A.4 Impact of Underwater Sound on Marine Species: Assessment Criteria

11A.4.1 Introduction

Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments may have an impact on the marine species in the area. The extent to which intense underwater sound might cause an adverse environmental impact on a particular species is dependent upon the level of the incident sound, its frequency content, its duration and/or its repetition rate (see, for example Hastings and Popper (2005)). As a result, scientific interest in the hearing abilities of aquatic animal species has increased.

A review by Popper *et al* (2006) suggests the use of unweighted sound exposure metrics, such as the peak level and the SEL of the noise, to develop interim guidance for estimating the injury range for fish from pile driving operations. Similarly, a review of the effects of underwater noise from offshore wind farms on marine mammals (Madsen *et al* (2006)) discusses the use of frequency weighting of the underwater noise in assessing its impact. The authors comment that the impact of underwater sound on the auditory system is frequency dependent and, ideally, noise levels should (as for humans) be weighted using the defined frequency responses of the auditory system of the animal in question.

The approach that has been adopted in this study has been to use unweighted sound level metrics to define the potential for gross damage, such as fatality, swim bladder rupture or tissue damage, since hearing is not involved in those impacts. The M-weighted Sound Exposure Levels suggested by Southall at al (2007) have been used to predict the potential for permanent threshold shift (PTS) onset in marine mammal species. As described above, these M-weighted SELs do not exist for fish.

To assess ranges at which an aversive response to the piling would be expected, frequency weighted measures of the sound, based on the hearing thresholds of the affected fish and marine mammal species, have been used.

11A.4.2 Lethality and Physical Injury and their Associated Sound Levels

<u>**Introduction**</u>

At the highest level, typically during underwater blast from explosives, sound has the ability to cause injury and, in extreme cases, the death of exposed animals.

Due to the current lack of information on potential lethal and physical injury effects from impact piling, this study has used the data from blast exposures to estimate impact zones. The waveforms from these two noise sources are rather different. The transient pressure wave from an impact piling operation has roughly equal positive and negative pressure amplitude components and a relatively long duration of up to a few hundred milliseconds. By contrast, blast waves have a very high positive pressure peak followed by a much lower amplitude negative wave due to the momentum imparted to the water surrounding the explosive gas bubble. The pressure of a blast wave is normally quantified in terms of the peak level, due to the dominance of the positive peak of the waveform. There is, therefore, a level of uncertainty as to whether a blast wave criterion can be directly applied to a transient waveform arising from an impact piling operation.

Criteria for Assessing Lethality and Physical Injury

The following criteria have been applied in this study for levels of noise likely to cause physical effects on marine biological receptors (Parvin *et al* (2007)), based on data in the studies of Yelverton *et al* (1975), Turnpenny *et al* (1994) and Hastings and Popper (2005):

- lethal effect may occur where peak-to-peak levels exceed 240 dB re 1 µPa, or an impulse of 100 Pa.s; and
- physical injury may occur where peak-to-peak levels exceed 220 dB re 1 µPa, or an impulse of 35 Pa.s.

It should be noted however that for smaller fish sizes of mass 0.01 g Hastings and Popper (2005), and Popper *et al* (2006) recommend an interim "no injury" criteria for fish exposed to impact piling noise of 208 dB re 1 µPa peak level (equivalent to 214 dB re 1 µPa peak-to-peak level) or a Sound Exposure Level of 187 dB re 1 $\mu Pa^2/s$. In view of the very small fish size that this limit addresses, and the fact that it is extrapolated from limited data, it has not been used in the present study. It is considered that the 220 dB re 1 µPa peak-to-peak criterion, which defines the onset of injury, is compatible with the figures above and is suitable to describe the risk of injury to fish species.

11A.4.3 Audiological Injury and its Associated Sound Levels

Introduction

The concept of auditory injury from exposure to noise is well established for airborne sound exposure of humans. At a high enough level of sound, traumatic hearing injury may occur even where the duration of exposure is short. Injury also occurs at lower levels of noise where the duration of exposure is long. In this case the degree of hearing damage depends on both the level of the noise and the duration of exposure to it.

Criteria for the Assessment of Audiological Injury

On the basis of a large body of measurements of fish avoidance of noise (Maes *et al* (2004)), and from re-analysis of marine mammal behavioural response to underwater sound, Nedwell *et al* (2007a) has suggested that the use of a level of 130 dB_{ht}(*Species*), similar to that used for human exposure in air, provides a suitable criterion for predicting the onset of traumatic hearing damage (i.e. where immediate traumatic and irreversible damage occurs), which recognises the varying hearing sensitivity of differing species.

Another set of criteria, based on the evidence from numerous studies of auditory damage, has been proposed by Southall *et al* (2007). That study, however, considers the likelihood of hearing damage (PTS) caused by accumulated noise exposure, rather than occurring as a result of a single event. Their auditory injury criteria, for various groups of marine mammals, are based on Peak Pressure Levels and M-weighted Sound Exposure Levels (dB re 1 µPa^2/s (M)). Only the M-weighted SELs have been used within the marine mammal impact assessments, however, as there is duplication been physical damage (Peak Pressure Level) and the unweighted 220 dB re 1 µPa metric described above. The criteria are given in Table 11A.2. The results of the modelling undertaken have been presented in terms of this SEL metric.

Table 11A.2: Proposed Injury Criteria for Various Marine Mammal Groups

Marine Mammal Group	Sound Type
	Single Pulse and Multiple Pulses
Low Frequency Cetaceans	
Peak Pressure Level	230 dB re 1 µPa
Sound Exposure Level	198 dB re 1 µPa^2/s (M_{lf})
Mid Frequency Cetacaens	
Peak Pressure Level	230 dB re 1 µPa
Sound Exposure Level	198 dB re 1 µPa^2/s (M_{mf})
High Frequency Cetaceans	
Peak Pressure Level	230 dB re 1 µPa
Sound Exposure Level	198 dB re 1 µPa^2/s (M_{hf})
Pinnipeds (in water)	
Peak Pressure Level	218 dB re 1 µPa
Sound Exposure Level	186 dB re 1 µPa^2/s (M_{pw})

The Southall study criteria can be used for both single pulse noise sources and multiple pulse noise sources. This report presents estimated ranges of effect for impact pile driving using Southall *et al*'s multiple impact SEL criteria. The modelling presented within this appendix has been carried out by assuming a swim speed and starting range for the animals and hence calculating the accumulated exposure as the animal moves away from the noise source. The M-weighted Sound Exposure Level at each range as the animal moves is calculated using the Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model (see Section 11A.4.5).

These figures suggest that pinnipeds are significantly more sensitive to potential PTS onset than cetaceans. However, recent research by Thompson and Hastie (2011) suggests that pinnipeds may respond to similar noise levels to cetaceans and thus the 186 dB Sound Exposure Level to induce PTS onset in pinnipeds may be overly conservative. However, until agreement is reached with stakeholders, the 186 dB criteria has been used to model noise doses sufficient to induce PTS onset in pinnipeds within *Chapter 14: Marine Mammals*.

In order to allow the visual contextualisation of the M-Weighted SEL criteria between the 198 and 186 dB re 1 µPa^2, modelling using the M-Weighted SEL criteria has been carried out over several increments between the two criteria for all cetaceans and pinnipeds. More detail on this is provided within Appendix 14B. Marine Mammals Piling Impact Assessment

Single strike' SEL noise modelling outputs were also provided to inform the modelling of the exposure of marine mammals to noise. Although not represented graphically within this appendix, outputs were provided to SMRU Ltd for all marine mammal species to populate the SAFESIMM model. SAFESIMM was then run by SMRU Ltd to predict potential numbers of individual animals that could be exposed to sufficient noise to induce PTS onset for all the scenarios described below in Table 11.18 and 11.19. Further details of this are provided in *Chapter 14: Marine Mammals* of the Environmental Statement.

11A.4.4 Behavioural Impacts and their Associated Sound Levels

Introduction

At levels lower than those that cause physical injury or permanent threshold shift noise may nevertheless have important behavioural effects on a species. The most significant effect is avoidance of the insonified area (the region within which noise from the source of interest is above ambient underwater noise levels). The significance of the effect requires an understanding of its consequences. For instance, avoidance may be significant if it impedes the migration of a species. However, in other cases the movement of species from one area to another may be of no consequence.

Strong avoidance behaviour appears to be associated with a sensation of "unbearable loudness". Hence, in order to judge the potential of a noise to cause avoidance, it is necessary to be able to ascertain the perception of the sound by the species, i.e. how loud the sound appears to individuals of that species. Individuals of species having poor hearing may perceive the level as low, and hence not react to the noise, whereas a species that is sensitive may find the level unbearably loud and react by swimming away. Therefore, of key importance in the process is an understanding of the hearing ability of the species that may be affected.

Criteria for Assessing Behavioural Response

If the level of sound is sufficiently high on the dB_{ht}(*Species*) scale, it is likely that an avoidance reaction will occur. The response from a species will be probabilistic in nature (e.g. at 75 dB_{ht}(*Species*)) one individual from a species may react, whereas another individual may not: the metric indicates the probability of an individual reacting), and may also vary depending upon the type of signal. A level of 0 dB_{ht}(*Species*) represents a sound that is at the hearing threshold for that species and is, therefore, at a level at which sound will start to be 'heard'. At this and lower perceived sound levels no response occurs as the receptor cannot hear the sound.

Currently, on the basis of a large body of measurements of fish avoidance of noise (Maes *et al* (2004)), and from re-analysis of marine mammal behavioural response to underwater sound, the following assessment criteria were published by the Department of Business, Enterprise and Regulatory Reform (BERR) (Nedwell *et al* (2007b)) to assess the potential impact of the underwater noise on marine species (Table 11A.3):

Table 11A.3: Assessment Criteria Used to Assess the Potential Impact of Underwater Noise on Marine Species

Level in dB_{ht}(*Species*)	Effect
75 and above	Significant avoidance reaction by in excess of 50% of individuals.
90 and above	Strong avoidance reaction by virtually all individuals.
Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.

It should be reiterated that the above values are only indicative of probabilities and can be influenced by a number of factors which could make a species more or less inclined to react. While the above table is considered to be appropriate to enable an impact assessment to be undertaken for fish (see Chapter 13: Natural Fish and Shellfish), further work has been undertaken to refine potential displacement of marine mammals as a consequence of construction related noise (see Chapter 14: Marine Mammals).

11A.4.5 Species Considered in this Assessment

Table 11A.4 below presents a summary of the species of interest to this study, along with some information regarding the availability of data concerning their sensitivity to underwater sound.

Table 11A.4: Summary of Marine Species Relevant to the Firth of Forth Region

Species	Audiogram available?	Surrogate used	Comments	Reference
Harbour Seal	Yes	-	No single audiogram dataset covering full audiometric range available. Data from two studies used.	Kastak and Schusterman (1998); Møhl (1968)
Grey seal	Partial – only upper frequencies	Harbour seal	No single audiogram dataset covering full audiometric range available. Data from two studies used.	Kastak and Schusterman (1998); Mohl (1968)
Harbour Porpoise	Yes	-	-	Kastelein (2002)

Species	Audiogram available?	Surrogate used	Comments	Reference
Minke Whale	No	None	Used a theoretical audiogram of the Humpback Whale as a surrogate.	Erbe (2002)
Bottlenose Dolphin	Yes	-	-	Johnson (1967)
White-beaked dolphin	No	Bottlenose dolphin	Audiogram data suggest bottlenose dolphin are most sensitive dolphin species to sound so may provide conservative indication of impacts.	Johnson (1967)
Herring	Yes	-	-	Enger (1967)
Plaice	No	Dab	Dab is the most sensitive species of flatfish with an available audiogram and therefore will provide a conservative indication of impacts on plaice.	Chapman and Sand (1974)
Salmon	Yes	-	-	Hawkins and Johnstone (1978)
Sandeels	No	Japanese Sand Lance	-	Suga *et al* (2005)
Trout	Yes	-	-	Nedwell *et al* (2006)
Cod	Yes	-	-	Chapman and Hawkins
Sandeel	No	Japanese sand lance	-	Suga *et al.* (2005)

Audiograms for the species listed in the table, where available, have been presented previously in Figure 11A.1 to Figure 11A.3.

The Use of Surrogates

In Table 11A.4 above it is shown that, for example, there is no known audiogram for the plaice and the audiogram for the dab has been used when making calculations for the plaice.

The dab is in the family Pleuronectidae. The audiogram for the dab (*Limanda limanda*), (from Chapman and Sand (1974)) is presented in Figure 11A.3, converted to units of sound pressure by Popper and Fay (1993). As can be seen in the figure, dab detect frequencies from below 30 Hz up to around 200 Hz, with sensitivities of around 90 dB re 1 µPa at 110 Hz. This indicates that dab have relatively poor hearing sensitivity compared to clupeids and therefore, in common with plaice and lemon sole, they may be classed as hearing generalists.

The plaice, too, is in the family Pleuronectidae. Because of the physical similarities between the place and dab species, the dab has been used as a surrogate for the plaice. Other surrogate species have been chosen due to similar family connections.

11A.5 Underwater Noise Modelling Methodology

11A.5.1 Modelling of Sound Propagation

Sound levels underwater are usually quantified in terms of the Source Level, which is a measure of the sound energy released by the source, and the Transmission Loss, which is a measure of the rate at which that energy is lost. Sound propagation is thus described by the simple equation:

eqn. 11.7 $$L(r) = SL - TL$$

where L(r) is the Sound Pressure Level at distance r from a source in metres, SL is the source level, which may be thought of as the “effective” level of sound at one metre from the source, and TL is the transmission loss (Kinsler *et al* (1982)). Transmission Loss (TL) is defined as:

eqn. 11.8 $$TL = 20 \ \log_{10}\left(\frac{P_0}{P_R}\right)$$

where P_0 is the effective acoustic pressure at a point at 1 m from the source, as per the Source Level above, and P_R is the acoustic pressure at range R away from it. The Transmission Loss is therefore a measure of the rate at which the sound energy decreases with increasing range.

Frequently a simplification is made by assuming that the Transmission Loss may be approximated due to spreading and absorption losses such that:

eqn. 11.9 $$TL = N \ \log_{10}(r) + \alpha$$

where r is the distance from the source in metres, N is the constant factor for attenuation due to geometric spreading, and α is a factor for the absorption of sound in water and at boundaries in dB/m (Urick (1983); Kinsler *et al* (1982)).

For instance, spherical spreading gives a value of N=20. By combining eqn. 11.7 and eqn. 11.8 the level of sound at any point in the water space can be estimated from the expression:

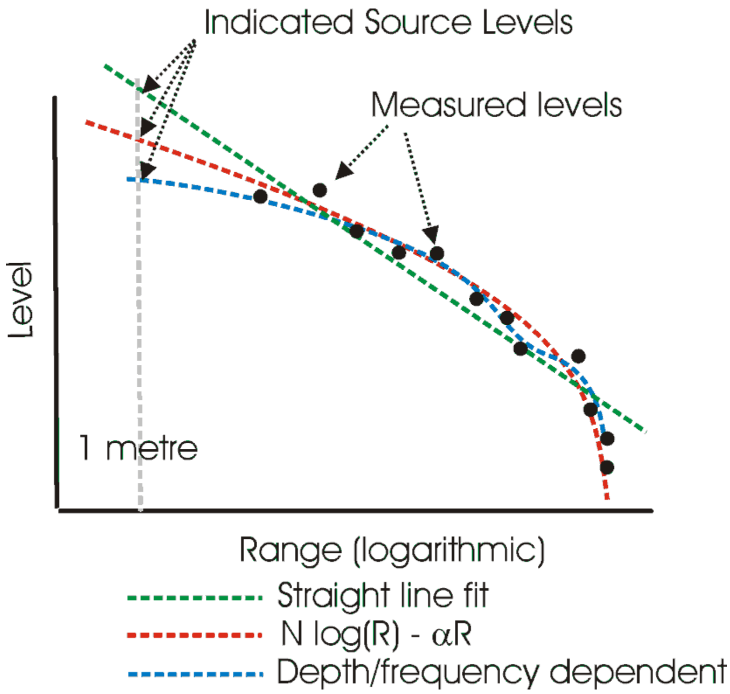
eqn. 11.10 $$L(r) = SL - N \ \log_{10}(r) - \alpha(r)$$

Over short distances absorption effects have little influence on the transmission loss and can often be ignored. The Source Level itself may be quoted in any physical quantity, e.g. a piling source may be expressed as having a “peak-to-peak Source Level of 200 dB re 1 µPa @ 1 m”.

This simple but convenient formulation ignores the practical difficulty of estimating the source level. Since the measurements are usually made at some distance from the source (in the acoustic far field) and extrapolated back to the source, the true level at 1 metre may actually be very different from the source level used in these equations.

It is often not realised that, since the value of Source Level quoted for a particular source is obtained by extrapolation, the value will depend on the model that is used to perform the extrapolation. Figure 11A.6 illustrates this point. The diagram illustrates a set of measurements made of the noise from piling. In the simplest case, in order to draw conclusions about the data, a straight-line model may be fitted to it — this is shown in the figure by the green line. Such a model effectively assumes that the noise level, NL, behaves as $L(r) = SL – N\log_{10}(r)$. This, however, will generally over-estimate the levels for low and high ranges, since it ignores the effects of absorption of the noise. The improved model including absorption, $L(r) = SL – N\log_{10}(r) – \alpha r$ (red line in the figure), gives a better fit to the data, and indeed this simple form is usually adequate for modelling sound propagation from a source in deep water of roughly constant depth. However, in the case of the shallow coastal waters where wind farms are typically situated, the depth may rapidly fluctuate between shallow water of a few metres and deeper water of tens of metres or more. In these circumstances the Transmission Loss becomes a more complex function of depth that depends heavily on the local bathymetry and hence must be calculated using a more sophisticated model, such as INSPIRE; the acoustic model used in this study. Where these effects are included, as illustrated by the blue line in the figure, yet another value of Source Level may result. Typically, using a more sophisticated model will result in lower levels of noise predicted near to the pile.

Figure 11A.6: Differences in Source Level Estimation Based on Various Models



Source Levels can also be expressed in the dB_{ht}(*Species*) metric, e.g. 170 dB_{ht} (*Clupea harengus*) @ 1 m. This approach is very convenient, as it allows the relative significance of various sources to be easily compared for different species or pile sizes. The levels can be analysed using INSPIRE model to determine impact ranges for fish and marine mammal species.

11A.5.2 Rank Ordering of Noise-sources

The SPEAR (Sound Propagation Estimation and Ranking) model has been developed using a substantial database of noise sources, and provides an indication of the typical levels of underwater noise generated by wind farm construction and operational related activities. The model allows the significance of a wide range of sources of underwater noise to be rank-ordered for a wide range of fish and marine animals.

In this instance, the SPEAR model has been used to make predictions for a number of representative scenarios for the various activities related to offshore wind farms. A summary of the various considerations and relating to construction and operation of the wind farm are given in the table below.

Summary of Noise Scenarios for SPEAR Modelling

Table 11A.5 provides a summary of the various parameters that have been inputted into the SPEAR model to account for the various scenarios considered during construction and operation of the wind farm. Detailed information relating to the exact time that some of the activities will be carried out, for example the duration a vessel will be on site or how long dredging may take, is not available at this stage. It has therefore been necessary to take a very worst estimation in terms of noise generation.

Table 11A.5: Summary of Parameters Taken into Account in the SPEAR Modelling

Activity	Parameters used for SPEAR modelling
Dredging	Suction dredger required for any seabed preparation for cables and foundations.
Drilling	Potentially required for pin pile installation.
Piling	Maximum 4.2 hours (worst case) or 2.1 hours (most likely) driving per pile. 2438 mm diameter piles. 4 piles (worst case) or 2 piles (most likely) installed per day per location. Up to two piling vessels operating in the area simultaneously.
Operational noise	Proposed 213 turbines, each spaced 820 m apart. Assumed 24 hours a day for operational wind turbines.
Cable laying	Required during inter-array and export cable installation.
Rock placement (including concrete mattressing)	Required during inter-array and export cable installation. Part of the scour protection for foundations.
Trenching (including Jetting and Rock Cutting)	Required during inter-array and export cable installation.
Vessel Noise	Large vessels required for piling and wind turbine generator (WTG) installation Other large and medium sized vessels will be on site to carry out construction jobs and anchor handling

<u>Results of SPEAR Modelling</u>

The SPEAR model outputs an approximate figure that represents the area of ocean which is rendered potentially unusable by a species as a result of a particular activity when using the Nedwell *et al* (2007b) criteria provided in Table 11A.3 above. The results in Figures 11A.7 to 11A.15 show 90 dB_{ht}(*Species*) impact ranges, which illustrate the differences between all the species for a single activity and the differences between noise sources for single species of interest.

Figure 11A.7: Spatial Extent of 90 dB$_{ht}$(*species*) Range from Piling a 2438 mm Diameter Pile, on Various Species of Importance

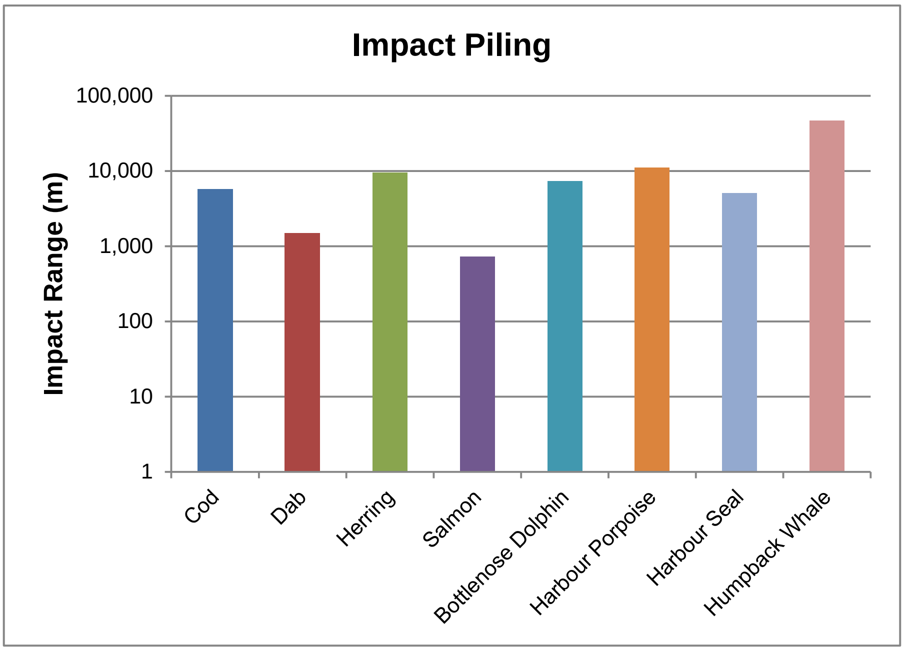


Figure 11A.8: Spatial Extent of the 90 dB$_{ht}$(cod) Range of Various Offshore Activities

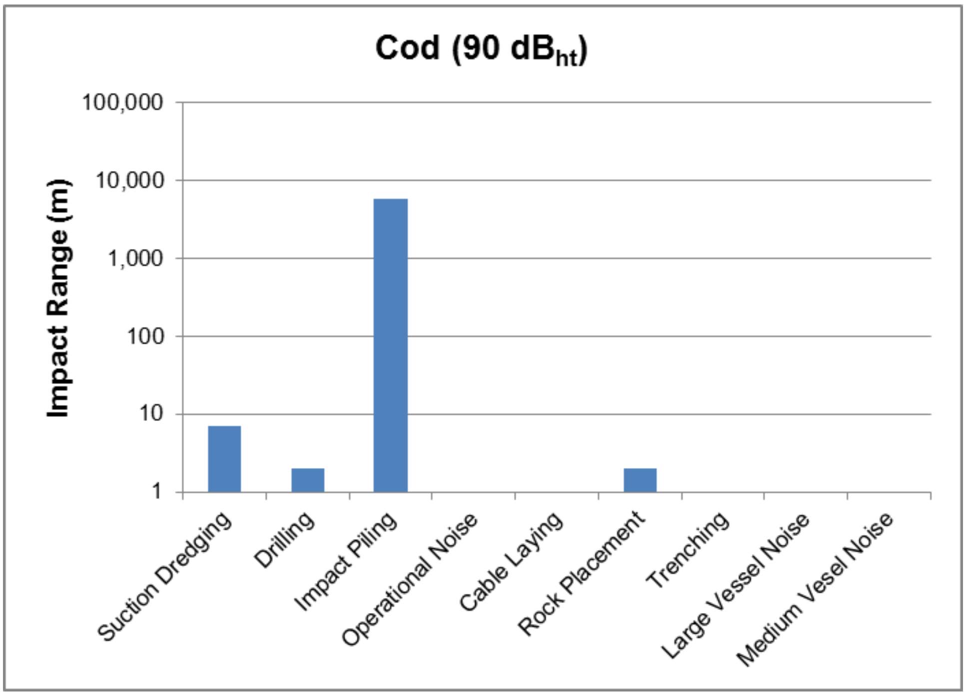


Figure 11A.9: Spatial Extent of the 90 dB_{ht}(dab) Range of Various Offshore Activities

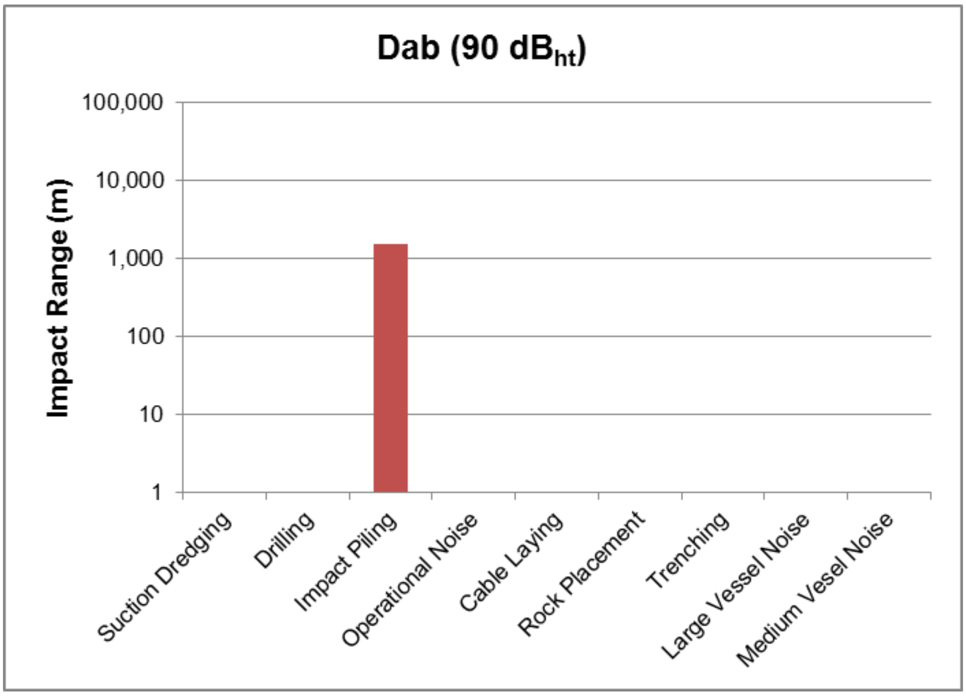


Figure 11A.10: Spatial Extent of the 90 dB_{ht}(herring) Range of Various Offshore Activities

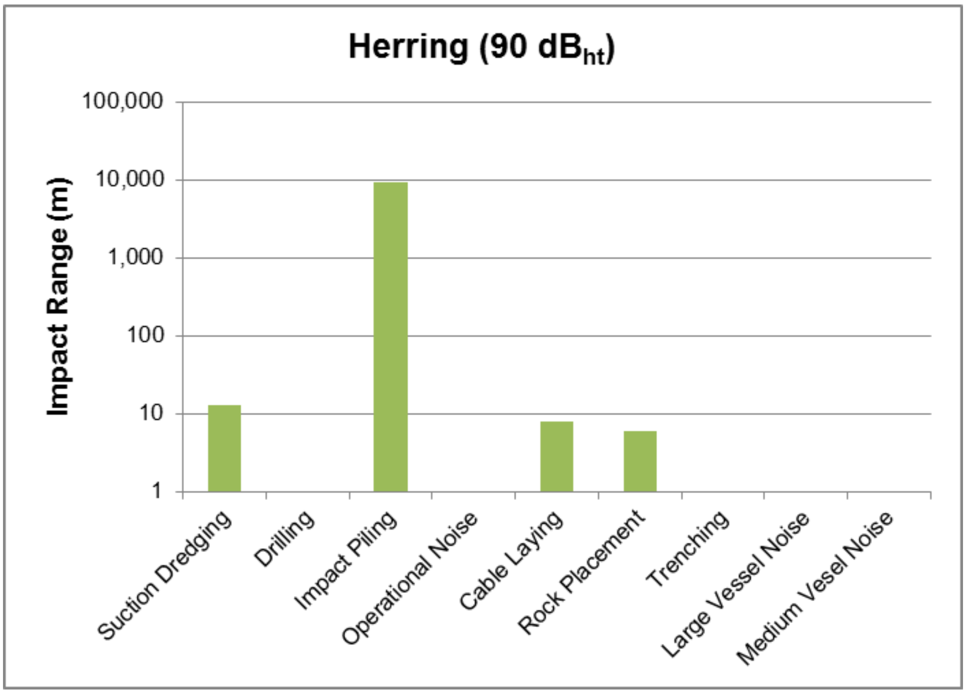


Figure 11A.11: Spatial Extent of the 90 dB_{ht}(salmon) Range of Various Offshore

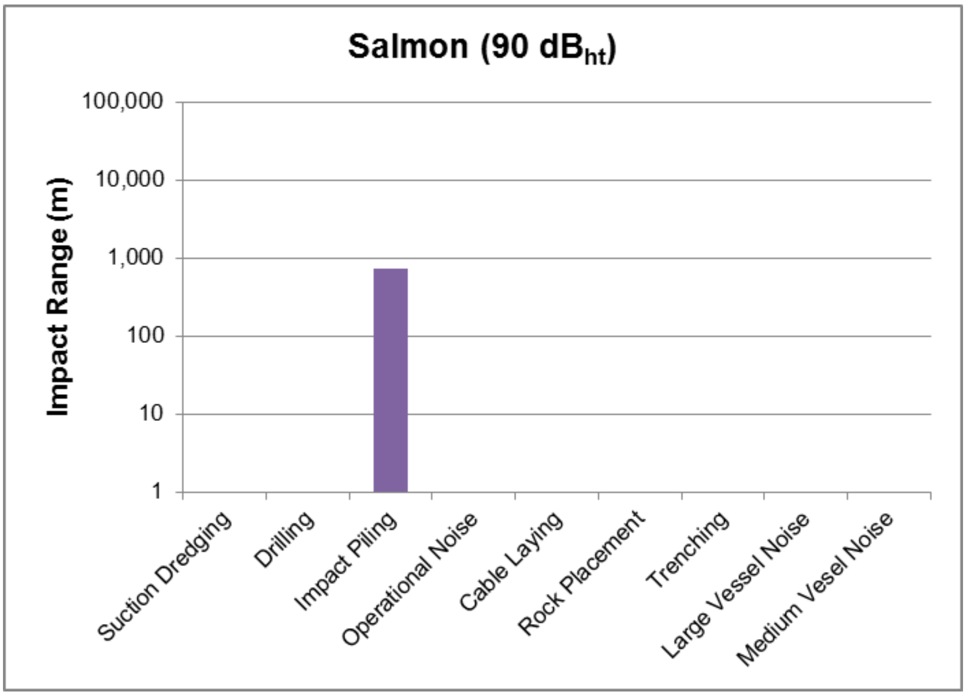


Figure 11A.12: Spatial Extent of the 90 dB_{ht}(bottlenose dolphin) Range of Various Offshore Activities

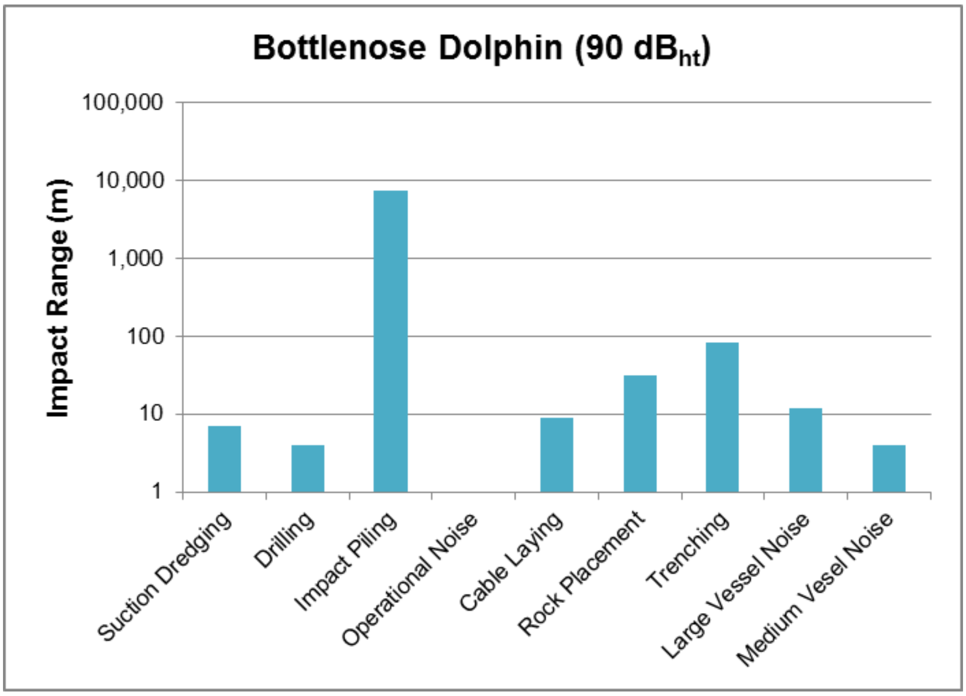


Figure 11A.13: Spatial Extent of the 90 dB_{ht}(harbour porpoise) Range of Various Offshore Activities

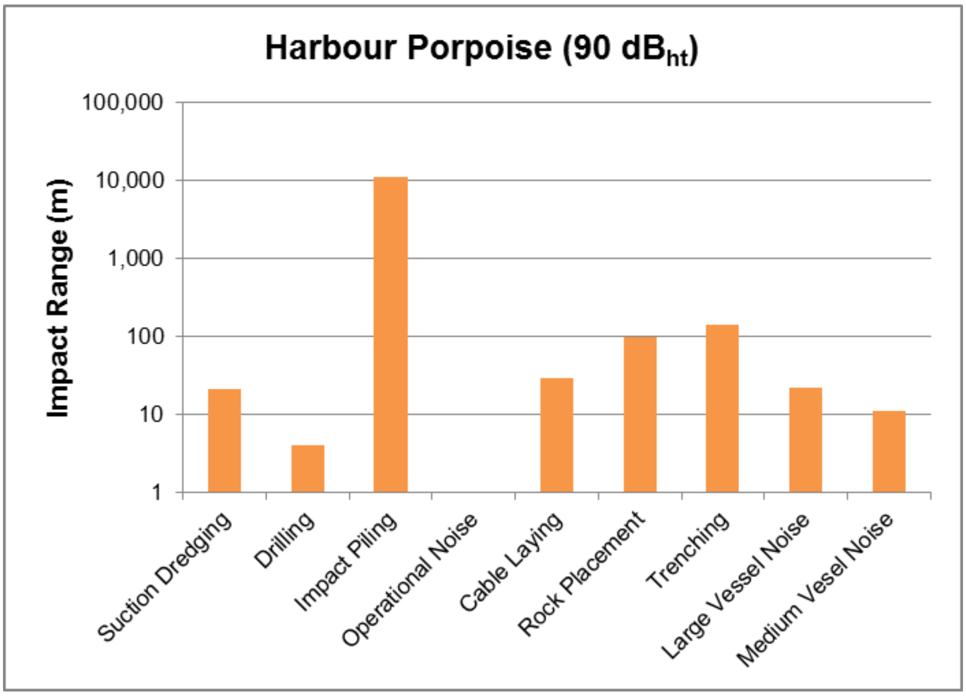


Figure 11A.14: Spatial Extent of the 90 dB_{ht}(harbour seal) Range of Various Offshore Activities

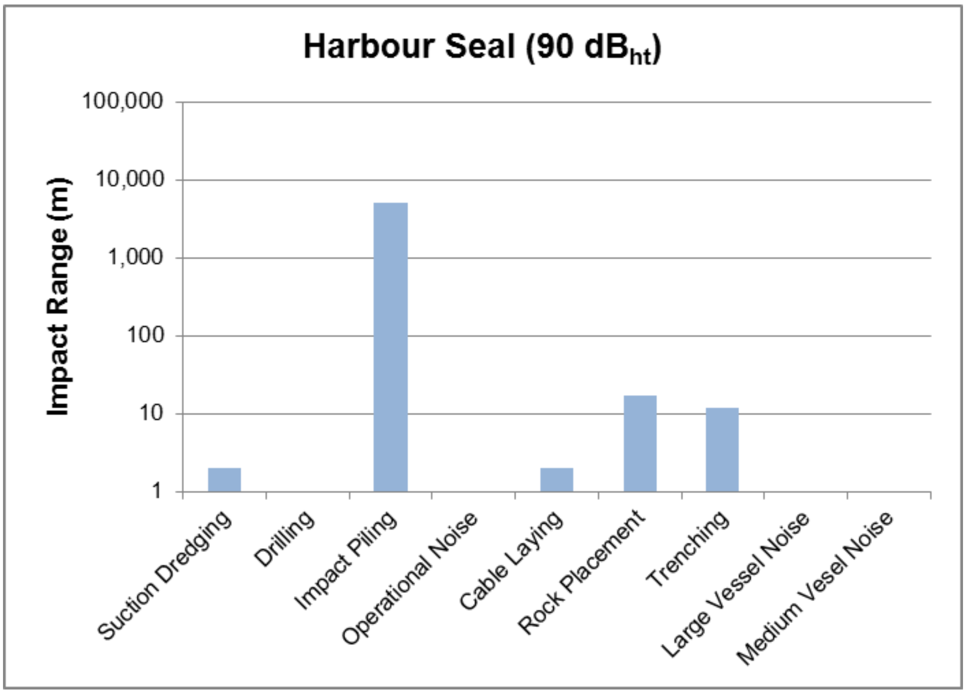
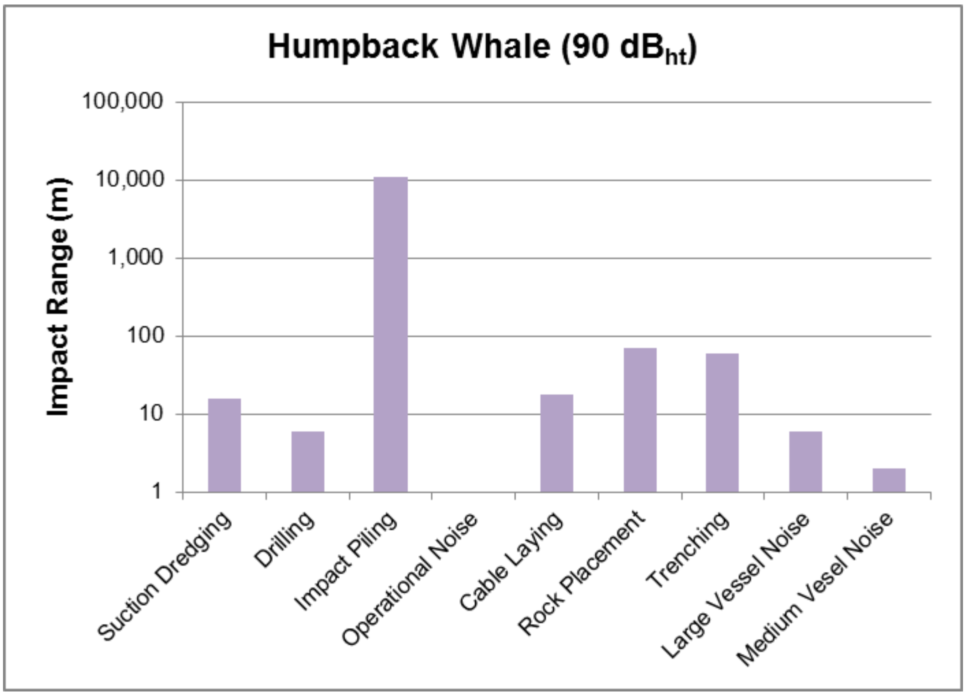


Figure 11A.15: Spatial Extent of the 90 dB_{ht}(humpback whale) Range of Various Offshore Activities (as a Surrogate for Minke Whale)



11A.5.3 Detailed Modelling of Impact Piling

From the SPEAR modelling it can be seen that impact piling is likely to generate the highest levels of underwater noise out of all the considered noise sources. It is therefore important to make an accurate estimate of the perceived noise resulting from piling activities so that its impact can be comprehensively assessed by marine ecologists. There are a variety of acoustic models for the estimation of underwater noise propagation in coastal and offshore regions, mainly developed as a result of military interests. However, the authors are not aware of any underwater broadband noise propagation models suitable for the much shallower environments typical of offshore wind farm construction, or for the highly impulsive time histories encountered from impact piling. In these environments and with these source types there is a greater capacity for underwater sound to be affected by absorptive processes in the seabed, resulting in propagation losses which typically increase with frequency but decrease with depth.

The INSPIRE model has been developed specifically to model the propagation of impulsive broadband underwater noise in shallow waters. It uses a combined geometric and energy flow/hysteresis loss model to conservatively predict propagation in relatively shallow coastal water environments, and has been tested against measurements from a large number of other offshore wind farm piling operations.

Transmission losses are calculated by the model on a fully range and depth dependent basis. The model imports electronic bathymetry data as a primary input to allow to calculate the transmission losses along transects extending from the pile location. For this study bathymetry data supplied by SeaZone (License number: 102011.006), with a detailed 30 m^2

resolution grid has been used. Other simple physical data are also supplied as input to the model. The model is able to provide a wide range of outputs, including the peak pressure, impulse, dB_{ht}, SEL, of the noise.

As well as calculating the SEL variation with range, the model incorporates a "fleeing animal receptor” extension which enables the noise dose an animal receives as it is moves away from a piling operation to be calculated. This feature permits the calculation of the nearest distance from a pile from which an animal must start moving away such that its noise dose just reaches the criterion value at the cessation of the piling operation. The term “fleeing” is a term used synonymously with “moving away” and the actual modelled speed of movement is stated separately.

In the following section, the INSPIRE model was used to assess in detail the ranges at which fatality, physical injury, auditory injury and behavioural avoidance had the potential to occur for a range of animal species.

11A.6 Predicted Impacts – Piling

11A.6.1 Details of Cases Modelled

The INSPIRE model has been used to make predictions for two broad categories of conditions:

- Predictions of ranges, from a single pile position, at which specified noise criteria are met. One criterion is the dB_{ht}(*Species*) value. The second is the M-Weighted SEL value, for low, mid and high-frequency cetaceans, and pinnipeds in water. The third is the dB re 1 µPa (peak to peak) values to model the potential for death and physical injury. For the SEL calculations a ‘fleeing animal’ case has been assumed, where the model calculates the distance from the pile at which the animal must start to move away such that, at the cessation of the piling operation, its noise dose will just reach, but not exceed, the criterion value. After refinement of the modelled behaviour of the fleeing animal when it reaches the coast (animal to remain in shallow water and continue to be exposed to noise rather than fleeing along the coast line), stakeholder agreement was obtained to use fleeing animal models only and that no modelling of noise doses for animals not fleeing in response was required; and
- Predictions of ranges, for a number of piles being driven simultaneously, to allow an estimation of the envelope of the area within which specified criteria are exceeded. Again the criteria are the dB_{ht}(*Species*) value, the four M-Weighted SEL and the dB re 1 µPa values, with the SEL modelling using the fleeing animal case, as described above.

The estimated ranges for the unweighted levels of 240 and 220 dB re 1 µPa (peak to peak), at which lethality and physical injury respectively occur, due to piling a 2438 mm pile using the maximum blow energy of 1080 kJ, are given in Table 11A.6 (parameters are provided in Chapter 11, Table 11.3). It should be noted that impact ranges for which these levels could potentially occur are very small and where mitigation measures are to be used, for example soft start and ramp up of blow energy as detailed in the JNCC guidelines, these levels should be reduced to such a range that no fatality or physical injury will occur.

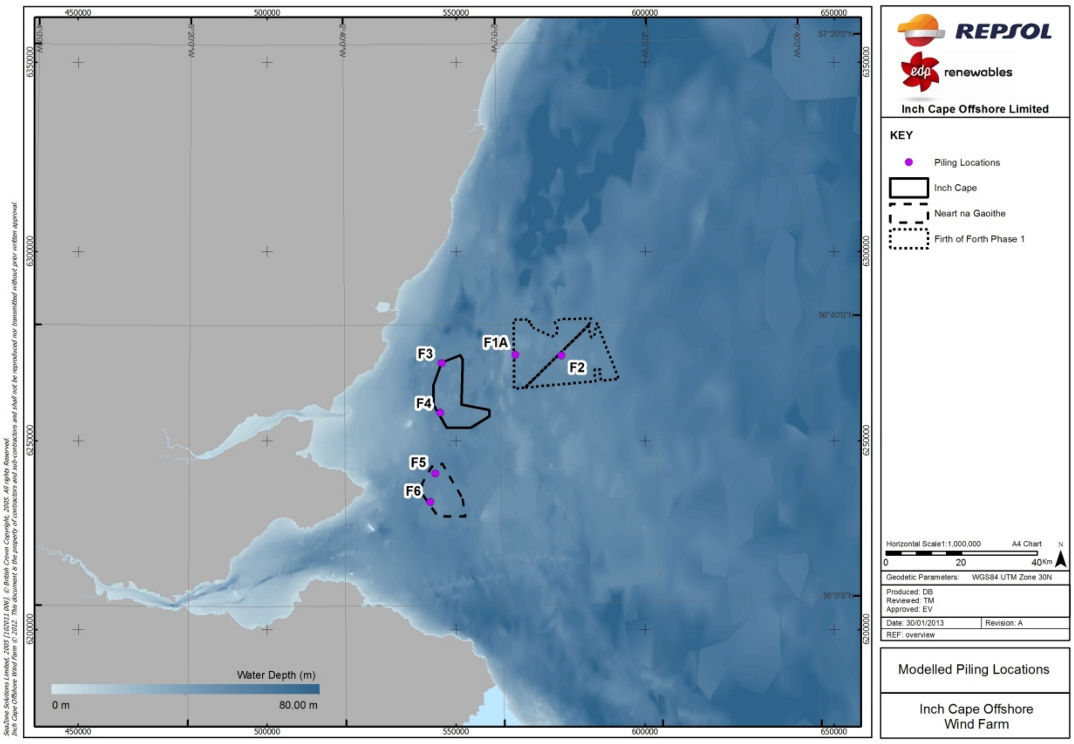
Table 11A.6: Maximum Ranges to Which Lethality and Physical Injury Could Occur

Unweighted level	Range (m)
240 dB re. 1 µPa (Lethality)	6
220 dB re. 1 µPa (Physical Injury)	40

Figure 11A.16 is a sketch map of the Forth and Tay Offshore Wind Developers Group (FTOWDG) area where the Inch Cape (IC), Neart na Gaoithe (NnG), and Firth of Forth Phase 1 (FoF) offshore wind farm sites are located. Modelling has been undertaken at NnG and Firth of Forth Phase 1 to consider the potential cumulative effects associated with concurrent piling at these sites along with the Inch Cape OWF. Figure 11A.16 shows the boundaries of the wind farm sites and the locations of the piling for which modelling has been undertaken. A summary of the cases considered is given in Tables 11A.12 to 11A.19.

It is worth noting that where piling occurs in multiple locations simultaneously, the greatest exposures will tend to occur in the geographical centre of the piling. For this reason, in the cumulative noise modelling outputs the contours will appear to focus on the development area.

Figure 11A.16: Map Showing the Locations Where Piling has been Modelled



For the six fish and six marine mammal species considered, calculations were made for a single pile being driven at either Location F3 or Location F4, within the development area, with a focus on marine species that could be most affected by the wind farm construction at those sites. Location F3 lies nearest to the coastline and was used in modelling to reflect the known distribution of bottlenose dolphin along the coast in shallower waters as well as for migratory fish species. Location F4 was used in modelling to best capture potential impacts on seal haul out sites. Details of the modelled locations for single piling events to focus on the most sensitive for each location is are provided in Table 11A.7. Further information on marine mammal and fish receptors and their distribution is provided in Chapter 13 (Natural Fish and Shellfish) and Chapter 14 (Marine Mammals).

Table 11A.7: Species Modelled at Inch Cape Locations

Location F3	Location F4
Bottlenose dolphin, humpback whale (as a surrogate for minke whale), harbour porpoise, Dab (surrogate for plaice), herring, salmon, sandeel (surrogate for sand lance), trout and cod.	Harbour seal (and as a surrogate for grey seal), bottlenose dolphin (as a surrogate for white-beaked dolphin)

For the low, mid, and high frequency cetacean and pinniped in water, calculations were made for two piles being driven sequentially in a 24 hour period in the most likely case and for four piles being driven sequentially in a 24 hour period in the worst case. More detailed information is provided in Table 11.3 and section 11.3 of Chapter 11: Underwater Noise. The soft start, ramp up, and maximum blow energies used for installing piles at the Inch Cape OWF are presented, along with those for NnG and Firth of Forth Phase 1 in Table 11A.8 to Table 11A.11.

Table 11A.8: Most Likely Predicted Profile Required to Drive a 2438 mm Diameter Pin Pile at the Inch Cape Site

Impact Energy (kJ)	Number of strikes	Duration (s)
180	360	1200
480	2400	1200
720	1200	600
1080	9000	4500

Table 11A.9: Worst Case Predicted Profile Required to Drive a 2438 mm Diameter Pin Pile at the Inch Cape Site

Impact Energy (kJ)	Number of strikes	Duration (s)
180	360	1200
480	2400	1200
720	1200	600
1080	24120	12060

Table 11A.10: Most Likely Predicted Piling Profile Required to Drive a 2500 mm Diameter Pin Pile at the Neart na Gaoithe Site

Impact Energy (kJ)	Number of strikes	Duration (s)
240	600	1200
996	5400	10800

Table 11A.11: Most Likely Predicted Piling Profile Required to Drive a 2000 mm Diameter Pin Pile at the Firth of Phase 1 Site

Impact Energy (kJ)	Number of Strikes	Duration (s)
180	223	298
420	527	702
660	478	637
900	217	289

Table 11A.12: Summary of Conditions Modelled for Piles Driven at Location F3

Number of Piles per Location	Species / Filter	Results shown	Figure No.
n/a	Dab (as a surrogate for Plaice)	90 and 75 dB_{ht} contours	Figure 11A.17
n/a	Herring	90 and 75 dB_{ht} contours	Figure 11A.18
n/a	Salmon	90 and 75 dB_{ht} contours	Figure 11A.19
n/a	Sand Lance (as a surrogate for Sandeel)	90 and 75 dB_{ht} contours	Figure 11A.20

Number of Piles per Location	Species / Filter	Results shown	Figure No.
n/a	Trout	90 and 75 dB_{ht} contours	Figure 11A.21
n/a	Cod	90 and 75 dB_{ht} contours	Figure 11A.21A
n/a	Bottlenose Dolphin	90 and 75 dB_{ht} contours	Figure 11A.22
n/a	Humpback Whale (as a surrogate for Minke Whale)	90 and 75 dB_{ht} contours	Figure 11A.23
n/a	Harbour porpoise	90 and 75 dBht contours	Figure 11A.24
2 piles sequentially	Low Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{lf}) for an animal fleeing at 1.5 m/s	Figure 11A.25
2 piles sequentially	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.26
2 piles sequentially	High Frequency Cetacean	198, 193, 188 and 186 dB re 1 µPa2s (Mhf) for an animal fleeing at 1.5 m/s	Figure 11A.27
4 piles sequentially	Low Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{lf}) for an animal fleeing at 1.5 m/s	Figure 11A.28
4 piles sequentially	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.29
4 piles sequentially	High Frequency Cetacean	198, 193, 188 and 186 dB re 1 µPa2s (Mhf) for an animal fleeing at 1.5 m/s	Figure 11A.30

Figure 11A.17: Location F3: 90 and 75 dB_{ht} Contours for Dab (as a Surrogate for Plaice)

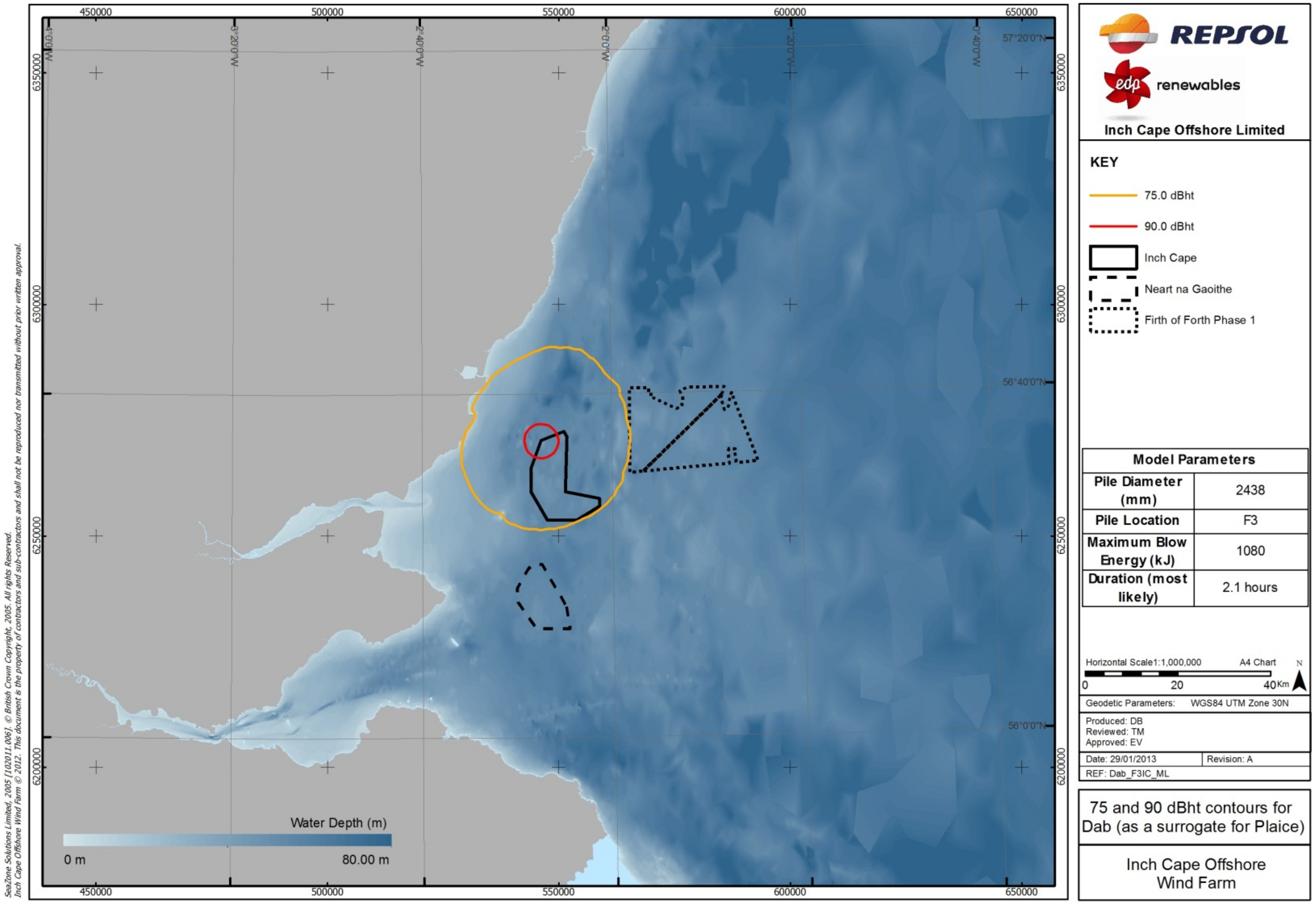


Figure 11A.18: Location F3: 90 and 75 dB_{ht} Contours for Herring

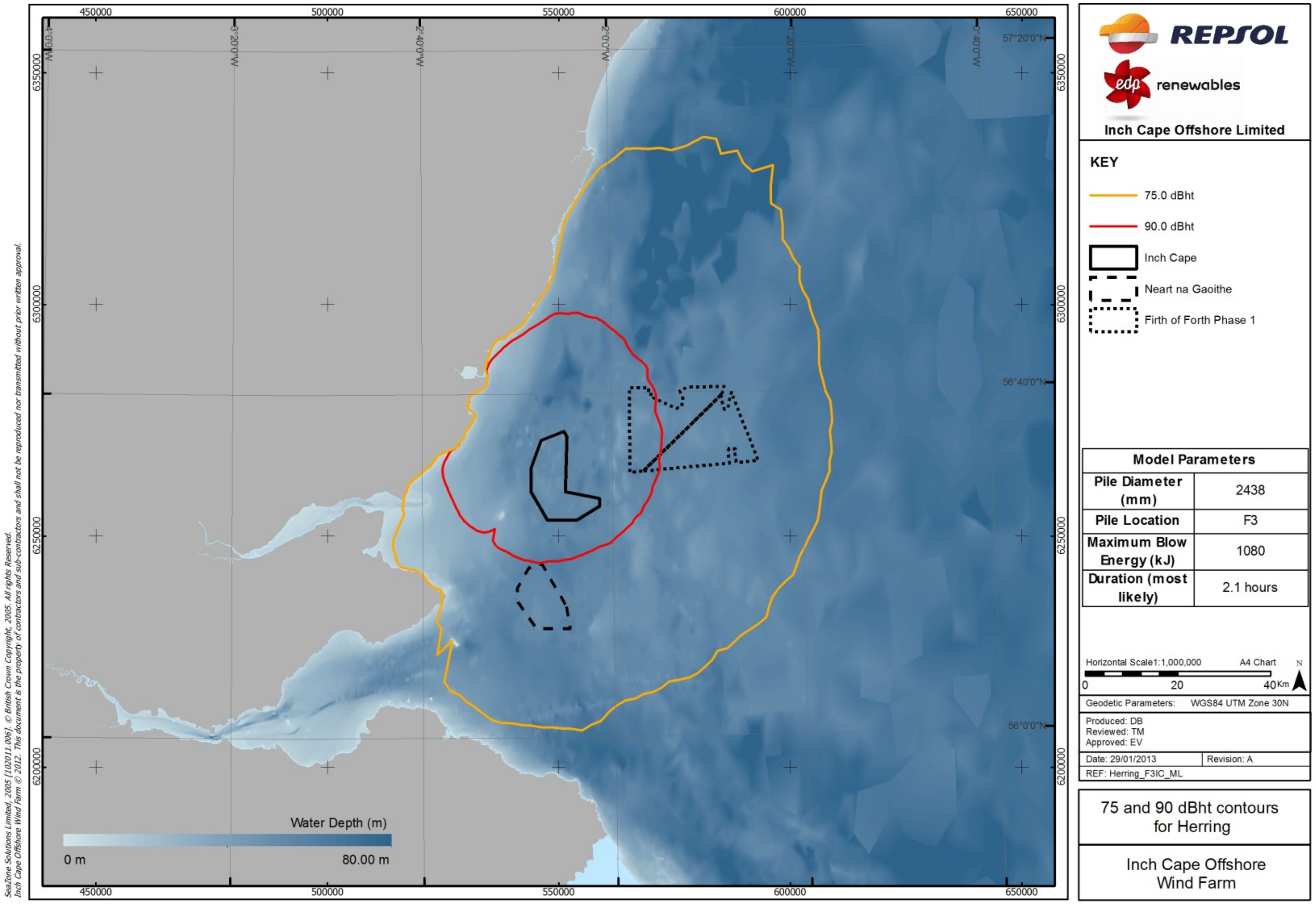


Figure 11A.19: Location F3: 90 and 75 dB_{ht} Contours for Salmon

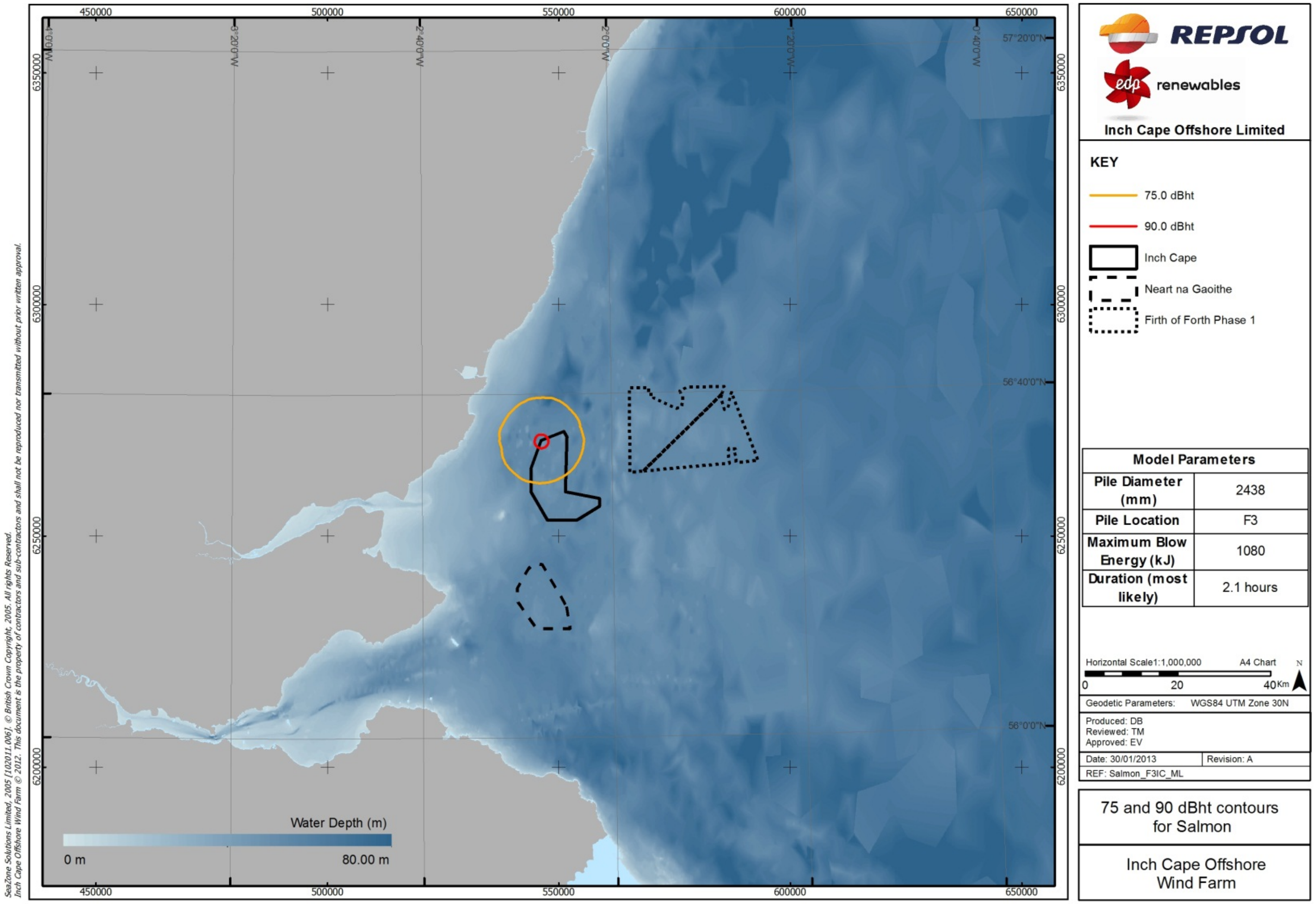


Figure 11A.20: Location F3: 90 and 75 dB_{ht} Contours for Sand Lance (as a Surrogate for Sandeel)

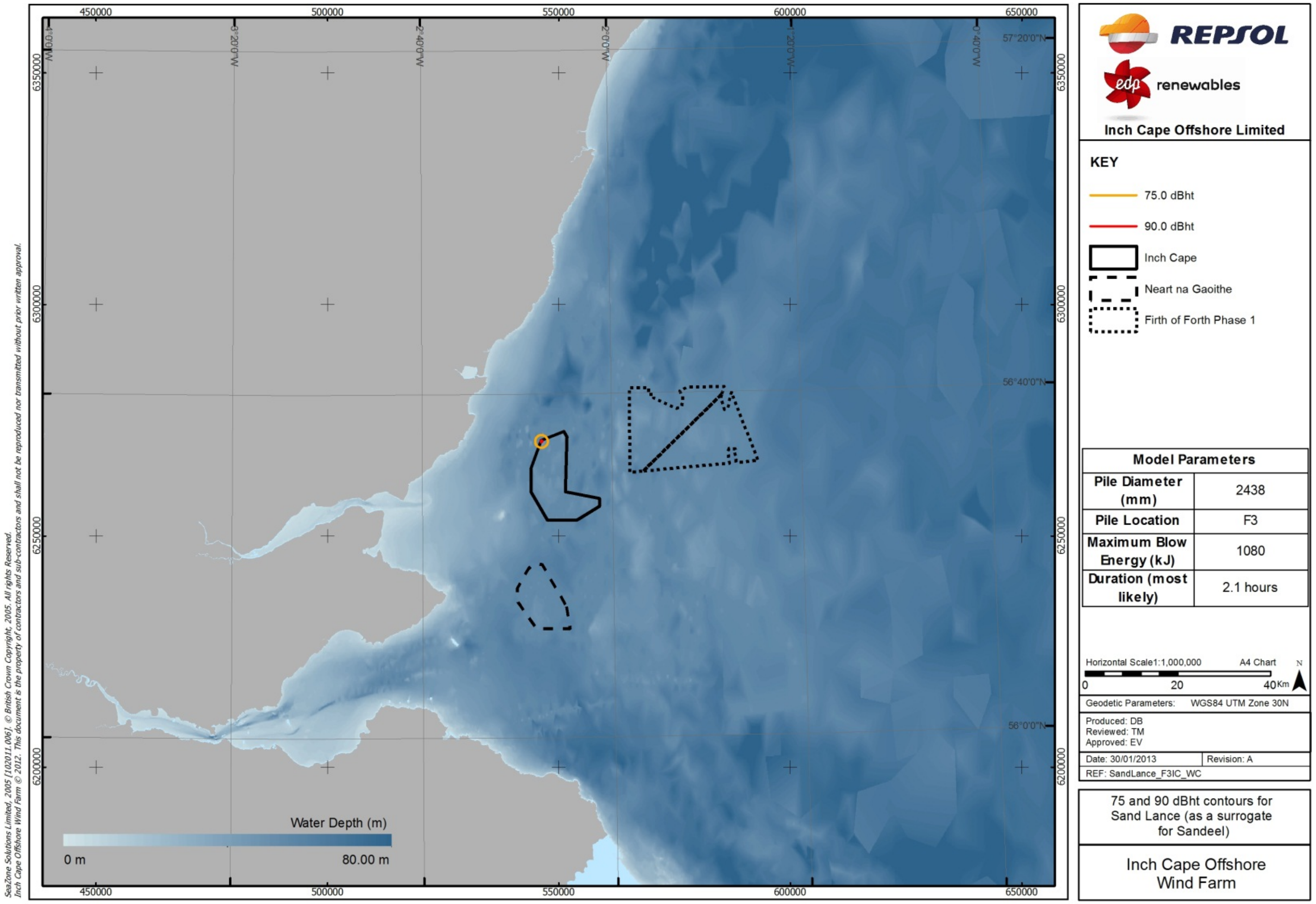


Figure 11A.21: Location F3: 90 and 75 dB$_{ht}$ Contours for Trout

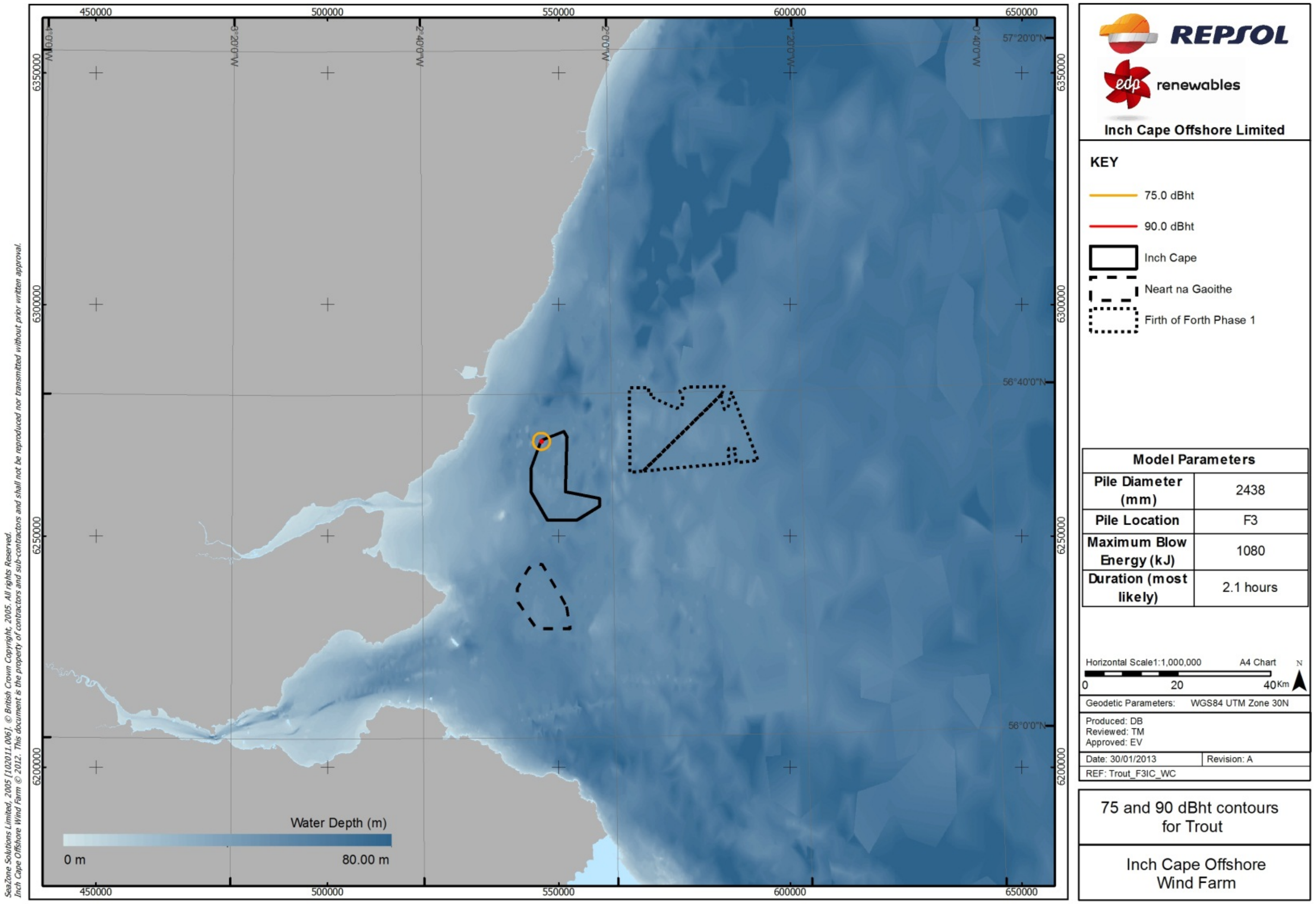


Figure 11A.21A: Location F3: 90 and 75 dB_{ht} Contours for Cod

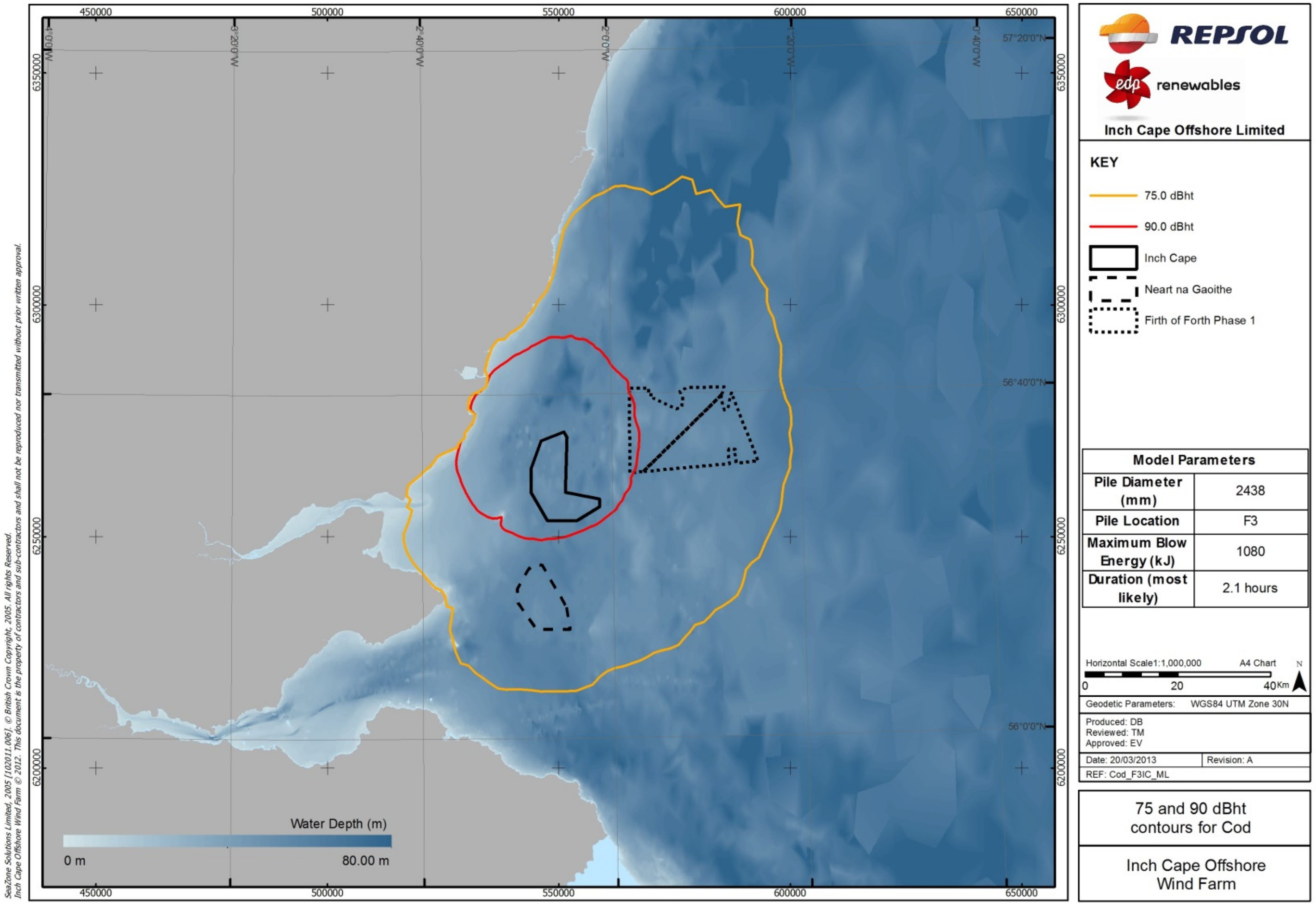


Figure 11A.22: Location F3: 90 and 75 dB_{ht} Contours for Bottlenose Dolphin

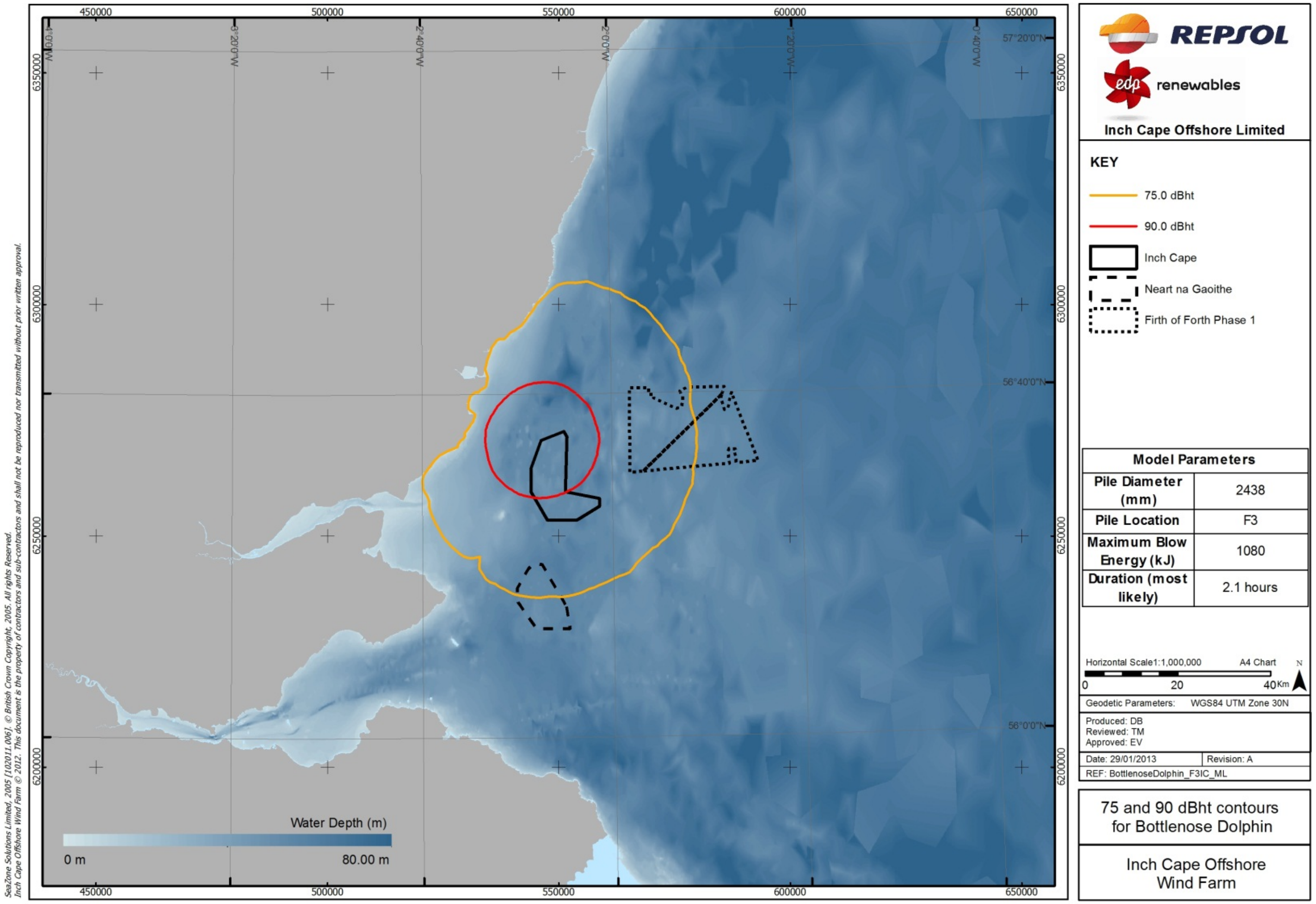


Figure 11A.23: Location F3: 90 and 75 dB_{ht} Contours for Humpback Whale (as a Surrogate for Minke Whale)

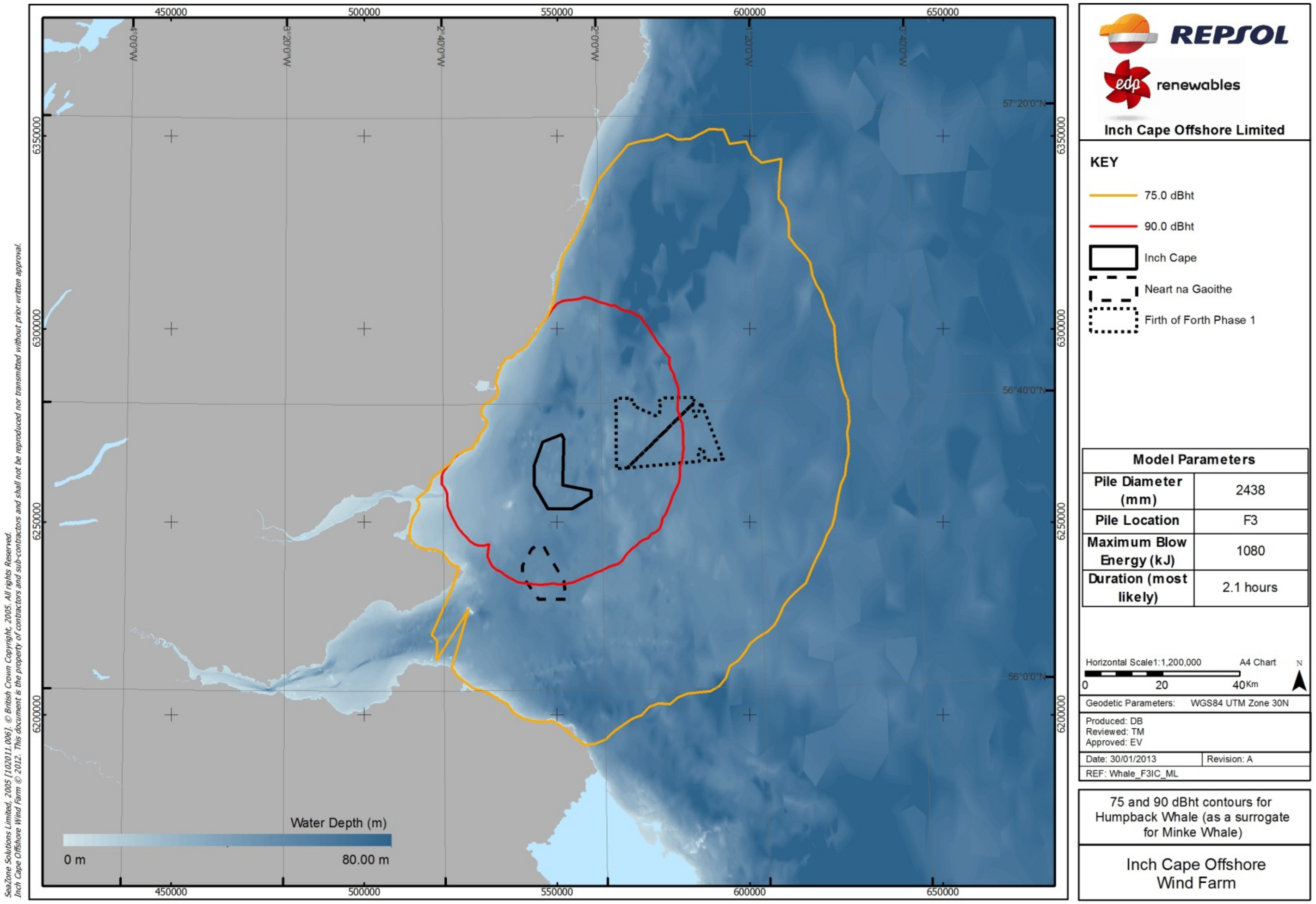


Figure 11A.24: Location F3: 90 and 75 dB_{ht} Contours for Harbour Porpoise

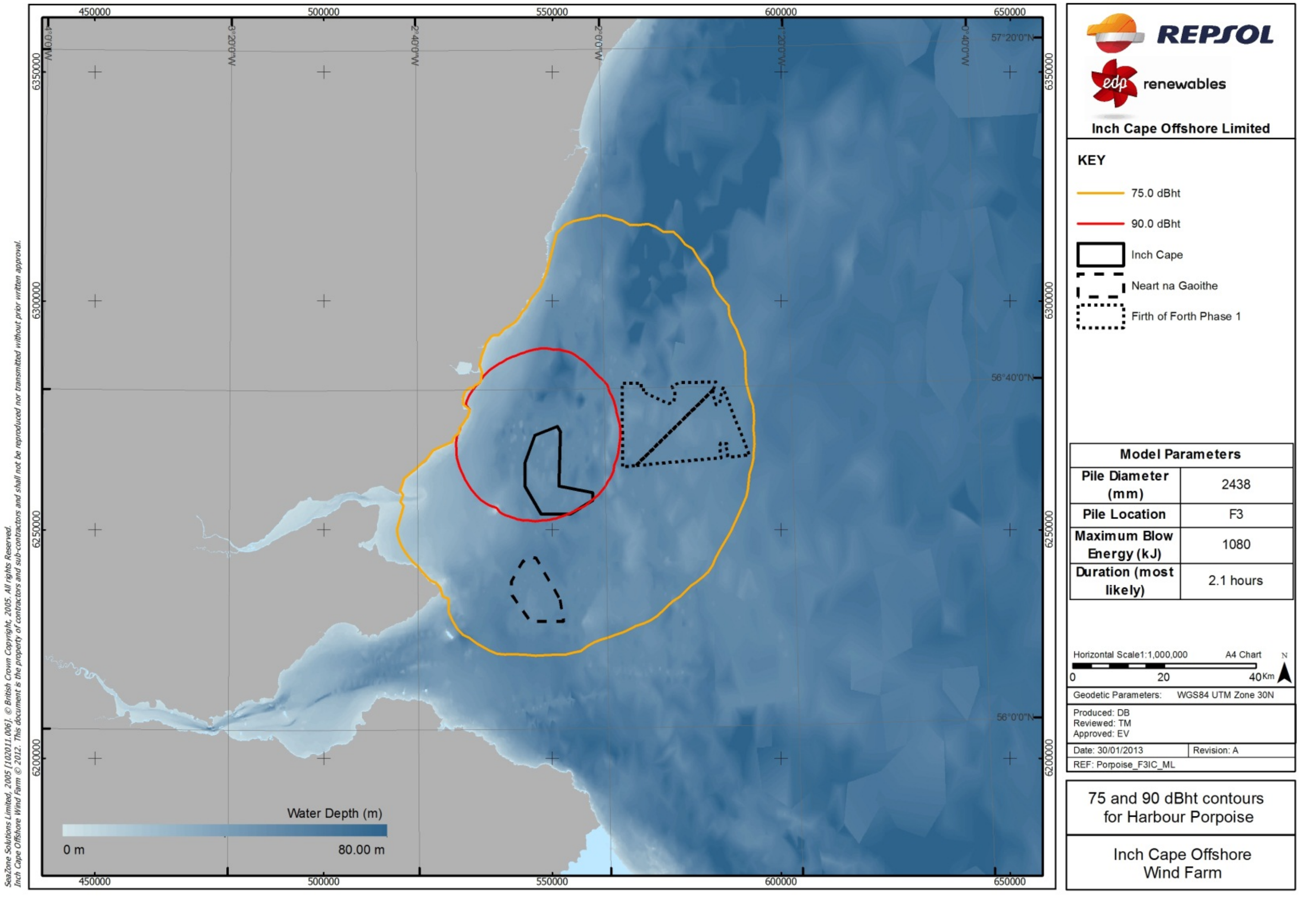


Figure 11A.25: Location F3: Starting Loci for Fleeing Low Frequency Cetaceans; Two Piles Driven Sequentially

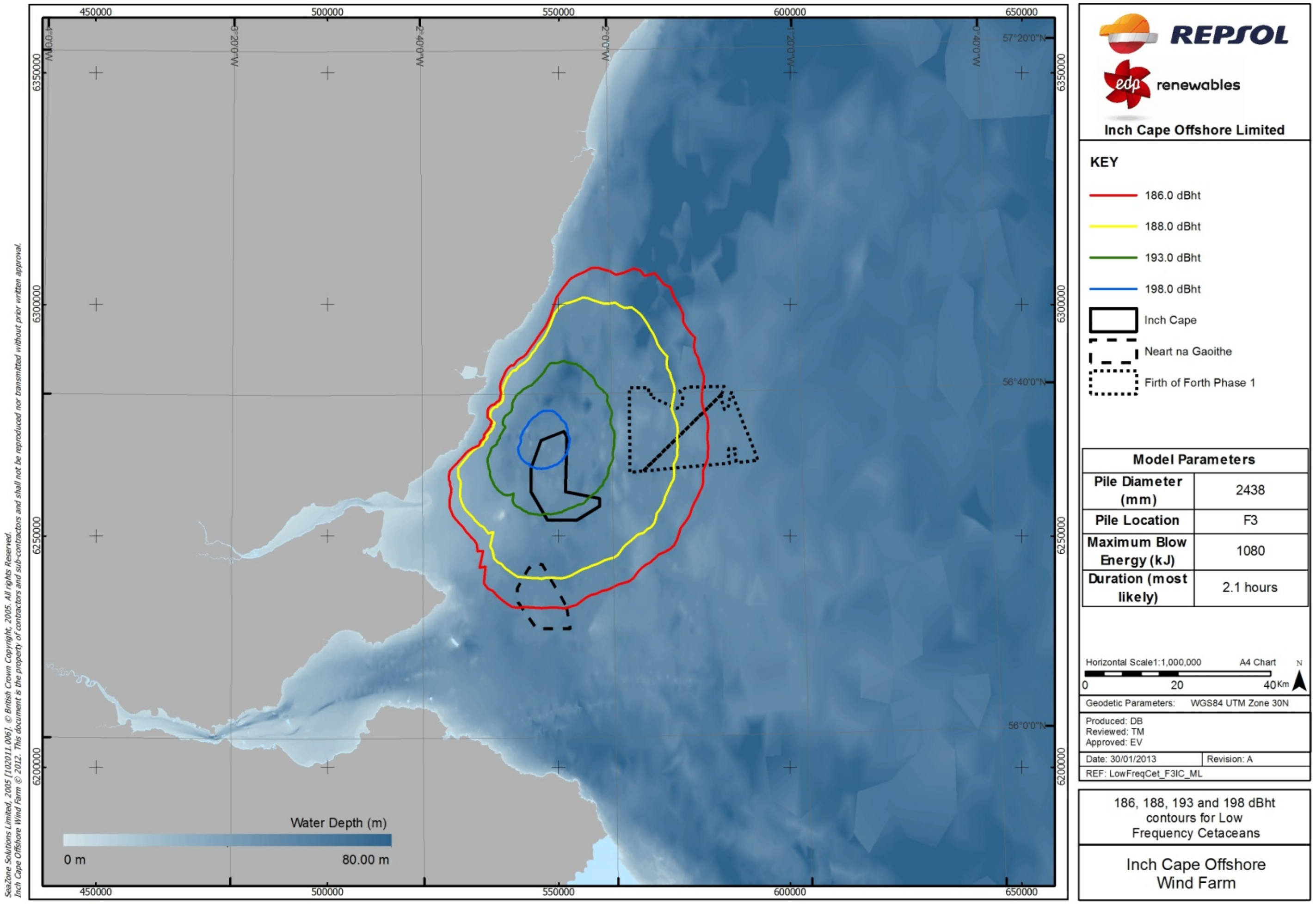


Figure 11A.26: Location F3: Starting Loci for Fleeing Mid Frequency Cetaceans; Two Piles Driven Sequentially

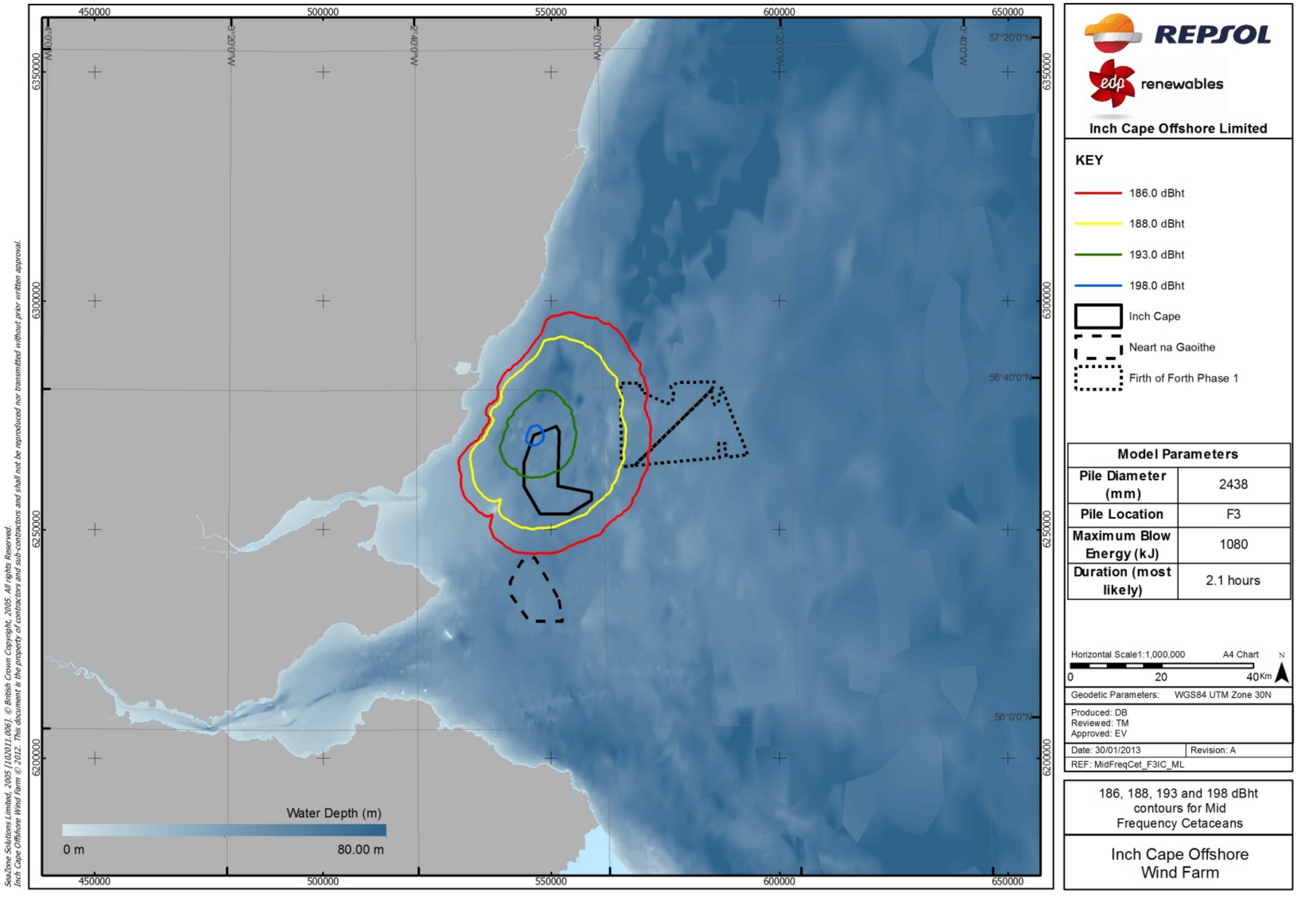


Figure 11A.27: Location F3: Starting Loci for Fleeing High Frequency Cetaceans; Two Piles Driven Sequentially

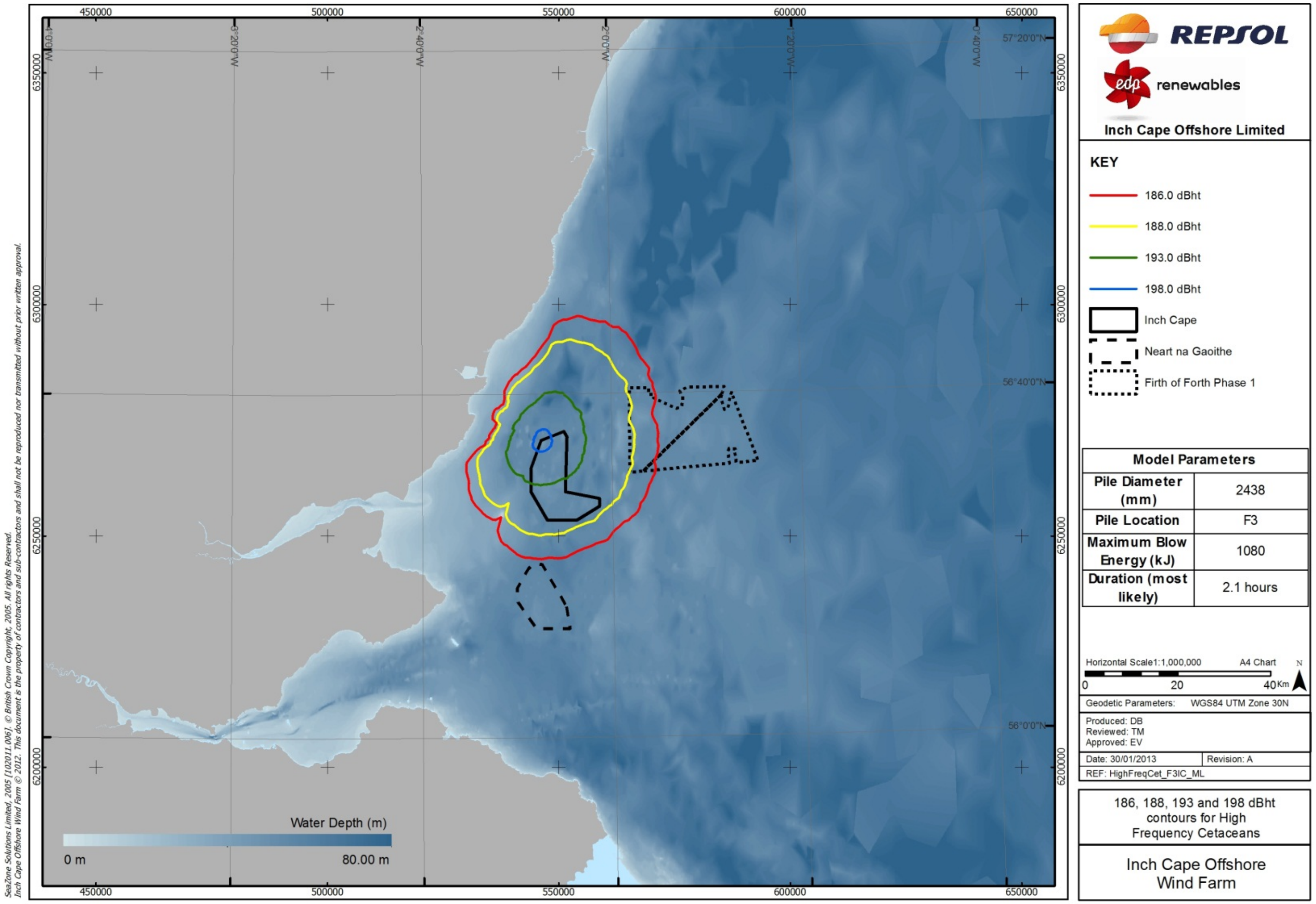


Figure 11A.28: Location F3: Starting Loci for Fleeing Low Frequency Cetaceans; Four Piles Driven Sequentially

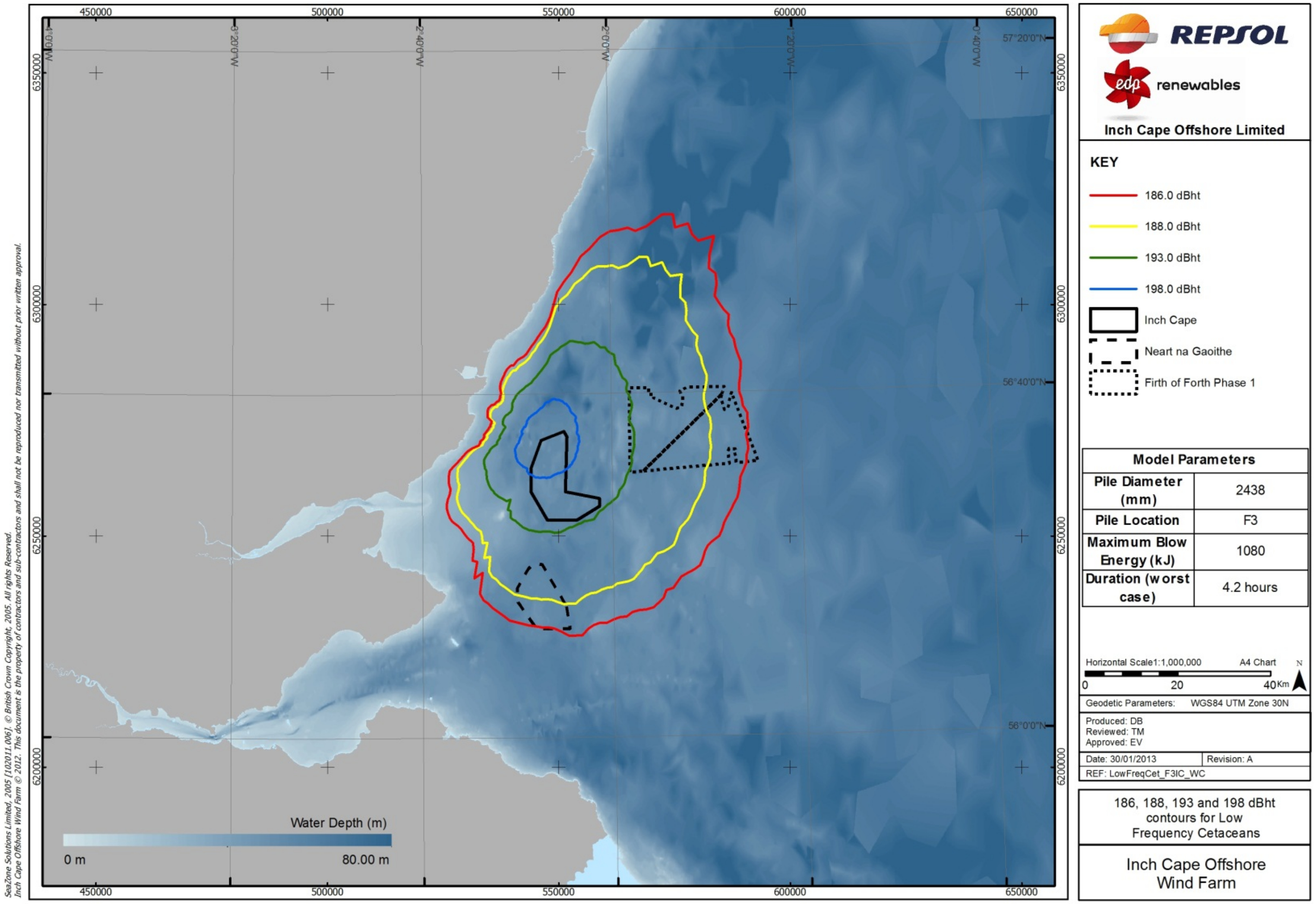


Figure 11A.29: Location F3: Starting Loci for Fleeing Mid Frequency Cetaceans; Four Piles Driven Sequentially

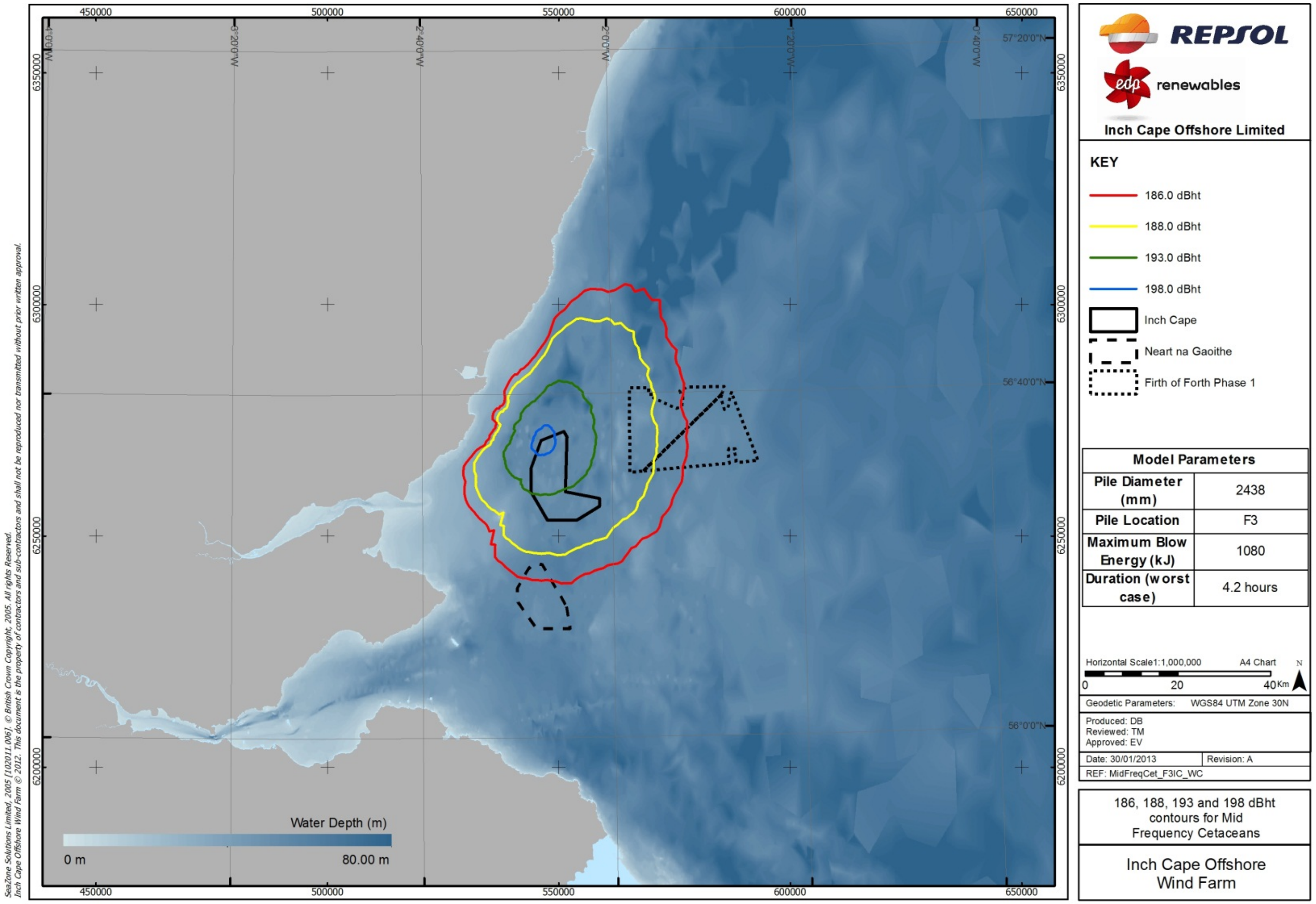


Figure 11A.30: Location F3: Starting Loci for Fleeing High Frequency Cetaceans; Four Piles Driven Sequentially

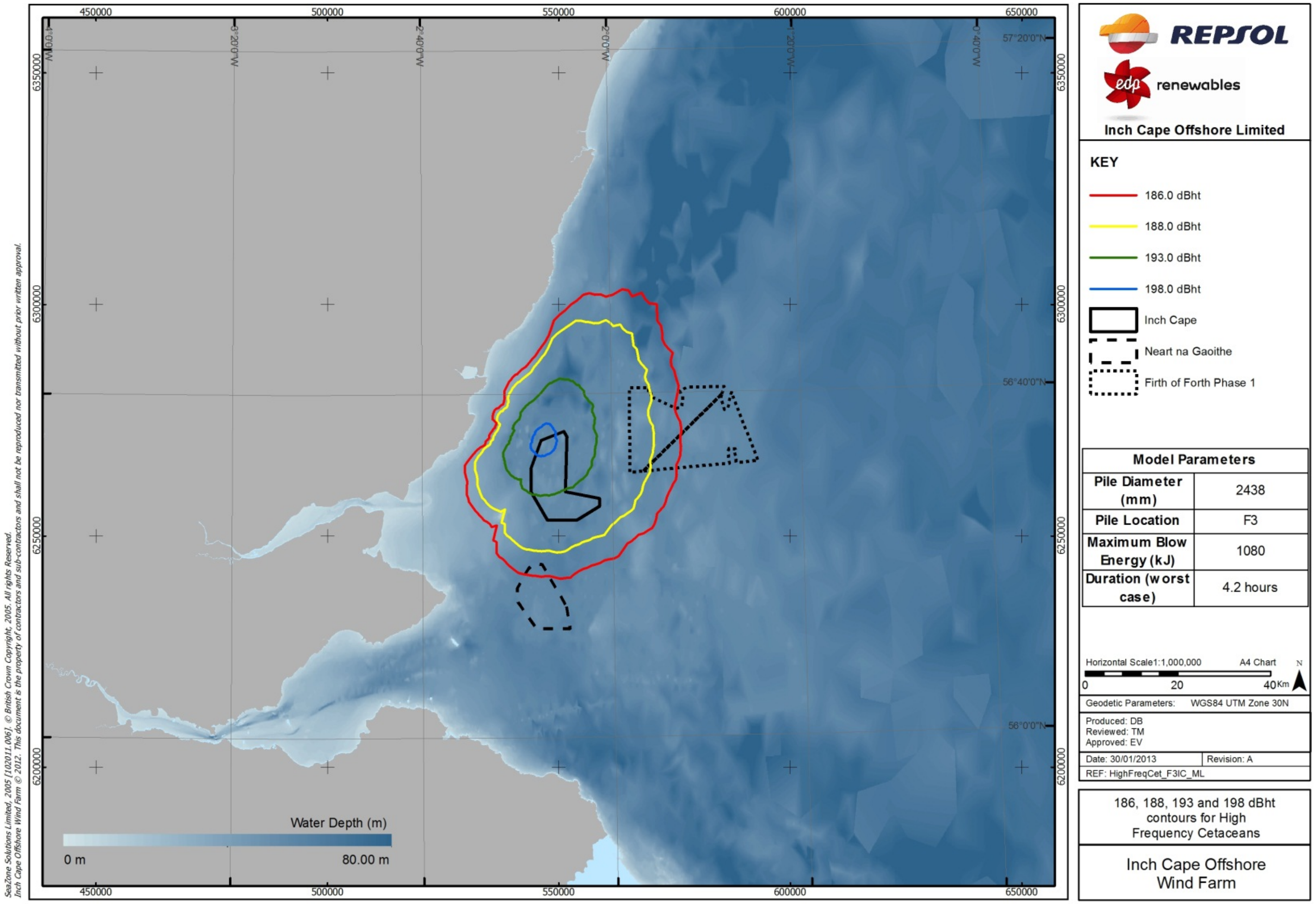


Table 11A.13: Summary of Conditions Modelled for Piles Driven at Location F4

Number of piles per location	Species / Filter	Results shown	Figure No.
n/a	Harbour Seal	90 and 75 dB_{ht} contours	Figure 11A.31
n/a	Bottlenose dolphin (as a surrogate for White-beaked dolphin	90 and 75 dB_{ht} contours	Figure 11A.32
2 piles sequentially	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.33
2 piles sequentially	Pinnipeds (in water)	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{pw}) for an animal fleeing at 1.5 m/s	Figure 11A.34
4 piles sequentially	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.35
4 piles sequentially	Pinnipeds (in water)	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{pw}) for an animal fleeing at 1.5 m/s	Figure 11A.36

Figure 11A.31: Location F4: 90 and 75 dB_{ht} Contours for Harbour Seal

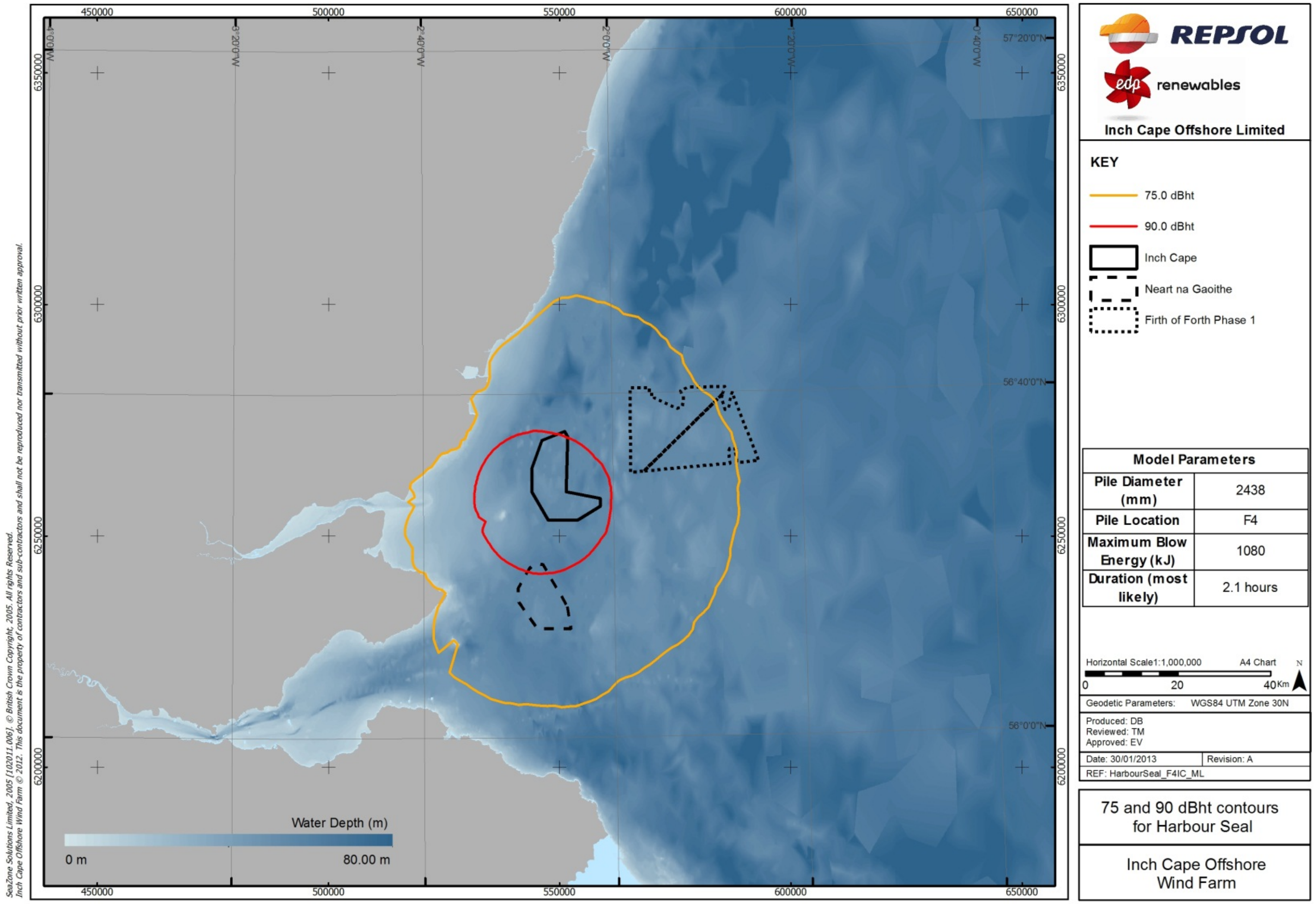


Figure 11A.32: Location F4: 90 and 75 dB_{ht} Contours for Bottlenose Dolphin (as a Surrogate for White-Beaked Dolphin)

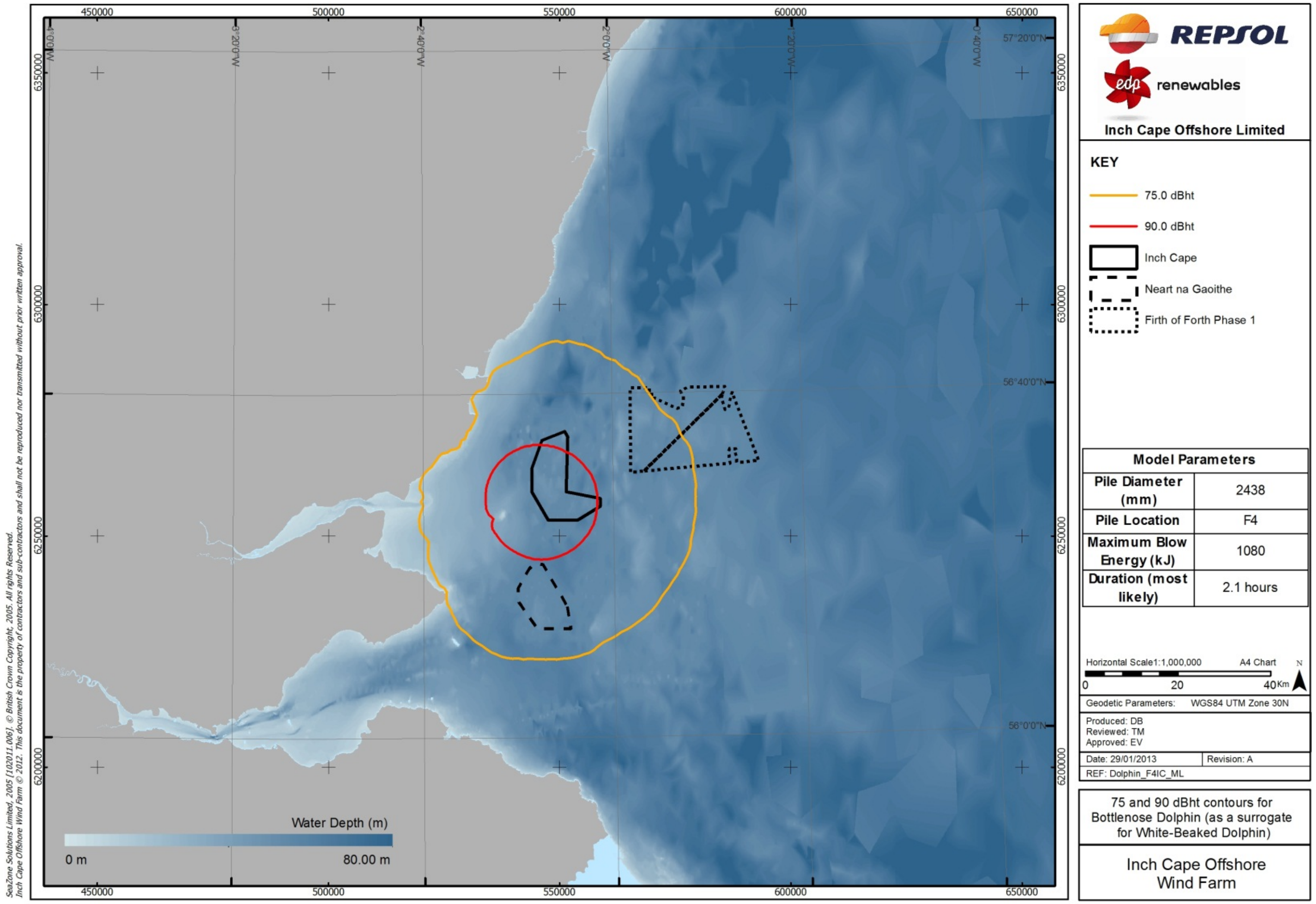


Figure 11A.33: Location F4: Starting Loci for Fleeing Mid Frequency Cetaceans; Two Piles Driven Sequentially

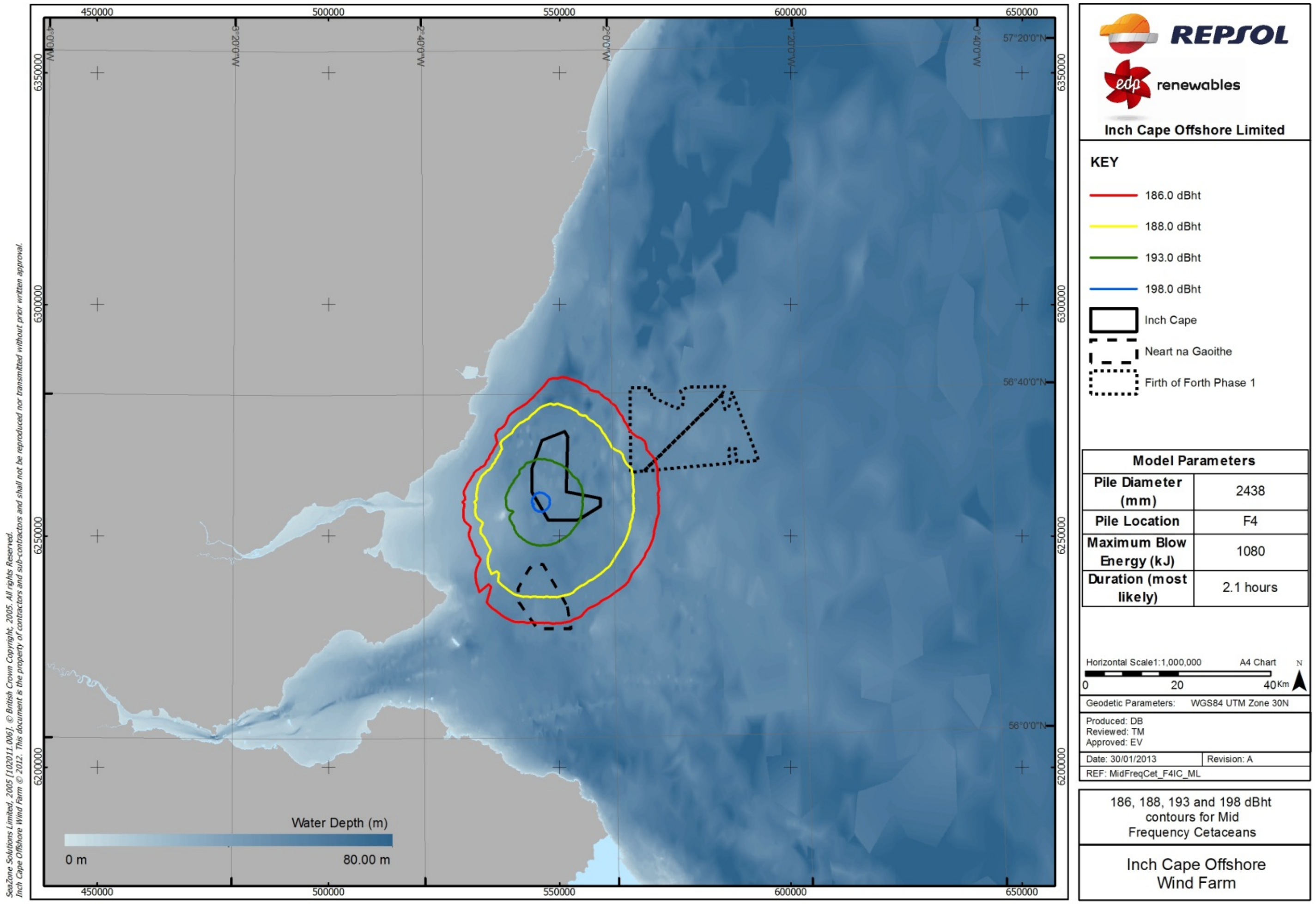


Figure 11A.34: Location F4: Starting Loci for Fleeing Pinnipeds (in water); Two Piles Driven Sequentially

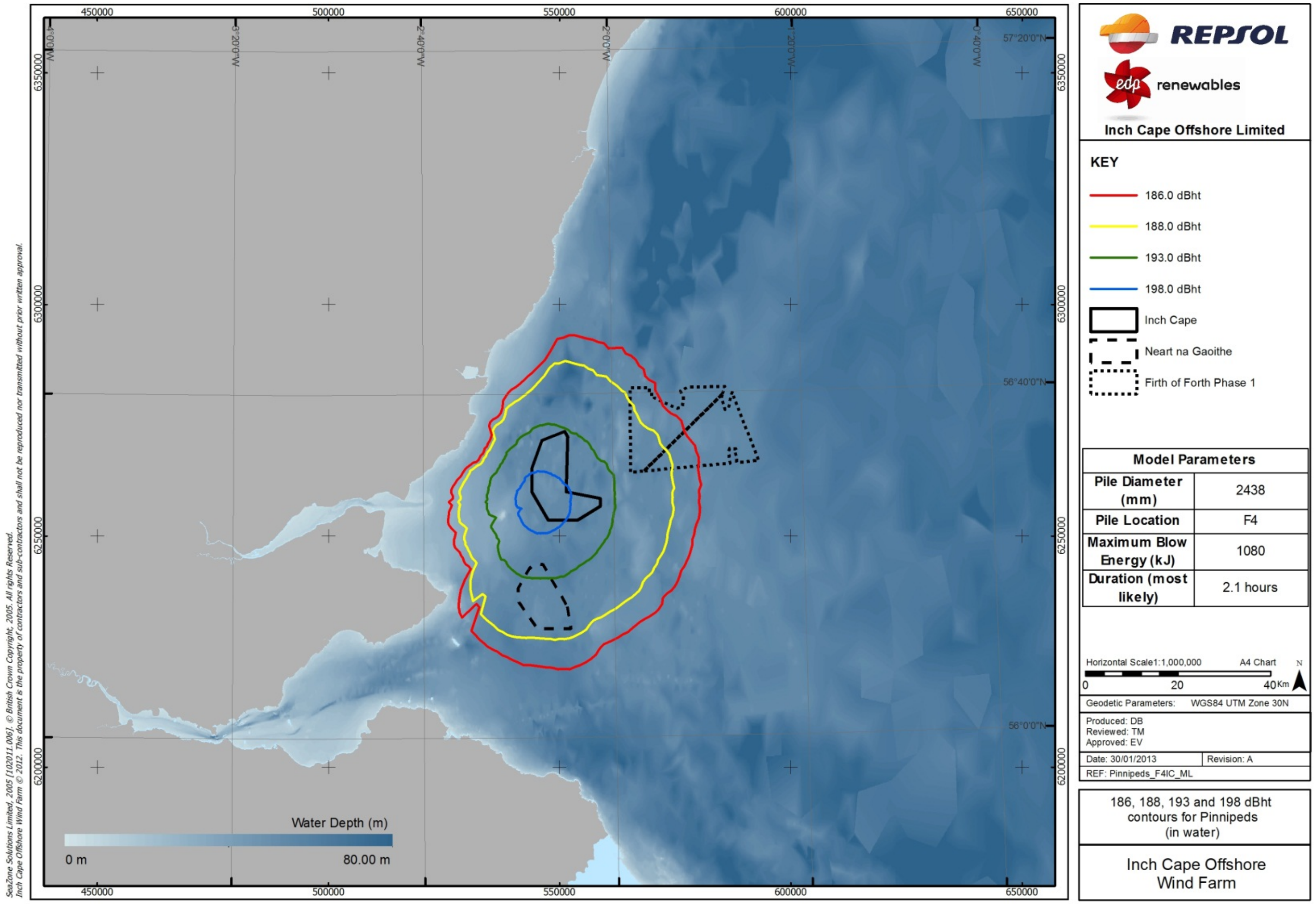


Figure 11A.35: Location F4: Starting Loci for Fleeing Mid Frequency Cetaceans; Four Piles Driven Sequentially

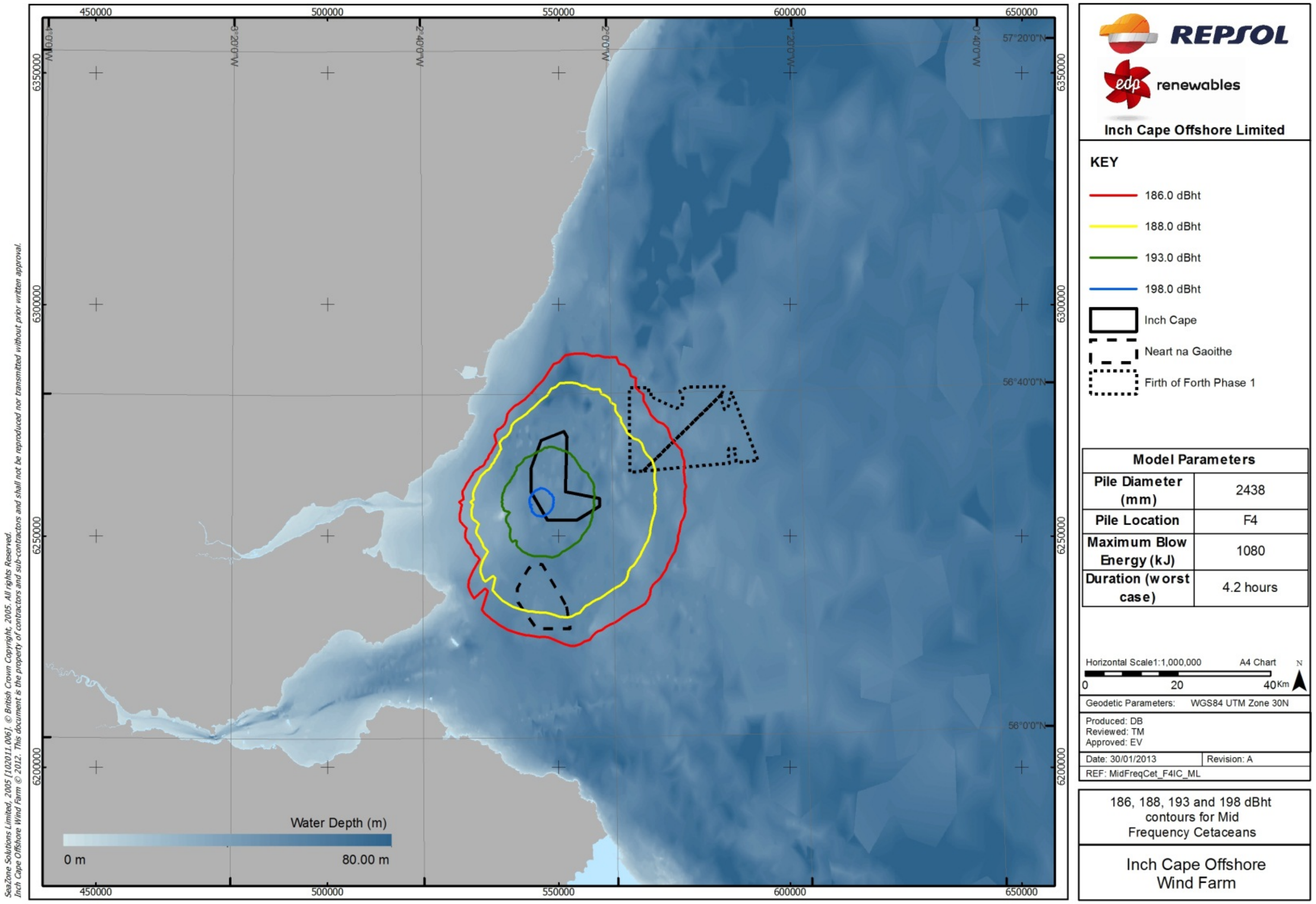


Figure 11A.36: Location F4: Starting Loci for Fleeing Pinnipeds (in water); Four Piles Driven Sequentially

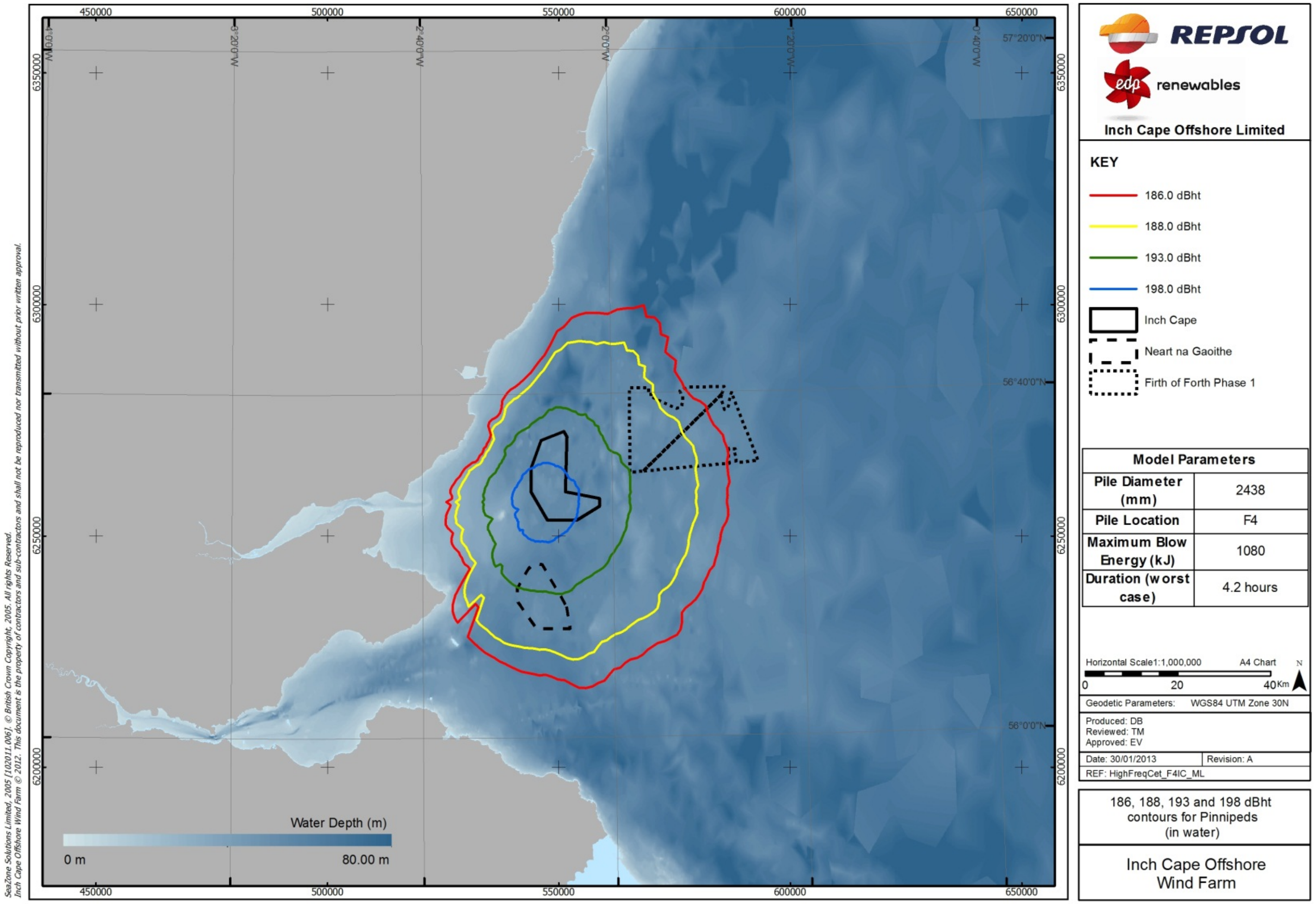


Table 11A.14: Summary of Conditions Modelled for Piles Driven at a Locations F3 and F4

Number of piles per location	Species / Filter	Results shown	Figure No.
n/a	Dab (as a surrogate for Plaice)	90 and 75 dB_{ht} contours	Figure 11A.37
n/a	Herring	90 and 75 dB_{ht} contours	Figure 11A.38
n/a	Salmon	90 and 75 dB_{ht} contours	Figure 11A.39
n/a	Sand Lance (surrogate for Sandeel)	90 and 75 dB_{ht} contours	Figure 11A.40
n/a	Trout	90 and 75 dB_{ht} contours	Figure 11A.41
n/a	Cod	90 and 75 dB_{ht} contours	Figure 11A.41A
n/a	Bottlenose Dolphin (and White-beaked dolphin)	90 and 75 dB_{ht} contours	Figure 11A.42
n/a	Harbour Porpoise	90 and 75 dB_{ht} contours	Figure 11A.43
n/a	Harbour Seal (and grey seal)	90 and 75 dB_{ht} contours	Figure 11A.44
n/a	Humpback Whale (as a surrogate for Minke Whale)	90 and 75 dB_{ht} contours	Figure 11A.45
2 piles sequentially	Low Frequency Cetacean	198, 193, 188 and 186 dB re 1 μPa^2s (M_{lf}) for an animal fleeing at 1.5 m/s	Figure 11A.46
2 piles sequentially	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 μPa^2s (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.47
2 piles sequentially	High Frequency Cetacean	198, 193, 188 and 186 dB re 1 μPa^2s (M_{hf}) for an animal fleeing at 1.5 m/s	Figure 11A.48

Number of piles per location	Species / Filter	Results shown	Figure No.
2 piles sequentially	Pinnipeds (in water)	198, 193, 188 and 186 dB re 1 µPa^{2}s (M_{pw}) for an animal fleeing at 1.5 m/s	Figure 11A.49
4 piles sequentially	Low Frequency Cetacean	198, 193, 188 and 186 dB re 1 µP a^{2}s (M_{lf}) for an animal fleeing at 1.5 m/s	Figure 11A.50
4 piles sequentially	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 µPa^{2}s (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.51
4 piles sequentially	High Frequency Cetacean	198, 193, 188 and 186 dB re 1 µPa^{2}s (M_{hf}) for an animal fleeing at 1.5 m/s	Figure 11A.52
4 piles sequentially	Pinnipeds (in water)	198, 193, 188 and 186 dB re 1 µPa^{2}s (M_{pw}) for an animal fleeing at 1.5 m/s	Figure 11A.53

Figure 11A.37: Location F3, F4: 90 and 75 dB$_{ht}$ Contours for Dab (as a Surrogate for Plaice)

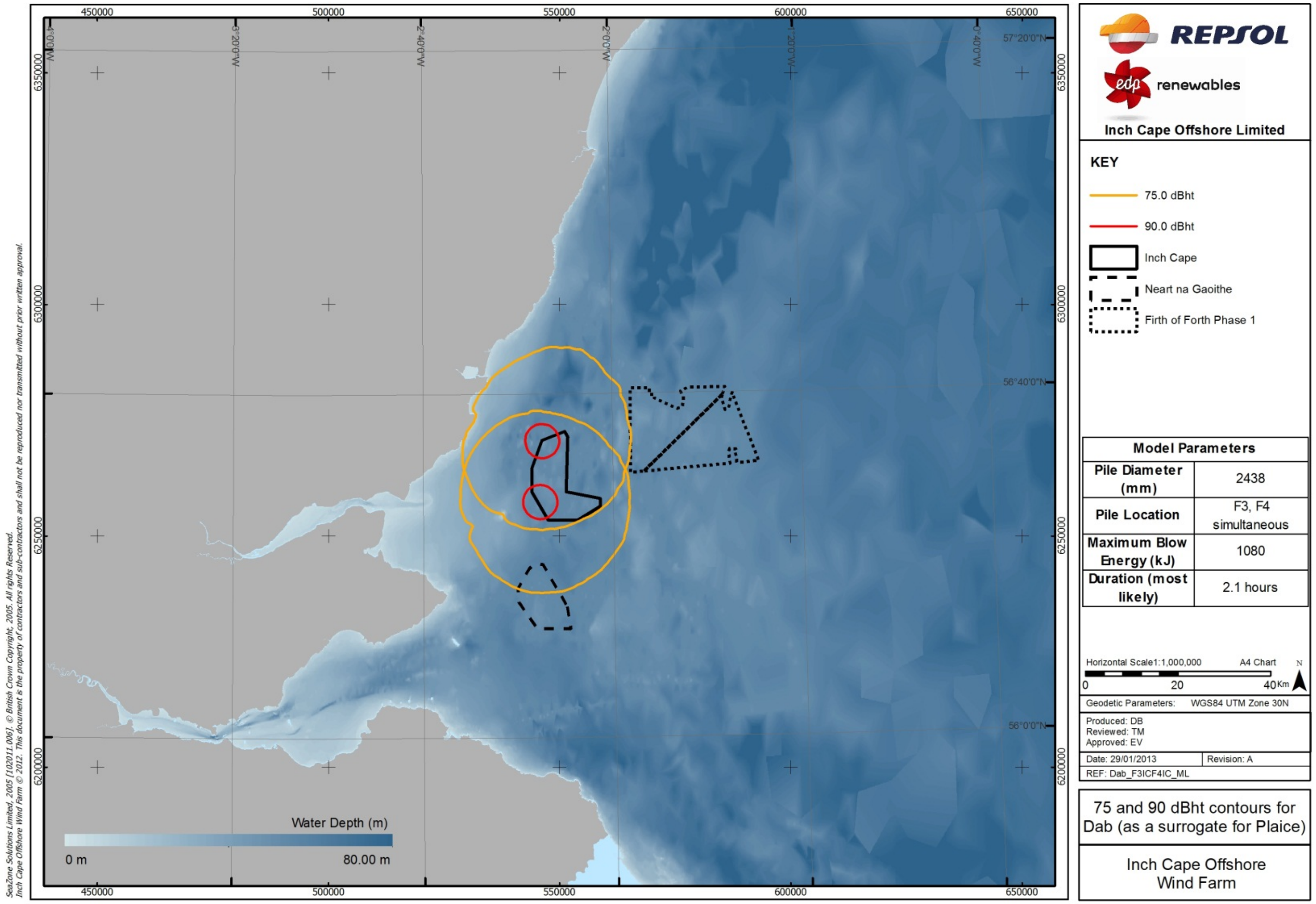


Figure 11A.38: Location F3, F4: 90 and 75 dB$_{ht}$ Contours for Herring

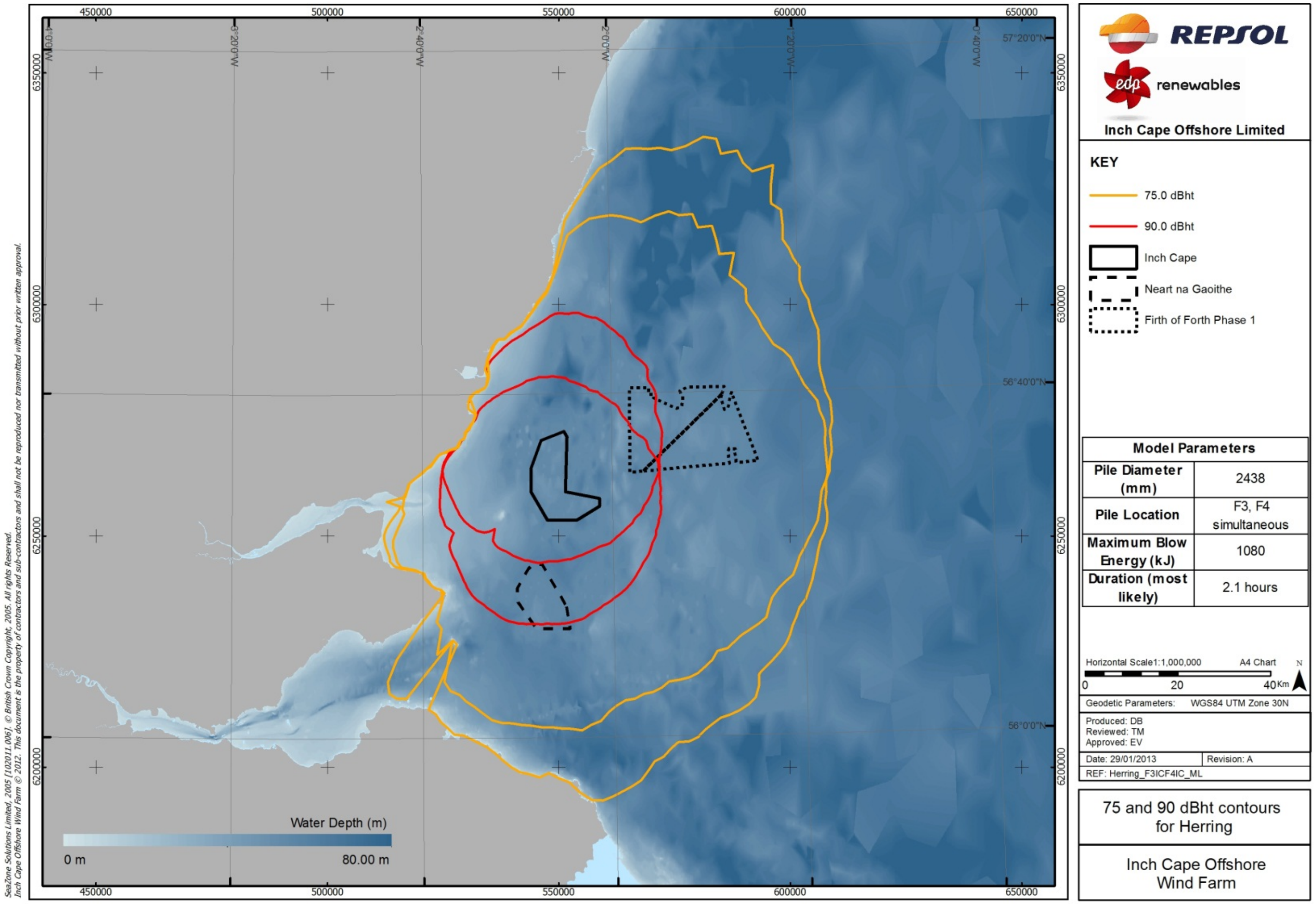


Figure 11A.39: Location F3, F4: 90 and 75 dB_{ht} Contours for Salmon

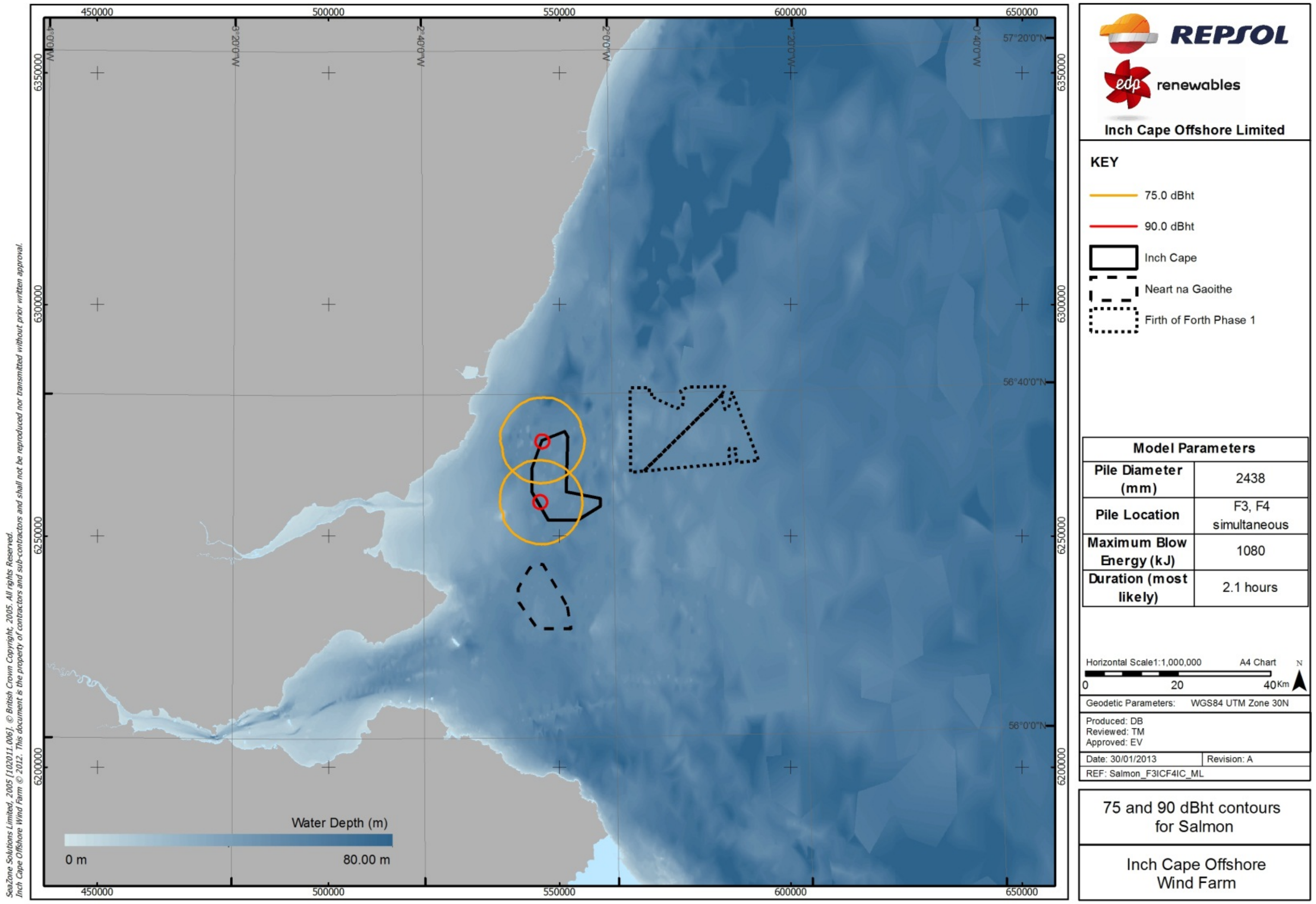


Figure 11A.40: Location F3, F4: 90 and 75 dB_{ht} Contours for Sand Lance (as a Surrogate for Sandeel) Simultaneously

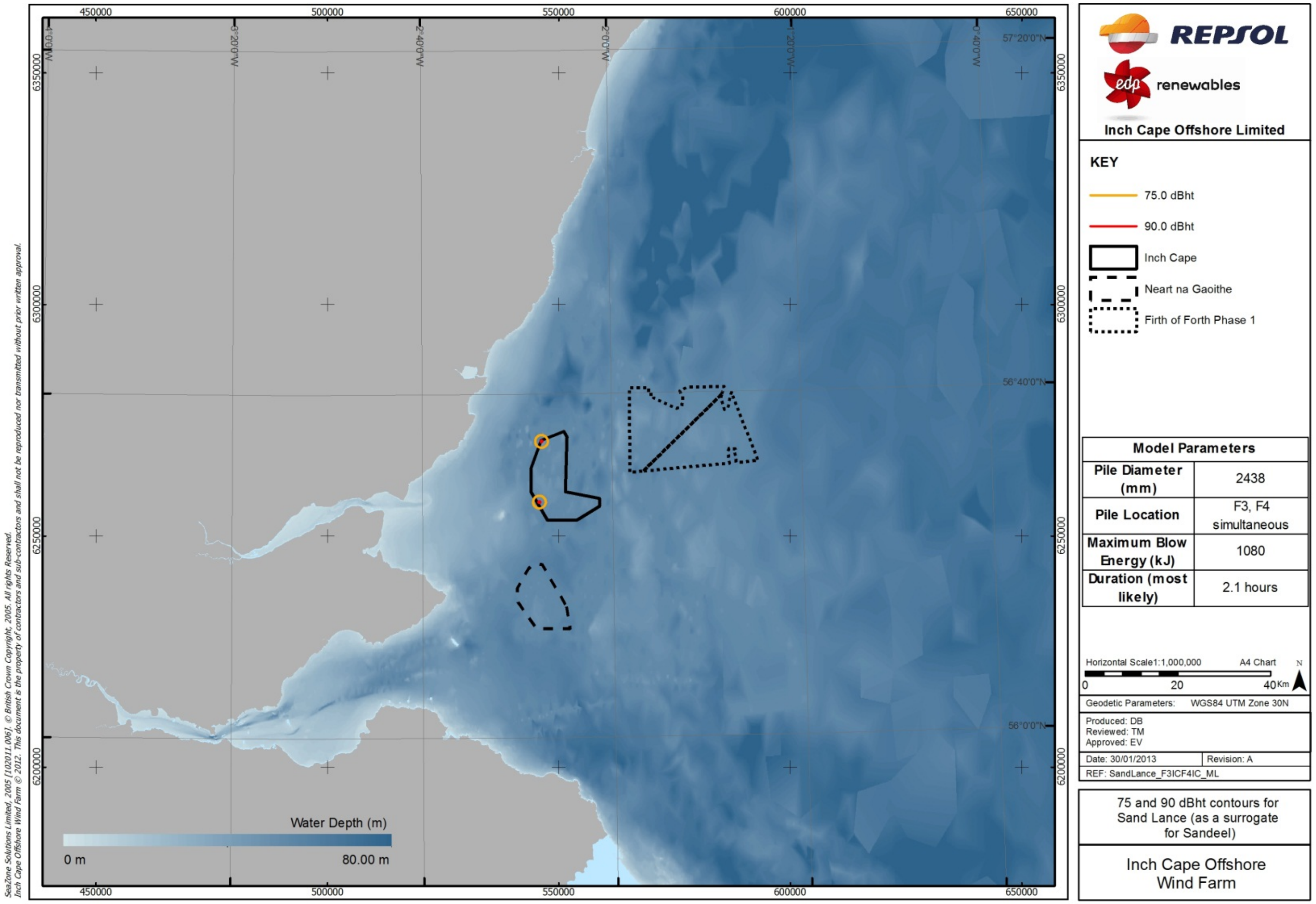


Figure 11A.41: Location F3, F4: 90 and 75 dB_{ht} Contours for Trout

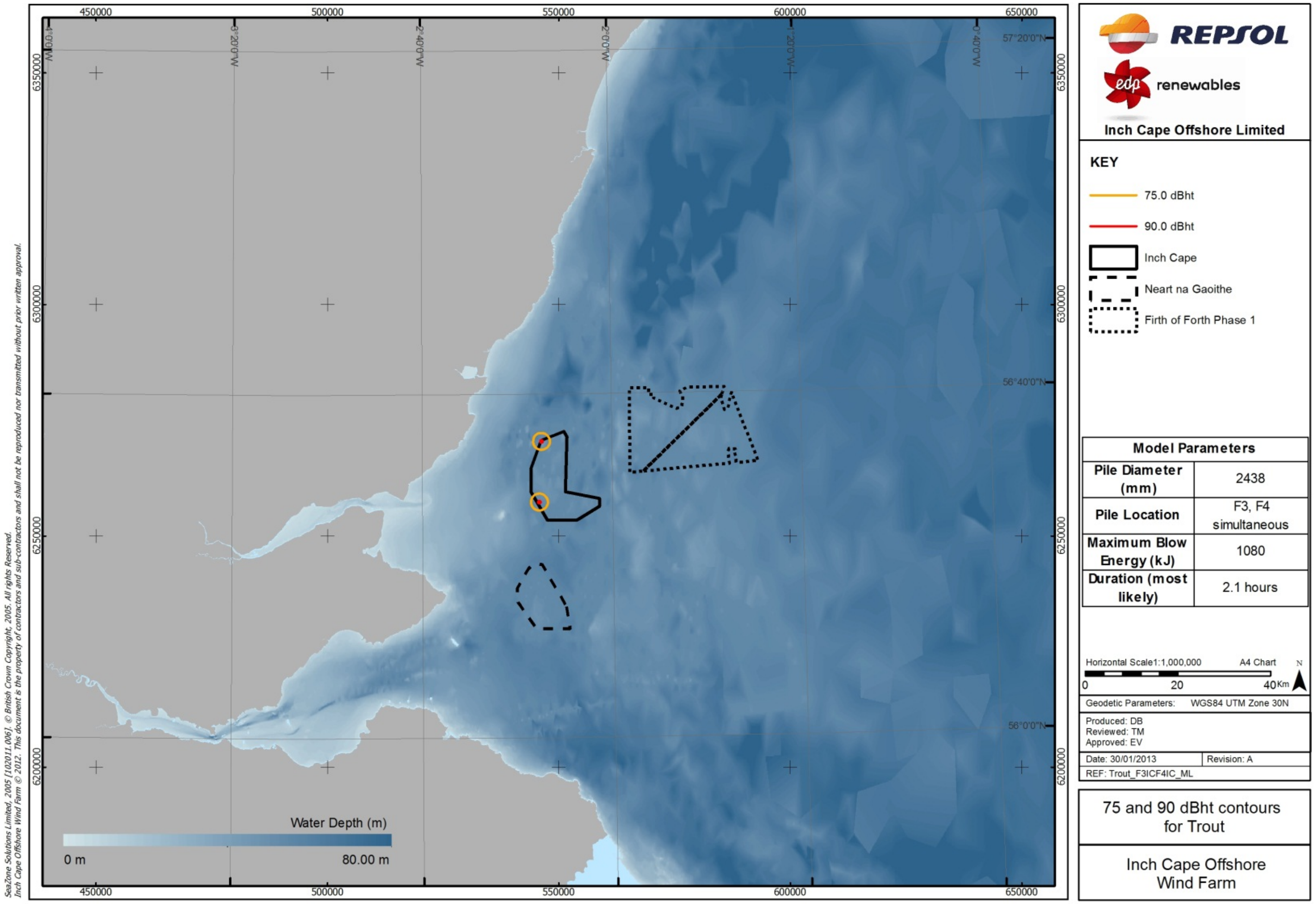


Figure 11A.41A: Location F3, F4: 90 and 75 dB_{ht} Contours for Cod

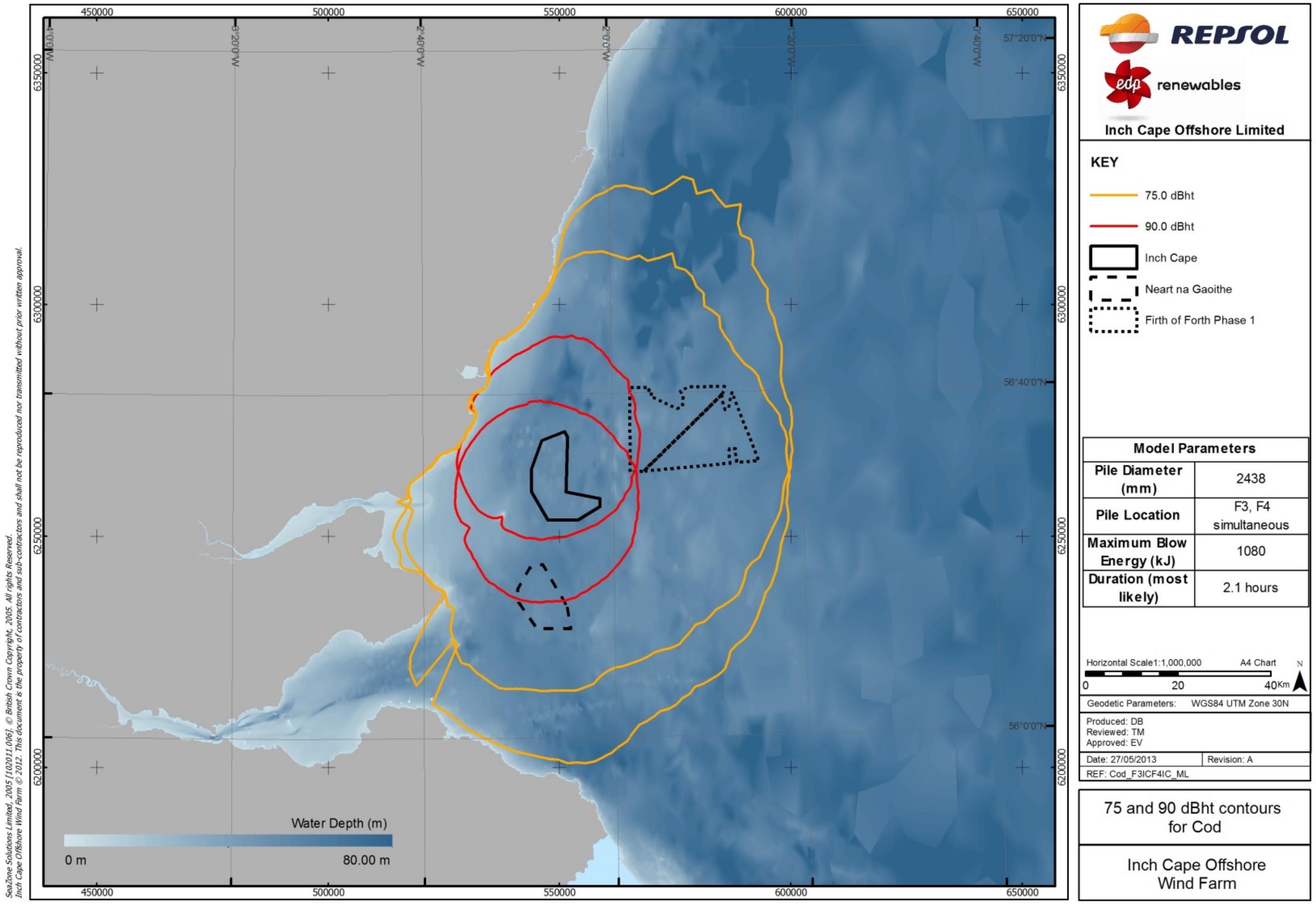


Figure 11A.42: Location F3, F4: 90 and 75 dB_{ht} Contours for Bottlenose Dolphin

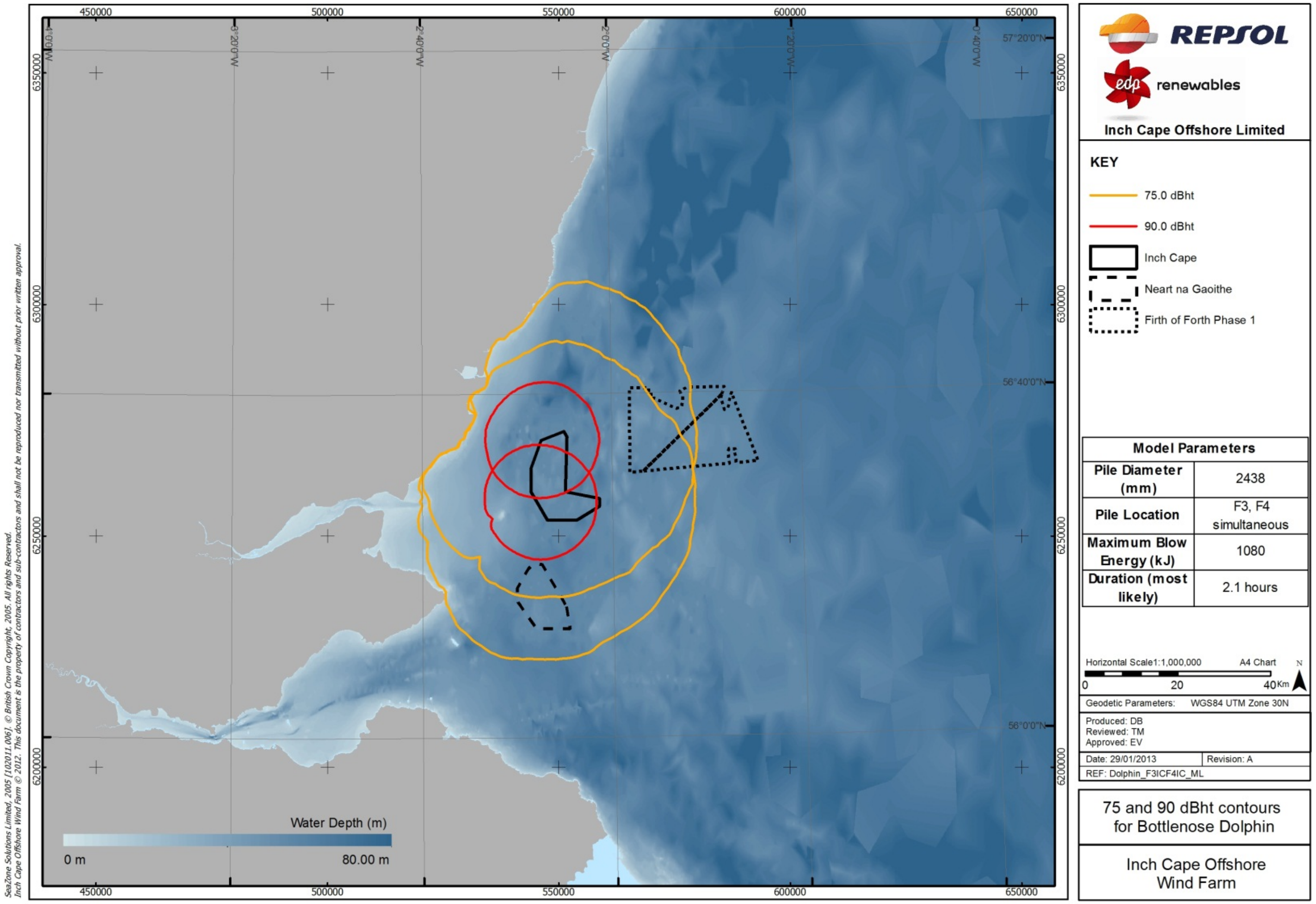


Figure 11A.43: Location F3, F4: 90 and 75 dB$_{ht}$ Contours for Harbour Porpoise

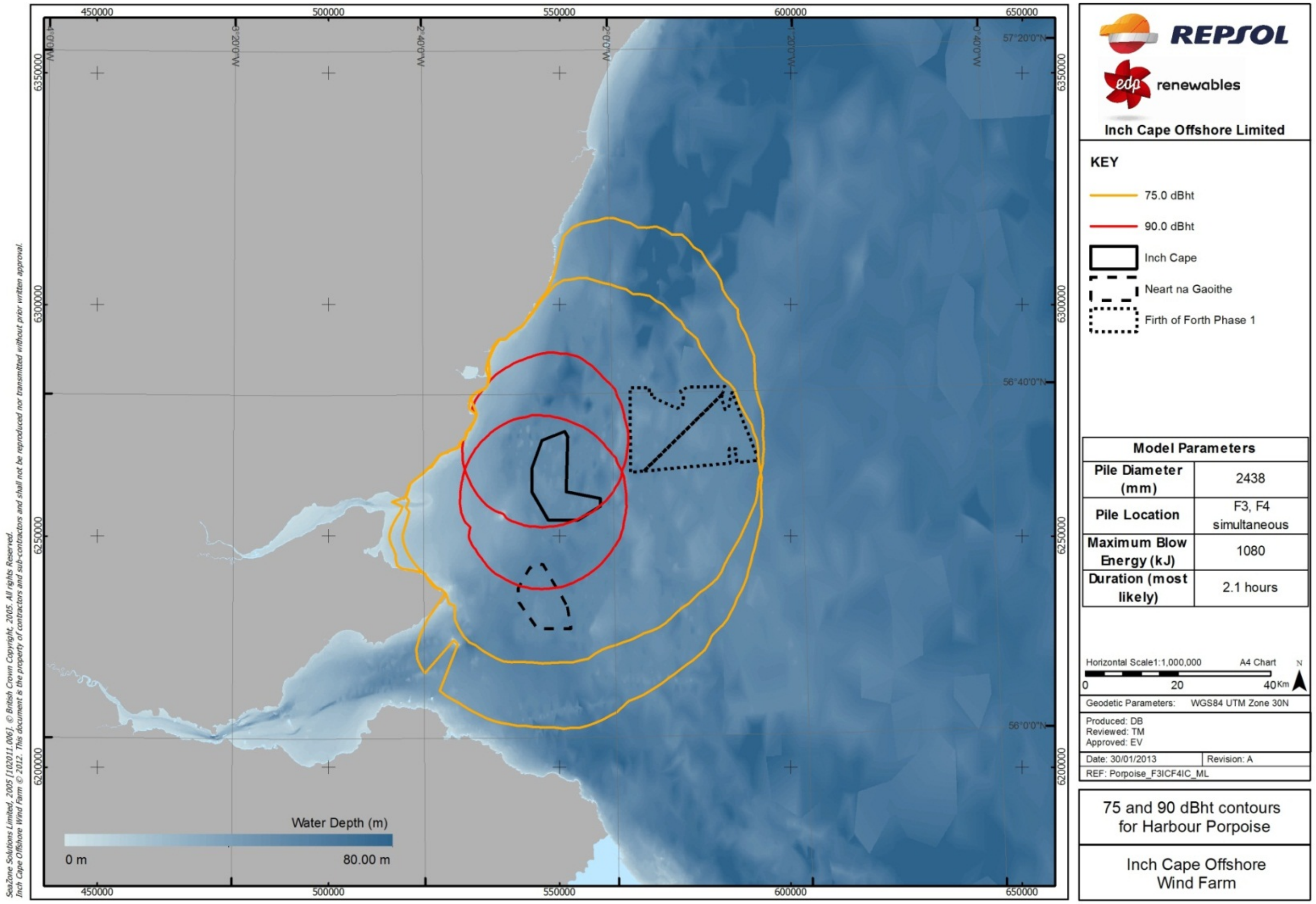


Figure 11A.44: Location F3, F4: 90 and 75 dB_{ht} Contours for Harbour Seal

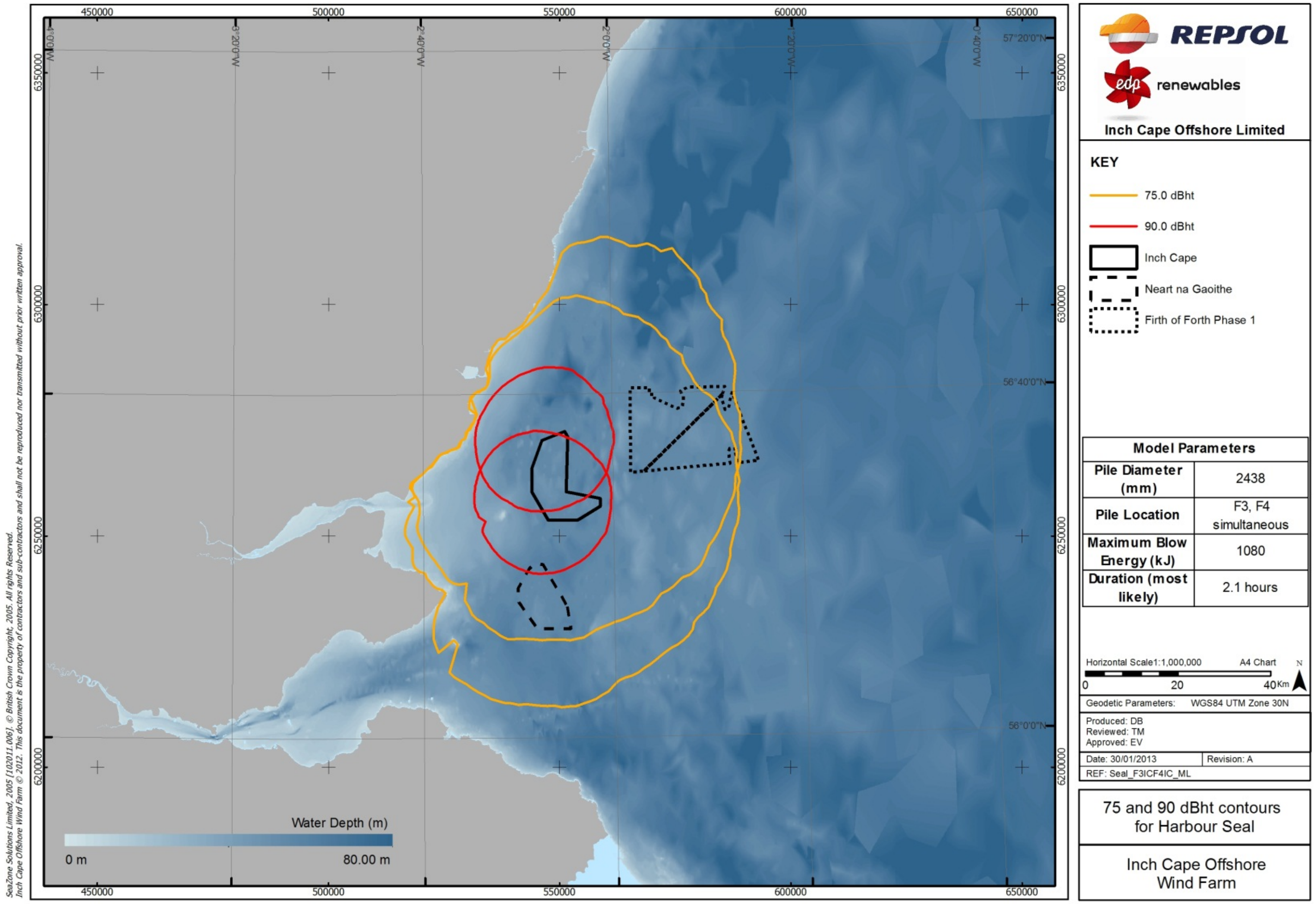


Figure 11A.45: Location F3, F4: 90 and 75 dB$_{ht}$ Contours for Humpback Whale (as a Surrogate for Minke Whale)

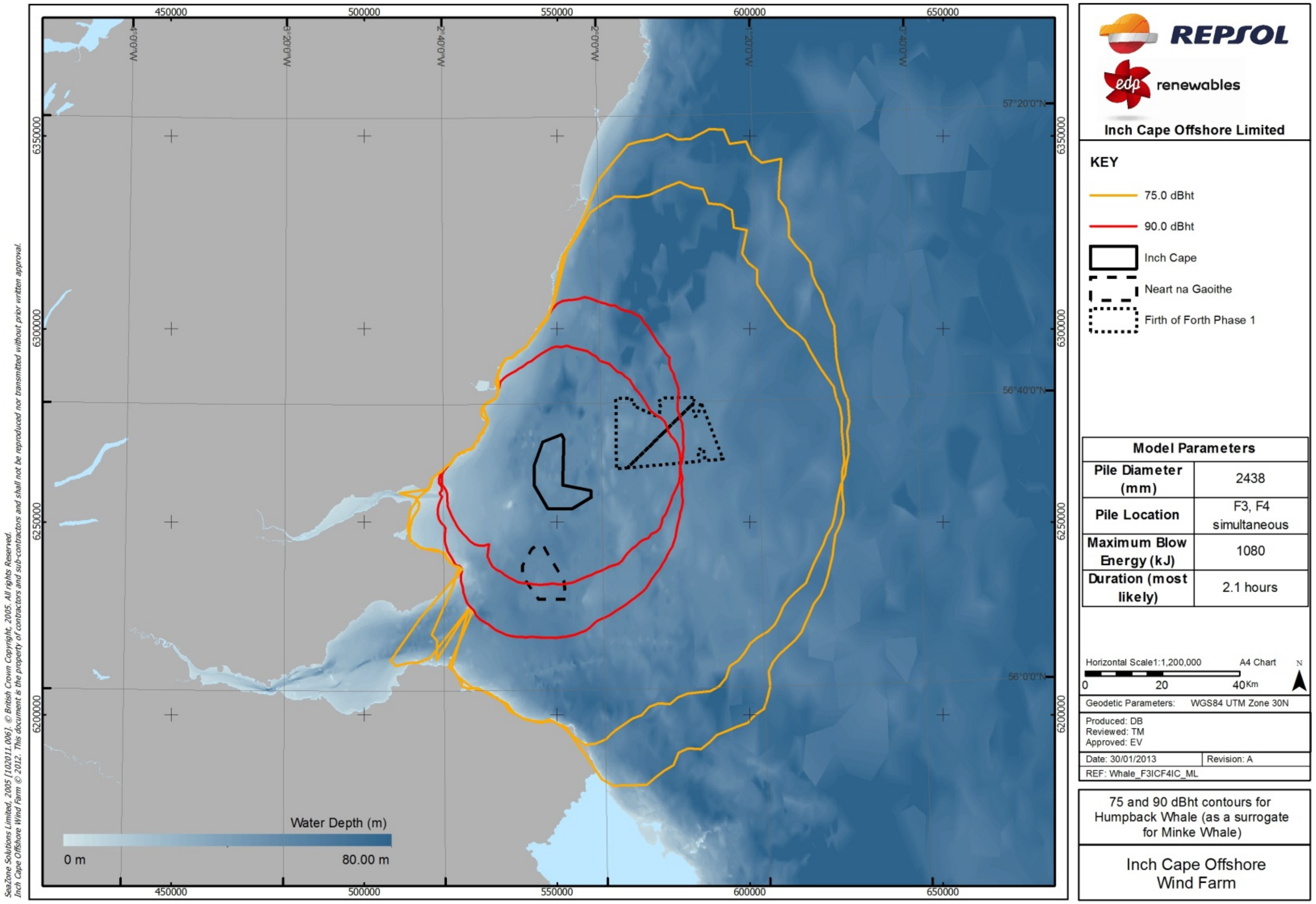


Figure 11A.46: Location F3, F4: Starting Loci for Fleeing Low Frequency Cetaceans; Two Piles Driven Sequentially

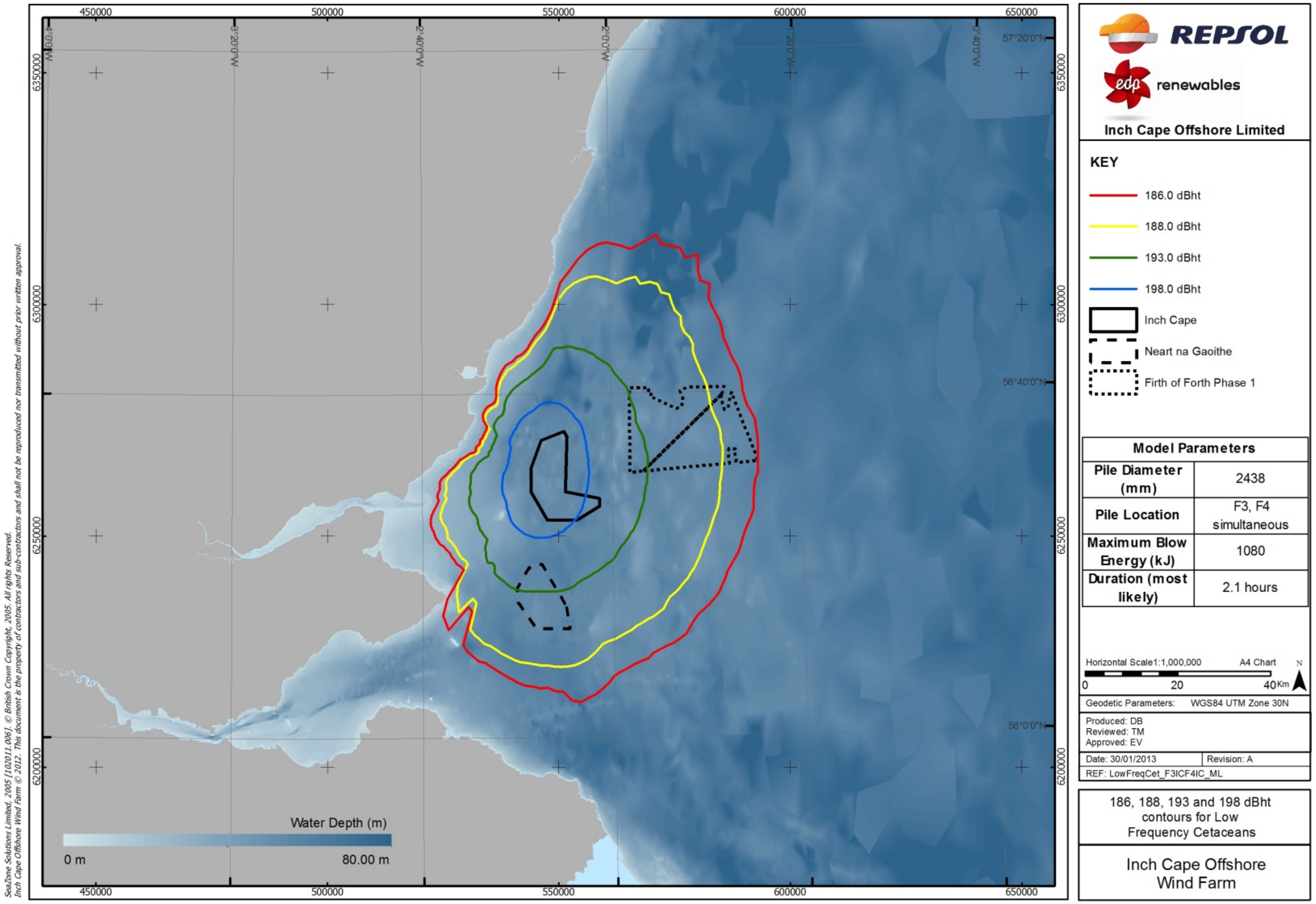


Figure 11A.47: Location F3, F4: Starting Loci for Fleeing Mid Frequency Cetaceans; Two Piles Driven Sequentially

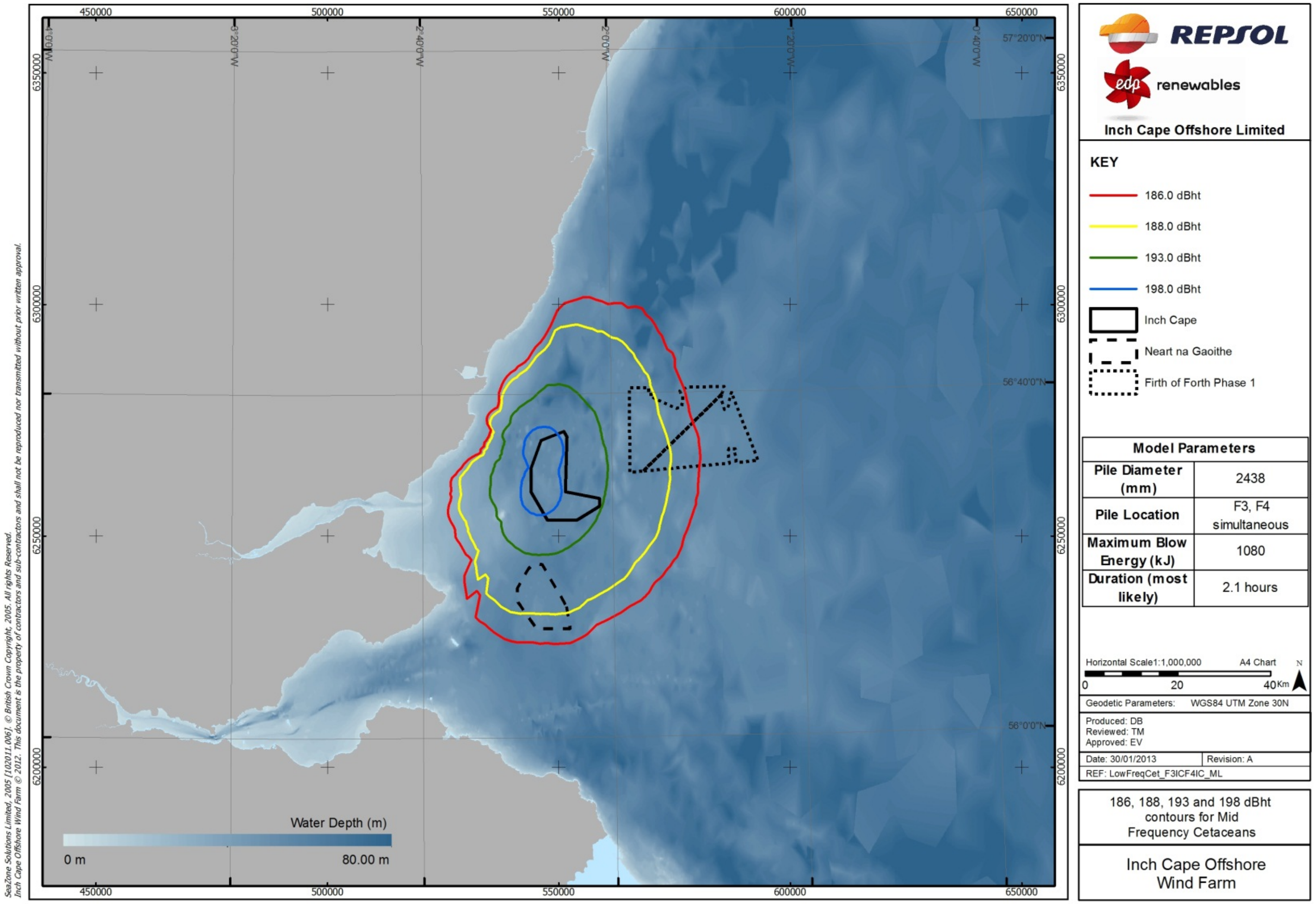


Figure 11A.48: Location F3, F4: StartingLloci for Fleeing High Frequency Cetaceans; Two Piles Driven Sequentially

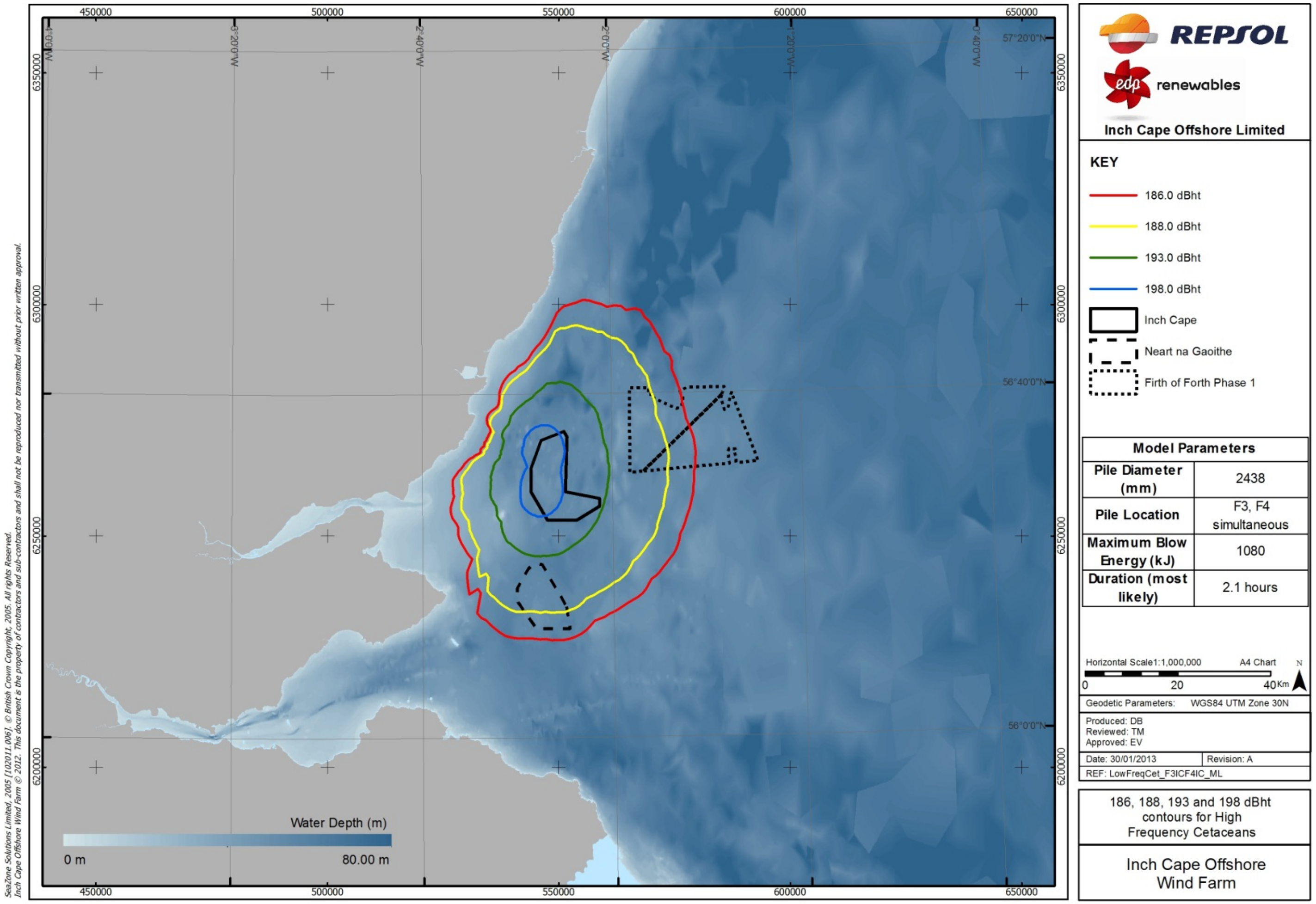


Figure 11A.49: Location F3, F4: Starting Loci for Fleeing Pinnipeds (in water); Two Piles Driven Sequentially at Locations F3 and F4

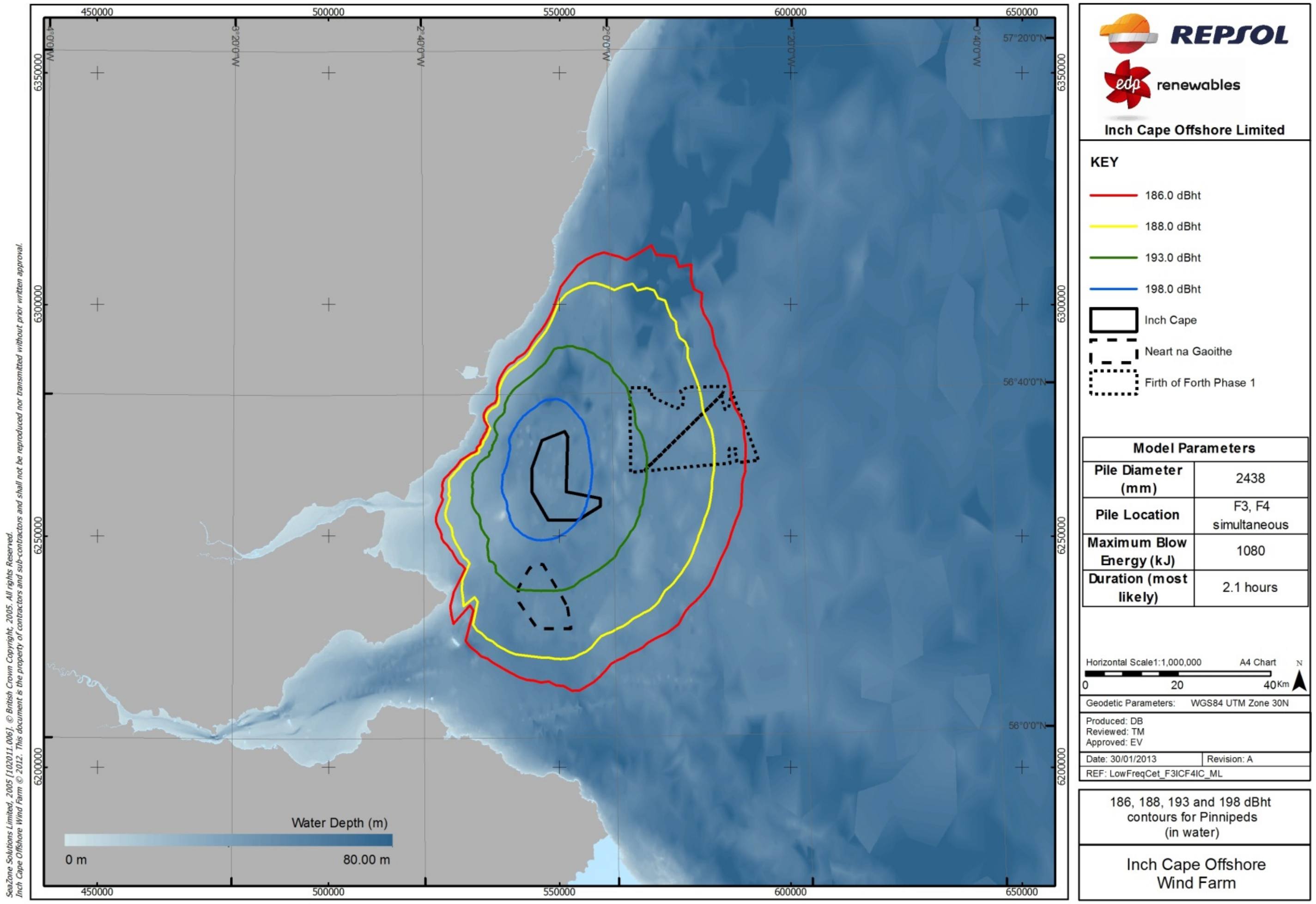


Figure 11A.50: Location F3, F4: Starting Loci for Fleeing Low Frequency Cetaceans; Four Piles Driven Sequentially

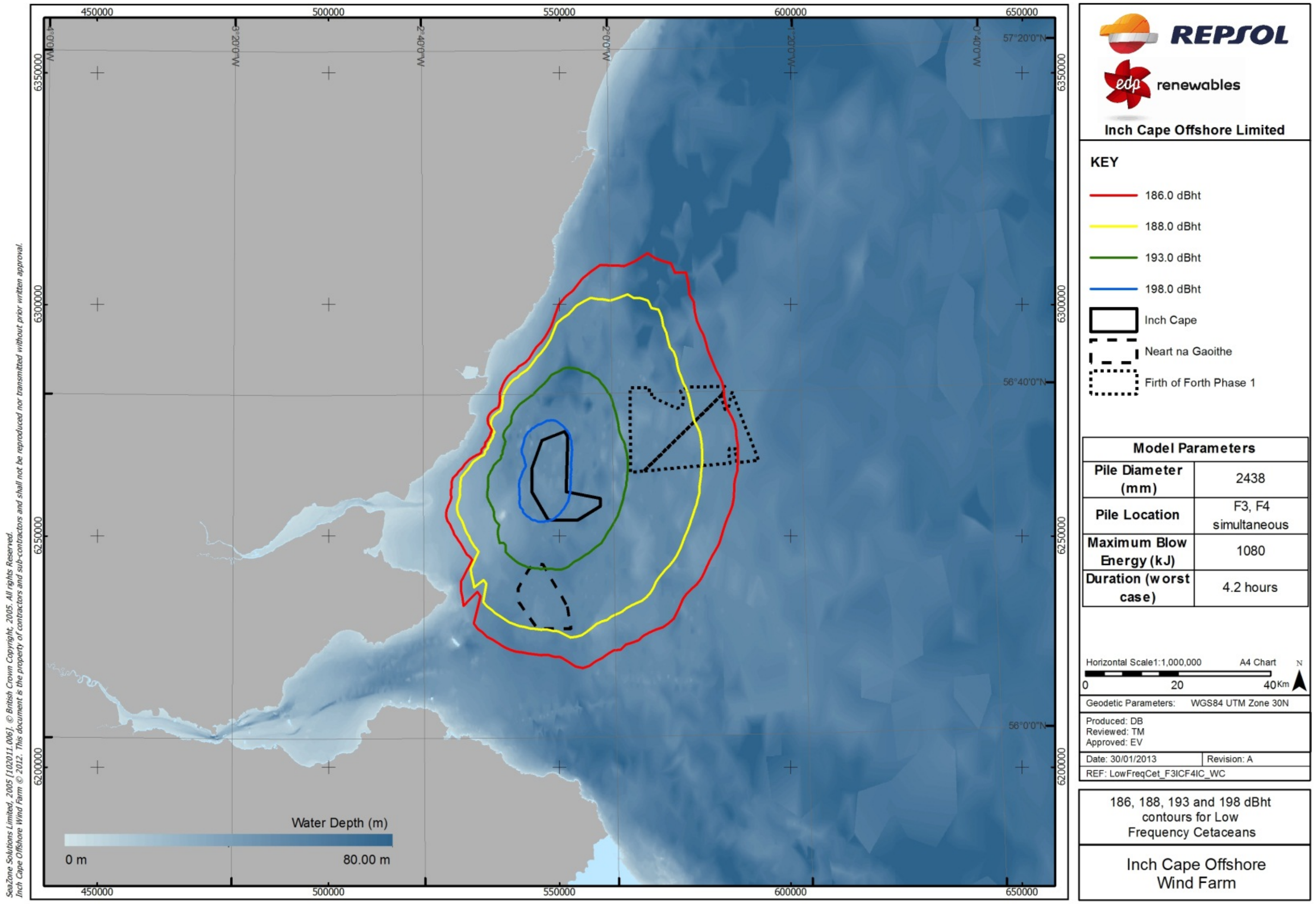


Figure 11A.51: Location F3, F4: Starting Loci for Fleeing Mid Frequency Cetaceans; Four Piles Driven Sequentially

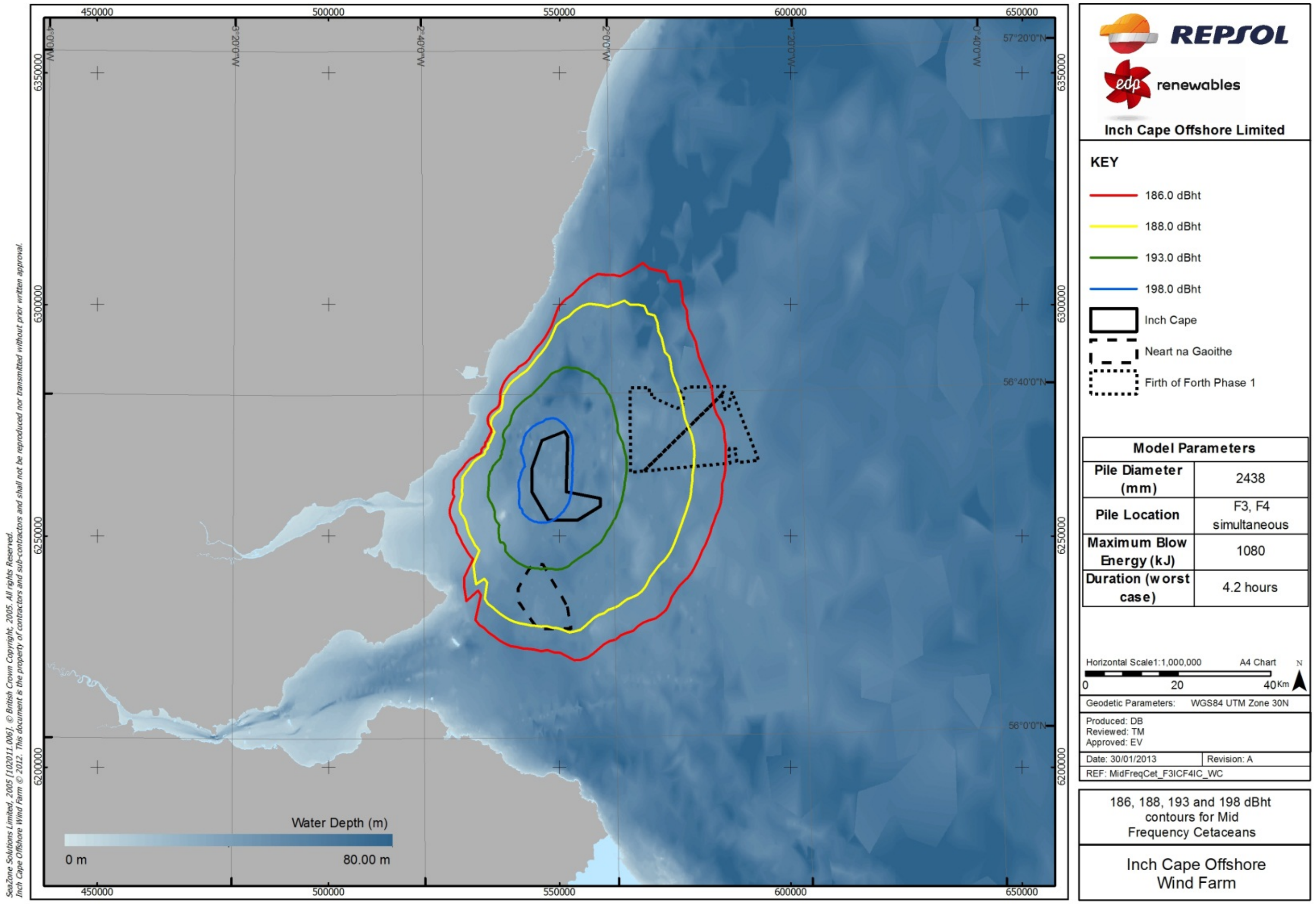


Figure 11A.52: Location F3, F4: Starting Loci for Fleeing High Frequency Cetaceans; Four Piles Driven Sequentially

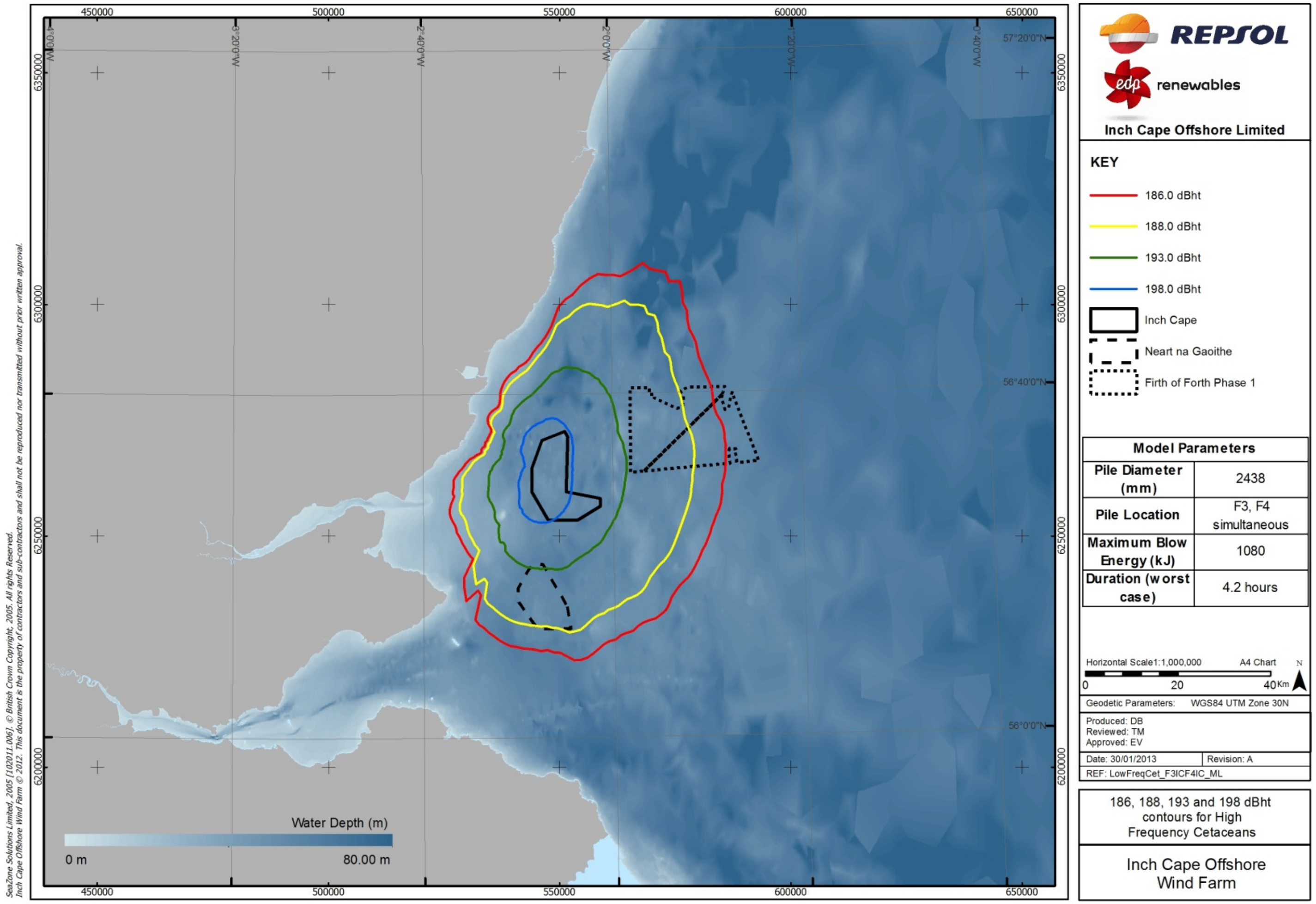


Figure 11A.53: Location F3, F4: Starting Loci for Fleeing Pinnipeds (in water); Four Piles Driven Sequentially

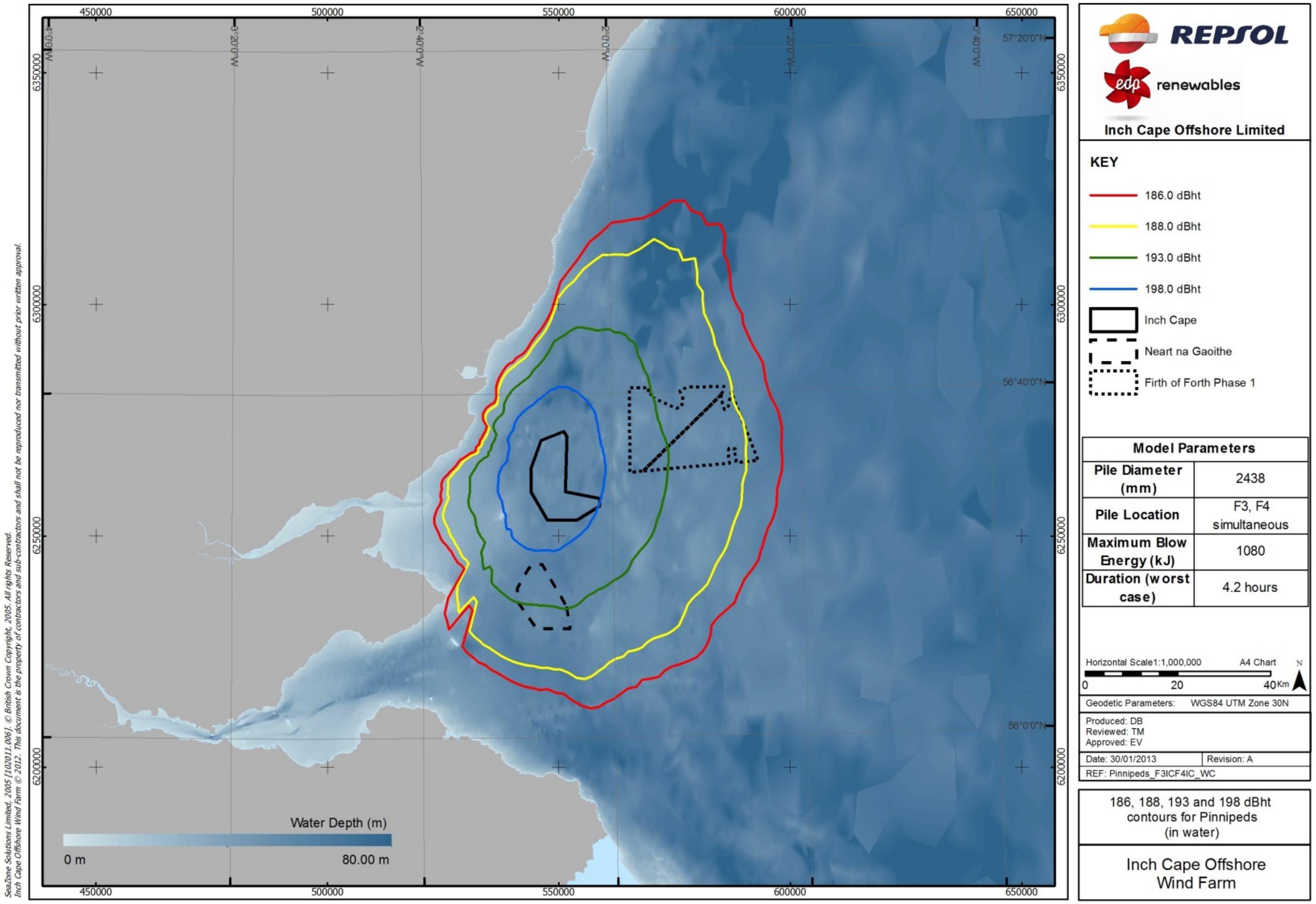


Table 11A.15: Summary of Conditions Modelled for Pile Driven Simultaneously at Location F3 (IC), Location F5 (NnG) and Location F1A (FoF) Using the Most Likely Predicted Piling Scenario

Number of piles per location	Species / Filter	Results shown	Figure No.
n/a	Dab (surrogate for Plaice)	90 and 75 dB_{ht} contours	Figure 11A.54
n/a	Herring	90 and 75 dB_{ht} contours	Figure 11A.55
n/a	Salmon	90 and 75 dB_{ht} contours	Figure 11A.56
n/a	Sand Lance (surrogate for Sandeel)	90 and 75 dB_{ht} contours	Figure 11A.57
n/a	Trout	90 and 75 dB_{ht} contours	Figure 11A.58
n/a	Bottlenose Dolphin	90 and 75 dB_{ht} contours	Figure 11A.59
n/a	Humpback Whale (surrogate for Minke Whale)	90 and 75 dB_{ht} contours	Figure 11A.60
2 piles sequentially at location F3, location F5 and location F1A	Low Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{lf}) for an animal fleeing at 1.5 m/s	Figure 11A.61
2 piles sequentially at location F3, location F5 and location F1A	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.62

Figure 11A.54: Locations F3, F5, F1A: 90 and 75 dB$_{ht}$ Contours for Dab (as a Surrogate for Plaice)

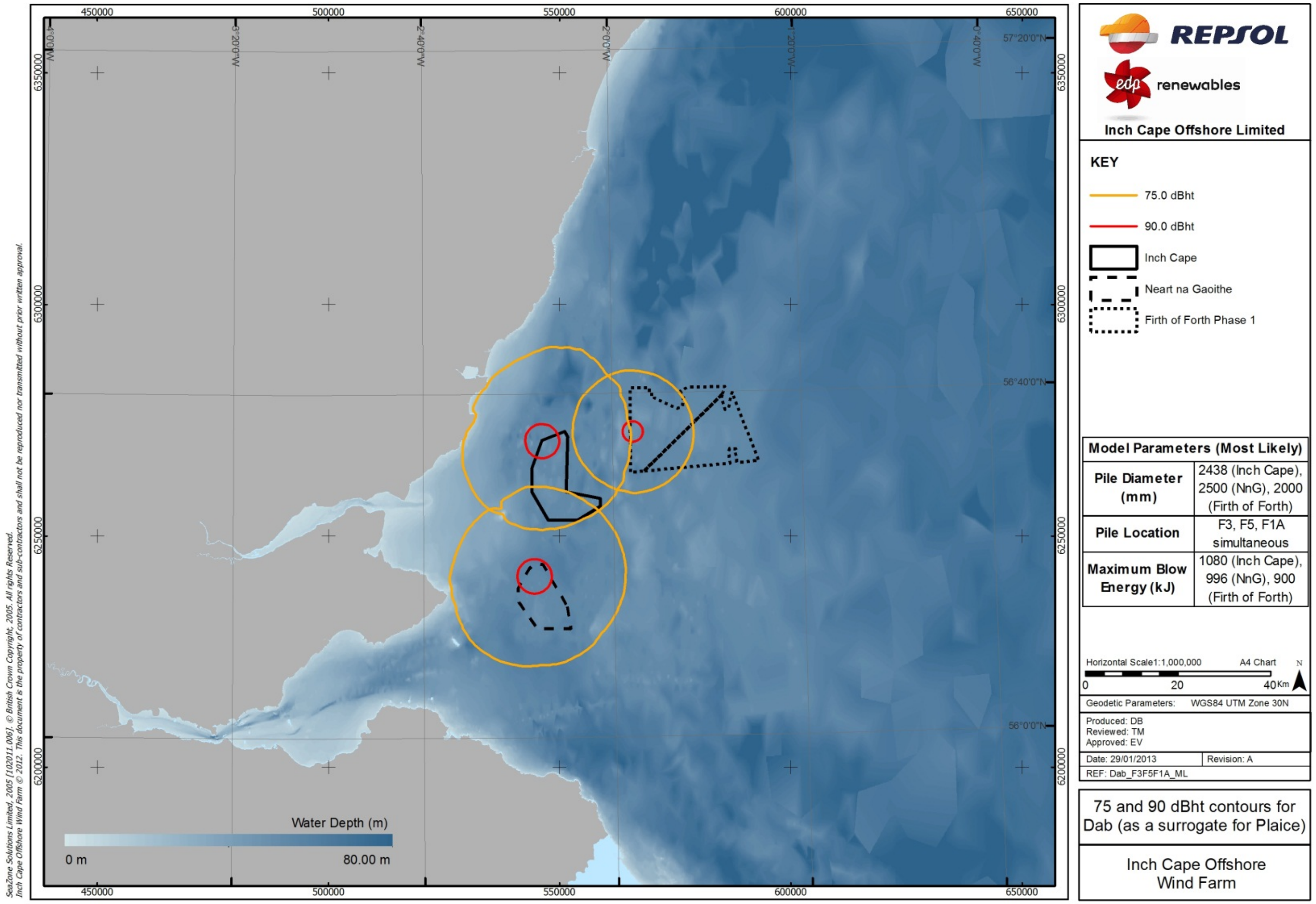


Figure 11A.55: Locations F3, F5, F1A: 90 and 75 dB_{ht} Contours for Herring

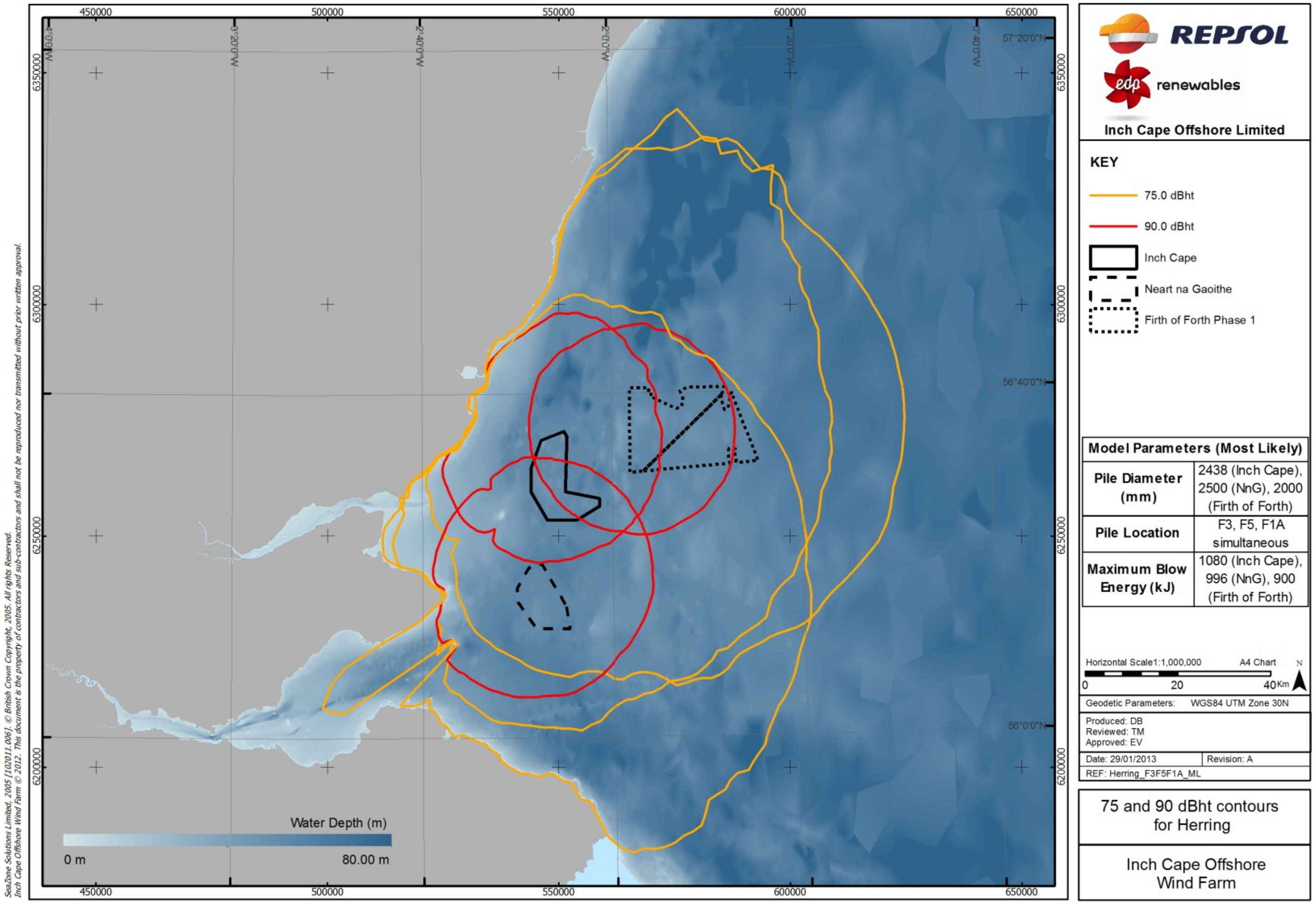


Figure 11A.56: Locations F3, F5, F1A: 90 and 75 dB_{ht} Contours for Salmon

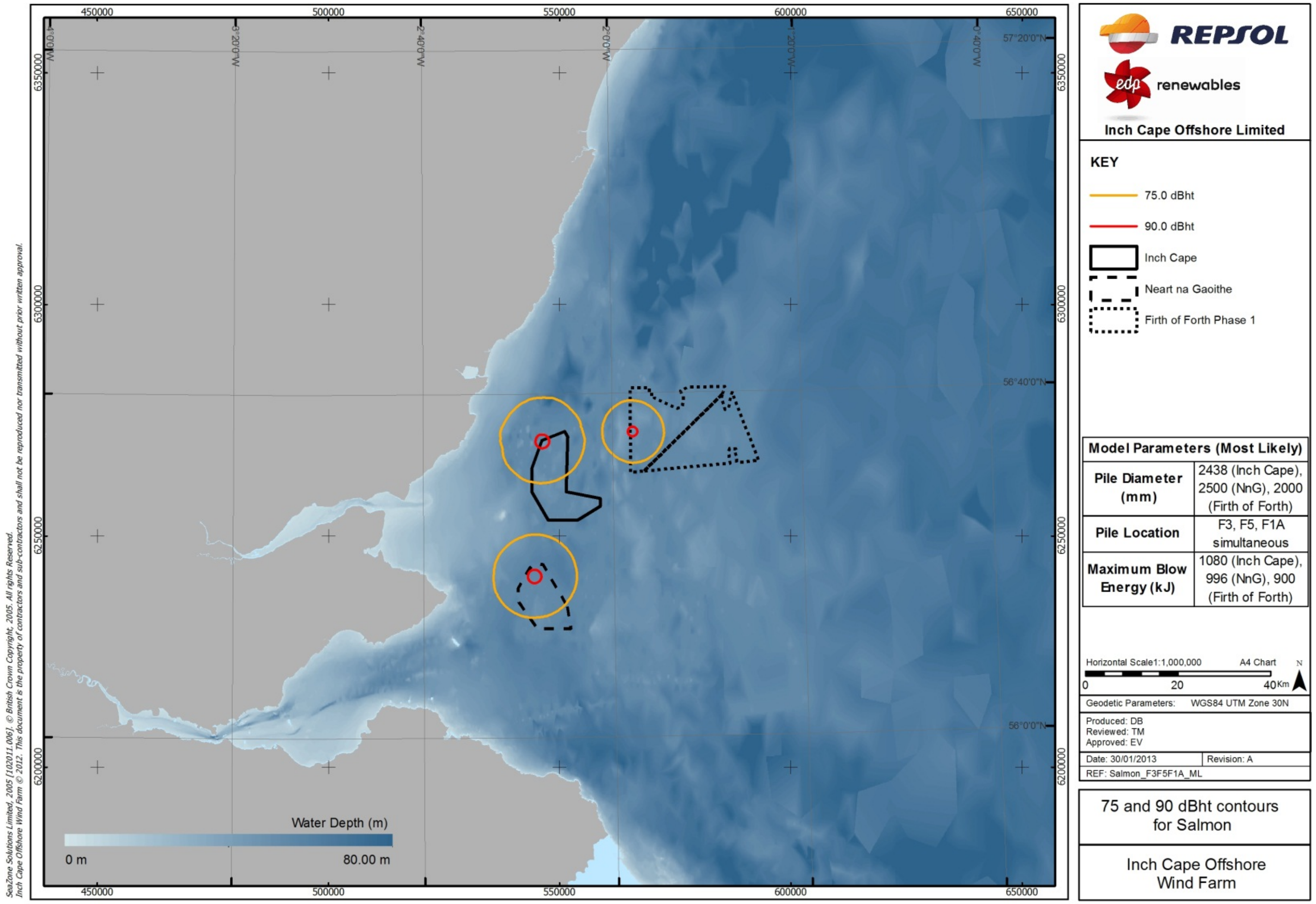


Figure 11A.57: Locations F3, F5, F1A: 90 and 75 dB_{ht} Contours for Sand Lance (as a Surrogate for Sandeel)

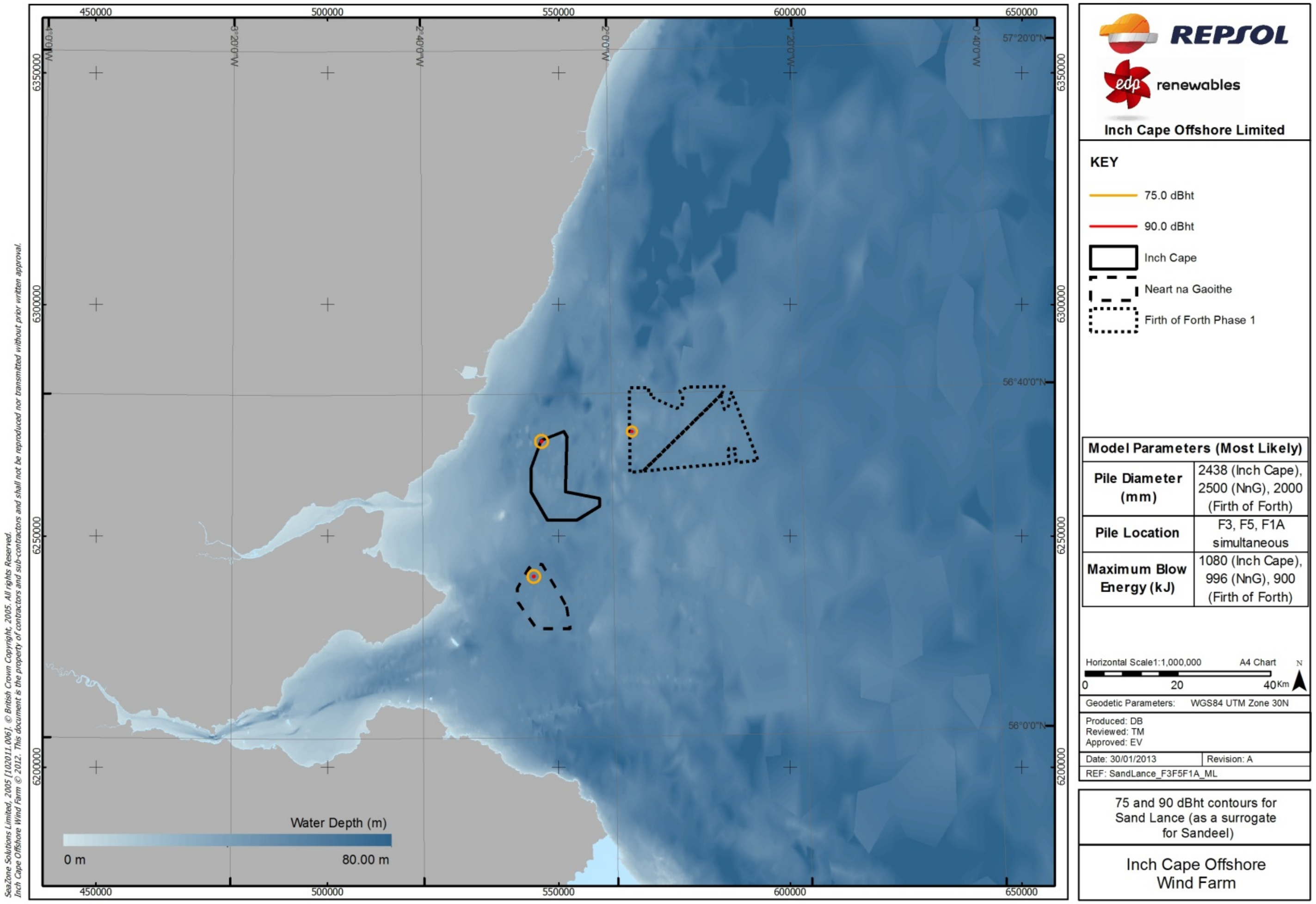


Figure 11A.58: Locations F3, F5, F1A: 90 and 75 dB_{ht} Contours for Trout

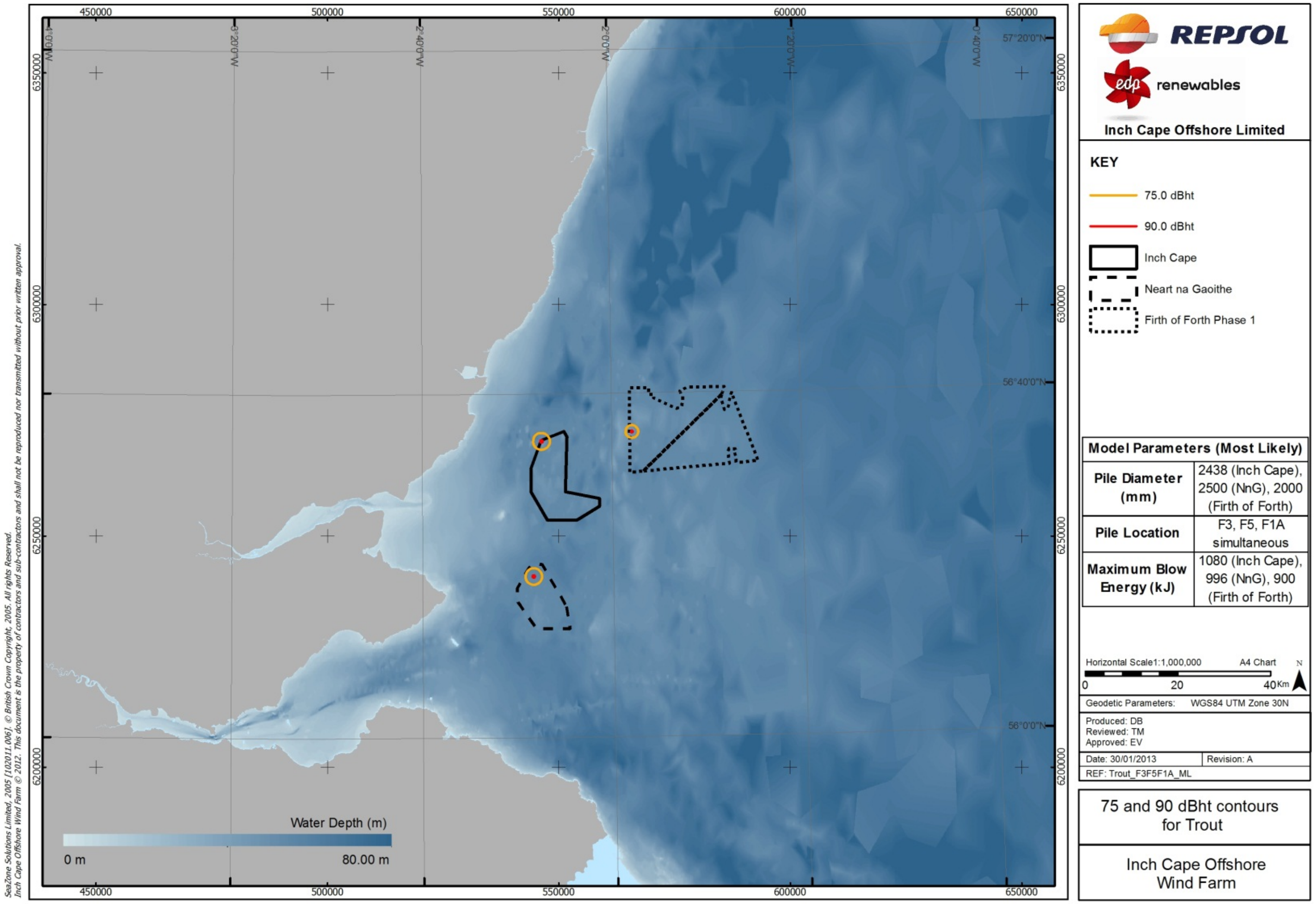


Figure 11A.59: Locations F3, F5, F1A: 90 and 75 dB$_{ht}$ Contours for Bottlenose Dolphin

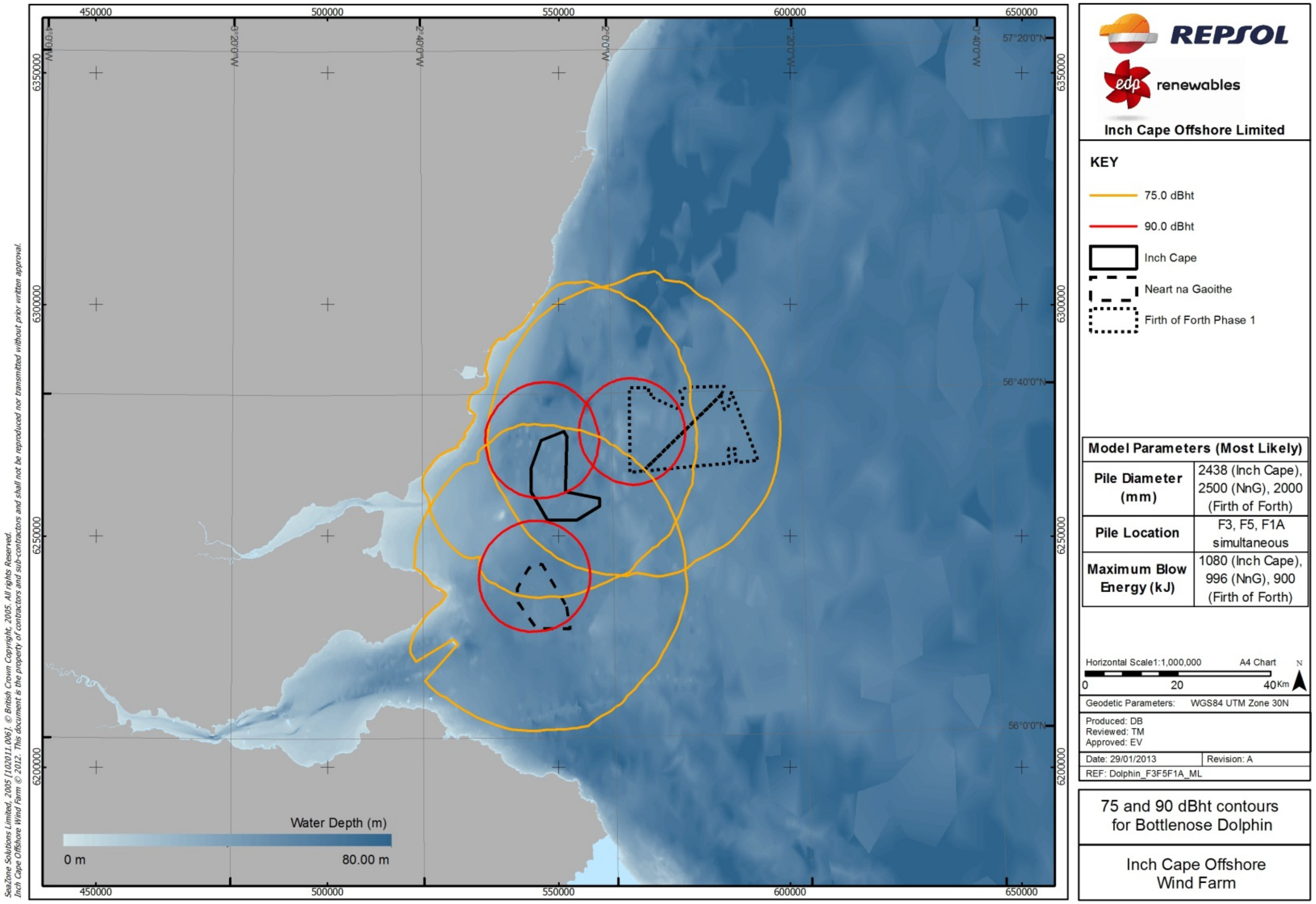


Figure 11A.60: Locations F3, F5, F1A: 90 and 75 dB_{ht} Contours for Humpback Whale (as a Surrogate for Minke Whale)

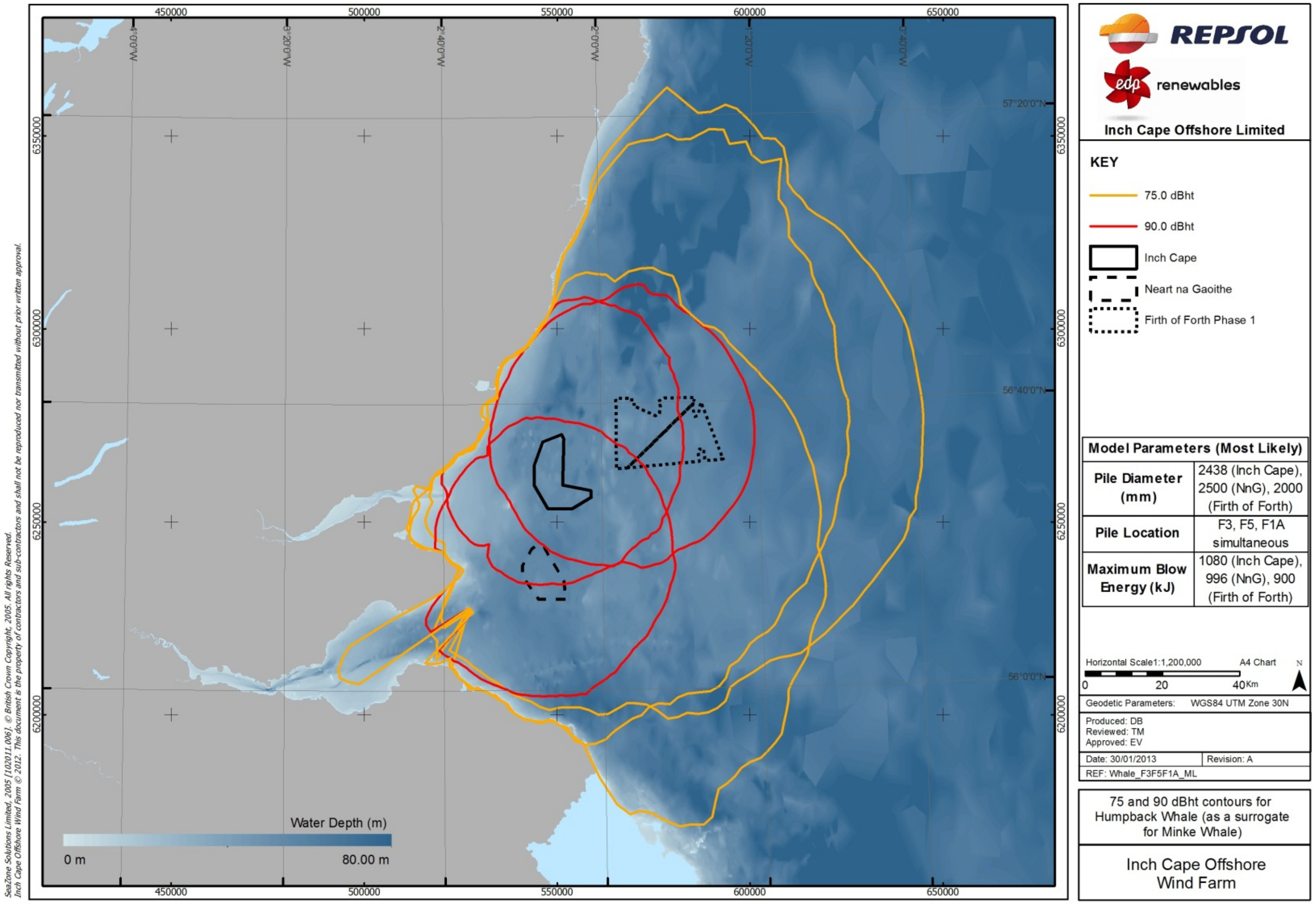


Figure 11A.61: Location F1A, F3, F5: Starting Loci for Fleeing Low Frequency Cetaceans; Two Piles Driven Sequentially at Location 3 at Inch Cape, One Pile Driven at Location 5 at NnG, and One Pile Driven at Location F1A at Firth of Forth Simultaneously

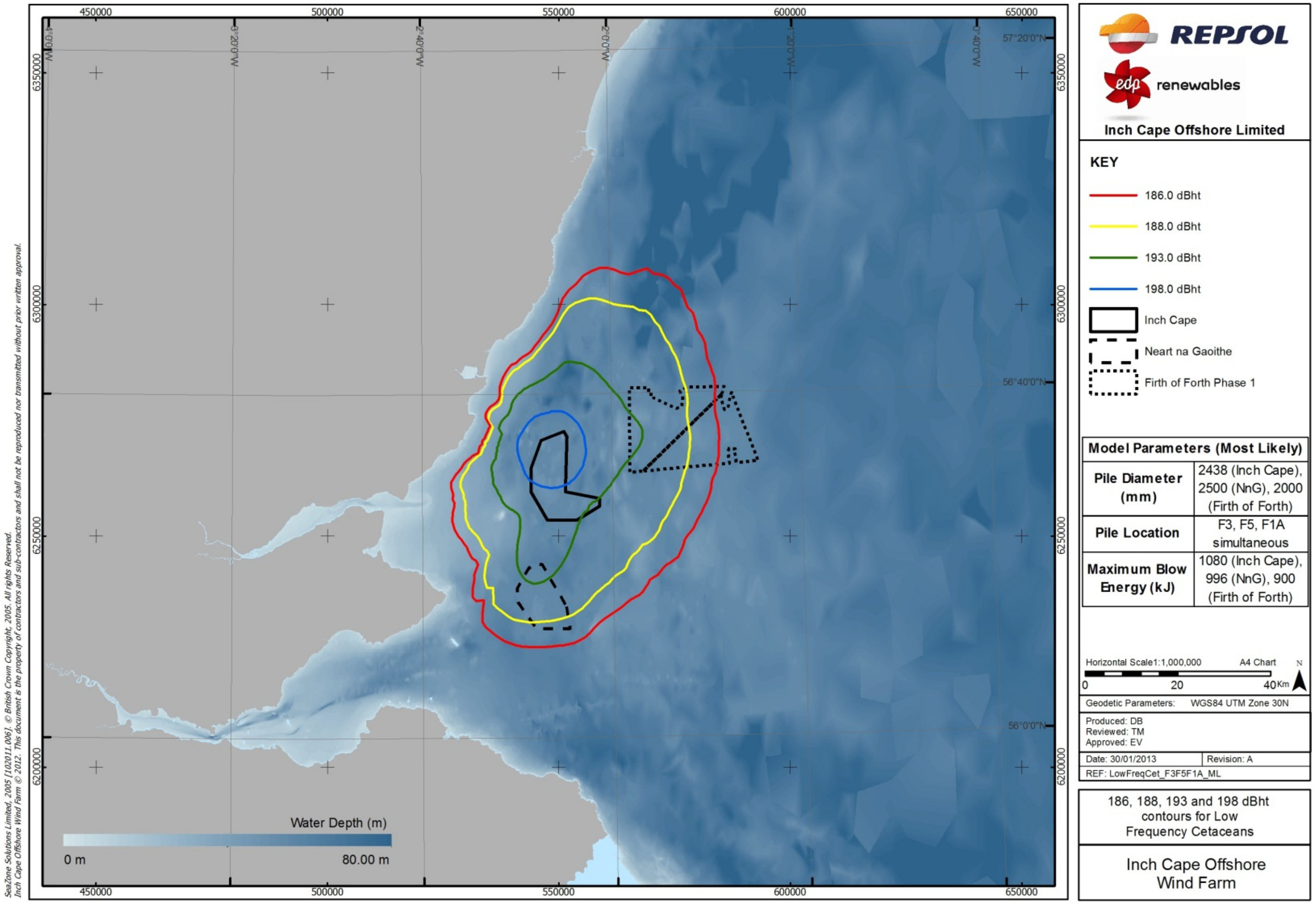


Figure 11A.62: Location F1A, F3, F5: Starting Loci for Fleeing Mid Frequency Cetaceans; Two Piles Driven Sequentially at Location 3 at Inch Cape, One Pile Driven at Location 5 at NnG, and One Pile Driven at Location F1A at Firth of Forth Simultaneously

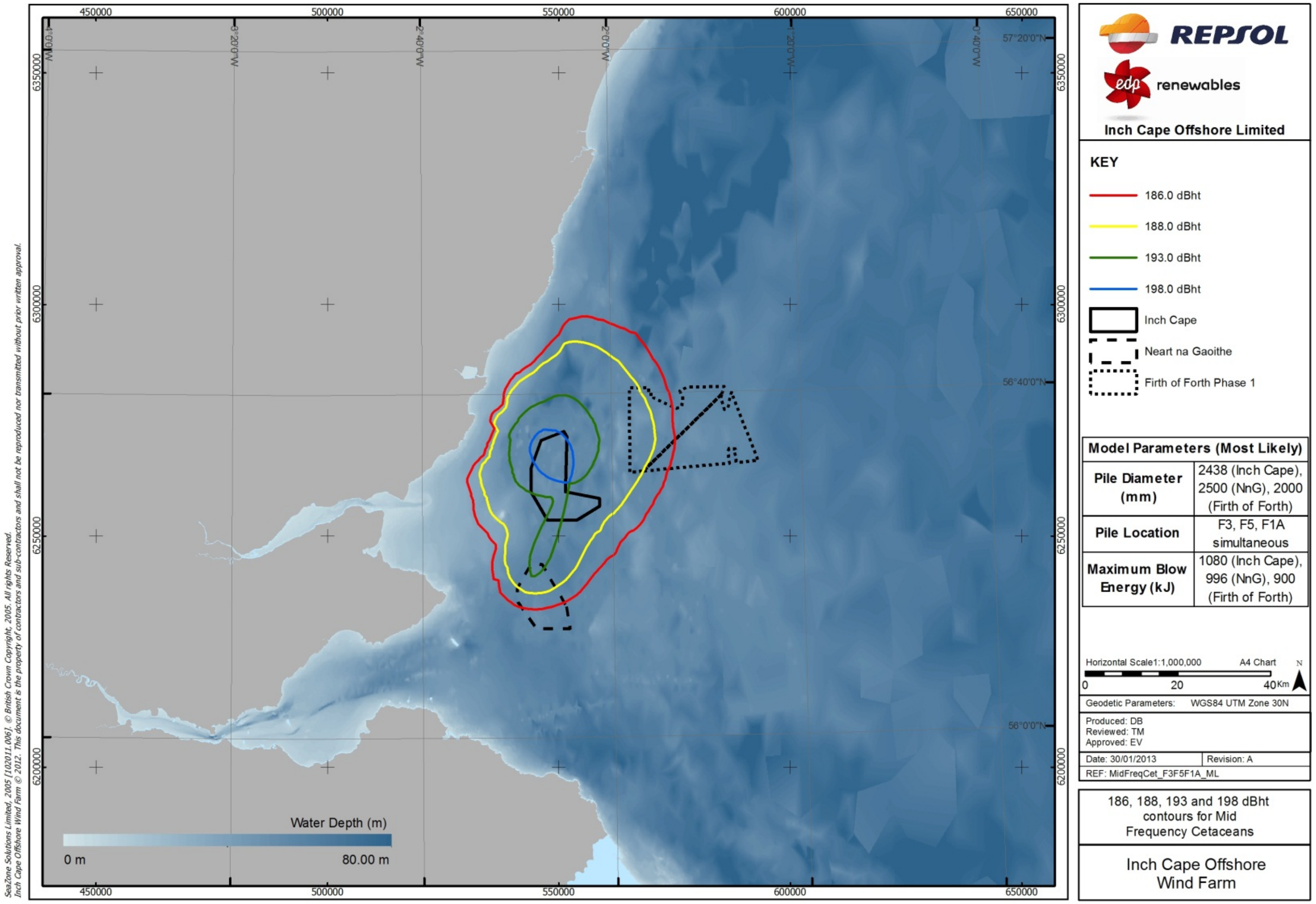


Table 11A.16: Summary of Conditions Modelled for Pile Driven Simultaneously at Location F4 (IC), Location F5 (NnG) and Location F1A (FoF) Using the Most Likely Predicted Piling Scenario

Number of piles per location	Species / Filter	Results shown	Figure No.
n/a	Harbour Seal	90 and 75 dB_{ht} contours	Figure 11A.63
2 piles sequentially at location F4, 1 pile at location F5 and 1 pile at location F1A	Pinnipeds (in water)	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{pw}) for an animal fleeing at 1.5 m/s	Figure 11A.64

Table 11A.17: Summary of Conditions Modelled for Pile Driven Simultaneously at Location F3 (IC), Location F5 (NnG) and Location F2/F1A (FoF) Using the Most Likely Predicted Piling Scenario

Number of piles per location	Species / Filter	Results shown	Figure No.
n/a	Harbour Porpoise	90 and 75 dB_{ht} contours	Figure 11A.65
2 piles sequentially at location F3, 1 pile at location F5 and 1 pile at location F1A	High Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{hf}) for an animal fleeing at 1.5 m/s	Figure 11A.66

Table 11A.18: Summary of Conditions Modelled for Pile Driven Simultaneously at Location F4 (IC), Location F5 (NnG) and Location F2/F1A (FoF) Using the Most Likely Predicted Piling Scenario

Number of piles per location	Species / Filter	Results shown	Figure No.
n/a	Bottlenose Dolphin (as a surrogate for White-beaked Dolphin)	90 and 75 dB_{ht} contours	Figure 11A.67
2 piles sequentially at location F3, 1 pile at location F5 and 1 pile at location F1A	Mid Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{mf}) for an animal fleeing at 1.5 m/s	Figure 11A.68

Figure 11A.63 Locations F4, F5, F1A: 90 and 75 dB_{ht} Contours for Harbour Seal

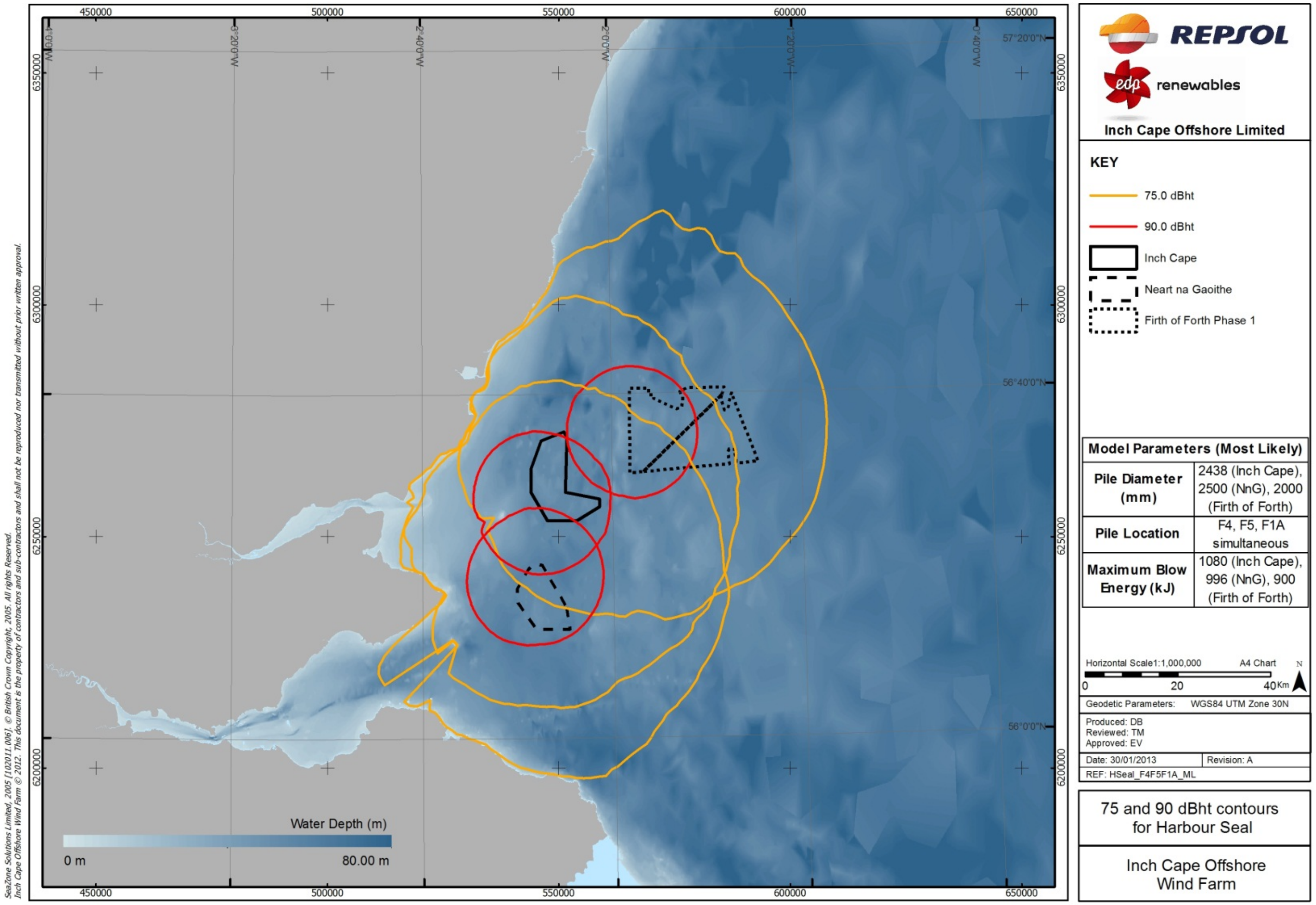


Figure 11A.64: Locations F4, F5, F1A: Starting Loci for Fleeing Pinnipeds (in water); Two Piles Driven Sequentially at Inch Cape, One Pile Driven at NnG, and One Pile driven at Firth of Forth Simultaneously

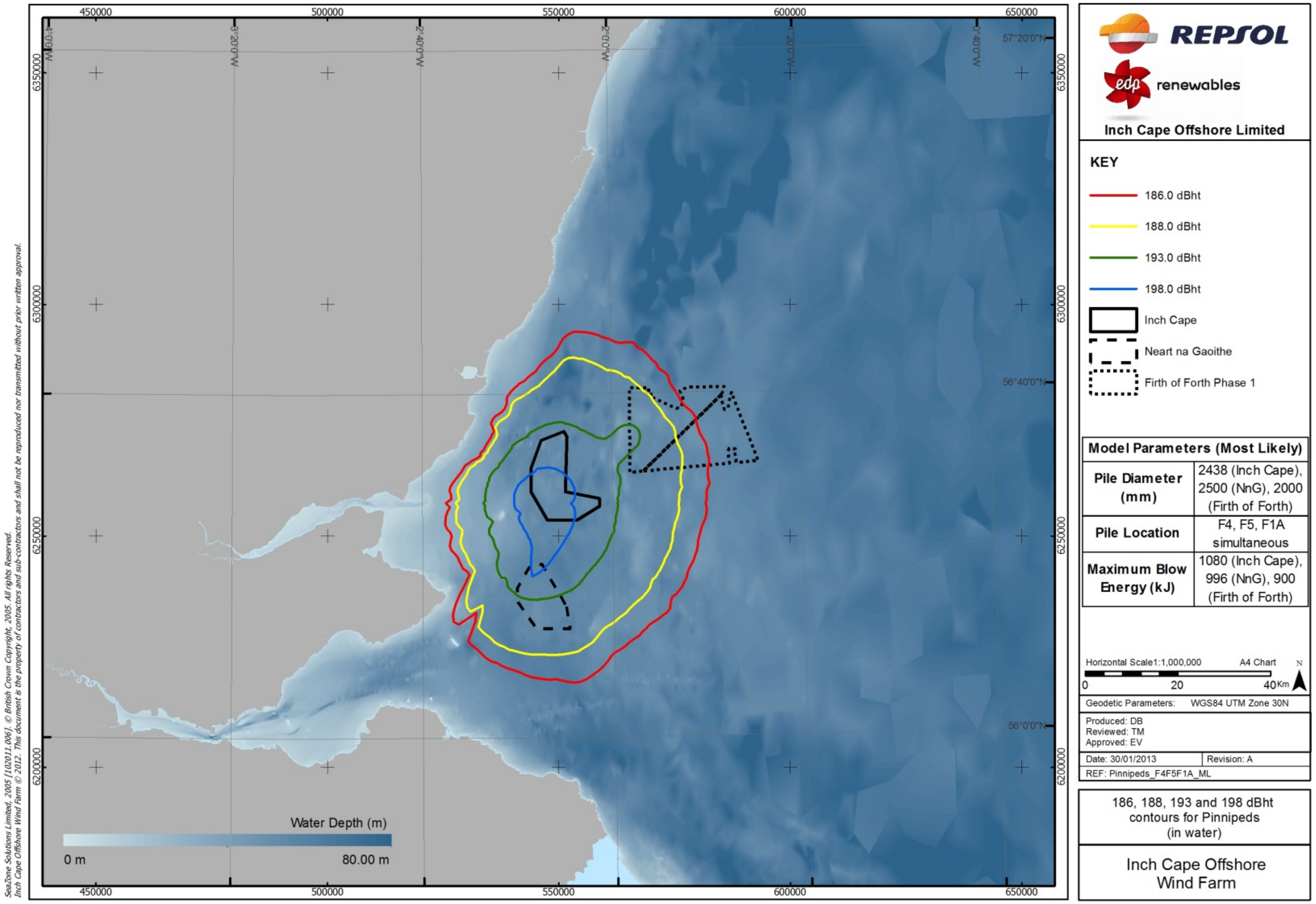


Figure 11A.65: Locations F3, F5, F2A: 90 and 75 dB_{ht} Contours for Harbour Porpoise

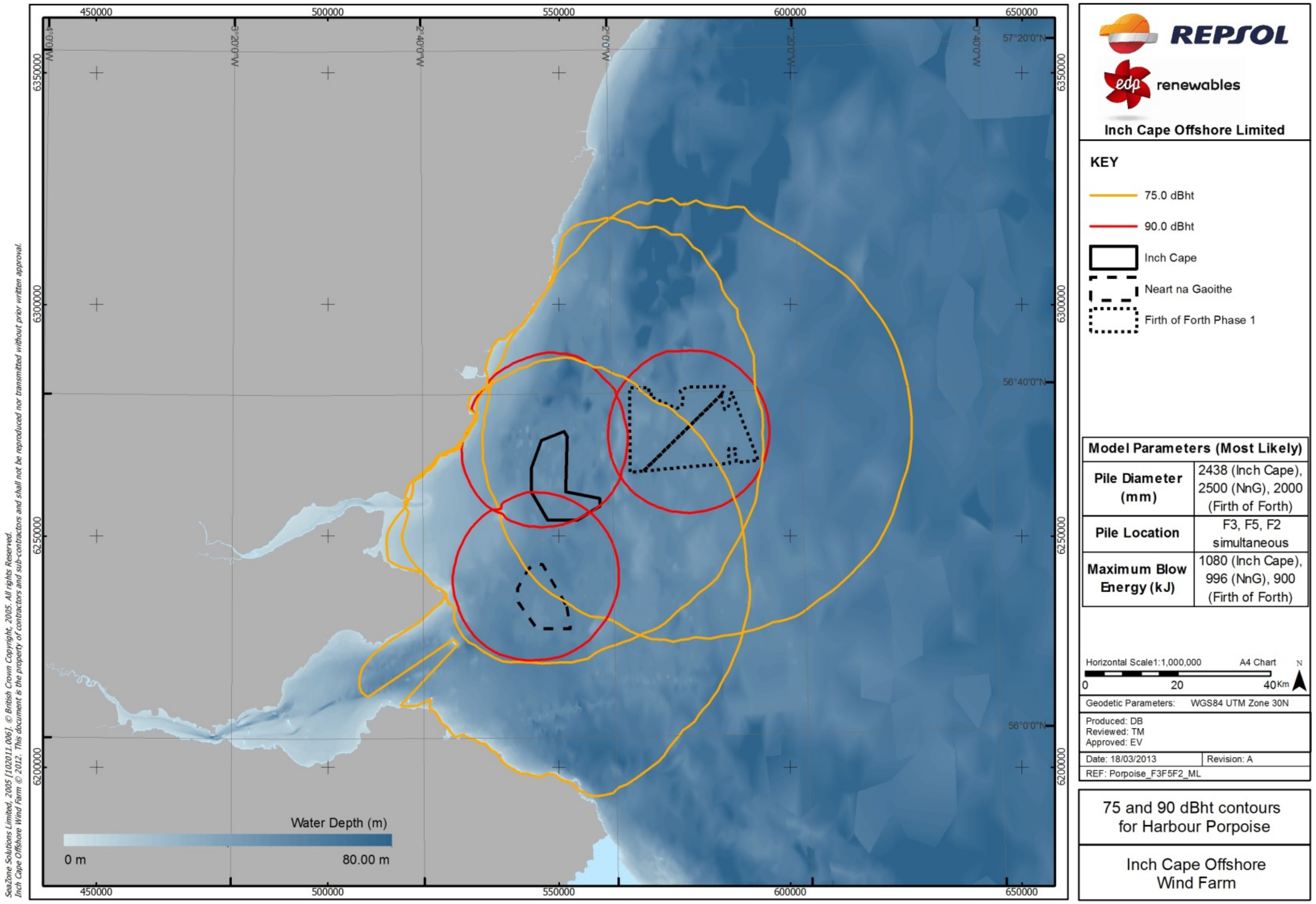


Figure 11A.66: Location F1A, F3, F5: Starting Loci for Fleeing High Frequency Cetaceans; Two Piles Driven Sequentially at Location 3 at Inch Cape, One Pile Driven at Location 5 at NnG, and One Pile Driven at Location F1A at Firth of Forth Simultaneously

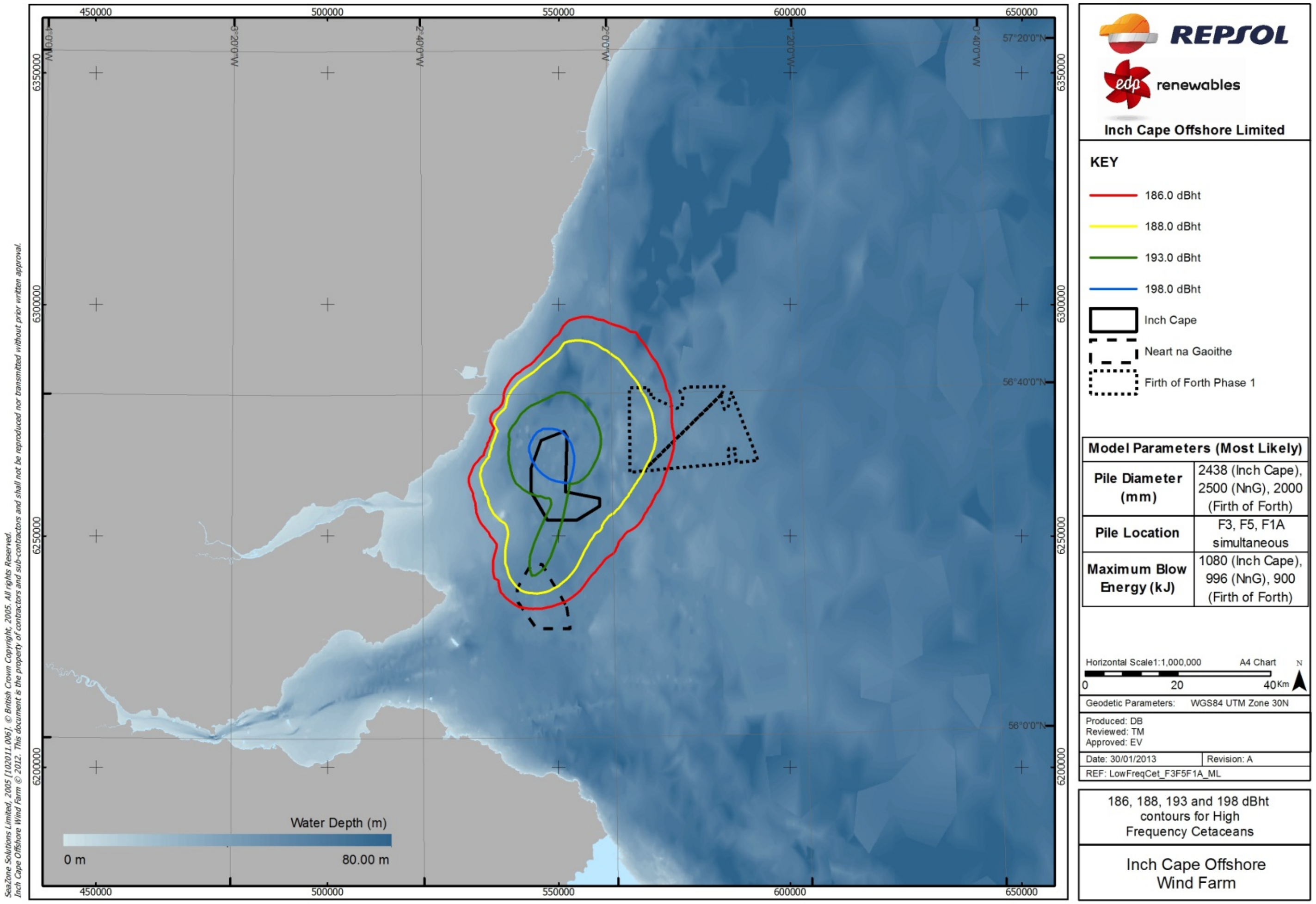


Figure 11A.67: Locations F4, F5, F2: 90 and 75 dB_{ht} Contours for Bottlenose Dolphin (as a Surrogate for White-Beaked Dolphin)

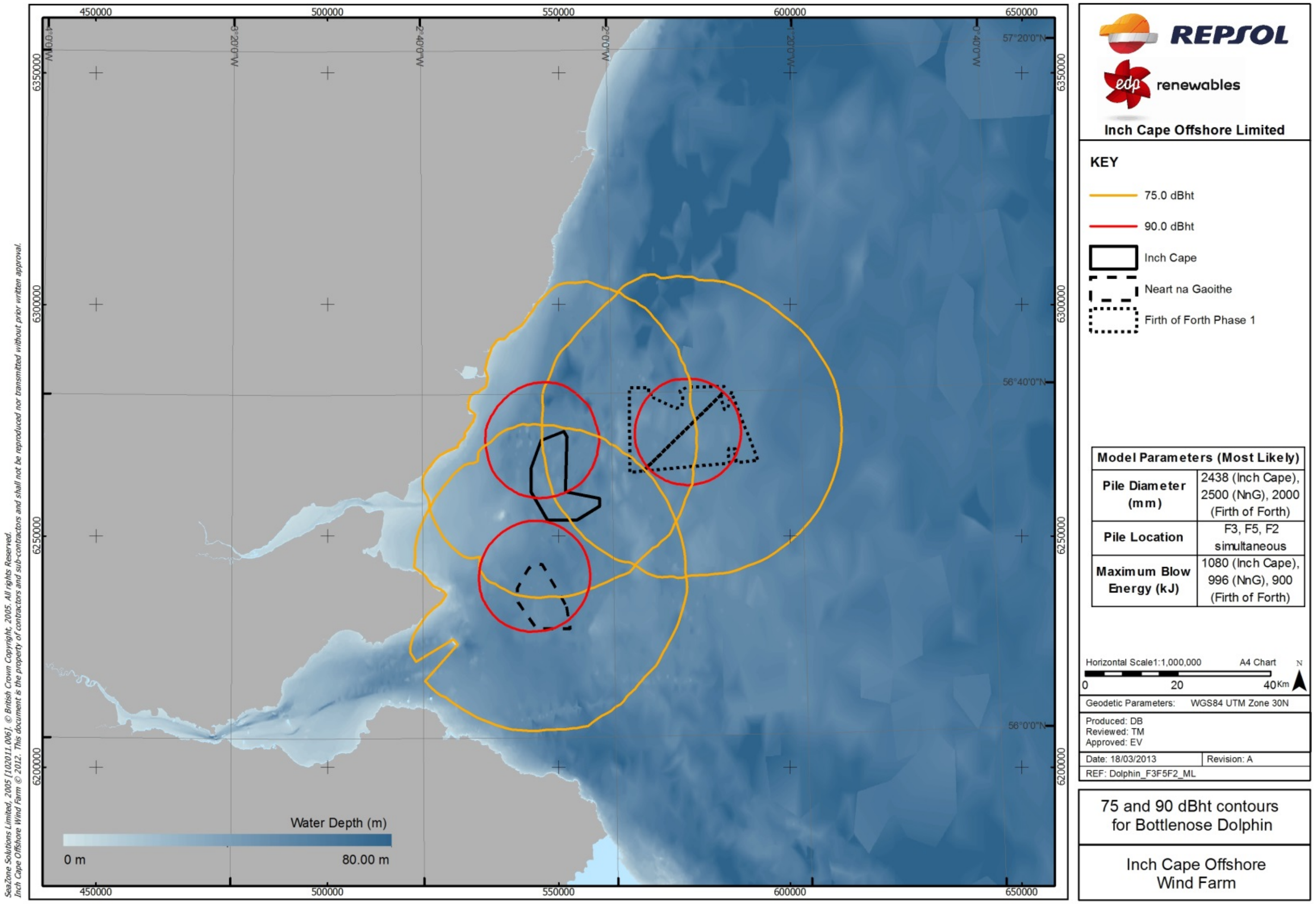


Figure 11A.68: Locations F4, F5, F1A: Starting Loci for Fleeing Mid Frequency Cetaceans; Two Piles Driven Sequentially at Inch Cape, One Pile Driven at NnG, and One Pile Driven at Firth of Forth Simultaneously

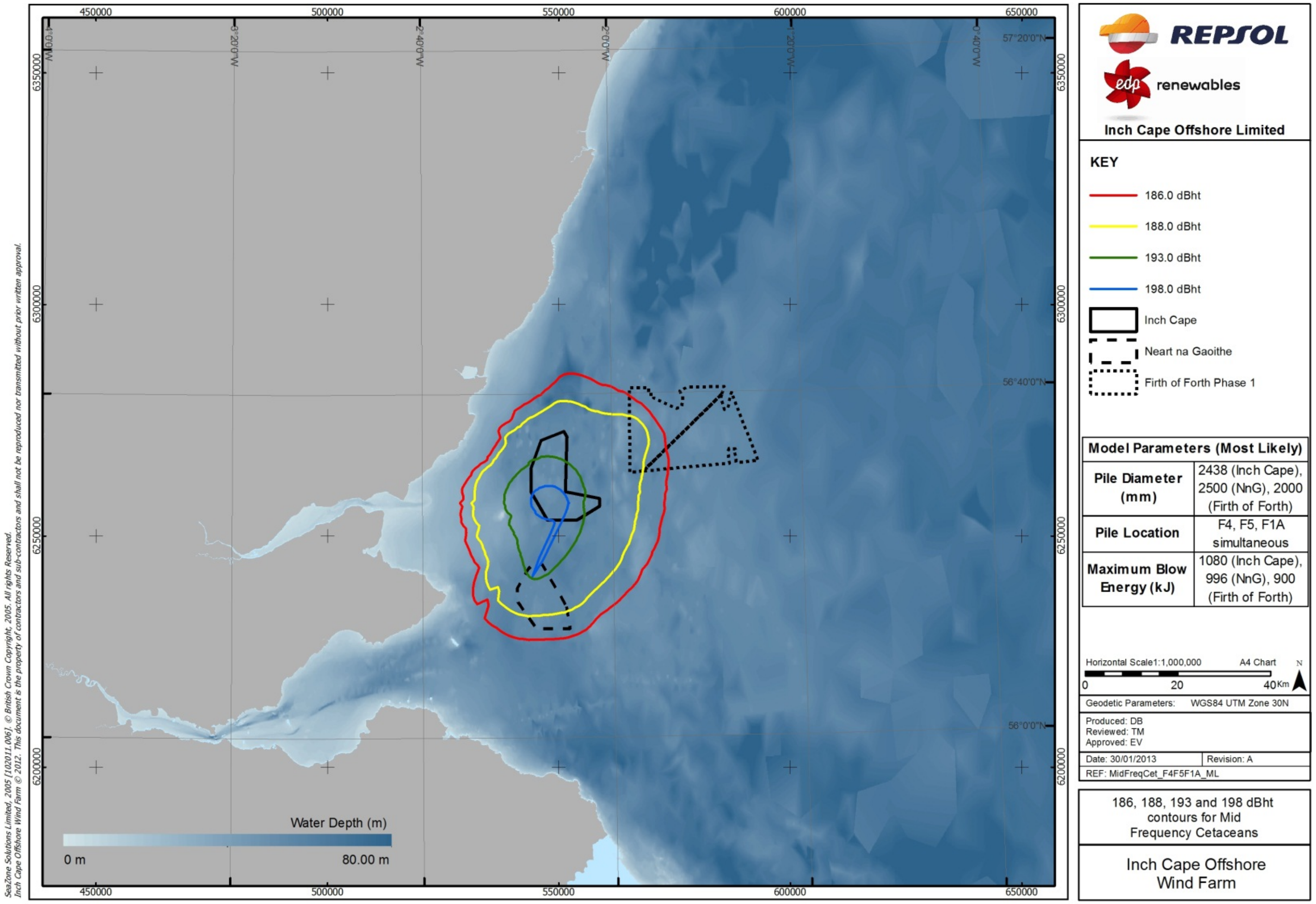


Table 11A.19: Summary of Conditions Modelled for Two Piles Driven Simultaneously at IC, NnG and FoF (Most Likely Predicted Blow Energy Profile)

Number of piles per location	Species / Filter	Results shown	Figure No.
n/a	Dab (as a surrogate for Plaice)	90 and 75 dB_{ht} contours	Figure 11A.69
n/a	Herring	90 and 75 dB_{ht} contours	Figure 11A.70
n/a	Salmon	90 and 75 dB_{ht} contours	Figure 11A.71
n/a	Sand Lance (as a surrogate for Sandeel)	90 and 75 dB_{ht} contours	Figure 11A.72
n/a	Trout	90 and 75 dB_{ht} contours	Figure 11A.73
n/a	Bottlenose Dolphin	90 and 75 dB_{ht} contours	Figure 11A.74
n/a	Harbour Porpoise	90 and 75 dB_{ht} contours	Figure 11A.75
n/a	Harbour Seal	90 and 75 dB_{ht} contours	Figure 11A.76
n/a	Humpback Whale (as a surrogate for Minke Whale)	90 and 75 dB_{ht} contours	Figure 11A.77
2 piles sequentially at locations F3 and F4. 1 pile at each F5, F6, F1A and F2. Piling at all six locations commences simultaneously.	Low Frequency Cetacean	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M_{lf}) for an animal fleeing at 1.5 m/s	Figure 11A.78
	Mid Frequency Cetacean		Figure 11A.79
	High Frequency Cetacean		Figure 11A.80
	Pinnipeds (in water)		Figure 11A.81

Figure 11A.69: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Dab (as a Surrogate for Plaice)

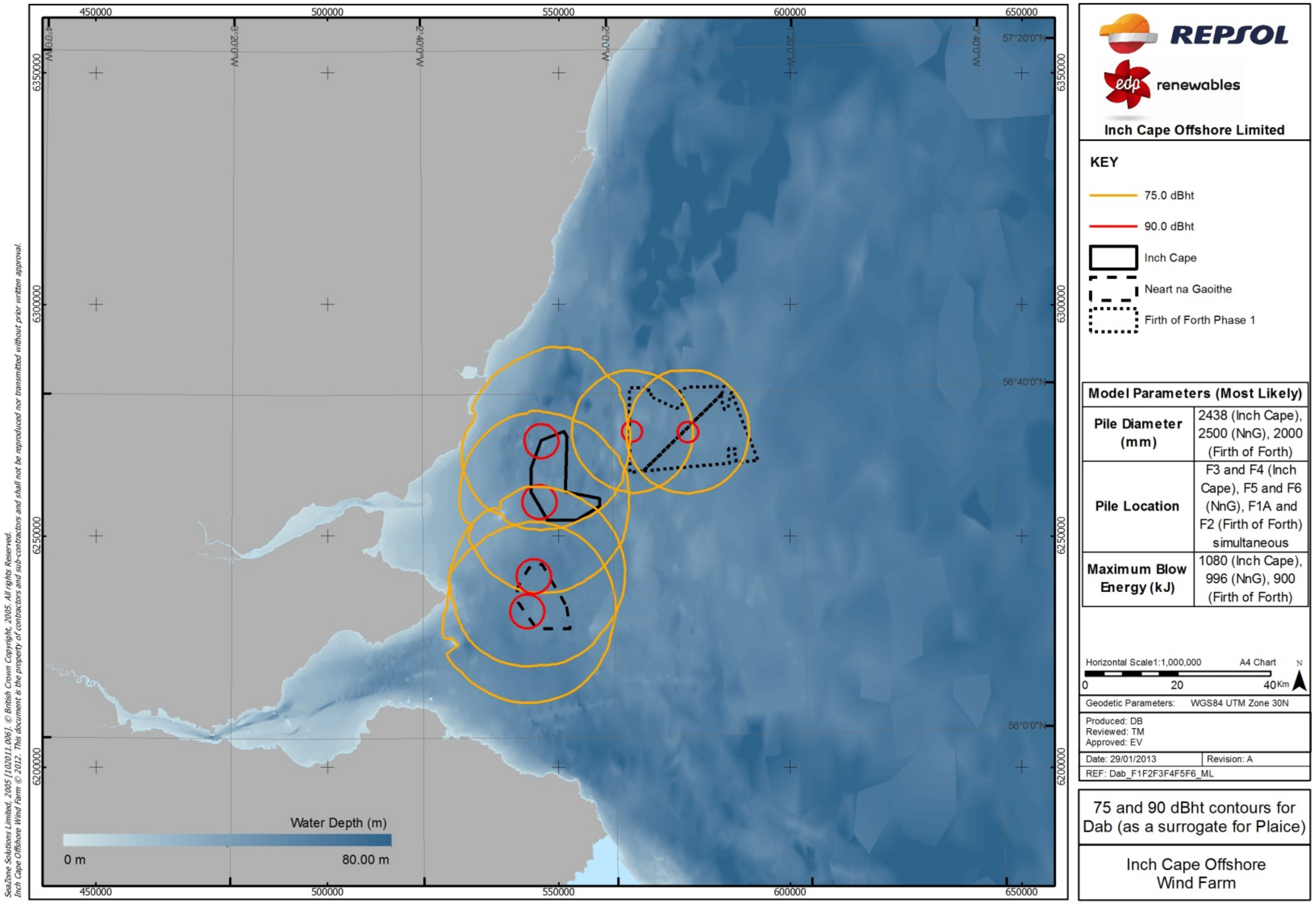


Figure 11A.70: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Herring

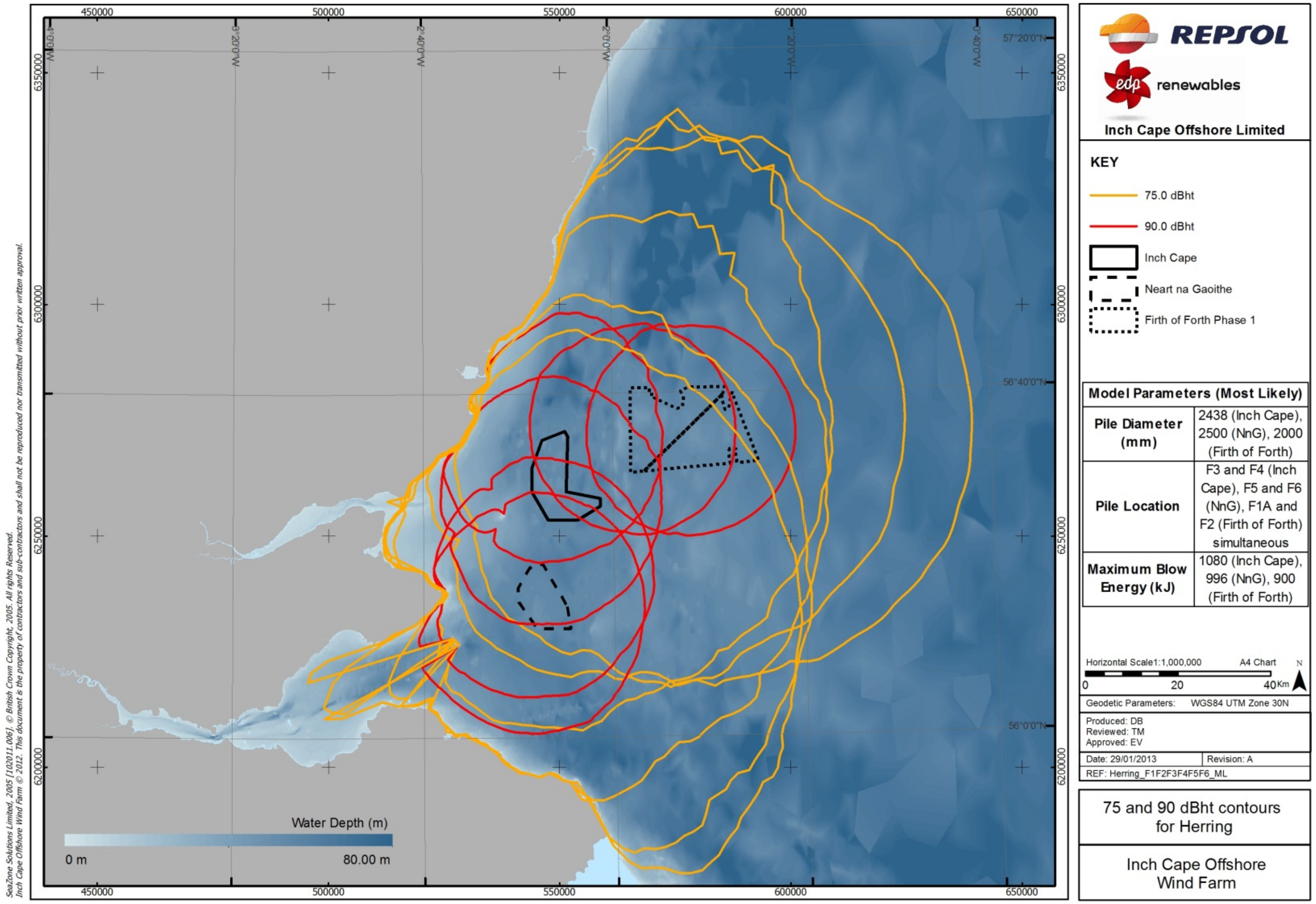


Figure 11A.71: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Salmon

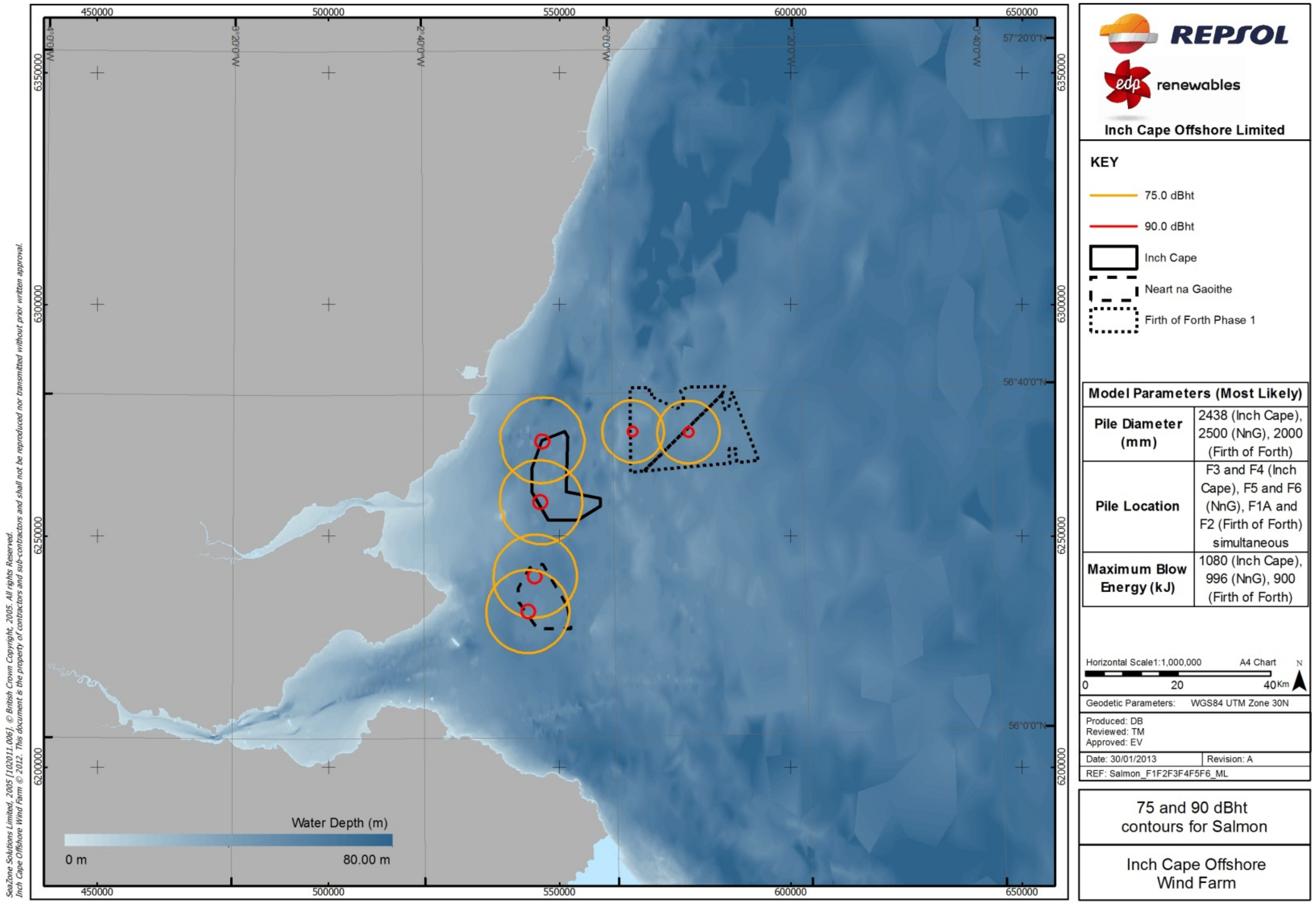


Figure 11A.72: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Sand Lance (as a Surrogate for Sandeel)

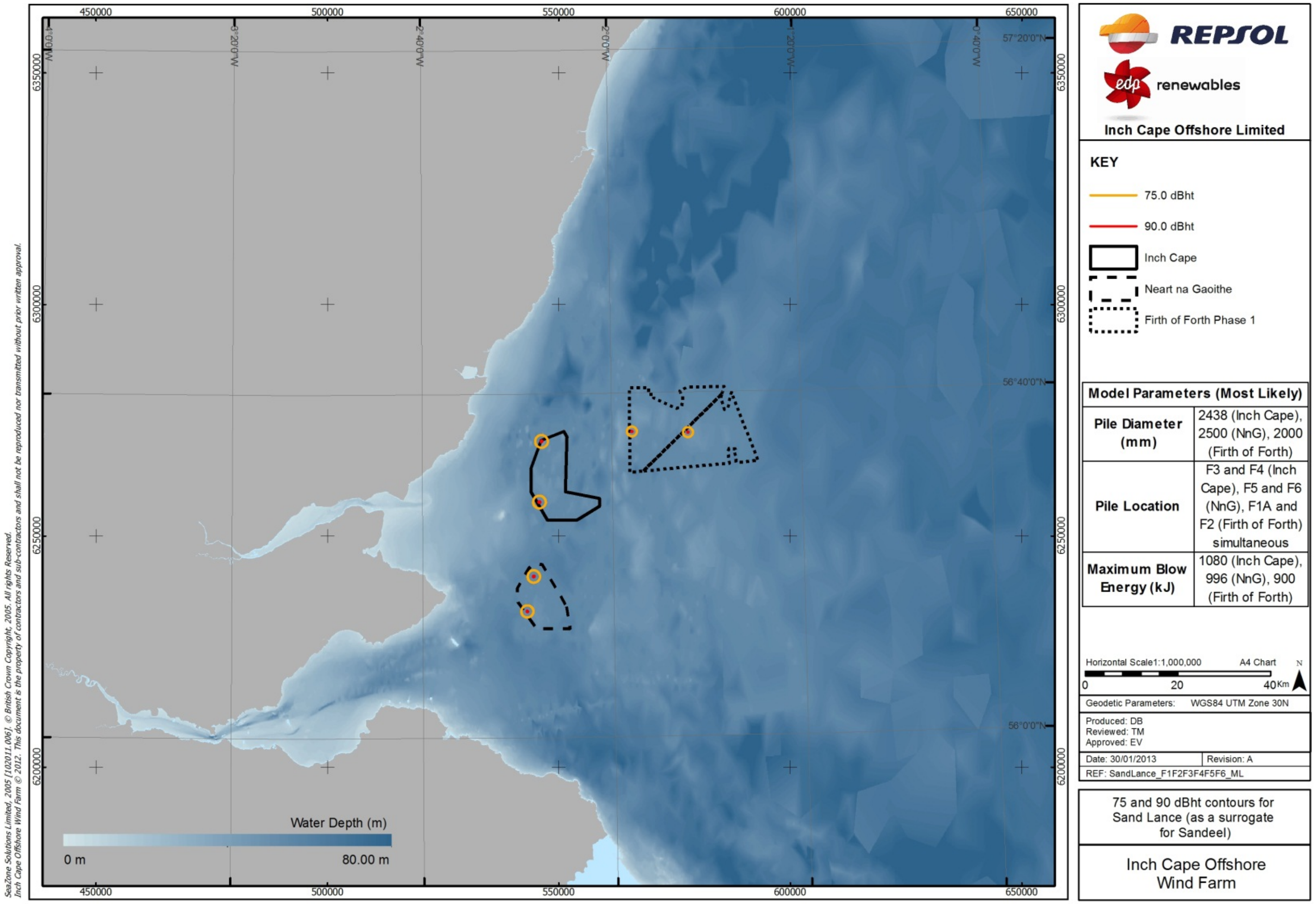


Figure 11A.73: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Trout

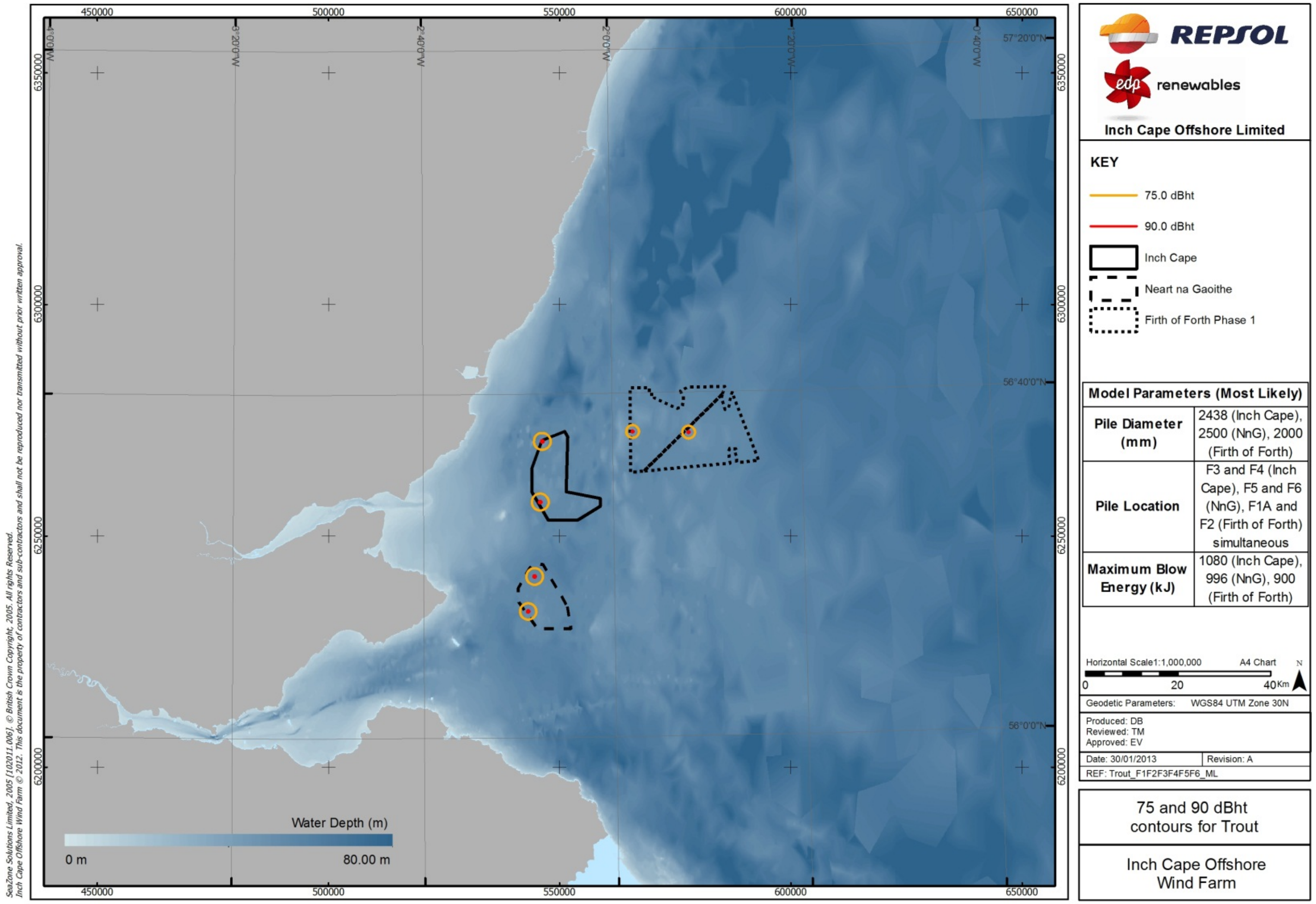


Figure 11A.74: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Bottlenose Dolphin

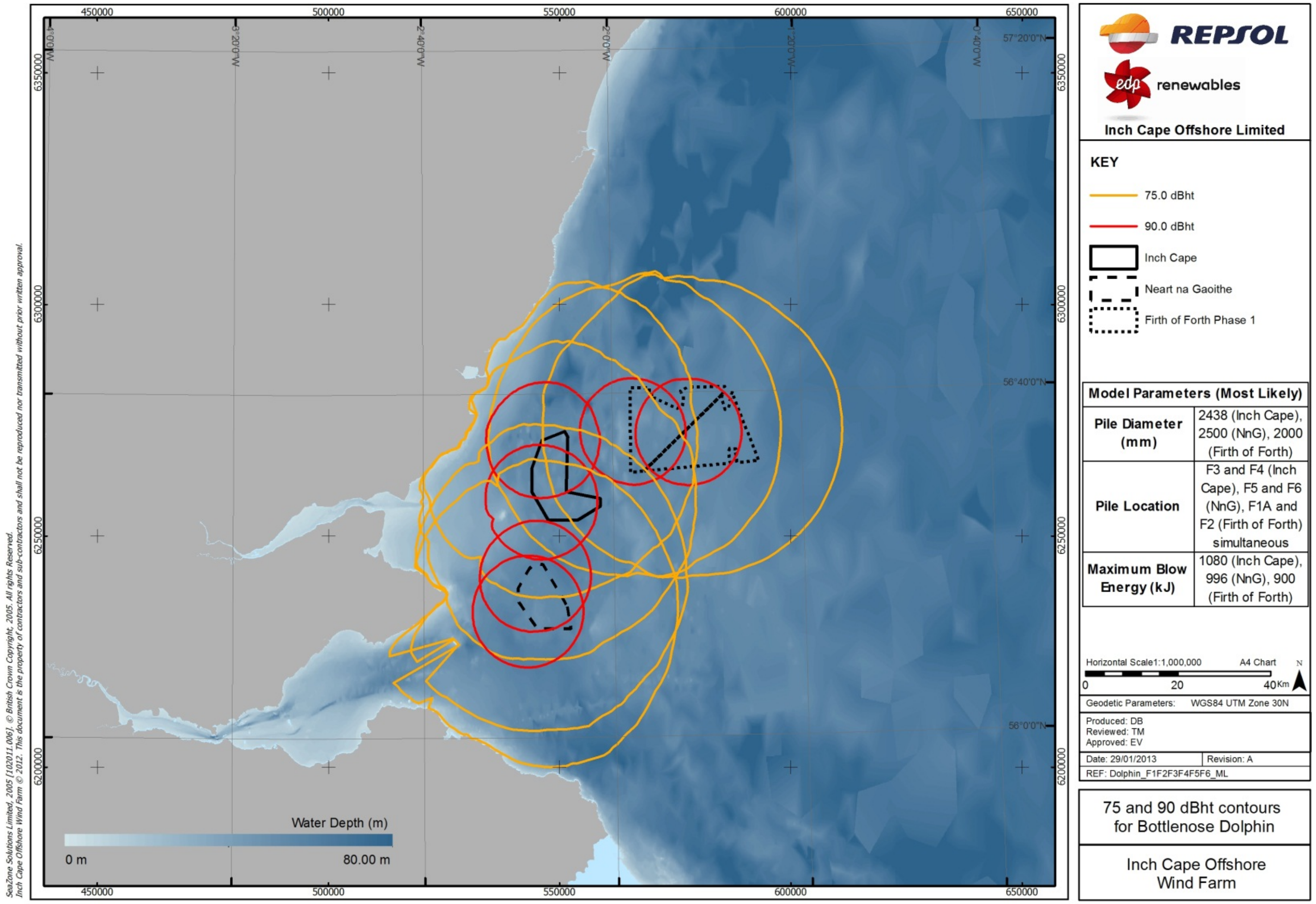


Figure 11A.75: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Harbour Porpoise

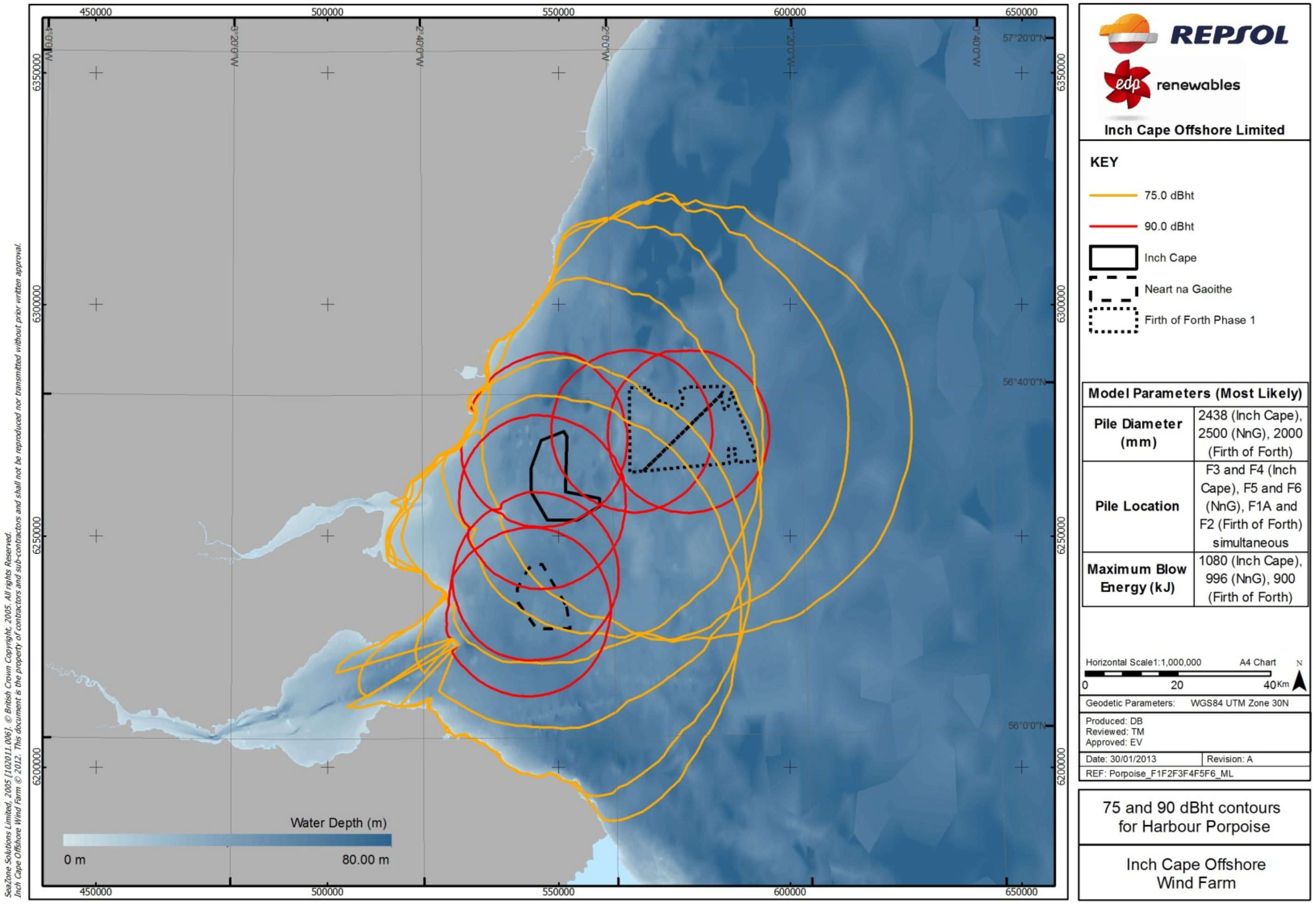


Figure 11A.76: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Harbour Seal

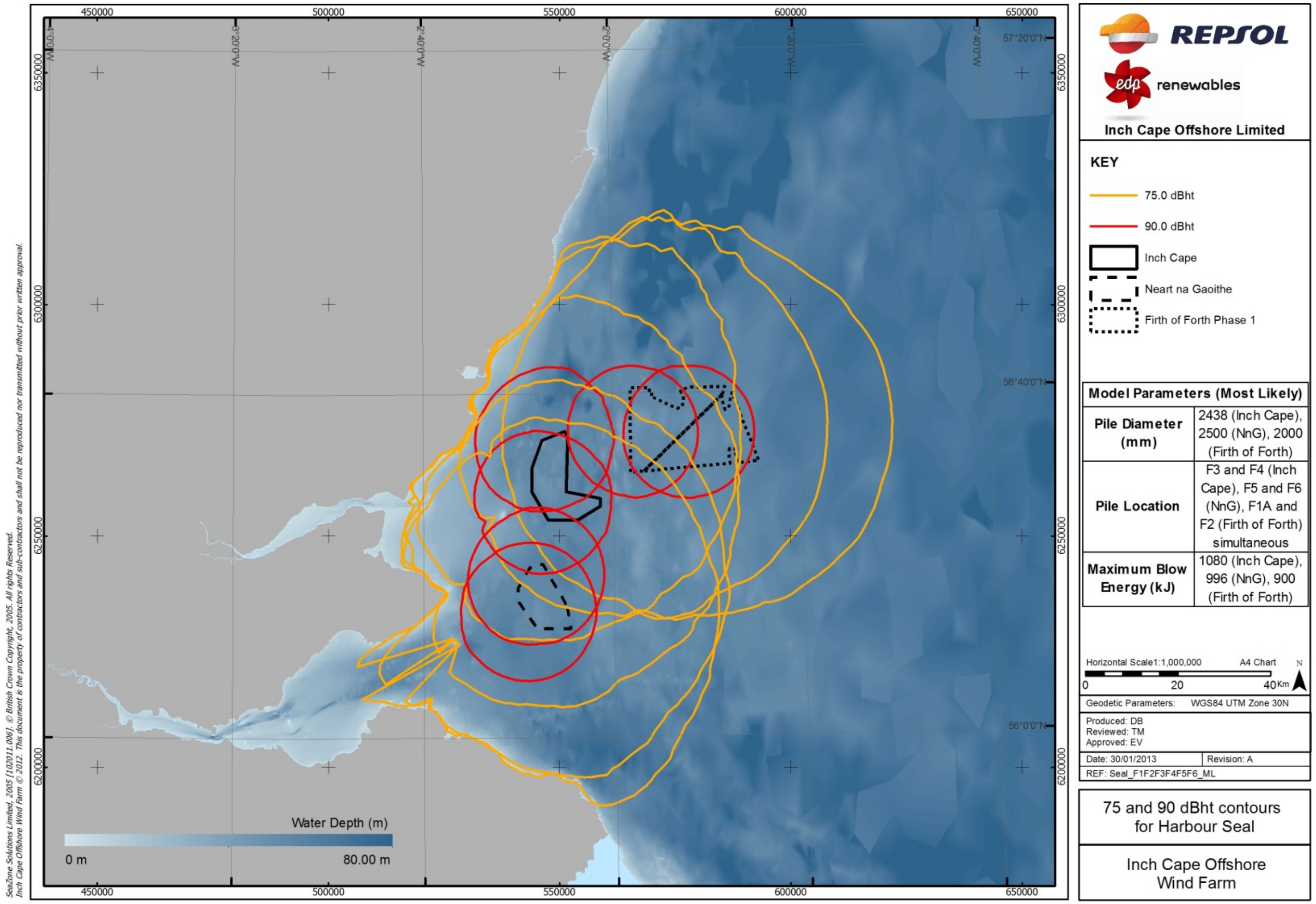


Figure 11A.77: Locations F1A, F2, F3, F4, F5, F6: 90 and 75 dB_{ht} Contours for Humpback Whale (as a Surrogate for Minke Whale)

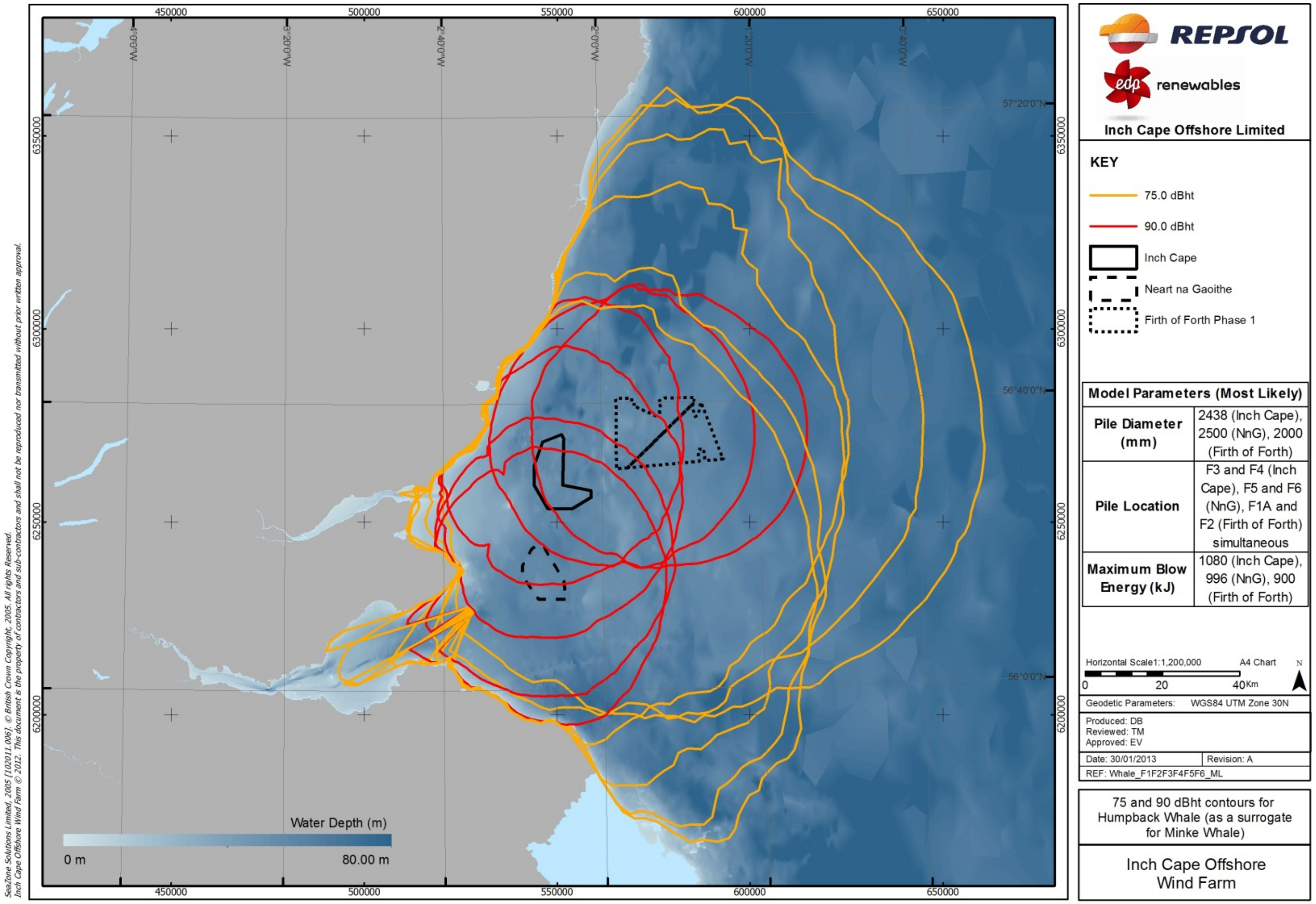


Figure 11A.78: Starting loci for Fleeing Low Frequency Cetaceans; Two Piles Driven Sequentially at Locations F3 and F4 at Inch Cape, One Pile Driven at Locations F5 and F6 at NnG, and One Pile Driven at Locations F1A and F2 at Firth of Forth Simultaneously

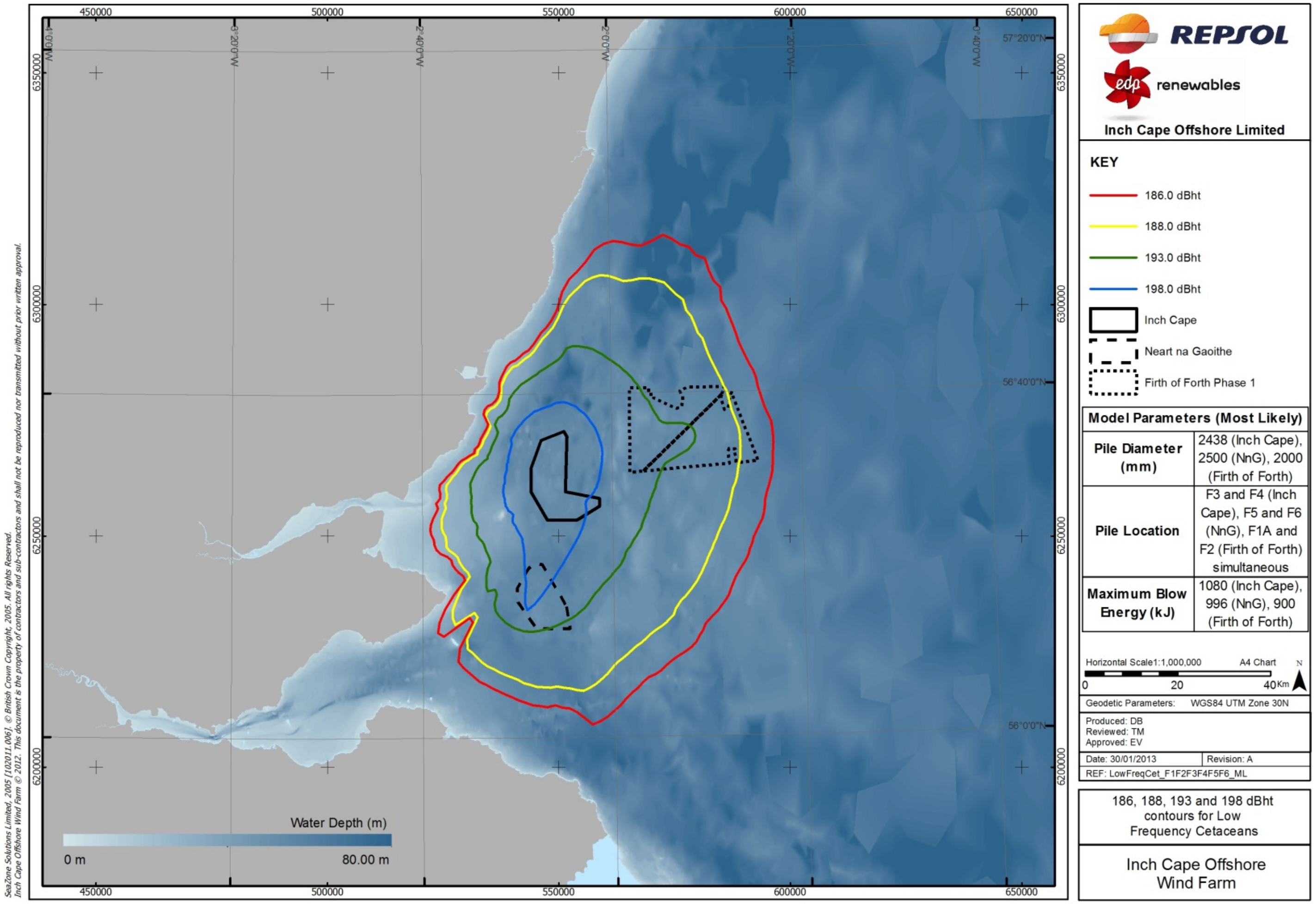


Figure 11A.79: Starting Loci for Fleeing Mid Frequency Cetaceans; Two Piles Driven Sequentially at Locations F3 and F4 at Inch Cape, One Pile Driven at Locations F5 and F6 at NnG, and One Pile Driven at Locations F1A and F2 at Firth of Forth Simultaneously

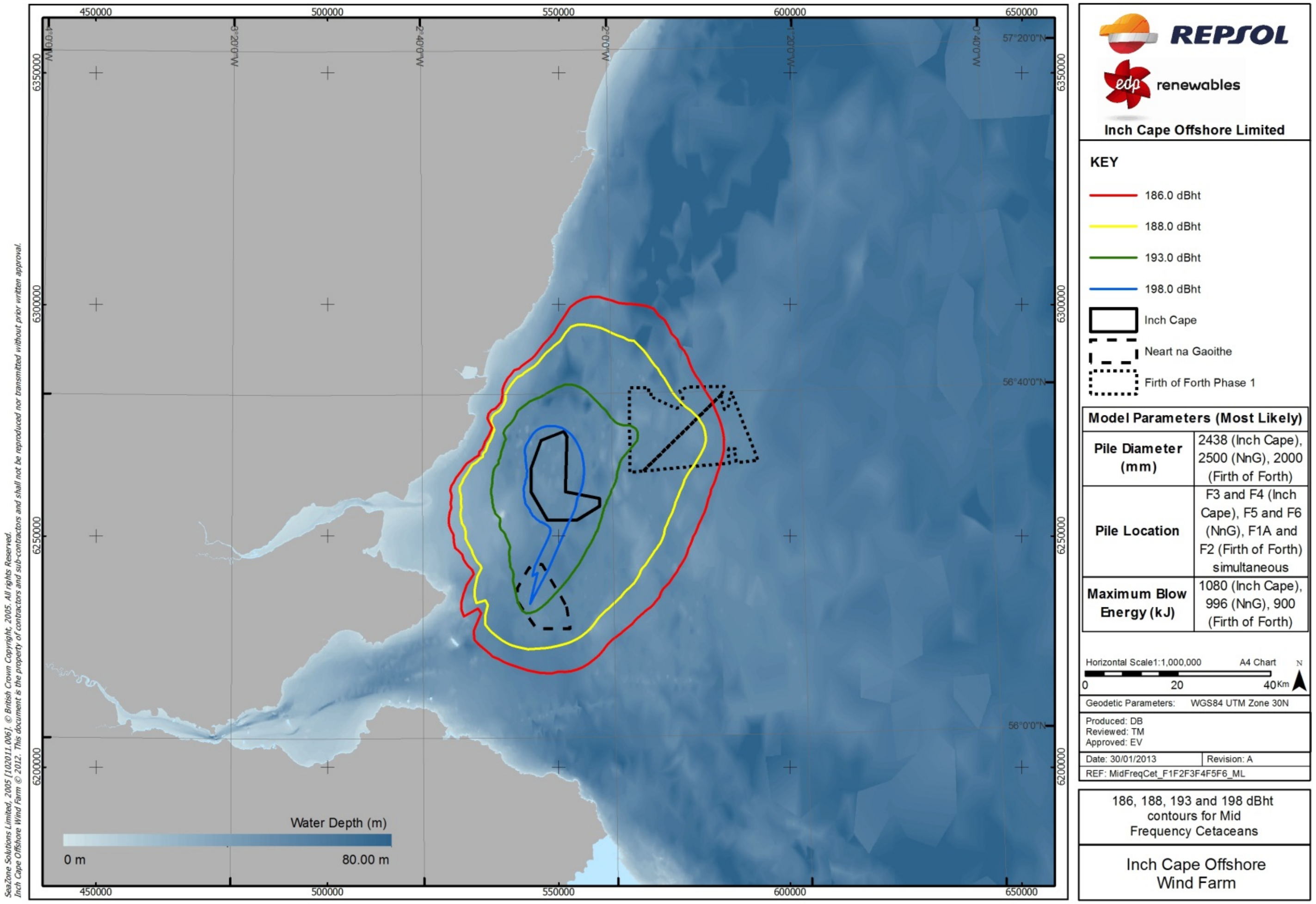


Figure 11A.80: Starting Loci for Fleeing High Frequency Cetaceans; Two Piles Driven Sequentially at Locations F3 and F4 at Inch Cape, One Pile Driven at Locations F5 and F6 at NnG, and One Pile Driven at Locations F1A and F2 at Firth of Forth Simultaneously

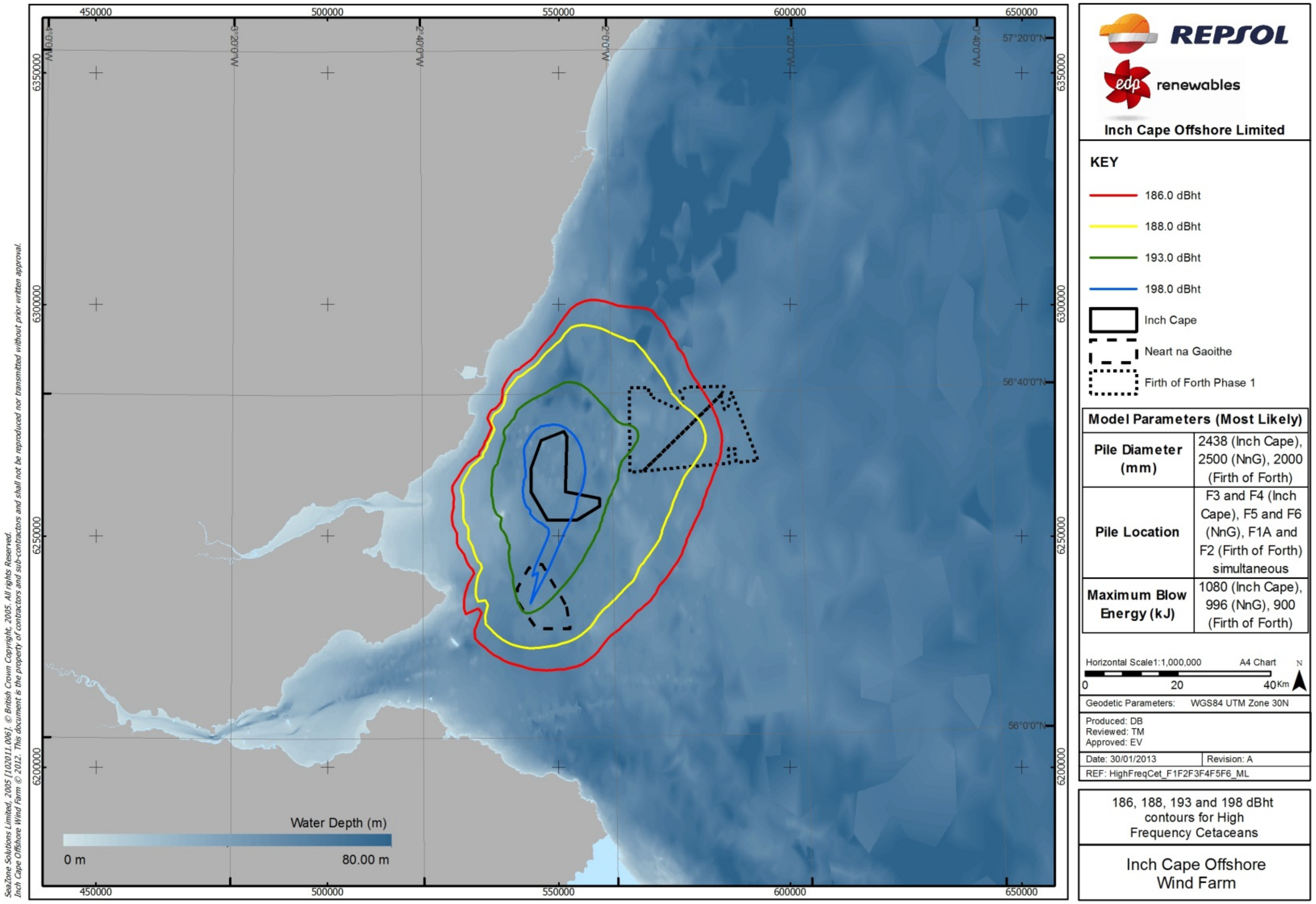
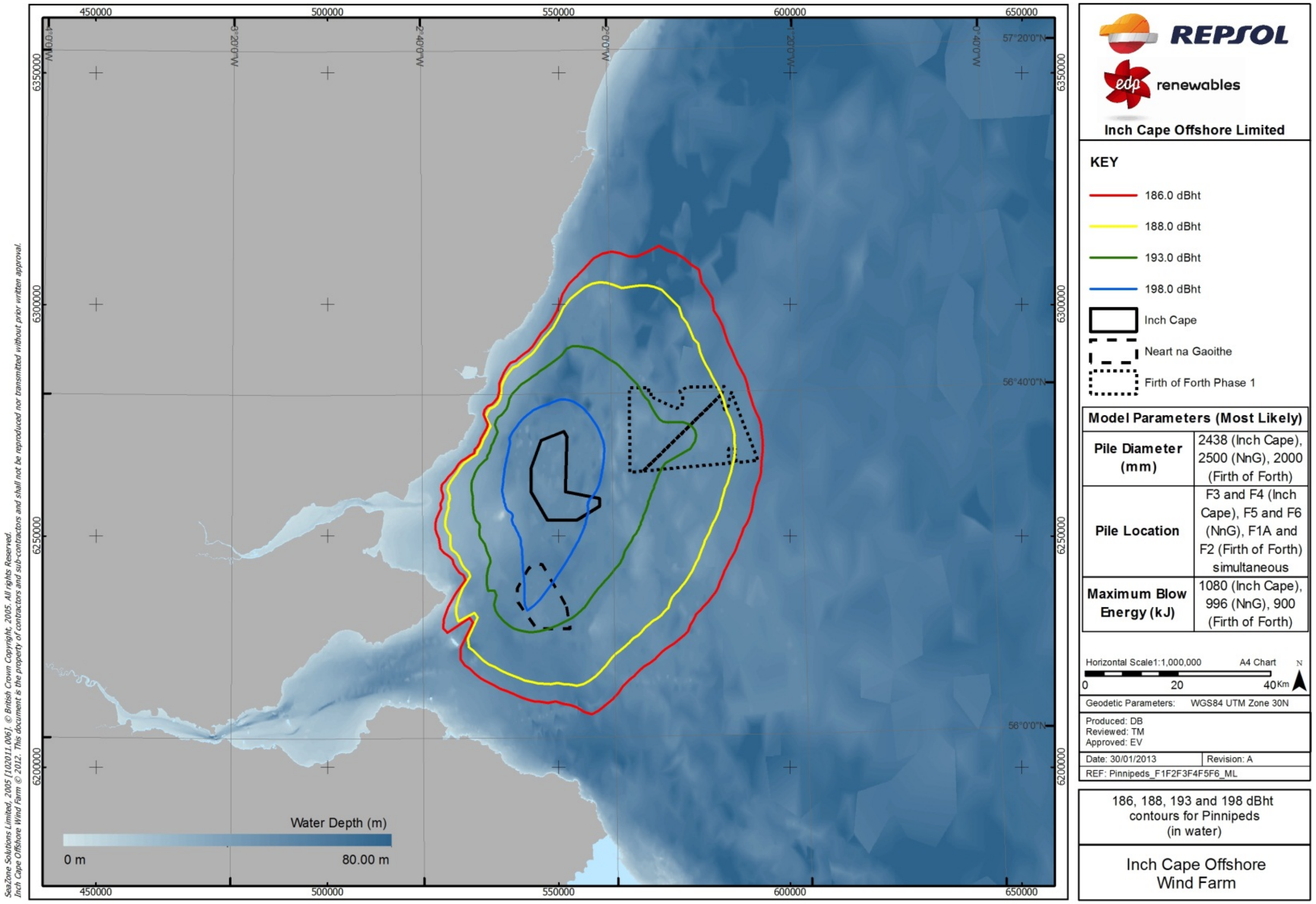


Figure 11A.81: Starting Loci for Fleeing Pinnipeds (in water); Two Piles Driven Sequentially at Locations F3 and F4 at Inch Cape, One Pile Driven at Locations F5 and F6 at NnG, and One Pile Driven at Locations F1A and F2 at Firth of Forth Simultaneously



11A.7 Summary

The ranges of propagated, perceptible noise and sound exposure levels of introduced noise as a result of impact piling in multiple locations during the construction of Inch Cape, as well as the nearby Neart na Gaoithe and Firth of Forth Phase I offshore wind farms, has been calculated using the proprietary INSPIRE noise modelling software. The range of noise emissions with reference to the different species has been calculated in respect of dB_{ht}(*Species*) and M-Weighted dB SEL to assess the potential impact of piling on marine species. This is both in terms of injury and behavioural response.

Audible noise ranges have also been calculated for non-piling construction and operation activities using the SPEAR model, and have been presented graphically as areas of sea likely to be exposed to disturbance related levels of noise.

These calculated levels have been used to inform the natural fish and marine mammal impact assessments.

References

Arons A B. (1954). *Underwater explosion shock wave parameters at large distances from the charge*. JASA, 26, 3, pp 3143.

Bebb A C, and Wright H C. (1953). *Injury to animals from underwater explosions*. Medical Research Council, Royal Navy Physiological Report 53/732, Underwater Blast Report 31, January 1953.

Bebb A C, and Wright H C. (1954a). *Lethal conditions from underwater explosion blast*. RNP Report 51/654, RNPL 3/51, National archives reference ADM 298/109, March 1954.

Bebb A C, and Wright H C. (1954b). *Protection from underwater explosion blast. III Animal experiments and physical measurements*. RNP Report 54/792, RNPL 2/54, March 1954.

Bebb A C, and Wright H C. (1955). Und*erwater explosion blast data from the Royal Navy Physiological Labs*. 1950/55. Medical Research Council, April 1955.
Blaxter J H S, Denton E J, and Gray J A B. (1981). *Acousticolateralis system in clupeid fishes*. Ed's Tavolga W, Popper A, Fay R. *Hearing and sound communication in fishes*. Springer Verlag, New York, pp 39-61

Chapman C J, and Sand O. (1974). *Field studies of hearing in two species of flatfish; Pleuronectes platessa (L.) and Limanda limanda (L.) (Family Pleuronectidae)*. Comp. Biochem. Physiol. 47A, pp 371-385

Cudahy E, and Parvin S J. (2001). *The effects of underwater blast on divers*. Naval Submarine Medical Research Laboratory Report 1218, Groton, CT 06349 62 p.

Enger P S. (1967). *Hearing in herring*. Comp. Biochem. Physiol., Vol 22: pp 527-538.

Erbe C. (2002). *Underwater noise of whale-watching boats and potential effects on killer whales (Orcinus orca), based on an acoustic impact model*. Mar. Mammal Sci. 18:394-418.

Goerner J F. (1982). *Underwater noise explosion safe ranges for sea mammals*. NSWC/WOL TR-82-188. Naval surface Weapons Centre, White Oak Laboratory, Silver Spring, MD, USA, NTIS AD-A139823.

Hastings M C, and Popper A N. (2005). *Effects of sound on fish*. Report to the California Department of Transport, under contract No. 43A0139, January 2005.

Hawkins A D, and Johnstone A D F. (1978). The hearing of the Atlantic salmon. J. Fish. Biol., 13:655-673.

Hawkins A D. (1981). *The hearing abilities of fish*. Ed's Tovolga W, Popper A, Fay R. *Hearing and sound communication in fishes*. Springer Verlag, New York, pp 109-139.
Hildebrand J. (2004). *Impacts of anthropogenic sound on cetaceans*. International Whaling Commission, IWC/SC/56/E13 report, Sorrento, Italy. Available at http://cetus.ucsd.edu/projects/pub/SC-56-E13Hilde.pdf

Hill S H. (1978). *A guide to the effects of underwater shock waves in arctic marine mammals and fish*. Pacific Mar. Sci. Rep. 78-26. Inst. Ocean Sciences, Patricia Bay, Sidney B.C. 50 pp

Johnson C S. (1967) *Sound detection thresholds in marine mammals*. In Tavolga W N (ed), Marine bioacoustics, Vol. 2, Pergamon, Oxford, UK.

Kastak D, and Schusterman R J. (1998). *Low frequency amphibious hearing in pinnipeds: Methods, measurements, noise, and ecology*. Journal of the Acoustical Society of America, 103(4), 2216-2228.

Kastelein R A, Bunskoek P, Hagedoorn M, Au W W L, and Haan D. (2002). *Audiogram of a harbour porpoise (Phocoena phocoena) measured with narrow-band frequency-modulated signals*. J. Acoust Soc Am, Vol. 113(2), pp 1130-1137.

Kinsler L E, Frey A R, Coppens A B, and Sanders J V. (1982). *Fundamentals of acoustics*. John Wiley and Sons, New York.

Lovell J M, Findlay M M, Moate R M, and Yan H Y. (2005). T*he hearing abilities of the prawn (Palaemon serratus)*. Comp. Biochem. Physiol. A Mol. Integr. Physiol. Vol 140/1 pp 89-100.

Madsen P T, Wahlberg M, Tougaard J, Lucke K, and Tyack P. (2006). *Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs*. Marine Ecology Progress Series, Vol. 309: pp 279-295, March 2006.

Maes J, Turnpenny A W H, Lambert D R, Nedwell J R, Parmentier A, Olivier F. (2004). *Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet*. J. Fish. Biol. 64, pp 938-946.

Møhl B. (1968). *Auditory sensitivity of the common seal in air and water*. Journal of Auditory Research, 8, 27-38.

Nedwell J R, Langworthy J, and Howell D. (2003). *Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore wind farms, and comparison with background noise*. Subacoustech Report ref: 544R0424, published by COWRIE, May 2003

Nedwell J R, Turnpenny A W H, Lovell J M, and Edwards B. (2006). An investigation into the effects of underwater piling noise on salmonids. J. Acoust. Soc. Am. Volume 120, Issue 5, pp 2550-2554.

Nedwell J R, Parvin S J, Edwards B, Workman R, Brooker A G, and Kynoch J E. (2007a). *Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters*. Subacoustech Report ref: 544R0738 to COWRIE ISBN: 978-09554279-5-4.

Nedwell J R, Turnpenny A W H, Lovell J, Parvin S J, Workman R, Spinks J A L, and Howell D. (2007b). *A validation of the* dB_{ht} *as a measure of the behavioural and auditory effects of underwater noise*. Subacoustech Report ref: 534R1231, published by the Department for Business, Enterprise and Regulatory Reform.

Parvin S J, and Nedwell J R. (2006). *Underwater noise survey during impact piling to construct the Barrow Offshore Wind Farm*. COWRIE Project ACO-04-2002, Subacoustech Report ref: 544R0602.

Parvin S J, Nedwell J R, and Harland E. (2007). *Lethal and physical injury of marine mammals, and requirements for Passive Acoustic Monitoring*. Subacoustech Report ref: 565R0212, report prepared for the UK Government Department of Business, Enterprise and Regulatory Reform.

Popper A N, and Fay R R. (1993). *Sound detection and processing by fish: critical review and major research questions*. Brain Behav. Evol. 41, 14-38.

Popper A N, Fewtrell J, Smith M E, and McCauley R D. (2004). *Anthropogenic sound: effects on the behaviour and physiology of fishes*. Marine Technology Soc. J. 37(4), pp 35-40.

Popper A N, Carlson T J, Hawkins A B, Southall B L, and Gentry R L. (2006). *Interim criteria for injury of fish exposed to pive driving operations*: A white paper.

Rawlins J S P. (1974). *Physical and patho-physiological effects of blast. Joint Royal Navy Scientific service*. Volume 29, No. 3, pp 124-129, May 1974.

Rawlins J S P. (1987). *Problems in predicting safe ranges from underwater explosions*. Journal of Naval Science, Volume 14, No.4 pp 235-246.

Richardson W J, Greene C R, Malme C I, and Thompson D H. (1995). *Marine mammals and noise*. Academic Press Inc., San Diego.

Richmond D R, Yelverton J T, and Fletcher E R. (1973). *Far-field underwater blast injuries produced by small charges*. Defence Nuclear Agency, Department of Defence, Washington, D.C. Technical Progress Report DNA 3081.

Southall B L, Bowles A E, Ellsion W T, Finneran J J, Gentry R L, Greene C R, Kastak D, Ketten D R, Miller J H, Nachtigall P E, Richardson W J, Thomas J A, and Tyack P L. (2007). *Marine Mammal Noise Exposure Criteria*. Aquatic Mammals, Vol 33(4).

Suga T, Akamatsu T, Sawada K, Hashimoto H, Kawabe R, Hiraishi T, and Yamamoto K. (2005). *Audiogram measurement based on the auditory brainstem response for juvenile Japanese Sand Lance (Ammodytes personatus)*. Fisheries Science, Volume 71, Number 2 (2005) pp 287-292.
Thompson, P. and Hastie, G. (2011). *Proposed revision of noise exposure criteria for auditory injury in pinnipeds*. Awaiting publication.

Thompson P, Hastie G, Nedwell J R, Barham R J, Brookes K, Cordes L, Bailey H, and McLean N. (2012). *Framework for assessing the impacts of pile-driving noise from offshore wind farm construction on the Moray Firth harbour seal population*. Awaiting publication.

Thomsen F, Lüdermann K, Kafemann R, and Piper W. (2006). *Effects of offshore wind farm noise on marine mammals and fish*. On behalf of COWRIE Ltd.

Turnpenny A W H, Thatcher K P, and Nedwell J R. (1994). *The effects on fish and other marine animals of high-level underwater sound*. Report FRR 127/94, Fawley Aquatic Research Laboratories, Ltd., Southampton, UK.

Urick R. (1983). *Principles of underwater sound*. New York: McGraw Hill.

Yelverton J T, Richmond D R, Fletcher E R, and Jones R K, (1973). Sa*fe distances from underwater explosions for mammals and birds*. DNA 3114T, Lovelace Foundation for Medical Education and Research, Final Technical Report, July 1973.

Yelverton J T, Richmond D R, Hicks W, Saunders K, and Fletcher E R. (1975). *The relationship between fish size and their response to underwater blast*. DNA 3677T, Lovelace Foundation for Medical Education and Research, Final Technical Report, June 1975.

Yelverton J T, and Richmond D R. (1981). *Underwater explosion damage risk criteria for fish, birds and mammals*. J. Acoust. Soc. Am. Volume 70, Issue S1, pp S84.