Discussion Paper on Particle Motion

Inch Cape Wind Farm

Inch Cape Offshore Ltd

SDIC Red Rock Power Limited

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1. Introduction

1.1. The Inch Cape project

Inch Cape Offshore Limited (ICOL) is progressing the development of the Revised Inch Cape Wind Farm and associated Revised Inch Cape Offshore Transmission Works (OfTW), the Revised Development. The Revised Development is located in the North Sea off the east coast of Angus, Scotland. It will comprise an offshore array of up to 72 Wind Turbine Generators (WTGs), connected by up to 190km of subsea inter-array cables. These will be connected to one or two Offshore Substation Platform(s) (OSPs) where power generated by the WTGs is transformed and subsequently carried approximately 83 km to the onshore landfall location at Cockenzie via two Offshore Export Cables (OEC). Foundations for WTGs and OSPs will be either be mounted on gravity base structures (GBS) or piled.

The Revised Development will comprise an offshore generating station with a capacity of greater than one megawatt (MW) and therefore requires Scottish Ministers' consent under section 36 of the Electricity Act (Section 36 Consent) to allow its construction and operation. Under the Marine (Scotland) Act 2010, the Revised Development will also require Marine Licences granted by the Scottish Ministers to allow for the construction and deposition of substances and structures in the sea and on the seabed.

A Scoping Report for the Revised Development was prepared in support of a request for a Scoping Opinion from Marine Scotland Licensing and Operations Team (MS-LOT) as to the scope of the information to be provided within the Revised Development Environmental Statement (ES). The Scoping Report was submitted to MS-LOT on 28th April 2017 and a Scoping Opinion received on 28th July 2017.

1.2. Purpose of this Document

This document has been produced in order to respond to the Scoping Opinion received from MS-LOT (See Box 1, below). The Scoping Report set out the approach to the Revised Development EIA, specifying which receptors and impacts should be considered. For the Natural Fish and Shellfish chapter ICOL proposed only one receptor and impact should be included within the impact assessment, that being the impact of construction noise on hearing specialist fish.

In the Scoping Opinion Scottish Ministers noted two potential impacts that may require further consideration within the impact assessment: Impact of suspended sediment and smothering on scallops and *Nephrops,* and particle motion. This document covers particle motion. The impacts of suspended sediment and smothering is covered by a separate document.

Box 1: Scoping Opinion received from MS-LOT (Text relating to particle motion)

Since the Original Development ES for the Inch Cape development was produced there has been a considerable increase in the relevant literature which suggests that there is potential for impacts from acoustic particle motion on fish and invertebrates. An issue that has been raised by MSS at the scoping meetings is the need to consider potential impact of acoustic particle motion on sensitive receptors in addition to the effects of sound pressure on fish species that are sensitive to this.

There is acknowledgement that understanding of the effects from particle motion, and extent of these effects, is currently an area for further development, and there are various initiatives being progressed. MSS considers that the currently available evidence suggests that particle motion could be an important mechanism of effect on fishes and invertebrates. As the 2017 EIA Regulations require the Scottish Ministers to come to a reasoned conclusion on the significant effects on the environment of the development, based on up to date information, this information needs to be taken into account. MSS has provided a list of references.

MSS suggests that ICOL takes the following approach:

- Provide an overview of currently available information on particle motion within the vicinity of noise producing construction and operational activities, including, for example, pile driving, dredging and explosions – both within the water column and the sea bed. This should include consideration of the likely distances at which elevated levels of particle motion may be detected.
- Provide an overview of the published information on sensitive species and potential physiological and behavioural effects of particle motion.
- Give consideration to the potential effects of particle motion on species known to occur around the development site, making use of information on species distribution from the Original Development ES and information which has become available since then. Particular attention should be given to potential effects on species of commercial or conservation concern.
- Provide information on opportunities that the Revised Development may present to investigate effects of particle motion on fish and invertebrates.

The Scottish Ministers agree that the potential impact of particle motion should be assessed and suggests that ICOL follows the approach outlined by MSS.

References which may be useful (not necessarily a comprehensive listing):

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Radford, CA, Montgomery, JC, Caiger P and Higgs DM (2012) Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts. The Journal of Experimental Biology 215, 3429-3435 http://jeb.biologists.org/content/jexbio/215/19/3429.full.pdf

Roberts L and Elliott M (2017) Good or bad vibrations? Impacts of anthropogenic vibration on the marine epibenthos. Science of the Total Environment 595:255-268.

Roberts, L. (2015). Behavioural responses by marine fishes and macroinvertebrates to underwater noise (Doctoral dissertation, University of Hull). https://hydra.hull.ac.uk/assets/hull:11515a/content

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Spiga I, Caldwell GS and Bruintjes R. (2016) Influence of Pile Driving on the Clearance Rate of the Blue Mussel, Mytilus edulis (L.). In: Fourth International Conference on the Effects of Noise on Aquatic Life. 2016, Dublin, Ireland: Acoustical Society of America.

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2. Approach

2.1. Introduction

This document aims to address the comments raised by Marine Scotland Science (MSS) and Scottish Ministers on the Natural Fish and Shellfish section of the Scoping Report for the Revised Development by undertaking a thorough review of the documents identified by MSS on particle motion, as well as other pertinent papers identified.

The comments from both MSS and Scottish Ministers relate to new evidence concerning particle motion which has been published since the submission of the Original Development ES (ICOL, 2013). This new evidence may challenge the assumptions made in the Original Development ES Natural Fish and Shellfish chapter and therefore question its conclusions (and therefore the conclusions in the Revised Development Scoping Report).

In order to achieve this, this document will:

- Review the papers specified by Marine Scotland;
- Review additional key papers identified;
- Discuss the appropriateness of the Original Development ES baseline in light of the new evidence;
- Discuss the validity of the conclusions drawn in the Original Development ES in light of the new evidence; and
- Recommend whether additional information needs to be included with the Revised Development EIA Report, or whether the Original Development ES chapter remains valid as was deemed to be the case within the Revised Development Scoping Report.
- Provide information on opportunities that the Revised Development may present to investigate effects of particle motion on fish and invertebrates.

3. Review of literature

3.1. Introduction

Documents cited by MSS for review are summarised in Table A1, Appendix 1. One of these references (Popper & Hawkins, 2016) was a collection of 162 papers relating to the effects of noise on aquatic life. Seven of those papers make reference to the term ‘particle motion’ and are considered informative for inclusion in this document. Pertinent points from each of these additional seven papers are summarised in Table A2, Appendix 1. Documents cited by MSS are marked in bold text in footnote references.

The papers cited for review addressed issues within one or more of the following four categories:

- How does the particle motion component of sound propagate from a source in a marine environment?
- What levels of particle motion are generated by anthropogenic activities?
- Can fish and marine invertebrates detect the particle motion component of sound at the intensities and frequencies they may be exposed to by anthropogenic marine activities?
- What effects might the levels of particle motion that fish and marine invertebrates are exposed to have upon them?

3.2. Particle motion and its propagation

Sound is vibratory energy that is propagated through a medium (Gans, 1992). Propagation occurs as vibrating particles cause those particles adjacent to them to vibrate and the energy is transmitted in a given direction, described as a wave (note, particles themselves do not travel through the medium, rather this vibratory energy is transferred) (Nedelec *et al*., 2016). This particle motion contains information on the directionality of the wave and can be measured through the displacement (m), velocity (ms^{-1}), or acceleration (ms^{-2}) of particles. In addition to this transmittal of energy through particle motion, sound energy can also be described through changes in pressure which is caused by the compression and rarefaction of these same particles (Martin *et al*., 2016).

The measurable attributes of particle motion are interrelated, and are affected by the angular frequency of the wave (a product of the frequency of the sound in Hertz and the waves spherical form, calculated as $2\pi f$). The relationship between acceleration, velocity and displacement can be described through the following equations which show a positive correlation between acceleration and velocity, and between displacement and velocity (at a constant frequency) (Nedelec *et al.,* 2016):

$$Acceleration = Velocity \times Angular\ frequency$$

And

$$Displacement = \frac{Velocity}{Angular\ frequency}$$

Under certain ‘ideal’ conditions, sound pressure and particle velocity (i.e. one of the components of particle motion) are significantly correlated (Ceraulo *et al*., 2016; Nedelec *et al*., 2016), yet sound propagation is highly site and signal specific and the conditions needed for such correlation are generally not met in the coastal and shelf seas (Ceraulo *et al*., 2016; Muelle-Blenke *et al*., 2012). In shallow water and in relative close proximity to the sound source, reflections and near field effects can influence the propagation of the particle motion, and as a consequence, particle motion levels cannot be inferred from sound pressure, with particle acceleration levels typically attenuating more rapidly than sound pressure levels in the near field (Muelle-Blenke *et al*., 2012; Casper *et al*., 2016; Normandeau Associates, Inc. 2012). In such environments, the only reliable way to derive the level of particle motion is direct measurement (Nedelec *et al*., 2016). However, as distance from the sound source increases (and as long as no sources of reflection are in proximity), the sound pressure to particle velocity ratio approximates that of a plane wave and inferences can be made with more certainty, as in a plane wave sound pressure and particle velocity are directly related (Nedelec *et al*., 2016; Radford *et al.,* 2012).

The propagation of particle motion is identified by many marine acousticians as a field of noise modelling where further research is a priority, particularly particle motion associated with anthropogenic sources of marine noise (including pile-driving and operational offshore wind turbines) (Martin *et al*., 2016; Mueller-Blenkle *et al*. 2010; Farcas *et al*., 2016; Normandeau Associates, Inc., 2012; Popper *et al*., 2014; Harding *et al*., 2016; Robinson *et al*., 2014; Sigray & Andersson, 2011; Thomsen *et al*., 2015). The need for the development of effective and cost efficient instruments and methods for measuring *in situ* particle motion levels has been repeatedly cited as a key limitation in the advancement of this field (Normandeau Associates, Inc., 2012; Popper *et al*., 2014). A range of protocols have been developed in recent years (Martin *et al.,* 2016; Radford *et al*., 2012; Nedelec *et al*., 2016; Sigray & Andersson, 2011) although presently there is no consensus of opinion as to how measurement of particle motion levels around offshore developments should be conducted. Despite continued progression in the characterisation of particle motion in the field, recordings from a range of sources, parameters, and conditions are still required (Farcas *et al*., 2016; Merchant *et al*., 2015).

3.3. Predicted levels of particle motion from anthropogenic sources

Data relating to particle motion levels resulting from construction phase pile-driving for offshore wind farms are very limited, particularly regarding measurements collected *in situ*. Thomsen *et al*. (2015) collected measurements of particle motion during construction phase pile-driving at a wind farm in the German part of the southern North Sea. Particle motion levels were recorded to be greater than ambient levels within 750 m of piling locations for most of the frequency spectrum. This study also observed that noise mitigation measures (bubble-curtains) were highly effective at reducing particle motion levels.

Other studies relating to particle motion resulting from pile driving have either not been conducted *in-situ* (i.e. tank-based studies (Mueller-Blenkle *et al*., 2010; Ceraulo *et al*., 2016; Harding *et al*., 2016; Spiga *et al*., 2016) at spatial scales much smaller than those where offshore wind farm piling is concerned), and/or have used play-back by speakers to simulate piling noise (Martin *et al*., 2016; Mueller-Blenkle *et al*., 2010; Roberts, 2015; Harding *et al*., 2016). Caution must be taken when applying conclusions from such studies to offshore pile-driving situations as particle motion propagation in tanks is very different to open sea conditions (Parvulescu, 1967) and particle motion caused by ‘real’ events may be quite different from that caused by play-back from submerged speakers (Mueller-Blenkle *et al*., 2010). Nevertheless, one generality that holds across all studies is that particle motion levels attenuate rapidly with distance from the acoustic source (Mueller-Blenkle *et al*., 2010; Radford *et al*., 2012; Roberts, 2015; Zhang *et al*., 2015; Casper *et al*., 2016). For example in an open-sea experiment at a coastal site using underwater speakers, particle motion (velocity) levels were observed to decrease rapidly within 30 m of the source and much more slowly further away (Mueller-Blenkle *et al*., 2010).

Another aspect of particle motion associated with marine pile-driving is propagation through the substrate (i.e. ground roll effect). As the concussive force associated with piling is directed into the sea bed, the acoustic signal not only propagates through the water column, but also through the sea bed (Nedwell *et al*., 2003). Substrate-borne particle motion may propagate further from source than particle motion in the water column (Mueller-Blenkle *et al*., 2010; Roberts & Breithaupt, 2016). Furthermore, substrate-borne particle motion may transfer into the water column at considerable distances from the source (Mueller-Blenkle *et al*., 2010; Roberts & Breithaupt, 2016). As such, gaining an understanding of the effects of particle motion on benthic organisms is cited by several studies as a priority area for further research (Normandeau Associates, Inc., 2012; Roberts, 2015; Miller *et al*., 2016; Roberts & Breithaupt, 2016).

In recent years several studies have measured particle motion in the vicinity of operational wind turbines. Sigray & Anderson (2011) recorded particle motion levels around the base of an operational steel monopile turbine at a wind farm in the Baltic Sea. They recorded the highest particle motion levels at 1 m from the turbine base; 1.2×10^{-2} to 9×10^{-3} m/s^2 at frequencies below 600 Hz. Thomsen *et al.* (2015) conducted on-site measurement of particle motion around several operational turbines at a wind farm in the German part of the southern North Sea. Around operational wind turbines particle motion levels were found to be measurably greater than background levels within 40 m of the turbine base, and emissions from steel monopole turbines were noted to be greater than those from jacket-based turbines. Frequency peaks of particle motion acoustic signals produced by the operational turbines were in the range of 400 to 1250 Hz.

3.4. Species sensitivity to particle motion

Sound pressure is what terrestrial vertebrate hearing systems detect and current models applied in EIAs (including the Original Development ES (ICOL, 2013) have considered only this component of underwater noise (Farcas *et al*., 2016). Fish and marine invertebrates (i.e. the vast majority of marine animals) however, primarily detect the particle motion component of underwater sound (Hawkins & Popper, 2016 & 2017; Normandeau Associates, Inc., 2012; Popper *et al.*, 2014; Roberts, 2015; Morley *et al*., 2014), although the former generally appear to be much more sensitive to this component of underwater noise than the latter (Roberts & Elliot, 2017; Fay & Simmons 1998).

3.4.1. Particle motion sensitivity in fish

Many literature reviews of the hearing capabilities of fish make reference to sensitivity to particle motion (Hawkins & Popper, 2016 & 2017; Normandeau Associates, Inc., 2012; Popper *et al*., 2014; Roberts, 2015). All fish are thought to directly sense the particle motion component of underwater acoustic stimuli (Fay, 1984), while relatively few are capable of detecting the sound pressure component (Popper & Fay, 1993).

The principal sensory organ used by fish to detect particle motion is the otolith within the inner ear. The otolith is a calcium carbonate structure, much denser than other tissues and also the surrounding water. As such the otolith moves differently relative to the rest of the body of a fish in the presence of sound waves, and sensory hair cells which surround the otolith can detect these displacements (Hawkins & Popper, 2017; Roberts, 2015; Martin *et al*., 2016).

A secondary method whereby fish detect particle motion is the lateral line system (Fay & Popper, 2000). These are tracts of motion sensitive epithelial cells which run along a fish's body and can detect vibration and pressure changes nearby. With regard to the detection of particle motion, the lateral line system is considered to be effective only over short ranges, and to be more sensitive to low frequency (<100 Hz) signals (Roberts, 2015).

Popper *et al.* (2014) classified fishes into three categories in terms of their auditory acuity and detection mechanisms:

- Type 1: Fishes without a swim bladder or any other gas filled body cavities. These species are considered to only be sensitive to particle motion and include flatfish species and sandeels.
- Type 2: Fishes with swim bladders or other gas filled body cavities which are not involved in hearing. These species are also considered only to be sensitive to particle motion and include salmonids and some pelagic species, such as mackerel.
- Type 3: Fishes with swim bladders or other gas filled body cavities which are involved in hearing. These species are considered to be sensitive to both particle motion and sound pressure and include gadoids, such as cod, and some pelagic species, such as herring. Due to their ability to detect the pressure component of underwater noise, the frequency sensitivity ranges of these species and their acuity levels are greater, hence this group is frequently referred to as the 'hearing specialists'.

Radford *et al*. (2012) consider it likely that all teleost fish (approximately 96% of extant fish species) have a similar ability to detect the particle motion component of the sound field. Inter-specific differences in auditory abilities are thought to primarily derive from abilities to transduce the pressure component of acoustic signals to the inner ear via ancillary hearing structures (Radford *et al*., 2012). Elasmobranchs, as Type 1 hearing group fish, are also thought to be capable of particle motion detection, although the species studied appear to be less sensitive across a range of frequencies than teleost fish (Casper *et al*., 2012).

The development of species specific particle motion audiograms has been identified as a priority research area (Lewandowski *et al*., 2016), and there are presently few studies detailing threshold ranges of sensitivity to particle motion. Popper *et al*. (2014) provide a summary of sensitivities for four species (Dab, *Limanda limanda*, and plaice, *Pleuronectes platessa*, both 'Type 1' species; Atlantic salmon, *Salmo salar*, a 'Type 2' species; and Atlantic cod, *Gadus morhua*, a ‘Type 3’ species), all of which have broadly similar profiles, with threshold ranges between approximately 20-40 dB re. 1 µm/s^2 and peak frequency sensitivities between 50 and 110 Hz. Similarly, Ladich & Fay (2013) state that, for ‘Type 1’ fish, particle motion thresholds are thought to be within the range of 30-70 dB re. 1 µ/m^2, with maximum acuity in the low frequency range (<100 Hz). Very few studies address the auditory capacity of larval fish (Popper *et al*., 2014), with most evidence suggesting that frequency sensitivities and behavioural threshold level are similar to those of adults (Popper *et al*., 2014).

Several studies have attempted to assess the possible spatial scales at which fish may detect particle motion created by various marine developments; specifically turbine base pile-driving and operational noise from turbines. Thomsen *et al*. (2015) considered that particle motion levels within approximately 750 m of a pile-driving location for an offshore wind turbine base were sufficiently above ambient levels as to be detectable by most fish species. The same authors also found particle motion to be measurably above ambient levels within 40 m of operational wind turbines, though they do not state whether they consider these levels to be detectable by fish. Particle motion levels measured 10 m from an operational turbine base by Sigray and Anderson (2011) have been noted to be similar to the low frequency (<20 Hz) hearing thresholds of juvenile salmon, eel and roach (Knudsen *et al*., 1992; Sand *et al*., 2000; Karlsen *et al*., 2004; Sonny *et al*., 2006), and hence 10 m may approximate to the distance at which fish species could detect an operational turbine.

3.4.2. Particle motion sensitivity in marine invertebrates

Given the lack of air filled spaces in most marine invertebrates, they are not considered to be sensitive to the pressure component of underwater acoustic stimuli (Mooney *et al*., 2010 & 2012).

The understanding of the sensitivity of marine invertebrates to the particle motion component of underwater sound is considered to be a field of bioacoustics which remains in its infancy (Lewandowski *et al*., 2016). Until recently, given the difficulties associated with measuring particle motion (Robinson *et al*., 2014) and invertebrate behaviour/response, there has been very little information available about the hearing capabilities of marine invertebrates (Normandeau Associates, Inc., 2012). Several reviews on this subject have been published in recent years (Hawkins & Popper, 2017; Roberts, 2015; Roberts & Elliot, 2017) primarily focusing on crustaceans and molluscs.

Marine invertebrates are thought to only detect the particle motion component of sound, particularly at low frequencies (Mooney *et al*., 2010 & 2012). As is also the case for fish, a need for the production of species specific audiograms has been identified as a priority (Lewandowski *et al*., 2016). Comparison of *in situ* measurements of particle motion levels associated with anthropogenic sources of underwater noise (particularly pile-driving) to the audiograms of marine invertebrates has not been conducted to date. Thomsen *et al.* (2015), however, note that elevations in particle motion levels recorded 750 m from a piling operation, which they consider may be detectable to fish species, were unlikely to be detectable by marine invertebrates.

Particle motion sensitivity in crustaceans

For decapod crustaceans at least three types of mechano-receptor systems are implicated in the detection of particle motion; namely superficial surface receptors, internal statocysts and chordontal organs (Roberts & Elliot, 2017). Superficial surface receptor systems are analogous to the lateral line system in fish, in that mechanical displacement of epithelial cells on the surface of the organism results in stimulation of sensory receptor cells (Roberts & Elliot, 2017). The statocyst, a fluid filled chamber containing a mass (the statolith) surrounded by sensory hair cells, may be functionally analogous to the otolith system described above for fish (Roberts & Elliot, 2017). Chordontal organs, which are located in the joints of appendages and play a role in limb extension and communication of positional changes, are also sensitive to vibration and may detect particle motion (Roberts & Elliot, 2017).

In the case of primarily benthic marine crustaceans, ground roll effects (i.e. substrate-borne particle motion) may have potentially similar or greater relevance than water-borne particle motion (Roberts & Breithaupt, 2016). Until recently relatively little information has been collected about the ability of UK coastal crustaceans to detect substrate-borne particle motion although several recent studies and reviews have focussed upon this (Roberts, 2015; Roberts & Briethaupt, 2016; Roberts & Elliot, 2017).

Experiments on *Nephrops norvegicus* have recorded physiological responses to noise indicative of an ability to detect particle motion at frequencies of 20-80 Hz less than 1 m from the source (Goodall *et al*., 1990). Preliminary studies by Roberts (2015) suggest that the barnacle species *Balanus crenatus* may also be sensitive to substrate-borne particle motion. Hermit crabs, *Pagurus bernhardus*, have been observed to have sensitivity behavioural thresholds to substrate-borne vibrations, where particle motion is considered to be the main stimulator, of approximately 0.11 to 0.29 ms^{-2} with greatest sensitivity at 90 Hz (Roberts, 2015). A review by Roberts and Breithaupt (2016) of published vibration sensitivities for several crab and shrimp species, noted particle motion thresholds (determined by either by observation or electrophysiological means) ranged between 0.0002 and 0.81 ms^{-2}, with the greatest sensitivities typically found at frequencies below 200 Hz. These low frequency sensitivities fall within the range of anthropogenic vibrations resulting from activities such as pile-driving.

Particle motion sensitivities observed for crustaceans have been demonstrated to fall within the range of actual anthropogenic vibrations caused by activities such as pile-driving (Roberts, 2015; Roberts & Breithaupt, 2016). Consequently, sensitivity of crustaceans to substrate vibrations is considered sufficient to enable them to potentially detect noise from these anthropogenic disturbances as it propagates through the seabed. Although detection of particle motion through the waterborne pathway may only be possible close to the source, crustaceans may be able to detect substrate-borne particle motion at greater distances from the source (Roberts & Breithaupt, 2016).

Particle motion sensitivity in molluscs

The means by which molluscs may detect particle motion are not well understood, as mechano-receptor systems in this group remain relatively unstudied (Roberts & Elliot, 2017). Molluscs possess statocysts (as described for crustacea, above) which may be sensitive to particle motion, these organs are considered to enable sound detection in cephalopods (Hanlon & Messenger, 1996; Kaifu *et al*., 2008). Superficial surface receptor systems may also be involved in particle motion detection (Roberts & Elliot, 2017). Some bivalves groups possess additional specialised sense organs, such as the abdominal sense organ in scallops, which are highly sensitive to water-borne vibrations (Zhadan, 2005).

In molluscs, work investigating particle motion detection has focussed upon cephalopods (Samson *et al*., 2016), with studies suggesting threshold amplitudes of 0.0003 to 1.1 ms^{-2} at frequencies between 1 and 300 Hz (Kaifu *et al*., 2008; Mooney *et al*., 2010; Sansom *et al*., 2016), though for some species upper frequency limits may be significantly higher (i.e. common octopus, *Octopus vulgaris*) (Sansom *et al*., 2016). Zhang *et al*. (2015) state that cephalopods are likely to be particularly sensitive to very low frequency acoustic stimuli (approximately 10 Hz).

As with crustaceans, substrate-borne particle motion induced vibration may potentially have more relevance than particle motion within the water column for benthic molluscs, such as bivalves (Roberts & Elliot, 2017). An example of evidence of particle motion detection in bivalves is thought to come from the small saltwater clam species, *Donax variabilis*, which has been shown to respond to sounds within the near field (particle motion dominated signals), rather than sounds within the far field (sound pressure dominated signals) (Ellers, 1995). Roberts *et al*. (2015) found strong evidence of substrate-borne particle motion sensitivity in blue mussels, *Mytilus edulis,* in their responses to vibration produced by an electromagnetic shaker. Similarly, Spiga *et al*. (2016), observed blue mussels to increase the rates at which they removed suspended particles from the water column in response to simulated pile-driving. Increased filtration rates are hypothesised to occur as a result of increased energetic demands as a result of a stress response to the substrate-borne particle motion produced by piling.

3.5. Potential effects of particle motion

3.5.1. Introduction

Elevated levels of underwater noise may have a diverse range of effects on fish and marine invertebrates. These may include causing injury leading to mortality or damage to anatomical structures, hearing impairment, or altering physiology, behaviour, or development (Knight & Swaddle, 2011). Presently the potential effects of the particle motion component of underwater noise are greatly understudied in comparison to sound pressure (Popper *et al*., 2014).

3.5.2. Injury

While exposure to very high amplitudes of the pressure component of underwater noise is well known to potentially result in tissue damage (barotrauma) (Carlson, 2012), injury resulting from extreme levels of particle motion is yet to be demonstrated for any source (Popper *et al*., 2014).

3.5.3. Hearing impairment

Increases in underwater noise may result in hearing impairment by directly damaging acoustic sensory organs (temporarily or permanently), or indirectly by contributing to ambient soundscapes and thereby making it more difficult for organisms to detect biologically relevant acoustic signals (i.e. predators, prey, communication sounds, etc.) (Popper *et al*., 2014). The latter, indirect effect is referred to as masking by bio-acousticians and is considered alongside potential behaviour effects, below.

Just as there are no studies demonstrating damage to body tissues caused by particle motion, there are also no studies providing evidence of particle motion damage to auditory sense organs. One study, however, by Zhang *et al*. (2015), which models the auditory capabilities of cephalopods, states that severe particle motion could potentially cause irreparable damage to the statocyst at short range. Particle motion levels exceeding 0.27 ms^{-2} were considered sufficient for such damage to potentially occur. These levels of water-borne particle motion are considered only to arise close to very intense sources of underwater noise (i.e. pile-driving) (Zhang *et al*., 2015).

3.5.4. Behavioural changes

Assessing behavioural responses of marine organisms to anthropogenic acoustic stimuli, and determining the significance of those responses, is generally difficult and costly, particularly *in situ* (Popper *et al*., 2014). Combined with the difficulties associated with measuring the particle motion component of underwater sound, it is therefore to be expected that very little information is available about the behavioural consequences to free-living fish and marine invertebrates of particular levels of particle motion resulting from human activities. Lab-based studies on captive animals have been conducted, but care should be taken with regards to drawing inferences about the behaviour of free-living individuals from such observations (Popper *et al*., 2014).

Fish

Several studies have demonstrated behavioural responses to played-recordings of pile-driving noise for fish species which are not considered to be responsive to the pressure component of underwater noise. For example, in a study conducted in large net pens in a Scottish sea loch, Mueller-Blenkle *et al*. (2010) observed played-back pile-driving noise to effect the behaviour of sole (*Solea solea*). These responses took the form of initial avoidance and significant increases in swimming speed. Similarly, Roberts (2015) observed shoals of free-living Atlantic mackerel (*Scomber scombrus*) to scatter and change depth in response to played-back pile-driving noise in an Irish sea lough.

These results constitute evidence of behavioural responses to particle motion in non-hearing specialist fish species. Such responses do not, however, appear to be universal, and are contradicted by the findings of other observations of non-hearing specialist fish species. For example, in a lab-based experiment, Harding *et al*. (2016), considered Atlantic salmon not to perceive played-back pile-driving noise as a stressor and observed no evidence of startle responses to play-back. This is consistent with findings from studies of brown trout (*Salmo trutta*), which have been observed to show no changes in behaviour to exposure to sound generated by a real piling event (Nedwell *et al.*, 2003).

For hearing specialist fish, determining behavioural responses to the particle motion component of underwater noise is complicated by separating them from behavioural responses to the pressure component. Hawkins and Popper (2017), point out that both acoustic components are likely to be processed simultaneously, thereby allowing hearing specialists to derive a more complex understanding of their surroundings from underwater noise than species which only perceive particle motion.

Marine invertebrates

While information on the potential effects of anthropogenic noise on the behaviour of marine invertebrates remains very limited, several recent studies have begun to alter traditional views in this area. A literature review from 2012 (Normandeau Associates, Inc., 2012) summarised the consensus opinion of the time, stating: “There are no data … to suggest whether man-made sounds would have any impact on invertebrate behaviour”, citing research by Andriguetto-Filho *et al*. (2005) which found no behavioural effects to shrimp from the effects of seismic exploration.

More recently several studies have, however, found evidence of man-made noise altering the behaviour of marine invertebrates. Roberts (2015) observed behavioural responses in hermit crabs and blue mussels in response to substrate-borne particle motion, and possible behavioural responses by European lobster (*Homarus gammarus*) to played-back pile-driving noise. Blue mussels have also been recorded to increase filtration rates in response to simulated pile-driving (Spiga *et al*., 2016); this may be interpreted as a physiological stress response. A wide range of behavioural and physiological responses to sound, such as inking, blanching body colour changes and startle responses, have also been recorded in cephalopods in response to anthropogenic noise or vibration (Samson *et al*., 2016).

3.5.5. Developmental changes

Exposure to elevated noise levels has been demonstrated to induce higher levels of the stress hormone cortisol in fish, which could disrupt growth, maturation and reproductive success (Pickering, 1993; Small, 2004). Juvenile rainbow trout (*Oncorhynchus mykiss*) have been observed to grow more slowly when exposed to high levels of noise in aquarium-based experiments (Davidson *et al*., 2009), and similar observations have been made for captive carp (*Cyprinus carpio*) adjacent to drilling activities (Sun *et al*., 2001).

4. Validation of existing baseline

The baseline described for the Original Development ES for fish and shellfish species took information from a number of sources including; site specific survey data, commercial landings data, data from scientific trawl surveys (e.g. international bottom trawl surveys), and published literature. From this data, key receptors were identified and information on their distribution within the Development Area and Offshore Export Cable Corridor was extrapolated in order to describe the baseline conditions of these areas.

This baseline, in conjunction with consultation with statutory and non-statutory consultees, allowed the identification of specific fish and shellfish receptors against which detailed impact assessment can be undertaken. As it is not possible to assess every fish and shellfish species against every impact, fish and shellfish species were grouped together in receptor groups in line with the IEEM (2010) guidelines. The receptors were grouped according to their life history characteristics, sensitivity, and relative conservation and ecological importance (Table 4.1). This approach remains in accordance with the revised CIEEM (2016) guidelines.

Table 4.1: Receptor groups used in the ES

Receptor Group	Key Species included
Mobile fish species	Whiting, plaice, haddock, mackerel, sea trout, European eel, sparling, squid, etc. (i.e. all species of fish not included in another specific receptor group).
Hearing specialists	Herring, sprat, allis shad, twaite shad and cod.
Prey species	Sandeel.
Electro-sensitive elasmobranchs	Ray and skate species, dogfish, spurdog, tope.
SAC qualifying feature species	Salmon, sea lamprey, river lamprey, Fresh Water Pearl Mussel.
Shellfish	Scallop, crab, lobster, *Nephrops*.

It was agreed with MS-LOT and the Scottish Ministers through scoping that the natural fish and shellfish baseline presented in the Original Development ES was valid for the purposes of scoping the Revised Development, with the exception of specific receptors for which it was considered that additional information was available, namely Atlantic salmon and scallops. Additional work has been undertaken and submitted to Marine Scotland that validate the conclusions of the Revised Development Scoping Report and show that the baseline for these species remains valid.

Nevertheless, following the review of documents undertaken as part of this document, more information can be presented about the hearing abilities of certain species within each receptor group, and a conclusion drawn as to whether the definition of these groups remains appropriate.

Mobile Fish Species

The majority of fish species within this group are either Type 1 or Type 2, i.e. are sensitive to particle motion only, with the exception of the European eel, which is a Type 3 species. However, the European eel is not considered to be particularly sensitive to sound as although it does have a connection between the swimbladder and its inner ear, this connection is long (due to the body shape and the location of the swimbladder) and does not therefore provide the sort of increased sensitivity seen in the majority of Type 3 fishes (Jerko *et al*., 1989). The inclusion of European eel within the group ‘mobile fish species’ is therefore considered to remain appropriate.

Hearing Specialists

All the species in the hearing specialist receptor group are Type 3 species. The Original Development ES pre-dated the Poppers and Hawkins (2014) paper, cod was included within the hearing specialist receptor group as the audiogram for the species showed hearing sensitivities approaching that of other Type 3 fish such as herring (Chapman & Hawkins, 1978). The definition of this group therefore remains appropriate.

Prey Species

Sandeels are a Type 1 species, and are the only species in this group which has been separated out due to their wider ecological importance. The definition of this group is deemed to remain appropriate

Electro-Sensitive Elasmobranchs

Species in the group 'electro-sensitive elasmobranchs' are all Type 1 species. Elasmobranchs were assigned their own group due to their high sensitivities to certain impacts, particularly in order to allow proper consideration of impacts of Electro-magnetic Fields (EMF). The definition of this group is considered to remain appropriate.

SAC qualifying feature species

Species in the group 'SAC qualifying feature species' are all Type 1 or Type 2 species (except the Fresh Water Pearl Mussel which is an invertebrate). SAC qualifying feature species were assigned their own group in order to allow their increased conservation importance to be considered within each impact assessment. The definition of this group is considered to remain appropriate

Shellfish

All species within the 'shellfish' receptor group are marine invertebrates. The definition of this group is considered to remain appropriate.

5. Validation of Original Development ES Conclusions

5.1. Approach to noise modelling

The Original Development ES modelled sound propagation (using pressure as the metric) based upon predicted source levels of a number of activities. Of the activities associated with the construction and operation of the Inch Cape Offshore Wind Farm, impact pile driving was considered the activity with the potential to result in the greatest impact in terms of underwater noise on fish and shellfish receptors. The models assumed a worst-case scenario of piling occurring simultaneously at two locations, one in the north and the other in the south of the Development Area.

In order to relate the unweighted noise propagation data to effects on individual fish species, the project used audiograms of key species, or suitable surrogates, to determine species specific thresholds to increased noise levels (i.e. the dBht (species) method).

The species modelled to allow impacts to be quantified for the various receptor groups were:

- Mobile fish species: dab and sea trout
- Hearing specialists: herring and cod
- SAC qualifying species: salmon
- Prey species: sand lance (surrogate for sandeel)

Thresholds for traumatic hearing loss (130 $dB_{ht\ (species)}$), strong behavioural response (90 $dB_{ht\ (species)}$), and mild behavioural responses (75 $dB_{ht\ (species)}$) were produced and impact ranges modelled. Lethal effects and physical injury distances were based upon the unweighted noise levels as these are not dependant on species sensitivity.

It should be noted that the audiograms obtained from literature were determined through a number of methods (e.g. behavioural responses, detection of nervous impulses, etc), and in a variety of locations (tank based or located on specialised testing rigs offshore) (Table A2, Appendix A). For all audiograms, sound pressure was the main metric used to describe the sound level in relation to the fish’s sensitivity, although almost all the studies conclude that particle motion was the driver of the responses seen in most species.

For many of the studies the determination of particle motion would not be possible through conversion from the pressure component, due to the reflections and scattering of the sound (e.g. from tank walls) that can result in large variations in particle motion in these areas (Hawkins & Popper, 2017). Direct measurement of particle motion is considered the only way to obtain levels in such boundary or interface areas (Nedelec *et al*., 2016; Hawkins & Popper, 2017), however this was presumably not possible during these studies due to the lack of availability of particle motion detection equipment (see Section 3), particularly considering the age of many fish audiogram studies.

5.2. Predictions of piling noise effects

To allow comparison of the modelled impact ranges in the Original Development ES to the available information about particle motion, the Impact Range Areas (IRAs) predicted from piling have been converted to Approximate Equivalent Radii (AERs) in order to provide a linear measurement of distance from the noise source at which the thresholds were met (Table 5.2, and Appendix 1, Table A4). This will allow some comparison with the published values of particle motion detection in fish species. The model outputs for each receptor group are discussed below in relation to the information reviewed as part of this document.

Table 5.1: Approximate Equivalent Radii derived from predicted pile-driving Impact Range Areas stated in the Original Development ES.

Receptor	Impact Range Areas (IRAs) (km^2)			Approximate Equivalent Radii (AERs) (km)		
	130 dBht	90 dBht	75 dBht	130 dBht	90 dBht	75 dBht
Mobile fish species	0.10	42.54	1,119.25	0.04	2.60	13.35 – 18.86
Hearing specialists	0.20	2,472.94	9,222.56	0.18	19.84 – 28.06	38.31 – 54.18
	0.20	1,821.00	7,452.00	0.18	17.02 – 24.08	34.44 – 48.70
Prey species	-	0.17	11.70	-	0.16	1.37
SAC qualifying feature species	0.01	13.89	475.08	40	1.49	8.70 – 12.30

5.2.1. Mobile fish species

The mobile fish species receptor group consists of fish species which are not included in any other specific receptor groups (see Table 3, Appendix 1), and also includes cephalopod molluscs.

Virtually no information exists regarding the levels of particle motion which may cause damage to marine organisms (i.e. equivalent to Trauma AER). As particle motion levels attenuate very rapidly, it is considered probable that levels which may result in trauma may occur only very close to very noisy underwater activities (i.e. piling). For fish species which have swim bladders barotrauma from exposure to extremely high levels of the sound pressure component of underwater noise may be more likely to be significant. As such levels predicted by the modelling are likely to represent a realistic worst case for trauma.

Information available for particle motion propagation suggests an initially rapid attenuation (particularly in the near field zone) for this component of underwater noise. The upper ranges hypothesised for particle motion levels which may result in negative effects on marine organisms are thought to be less than 1 km (Thomsen *et al*., 2015; Miller *et al*., 2016) (although there is very little available information about this, and consequently great uncertainty). As such, the avoidance AERs (both strong and mild) derived from the noise modelling conducted for the Original Development ES appear to be much larger than those that may result from avoidance of the particle motion component of underwater noise.

In terms of sea-bed transmittal of underwater noise (ground roll effects), it is recognised that these may be detectable beyond the limits of water borne particle motion in many species considering species' life history traits, although again, the large avoidance AERs (both strong and mild) derived from the noise modelling conducted for the Original Development ES are likely to be provide conservative areas of impact in this regard.

5.2.2. Hearing specialists

The hearing specialists receptor group consists of fish species which have a swim bladder which is linked to the inner ear, or are considered more sensitive to noise than other hearing generalists. Type 3 species within this group are capable of detecting both the particle motion and sound pressure components of underwater noise. Key species in this group include herring, sprat, allis shad, twait shad and cod.

As for the mobile fish species receptor group, the AER values derived from the sound modelling conducted for hearing specialists for the Original Development ES generally appear to be conservative in comparison to published information on particle motion propagation. For this receptor group, estimating impact areas by using sound pressure based underwater noise models appears to be the most appropriate assessment method, and this approach should be followed in preference of possible particle motion based approaches which may become possible in the future.

5.2.3. Prey species

This receptor group consists of sandeel species. Sandeels may detect particle motion, but do not have a swim bladder and are therefore not considered able to detect the sound pressure component of underwater noise. Sandeels are also thought to be relatively insensitive to noise stimuli, a fact that is reflected in the relatively small impact ranges derived by the modelling exercise.

The upper ranges hypothesised for particle motion levels which may result in negative effects on marine organisms are thought to be less than 1 km (Thomsen *et al*., 2015; Miller *et al*., 2016) and the AER ranges modelled for prey species (for strong and mild behavioural responses) are broadly in line with these published values. As previously noted, particle motion transmission through the substrate may propagate further than water borne particle motion, and it may be that this element is detectable over a greater area by this benthic dwelling receptor group.

5.2.4. SAC qualifying feature species

The SAC qualifying feature species receptor group consists of species of high conservation status from designated sites on the east coast of Scotland, namely; Atlantic salmon, sea lamprey, river lamprey and freshwater pearl mussel. All of these species are considered to be sensitive to the particle motion component of underwater noise, but not the sound pressure component.

As for the mobile fish species receptor group, the AER values derived from the sound modelling conducted for the SAC qualifying feature species for the Original Development ES generally appear to be conservative in comparison to published information on particle motion propagation, and its effects on fish species.

5.2.5. Electro-sensitive elasmobranchs

The electro-sensitive elasmobranchs receptor group consists of skates, rays and small shark species. None of these species possess swim bladders and they are thus considered only to be sensitive to the particle motion component of underwater noise and not to the sound pressure component. In the Original Development ES elasmobranch are therefore classed as hearing generalists and the conclusions applied to mobile fish species are also applied to this receptor group.

As for the mobile fish species receptor group (Section 5.2.1), the AER values derived from the sound modelling conducted for the electro-sensitive elasmobranchs for the Original Development ES generally appear to be conservative in comparison to published information on particle motion propagation.

5.2.6. Shellfish

The shellfish receptor group consists of crustacean and mollusc species excluding cephalopods; with the key species identified as scallops, crabs, lobster and *Nephrops*. These species are considered to be sensitive to the particle motion component of underwater noise, but not the sound pressure component. The sensitivity of this group to particle motion is considered to be much less than that of fish, however substrate-borne particle motion is likely to be relevant to these species.

In the Original Development ES no underwater noise modelling was carried out for this receptor group as no audiograms exist from which to model thresholds.

Evidence was provided that indicated there would be no deleterious effects from high intensity underwater noise from piling. Recent studies have shown that invertebrates do have the potential for detecting particle motion, with physiological and behavioural responses possible (e.g. Roberts, 2015), however due to their much lower sensitivity (relative to fish), the areas over which they are likely to be able to detect sound through particle motion are likely to much smaller than those areas identified for fish species (Thompson *et al.,* 2015).

5.3. Predictions of other construction noise effects

The estimated impact ranges associated with non-piling construction activities which are provided in the Underwater Noise chapter of the Original Development ES are all derived for the sound pressure component of underwater noise. The impact ranges for different activities and different receptor groups are all less than 66 m. As the particle motion component of underwater noise typically attenuates more rapidly than the sound pressure component in the near field, it is considered likely that particle motion levels which may invoke avoidance responses would only be present in very close proximity to the source. As such, the non-piling construction noise impacts assessed in the Original Development ES are considered to be conservative when taken as a proxy for particle motion.

5.4. Predictions of operational noise effects

The Original Development ES underwater Noise chapter stated that 'Wind Turbine Generator noise is not estimated to exceed the mild avoidance behavioural threshold (including for hearing specialists) at the point of emission from the Wind Turbine Generator tower'.

Published data on particle motion levels for an operational wind turbine indicate particle motion to be measurably above ambient levels within 40 m of operational wind turbines (monopile construction), although it is considered these levels may only be detectable to fish within 10 m of the turbine (Sigray & Anderson, 2011). Studies of noise emissions from steel monopole turbines were also noted to be greater than those from jacket-based turbines.

As such, it is considered that avoidance ranges associated with elevated particle motion levels are likely to be very small for all receptor groups and that impact ranges assessed for operational noise impacts in the Original Development ES are considered to be appropriate, if not conservative.

5.5. Predicted levels of impact and Original Development EIA conclusions

The findings of this review, in relation to the predicted level of impact from the Original Development ES are presented below for mortality and injury, and behavioural responses to underwater noise to each of the receptor groups (Table 5.1).

Table 5.2: Comparison of Original Development ES receptor group construction noise impact assessments to estimated particle motion impacts

Receptor Group/ Impact	Original Development ES Conclusion	New Relevant Information	Validation
Mobile Fish Species (Hearing Generalists) and Electro-sensitive elasmobranchs Mortality, Physical and Auditory Injury	The resultant area affected by noise levels that is likely to cause mortality, physical and auditory injury in fish species is restricted to a maximum of 0.01 km^2. It should also be noted that the implementation of soft-start procedures will result in many fish being displaced from the area of effect before noise levels reach the levels that injury and mortality are predicted. The magnitude of this effect is judged to be negligible as any death or injury of fish species has little potential to create impacts on the size and structure of the overall stock. The sensitivity of this receptor is judged to be low, therefore, with respect to mortality, physical injury, and auditory injury due to piling noise, a negligible/minor impact is predicted on mobile fish species.	Injurious effects resulting from particle motion are yet to be demonstrated for any source (Popper *et al*., 2014). There are also no studies providing evidence of particle motion damage to auditory sense organs, although it is considered that effects may be possible at very high levels of particle motion, however these would only occur in very close proximity to the noise source (Zhang *et al*., 2015).	Original Development ES conclusions considered to be conservative. Magnitude of particle motion effects considered likely to be smaller than assessed for sound pressure. Original Development ES conclusion remains valid.
Mobile Fish Species (Hearing Generalists) and Electro-sensitive elasmobranchs Behavioural Responses	The spatial extent of areas affected by noise levels that will produce strong avoidance (90 $dB_{ht\ (dab)}$) and mild avoidance (75 $dB_{ht\ (dab)}$) responses exceeds the boundary of the Development Area (42.54 km^2, and 119.25 km^2 respectively), however the actual physical response at each of these levels is still relatively uncertain and variable. In summary, for fish hearing generalists, including dab and sea trout, the noise impact areas that will produce behavioural responses (avoidance) as predicted by the noise modelling are small in proportion to the spatial extent of similar areas of habitat in the wider region, resulting in a low magnitude of effect. The sensitivity of the mobile fish receptor group is defined as low, therefore a minor impact is predicted on mobile fish due to subsea noise generated via piling in the construction phase.	Particle motion levels have been recorded to be greater than ambient levels within 750 m of piling locations for most of the frequency spectrum (Thomsen *et al*. 2015). All studies agree that particle motion levels attenuate rapidly in the near field. Studies of behavioural responses to high intensity sound by hearing generalist fish (i.e. those who can only detect particle motion) show variable results, depending on species.	Original Development ES conclusions considered to be conservative. Magnitude of particle motion effects considered likely to be smaller than those assessed for sound pressure. Original Development ES conclusion remains valid.

Receptor Group/ Impact	Original Development ES Conclusion	New Relevant Information	Validation
Hearing specialists Mortality, Physical and Auditory Injury	The impact area for herring at 130 dB_{ht} (injury) is 0.2 km^2. Data from the baseline surveys and also review of ICES landings data indicates that the distribution of herring within the Development Area is limited. The limited spatial extent of noise levels resulting in mortality or injury (physical or auditory) is highly unlikely to overlap with aggregations of herring congregating on spawning grounds. Therefore, the magnitude of this effect is judged to be negligible as the limited spatial extent of this effect should only have a small impact on the overall size or structure of wider herring, sprat, and cod stocks in the region. The sensitivity of the hearing specialist receptor is judged to be moderate. Therefore a minor impact on hearing specialists via injury and mortality from piling noise is predicted.	Injurious effects resulting from particle motion are yet to be demonstrated for any source (Popper *et al*., 2014). There are also no studies providing evidence of particle motion damage to auditory sense organs, although it is considered that effects may be possible at very high levels of particle motion, however these would only occur in very close proximity to the noise source (Zhang *et al*., 2015).	Original Development ES conclusions considered to be conservative. Magnitude of particle motion effects considered likely to be smaller than assessed for sound pressure. Original Development ES conclusion remains valid for particle motion for the scope of the Revised Development. It is worth noting that due to the increased hammer energies, noise modelling will be undertaken for hearing specialists in the Revised Development ES. While this may not incorporate particle motion modelling, as it is based on the fishes reaction to noise it incorporates particle motion.

Receptor Group/ Impact	Original Development ES Conclusion	New Relevant Information	Validation
Hearing specialists Behavioural Responses	The impact areas for herring at 90 dB_{ht} and 75 dB_{ht} are 2,473 km^2 and 9,223 km^2 respectively. These areas exceed the boundary of the Development Area and overlap with adjacent herring spawning grounds. The spawning grounds affected lie on the periphery of much wider spawning areas, and data suggests that spawning intensity is greater further north than the 75 $dB_{ht\ (herring)}$ noise contour. As herring (and sprat) are highly mobile species any avoidance of the noise contour area during piling will not result in exclusion of individuals from the wider available spawning locations. The magnitude of this effect is judged to be moderate. Coupled with a receptor sensitivity of moderate, a moderate impact is predicted on Herring. As cod and sprat spawning grounds occur across much of the North Sea, displacement of adults during the respective spawning seasons will not affect the spawning success of these species. Nursery grounds for cod and sprat are common and widely distributed. These species are considered to have a moderate sensitivity, and due to the distribution of each species the magnitude of this effect will be low. This results in an overall impact of minor/moderate.	Particle motion levels have been recorded to be greater than ambient levels within 750 m of piling locations for most of the frequency spectrum (Thomsen *et al*., 2015). All studies agree that particle motion levels attenuate rapidly in the near field. For hearing specialist fish, determining behavioural responses to the particle motion component of underwater noise is complicated by separating them from behavioural responses to the pressure component but both acoustic components are likely to be processed simultaneously allowing hearing specialists to derive a more complex understanding of their surroundings from underwater noise than species which only perceive particle motion.	Original Development ES conclusions considered to be conservative. Magnitude of particle motion effects considered likely to be smaller than those assessed for sound pressure. Original Development ES conclusion remains valid.
Prey species Mortality, Physical and Auditory Injury	As a result of the low sensitivity of sandeels to subsea noise effects, the spatial extent of noise levels that would cause mortality and/or injury were too small to model. Studies of sandeels during seismic surveys have shown no increase in mortality or injurious effects in treatment groups exposed to seismic shooting, and no reduction in sandeel abundance after the seismic activity had ceased (Hassel *et al*., 2004). A negligible magnitude is predicted on sandeels from mortality and injury effects. The sensitivity of this receptor has been defined as moderate; therefore a minor impact is predicted.	Injurious effects resulting from particle motion are yet to be demonstrated for any source (Popper *et al*., 2014). There are also no studies providing evidence of particle motion damage to auditory sense organs, although it is considered that effects may be possible at very high levels of particle motion, however these would only occur in very close proximity to the noise source (Zhang *et al*., 2015).	Original Development ES conclusions considered to be accurate. Magnitude of particle motion effects are likely to be similar than those assessed for sound pressure, though impact ranges still probably very small. Original Development ES conclusion remains valid.

Receptor Group/ Impact	Original Development ES Conclusion	New Relevant Information	Validation
Prey species Behavioural Responses	The impact ranges for behavioural responses in sandeels are limited compared to hearing specialists, with an area of 11.70 km^2 affected by the 75 dB_{ht} contour. Seismic surveys of sandeels has shown some behavioural reactions are likely to occur, with direct video observations showing increased tail motion, bending of the body and fleeing out of site during seismic shooting No observations of sandeels seeking refugia within the sediments were seen during seismic activity, and after the seismic shooting had ceased, normal behaviour was resumed (Hassel *et al*., 2004). Effects on sandeels are likely to be short term, localised and constrained to behavioural level effects, with no longer term effects likely. As such, the effect of underwater noise on sandeels is considered of low magnitude. Due to the ecological and conservation status of sandeels, they are considered to be of moderate sensitivity, and as such, combined with a negligible magnitude, a minor/moderate impact is predicted.	Particle motion levels have been recorded to be greater than ambient levels within 750 m of piling locations for most of the frequency spectrum (Thomsen *et al*., 2015). All studies agree that particle motion levels attenuate rapidly in the near field. Studies of behavioural responses to high intensity sound by hearing generalist fish (i.e. those who can only detect particle motion) show variable results, depending on species.	Original Development ES conclusions considered to be accurate. Magnitude of particle motion effects are likely to be similar to those assessed for sound pressure, and impact ranges probably very small. Original Development ES conclusion remains valid.
SAC qualifying feature species Mortality, Physical and Auditory Injury	Noise modelling indicates injurious effects are likely to occur less than 0.1 km from source. As the effect will be intermittent and no wider effects on the size or structure of stocks that represent qualifying features of local SACs is predicted, the magnitude of this effect on salmon is judged to be negligible. The sensitivity of this receptor is judged to be high due its designation as a qualifying feature for local SACs, therefore combined with a negligible magnitude, a minor/moderate impact is predicted.	Injurious effects resulting from particle motion are yet to be demonstrated for any source (Popper *et al*., 2014). There are also no studies providing evidence of particle motion damage to auditory sense organs, although it is considered that effects may be possible at very high levels of particle motion, however these would only occur in very close proximity to the noise source (Zhang *et al*., 2015).	Original Development ES conclusions considered to be conservative. Magnitude of particle motion effects considered likely to be smaller than assessed for sound pressure. Original Development ES conclusion remains valid.

Receptor Group/ Impact	Original Development ES Conclusion	New Relevant Information	Validation
SAC qualifying feature species Behavioural Responses	Noise modelling indicates an area of approximately 14 km^2 may be affected by noise levels that would create a strong avoidance reaction in salmon (90 dB_{ht}) and 475 km^2 affected by noise levels that would potentially create mild avoidance reactions (75 dB_{ht}). Noting the distances between the estuaries of SAC rivers and the Development Area (>20 km) and the fact that the maximum extent of noise effects have been predicted to be no more than 10 km (for a minor avoidance reaction), no barriers to migration as a result of subsea noise are predicted for adult salmon returning to any of the local rivers designated as SACs. Smolt leaving their natal rivers for the first time may pass through the Development Area, however the extent of the area affected by piling noise does not represent a complete barrier to this migration. As such the effect of piling noise on salmon (both returning adults and smolts/kelts leaving rivers) is considered to be of low magnitude as the behavioural responses that may arise via these noise levels are only predicted to result in small effects on the size or structure of salmon stocks in the wider region that form qualifying features of SACs and will not form a barrier to migration. With the sensitivity of this receptor being high combined with low magnitude, a moderate impact is predicted for behavioural responses to piling noise by migrating salmon. The effect on sea lampreys is considered to be of low magnitude as the behavioural responses that may arise via these noise levels are only predicted to result in small effects on the size or structure of sea lamprey stocks in the wider region that form qualifying features of SACs. With the sensitivity of this receptor being high, a moderate impact is predicted for behavioural responses to piling noise by sea lamprey.	Particle motion levels have been recorded to be greater than ambient levels within 750 m of piling locations for most of the frequency spectrum (Thomsen *et al*., 2015). All studies agree that particle motion levels attenuate rapidly in the near field. Studies of behavioural responses to high intensity sound by hearing generalist fish (i.e. those who can only detect particle motion) show variable results, depending on species.	Original Development ES conclusions considered to be conservative. Magnitude of particle motion effects considered likely to be smaller than assessed for sound pressure. Original Development ES conclusion remains valid.

Receptor Group/ Impact	Original Development ES Conclusion	New Relevant Information	Validation
Shellfish Mortality, Physical and Auditory Injury, and Behavioural Responses	The impact of piling noise on shellfish is likely to be negligible. Studies have shown no effect on mortality, appendage loss or the ability of animals to regain normal posture after exposure to very high sound levels (>220 dB), although some avoidance behaviour can be expected (Payne *et al*., 2007). These reactions to noise and vibration should not interfere with the ecological functioning of the organisms with mobile species likely to return to the areas soon after cessation of the impacting activity. The magnitude of the effect of underwater noise to mobile invertebrates is considered to be negligible. The sensitivity of these species is considered to be low, and therefore a negligible/minor impact is predicted. Results from studies on the impacts of seismic activity on scallops (*Pecten fumatus*) also indicate that no deleterious effects are likely (Harrington *et al*., 2010). Studies have examined both lethal and sub-lethal (reduced growth, gonad condition, etc.) effects both immediately after seismic activity and after a duration of two months post seismic activity, and found no effects that were detectable (Harrington *et al*., 2010). Furthermore, other marine bivalves (e.g. mussels (*Mytilus edulis*) and periwinkles (*Littorina* spp.)) exposed to a single airgun at a distance of 0.5 m also have shown no effects after exposure (Kosheleva, 1992). As such no impacts on sedentary macro-invertebrates are predicted.	Injurious effects resulting from particle motion are yet to be demonstrated for any source (Popper *et al*., 2014). There are also no studies providing evidence of particle motion damage to auditory sense organs, although it is considered that effects may be possible at very high levels of particle motion, however these would only occur in very close proximity to the noise source (Zhang *et al*., 2015). Particle motion levels have been recorded to be greater than ambient levels within 750 m of piling locations for most of the frequency spectrum (Thomsen *et al*., 2015). All studies agree that particle motion levels attenuate rapidly in the near field. New studies have shown physiological responses to high noise levels in a number of invertebrate species.	Original Development ES conclusions considered to be accurate. Magnitude of particle motion effects are likely to be similar than assessed in Original Development ES, and impact ranges probably very small. Original Development ES conclusion remains valid.

6. Opportunities and Recommendations

The scoping opinion asks for '*information on opportunities that the Revised Development may present to investigate effects of particle motion on fish and invertebrates*'.

Such opportunities can be classified into two separate groups; theoretical studies, and practical studies or observations.

With respect to theoretical studies, it has been noted that accurately modelling particle motion in shallow shelf seas is not possible as particle motion cannot be predicted in boundary environments where the plane wave state does not persist (Nedelec *et al*., 2016; Radford *et al.,* 2012). As such, all that could reasonably be undertaken is a review of all available data to allow predictive statements to be made regarding effects on fish and invertebrate species, as has been carried out within this report.

Field studies or observations of particle motion effects on marine organisms, although theoretically possible in a shelf sea environment, are not realistically achievable. In order to provide any certainty in the results of such studies, they must be undertaken in controlled environments where additional factors which may illicit effects may be controlled and/or accounted for. Such studies cannot therefore be reasonably undertaken in an open water environment as sufficient controls cannot be applied to ensure the reliability of any results.

Following the review of currently available data on particle motion, it is therefore the opinion of this report that there are no practical opportunities that are presented by the Revised Development that would allow investigation of the effects of particle motion on fish and invertebrates.

7. Conclusions

This document has reviewed a large body or literature on particle motion, including information on how particle motion propagates, as well as potential effects of particle motion on marine fauna.

In summary:

- Although particle motion and sound pressure can be measured independently, and have different properties, they are both attributes of sound and are consequently interrelated;
- The development of methodologies and equipment for measuring particle motion levels around offshore pile-driving appears to be ongoing, although this is a field which remains in relative infancy. Consequently particle motion propagation mapping in relation to offshore developments remains unfeasible and direct measurement is the only method of accurately determining particle motion at a given location (unless the sound wave is in an ideal environment);
- Particle motion (velocity) attenuates rapidly in close proximity to the source, and as such detectably elevated levels tend to occur close to the source. An exception to this, however, is substrate-borne particle motion, which may propagate much greater distances than particle motion propagating through the water column, although evidence of substrate-borne particle motion effecting marine organisms at such distances is yet to be demonstrated by field-based studies;
- There is a sizeable body of evidence that all fish (or a large majority of species) can detect the particle motion component of underwater noise. Acuity levels may mean that detection ranges are relatively small (particularly relative to the ranges at which hearing specialists can detect the sound pressure component of underwater noise);
- Limited evidence also suggests that a wide range of marine invertebrate species can also detect particle motion, although the sensitivities of these species are generally considered to be much lower than those of fish;
- The *in situ* particle motion detection thresholds for various groups are still not well understood. Particle motion audiograms do not exist for most species (although many audiograms of hearing generalists do exist, the receiving noise levels were recorded as pressure). It is therefore generally not possible to be sure of hearing thresholds at varying frequencies; and
- Response thresholds of various groups to the particle motion component of underwater sound are not well understood. For example thresholds for mild and strong avoidance behaviours, and particularly thresholds at which trauma may occur.

The purpose of this document was to determine whether the conclusion of the Revised Development Scoping Report (i.e. that the underwater noise impacts assessed for the Natural Fish and Shellfish chapter of the Original Development ES remain valid for all species except hearing specialists) remained valid in light of any new evidence on particle motion propagation and its effects on marine fauna.

Following the review of the available information highlighted by Marine Scotland in their Revised Development Scoping Opinion, as well as a number of additional papers found during the review, it can be concluded that the Original Development ES conclusions remain valid for all receptor groups and therefore the conclusions of the Revised Development scoping report are considered to still be appropriate. As such noise impacts on all species except hearing specialists should be scoped out of the Revised Development EIA Report.

The assessment for hearing specialists within the Revised Development EIA Report will continue to use sound pressure as a modelling unit as it is not possible to reliably predict particle motion through modelling at this time and as it has been shown that sound pressure modelling produces (in terms of particle motion) conservative impact ranges when behavioural thresholds are specified for this receptor group. Non behavioural effects (i.e. lethal effects and physical injury) are only described through levels of sound pressure so pressure based modelling remains the only means of quantifying the distance over which these levels of harm exist.

Following the review of currently available data on particle motion, it is the opinion of this report that there are no practical opportunities that are presented by the Revised Development that would allow investigation of the effects of particle motion on fish and invertebrates. Furthermore, as it has concluded following this review that the conclusions in the scoping report remain true (that noise impacts, which include particle motion, can be scoped out for all specie except hearing specialists – for whom the pressure component is of greater relevance), it is considered that no further work is required to mitigate any potential effects of particle motion on fish and invertebrate species.

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Appendices

A. Appendix 1

Table A1: Documents referred to by MSS in scoping response

<table>
<tr><th>Document Number and Authors</th><th>Summary</th></tr>
<tr><td>Ceraulo et al., 2016</td><td>A conference poster comparing direct measurements of sound pressure level and particle motion generated by experimental pile driving in a former shipbuilding dock.
A significant correlation was found between broadband sound pressure level and particle motion, however this correlation was poor at frequencies below 400 Hz.</td></tr>
<tr><td>Farcas et al., 2016</td><td>A paper which reviews the process of underwater noise modelling and explores factors affecting predictions of noise exposure e.g.: model selection, bathymetry, sea bed, water column, tidal effects and temperature. The take home message from this review is that there are errors and uncertainties when modelling.
Most of the paper relates to the pressure component of underwater noise. Particle motion propagation is mentioned as a field of noise modelling in which further research is required.</td></tr>
<tr><td>Harding et al., 2016</td><td>A two-part paper investigating hearing in Atlantic salmon (Salmo salar).
Part one focuses upon the production of audiograms in response to the pressure component of underwater noise for Atlantic salmon. The authors stress, however, that this species is considered likely to respond predominantly to the particle motion component of underwater noise. To determine the spatial scale of detection of anthropogenic noise, open water experiments, using in situ accelerometers to measure particle motion, are suggested.
Part two assess the impacts of pile-driving playback on the behaviour and physiology of Atlantic salmon. Experiments were conducted in tanks, and both sound pressure and particle motion propagation were measured. Piling noise was considered unlikely to be an important factor in determining differences between the behaviour of test and control groups. Furthermore, no evidence was recorded of any startle response to playback of individual strikes. Atlantic salmon were considered not to perceive playback pile-driving noise as a stressor; a finding consistent with studies of the closely related brown trout (Salmo trutta), which has been observed to show no changes in behaviour in relation to exposure to a real piling event (Nedwell et al., 2003).</td></tr>
<tr><td>Hawkins & Popper, 2017</td><td>A three part paper concerning the assessment of underwater noise impacts on marine fish and invertebrates.
Part one provides a background on underwater acoustics including an explanation of the particle motion component of underwater sound propagation.
Part two provides an overview of available information relating to the hearing capabilities of fish and marine invertebrates, and the potential effects of anthropogenic noise on these groups. This includes sensitivity to particle motion.
Part three discusses how to assess the effects of exposure to anthropogenic noise on fish and marine invertebrates.</td></tr>
<tr><td>Mueller-Blenkle et al., 2010</td><td>A summary of research looking at the response of cod (Gadus morhua) and sole (Solea solea) to playback of pile-driving noise. This research included measurements of particle motion and was conducted in large net pens in a Scottish coastal bay.
The objectives and results of the research is summarised in Table 1, below.
Table 1 – Summary of findings<table><tr><td>Objective</td><td>Results</td></tr><tr><td>Understand the effects of pile-driving sound sources on the behaviour of marine fish</td><td>First field relevant experimental proof that pile-driving sound affects the behaviour of cod and sole</td></tr></table></td></tr>
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<table>
<tr><td></td><td>Identify the threshold of exposure that lead to behavioural responses</td><td>Not a single threshold but range over which behavioural response occurs; cod = 140-161 dB re 1μPa peak; sole = 144-156 dB re 1μPa peak, particle motion between 6.51x10-3 and 8.62 x10-4 m/s2 peak</td></tr>
<tr><td></td><td>Define the characteristics, scale and duration of responses as a function of exposure conditions</td><td>Cod = tendency for higher swimming speed, significant freezing response, documented initial avoidance;
Sole = significant increase in swimming speed, and initial avoidance</td></tr>
<tr><td></td><td>Interpret the results with regard to pile-driving operations in the marine environment</td><td>Reduction of uncertainty about behavioural reaction of marine fish to pile-driving sound; Incorporation of results of this study into offshore wind farm EIAs; further development of mitigation measures</td></tr>
<tr><td>Nedelec et al., 2016</td><td colspan="2">An introduction to the topic of underwater particle motion and particle motion reception by marine organisms. The authors have developed a computer program which allows users to “determine whether they are working in conditions where measurement of particle motion may be relevant.”</td></tr>
<tr><td>Normandeau Associates, Inc., 2012
(Principle authors: Hawkins & Popper)</td><td colspan="2">A literary synthesis providing a comprehensive review of literature relating to the effects of noise on fish and marine invertebrates. It particularly identifies data gaps, highlighting where information is considered to be lacking and further research is required.
Research into particle motion levels associated with human activities in the marine environment are highlighted as a particular area where further research is a priority; specifically how particle motion propagates from anthropogenic noises sources. The authors state that there is a need for the development of effective instrumentation to characterise particle motion from various sound sources.
Understanding potential effects of particle motion on benthic organisms is highlighted as being of particular relevance as particle motion through the sea bed may play an important additional role (i.e. ground roll effects).
The use of appropriate auditory metrics (particle motion or pressure) should be considered for different groups of marine organism (as per Ellison and Frankel, 2012) Specifically, the metric used should relate to the auditory capabilities of the organism of interest. For example, for fish which are sensitive to sound pressure, pressure may be the most appropriate metric to use when assessing potential impacts of a source of underwater noise. For species considered to be incapable of detecting the pressure component of underwater noise, particle motion may be a more appropriate metric.</td></tr>
<tr><td>Popper et al., 2014</td><td colspan="2">A technical report presenting the outcomes of a working group aimed at determining underwater sound exposure guidelines for fish and sea turtles. Particle motion measurement is identified as one of the most important issues where further research is required. The development of standardised devices and protocols to measure particle motion is raised as a particular area of priority.
Sensitivity of adult and larval fish to particle motion is addressed in Chapter 4, while data available on effects of exposure is summarised in Chapter 5.</td></tr>
<tr><td>Radford et al., 2012</td><td colspan="2">A comparison of the particle acceleration and pressure auditory thresholds of three teleost fish species, using three different methods of determining particle acceleration. The paper suggests that all teleosts have a similar ability to detect the particle motion component of the sound field and inter-specific differences in hearing ability derive from their ability to transduce the pressure component of the sound field to the inner ear via ancillary hearing structures.</td></tr>
<tr><td>Roberts, 2015</td><td colspan="2">A PhD thesis which evaluates the key behavioural responses of coastal UK marine fish and macroinvertebrate species to anthropogenic noise.
Part 1 – Literature review
Part 2 – Using acoustic imaging to assess responses of free-living costal pelagic fish to impulsive sounds from submerged speakers.
Part 3 – The use of baited video cameras to investigate responses of individual free-living fish</td></tr>
</table>

	and crustaceans to impulsive and continuous sounds. Part 4 – Assessing sensitivity and behavioural responses of the hermit crab Pagurus bernhardus to substrate-borne vibration Part 5 – Assessing sensitivity and behavioural responses of the blue mussel to substrate-borne vibration
Roberts & Elliot, 2017	A review of studies regarding the sensitivities and responses of marine invertebrates to substrate-borne vibration. A useful summary of the terms 'vibration', 'noise' and 'particle motion' and their uses in the context of marine disturbance. Crustaceans – Various organs have been demonstrated (or are suspected) to detect particle motion, primarily at low frequencies, although the sensitives of these receptors are much lower than analogous systems in fish. Bivalve molluscs – Particle motion detection has been demonstrated. Primary organ implicated in detection of particle motion is the statocyst (although other systems also appear to play a role for some groups).
Robinson *et al*., 2014	A good practice guide for the measurement of underwater noise. "The guidelines in this document cover only the measurement of sound pressure in the water column [i.e. not particle motion]. The techniques and sensors for measuring [particle motion] are currently relatively immature, and there is a lack of calibration standards. There is also a lack of knowledge of what levels of these parameters would cause an effect, and indeed little knowledge of what background levels exist in the ocean."
Sigray & Anderson, 2011	A summary of the results of field trials using novel instrumentation to measure particle motion levels around an operational wind turbine at Utgrunden Wind Farm in the Baltic Sea. Comparison of recorded particle motion levels to audiograms of cod and plaice.
Spiga *et al*., 2016	Blue mussels (*Mytilus edulis*) were observed to increase the rates at which they removed suspended particles from the water column in response to simulated pile-driving. Increased filtration rates are hypothesised to occur as a result of increased energetic demands as a result of a stress response to piling. Particle motion and / or vibration were considered as the means by which the piling was detected.
Thomsen *et al*., 2015	Field measurements of particle motion for construction and operational phase offshore wind farms noted as being an area where existing data was limited and collection of such information was identified as being a high priority. A latter part of this paper summarised on site measurement of particle motion at construction and operation phase wind energy developments. Key results: Particle motion is measurable from an operational offshore wind turbine at a range of 40 m and emission levels by steel monopile turbines are greater than jacket-based turbines. Frequency peaks of emissions – 400 Hz to 1250 Hz. During construction phase piling particle motion levels at 750 m are above ambient levels for most of the frequency spectrum (i.e. detectable by most fish species, but considered not to be detectable by most invertebrates). Noise mitigation measures (bubble – curtains) were observed to be effective in reducing particle motion levels associated with piling.
Zhang *et al*. 2015	Quantitative models of the statocyst (auditory/balance) system of three cephalopod species (an octopus, cuttlefish and squid) agree with reviewed experimental data that cephalopods are sensitive to underwater particle motion, particularly at low frequencies (c. 10 Hz). "Severe particle motion could potentially cause irreparable damage in the cephalopod statocyst at short range." A damaging level of particle motion for these cephalopod species is estimated to be 0.27 m/s2. Such levels are considered only to occur close to the most intense sources (i.e. pile driving), as particle motion attenuates very rapidly from the source.

Table A2: Relevant papers from Popper and Hawkins (2016)

Document Number and Authors	Summary
Casper *et al*., 2016	A study investigating impulsive pile-driving induced sound pressure effects on several fish species. Particle motion is referred to in the conclusions as an additional factor which should be considered close to the source of the sound.
Hawkins & Popper, 2016	A paper discussing the development of impact criteria for sound effects on fish. Stresses that many or most species do not respond to the sound pressure component of underwater sound and therefore that modelling and criteria which focus on pressure alone may be of limited value. Recommends that models of sound propagation should account for particle motion.
Lewandowski *et al*., 2016	A gap analysis identifying areas of priority for research in studies of anthropogenic noise effects on aquatic life. Understanding of marine invertebrate hearing is considered to be in its infancy. For fish and marine invertebrates the production of species specific audiograms accounting for sensitivities to particle motion was identified as a pressing challenge.
Martin *et al*., 2016	An evaluation of three types of sensor for measuring particle motion: a three-axis accelerometer, a three-axis velocity sensor, and two 4-element hydrophone arrays.
Miller *et al*., 2016	A paper discussing the methods and results from modelling used to estimate the impact range of pile-driving on American lobster and flounder at a shallow-water site near Rhode Island, USA. For lobsters, there may be effects out to 500 m from the pile driving for a single strike. Using a very conservative criterion proposed for fish that have a swim bladder, the effects are limited to 250 m from the pile driving for 960 strikes.
Roberts & Breithaupt, 2016	Investigation of the sensitivity of crustaceans to substrate-borne vibration. Includes review of literature and experimental observations of hermit crabs exposed to varying amplitudes and frequencies of vibration. Clear behavioural changes were observed, with greatest sensitivities recorded to signals at a frequency of 10 Hz.
Samson *et al*., 2016	A review of the frequency ranges and sound levels that generate behavioural responses in cephalopods and the nature of those responses. The hearing range of the various cephalopod species for which data are available appear to lie between approximately 1 and 2,000 Hz. Threshold sound levels to elicit behaviour responses vary with frequency. A wide range of behavioural and physiological responses to sound have been observed, though the biological significance of responses is not clear.

Table A3: Determination of fish audiograms

Species modelled	Reference	Methods of Audiogram determination
Herring	Enger (1967)	Environment: Laboratory tank Acoustic source: Single underwater speaker Audiogram determination: Monitored electrical nervous activity in acoustic region of the subject's brain. Sound measurements: Sound pressure via hydrophone Comments: Author states that it was found that near-field effects did not stimulate the hearing receptors in this species, presumably because the ear with the air-filled bullae are all enclosed in the skull. Near-filed vibration will not produce pressure changes in the bullae and therefore no displacement of the prootic membrane. The swimbladder seems to play little role in hearing, probably because the duct connecting it to the ear is thin and rapid pressure changes would be highly damped.
Dab	Chapman & Sand, (1974)	Environment: Offshore (Upper Loch Torridon, Scotland) Acoustic source: 2 underwater sound projectors Audiogram determination: Cardiac conditioning (monitored electrical energy from the heart). Sound measurements: Sound pressure via hydrophone Comments: By having 2 projectors at different distances authors were able to distinguish between pressure and particle displacement responses.
Trout	Nedwell *et al*., (2006)	Environment: Laboratory tank Acoustic source: 2 underwater sound projectors Audiogram determination: Auditory Brainstem Response (electrodes placed cutaneously on the cranium such that they spanned the VIIIth nerve) Sound measurements: Sound pressure Comments:
Salmon	Hawkins & Johnstone (1976)	Environment: Laboratory tank and offshore Acoustic source: underwater speaker Audiogram determination: Cardiac conditioning (monitored electrical energy from the heart). Sound measurements: sound pressure and particle motion Comments: The fish responded only to low frequency tones (below 380 Hz), and particle motion, rather than sound pressure, proved to be the relevant stimulus.
Japanese Sand Lance	Suga *et al*., (2005)	Environment: Laboratory tank Acoustic source: in Air speaker Audiogram determination: : Auditory Brainstem Response (electrodes placed cutaneously on the cranium such that they spanned the VIIIth nerve) Sound measurements: Sound pressure Comments: These results indicate that Japanese sand lance can detect low frequency sound but are less sensitive than other fish species. These

Species modelled	Reference	Methods of Audiogram determination
		high thresholds are probably caused by the lack of a swim bladder.
Cod	Chapman & Hawkins (1973)	Environment: Offshore Acoustic source: 2 underwater sound projectors Audiogram determination: Monitored electrical energy from the heart Sound measurements: sound pressure via hydrophone Comments: Sensitivity to sound pressure indicates that the gas-filled swim bladder may be involved in the hearing of cod, although there is no direct coupling with the labyrinth. At lower frequencies high amplitudes were obtained close to source suggesting sensitivity to particle displacement. Hearing thresholds are determined by the sensitivity of the otilith organs to particle displacements re-radiated from the swimbladder.

Table A4: Calculations to convert Impact Range Area (IRA) to Approximate Equivalent Radii (AER) and worked examples

When IRA < 226 km² (i.e. Isobel radii from modelled simultaneous piling events are assumed not to overlap)	When IRA > 226 km² (i.e. Isobel radii from modelled simultaneous piling events are assumed to overlap)
$AER = \sqrt{\frac{IRA \times 10^6}{2\pi}}$	$\sqrt{\frac{IRA \times 10^6}{2\pi}} < AER < \sqrt{\frac{IRA \times 10^6}{\pi}}$
Example: For dab, at noise levels exceeding 130 dBht, IRA = 0.01 km² $AER = \sqrt{\frac{0.01 \times 10^6}{2\pi}}$ $AER = 40\ m$	*Example: For herring, at noise levels exceeding 75 dBht, IRA = 9,222.56 km²* $\sqrt{\frac{9{,}222.56 \times 10^6}{2\pi}} < AER < \sqrt{\frac{9{,}222.56 \times 10^6}{\pi}}$ $38{,}312\ m < AER < 54{,}181\ m$

Table A5: Impact ranges predicted in Chapter 11 of the original Inch Cape ES for non-piling construction activities.

		Maximum ranges (m)													
		Suction dredging		Drilling		Cable laying		Rock placement		Trenching		Medium vessel activity		Large vessel activity	
Receptor	Species	90 dBht*1	75 dBht*2	90 dBht*1	75 dBht*2	90 dBht*1	75 dBht*2	90 dBht*1	75 dBht*2	90 dBht*1	75 dBht*2	90 dBht*1	75 dBht*2	90 dBht*1	75 dBht*2
Mobile fish species	Dab	1	7	<1	1	<1	1	<1	4	<1	<1	<1	<1	<1	<1
Hearing specialists	Herring	13	65	1	12	8	66	6	62	<1	27	<1	3	1	10
	Cod	7	39	2	14	1	20	2	25	1	16	<1	1	<1	8
SAC qualifying feature species	Salmon	1	5	<1	1	<1	1	<1	4	<1	2	<1	<1	<1	<1

*1 *Strong avoidance reaction by virtually all individuals.*

*2 *Mild avoidance reaction by the majority of individuals. At this level individuals will react to the noise, although the effect will probably be transient and limited by habituation.*

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Natural Power is a leading independent renewable energy consultancy and products provider. The company offers proactive and integrated consultancy, management and due diligence services, backed by an innovative product range, across the onshore wind, offshore wind, wave, tidal, renewable heat, solar pv and hydro sectors, whilst maintaining a strong outlook on other new and emerging renewable energy sectors.

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