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APPENDIX 13-B UNDERWATER NOISE IMPACT STUDY

KONGSBERG

Underwater noise impact study for Aberdeen Harbour Expansion Project: Impact of construction noise

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CONTENTS

APPROVALS

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Underwater noise impact study for Aberdeen Harbour Expansion Project: Impact of construction noise

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EXECUTIVE SUMMARY

This report has been prepared by Kongsberg Maritime Ltd for Fugro EMU Ltd. The report provides an assessment of the potential impact of man-made underwater noise on marine life arising during the construction phase of the Aberdeen Harbour Expansion Project.

The report commences with a brief overview of the activities likely to arise during the construction stage. These consist of seabed dredging, underwater piling, underwater drilling, rock blasting, material disposal and material transport. Each process is discussed as a noise generating process and likely values for their overall source level and frequency spectrum are assigned using data from the peer-reviewed literature.

Subsequently acoustic modelling was undertaken using a suite of computer programs to investigate the underwater noise propagating along a set of transects radiating from a number of construction sites in Nigg Bay. The programs themselves are based on mature and rigorous scientific methodologies that have been reviewed extensively in the international literature over a number of years. It is considered of fundamental importance that acoustic modelling is not based on "in-house" solutions using non peer-reviewed techniques as this could compromise the developer in the event that the environmental impact assessment documents become subject to scrutiny.

A scoping study has identified a number of species of marine animals that are local to the area and of concern to the Development. Of the mammals, these are harbour porpoise (*Phocoena phocoena*); bottlenose dolphin (*Tursiops truncatus*); grey seal (*Halichoerus grypus*); harbour seal (*Phoca vitulina*); and European otter (*Lutra lutra*). Numerous species of fish have been identified – these are the sea lamprey (*Petromyzon marinus*) and river lamprey (*Lampetra fluviatilis*); eel (*Anguilla anguilla*); sea trout (*Salmo trutta*); cod (*Gadus morhua*); herring (*Clupea harengus*); and Atlantic salmon (*Salmo salar*). It is noted that the cetaceans are all classified as European Protected Species while additionally the harbour seal, grey seal, harbour porpoise, bottlenose dolphin and Atlantic salmon require legal protection from human activities as defined under the Habitats Directive.

Data are presented using underwater noise impact assessment metrics for generic species of marine animal, with zones of influence based on impact criteria derived from various studies. The thresholds themselves relate to fatality, auditory injury, temporary deafness and behavioural reactions. It is worth noting that for marine mammals, currently these criteria have had little or no validation under open water conditions. Auditory injury data from controlled tests with a few captive animals have been used as the basis for developing the relevant impact criteria. Observations of behavioural avoidance with concurrent acoustic measurements are sparse, and hence the behavioural avoidance criteria must be considered speculative. By contrast, although relatively few of the 30,000+ species of fish have been tested for auditory injury, at least the sample sizes indicate that the results are statistically significant. The current study makes no judgement as to the validity of the impact criteria, but applies the metrics to the predicted noise levels in order to determine the range over which the effect arises.

Client discussions indicate that each of the construction activities involves a number of general and specialist vessel types each of which has an acoustic footprint associated with it. The total noise field is a function therefore of several individual noise sources operating in relatively close proximity to each other and for which, the individual impact zones from the adjacent sources may overlap. The resulting vessel spread gives rise to a cumulative impact and this is assessed using the impact criteria discussed above.

It is concluded that, with the exception of explosive blasting, the construction activities generate relatively low levels of underwater noise hence lethality and auditory injury for the dolphin, porpoise, seal and otter are unlikely to occur. Similarly, physical damage to fish, as indicated by the no-injury criterion, will not arise. Aversive behavioural reactions in the harbour porpoise may be seen at distances up to 390 m from the noise source. Percussive piling may give rise to longer range impacts. In this case, aversive behaviour may be noted up to 1344 m from the construction site.

Explosive blasting takes place in predrilled boreholes hence the rock overburden absorbs much of the acoustic energy. In order to survive the blast from a 20 kg explosive charge, a fish of body weight 0.2 kg must be greater than 24 m from the detonation site. This distance falls to 11 m for a 10 kg fish. The results indicate that for the same body weight, a marine mammal is more sensitive to the impact of explosive blast. The more precautionary Level A-Auditory Injury criteria for pinnipeds and cetaceans are met at ranges of 200 m and 820 m respectively.

Of all the impacts, only the Level B-Harassment criterion occurs at long range. This criterion is defined as harassment having the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering. Whether this criterion is relevant in the current study though depends largely on prevailing background noise levels. Specific background noise levels for Nigg Bay are not known. On the basis that the Aberdeen harbour site has relatively high levels of vessel activity, it is assumed that noise levels may lie in the range 120-130 dB re 1 μPa. If the background level is as high as 130 dB 1 μPa, then the vessel spread noise slips into the background at a distances varying between 12 km and 69 km depending on the season and vessel spread considered. The significance of the Harassment impact for vessel spread noise in an environment where background noise levels may exceed the impact threshold is unclear. By contrast, if background noise levels are as low as 100 dB re 1 μPa – indicative of calm wind and wave conditions and little or no passing vessel traffic (which is deemed very unlikely in the vicinity of Aberdeen Bay), vessel noise may remain audible out to ranges of 191 km in winter and 55 km in summer.

It is noted that if the breakwaters at the seaward end of Nigg Bay are built early on in the construction process, then the breakwater walls will tend to reflect construction noise back into the bay. The result of this is that the region of the North Sea beyond Nigg Bay will not be subsequently impacted by man-made noise and the Level B-Harassment criterion in this region will no longer apply.

ABBREVIATIONS

AHB	Aberdeen Harbour Board
ANSI	American National Standards Institute
BAP	Biodiversity Action Plan
BC	Bern Convention
BHD	Backhoe dredger
BHP	Brake horse power
CITES	Convention on International Trade in Endangered Species
dB	Decibel
dBht	Decibel hearing threshold
DEM	Digital elevation model
EIA	Environmental impact assessment
EPS	European Protected Species
EU MP	European Union Management Plan,
FHWA	Federal Highways Administration
FHWG	Fisheries Hydroacoustic Working Group
Hab Dir	Habitats Directive
Hz	Hertz
IUCN	International Union for Conservation of Nature
KML	Kongsberg Maritime Ltd
kW	Kilo-Watts
m	metre
N	Newton
NERC PI	Natural Environment Research Council Principle Importance
NMFS	National Marine Fisheries Service
OSPAR	Oslo-Paris convention 1992
Pa	Pascals
PMF	Priority Marine Feature
PTS	Permanent threshold shift
RAM	Rapid Acoustic Model
RL	Received level
RMS	Root mean square
SAC	Special Area of Conservation
SE	Sound exposure
sec	second
SEL	Sound exposure level
SL	Source level
SPL	Sound pressure level
TL	Transmission
TSHD	Trailing suction hopper dredger
TTS	Temporary threshold shift
US	United States
WOA	World Ocean Atlas

1. INTRODUCTION

This document has been prepared by Kongsberg Maritime Ltd for Fugro EMU Ltd in connection with the Aberdeen Harbour Expansion Project underwater noise study.

Aberdeen Harbour Board has proposed the design and construction of a new harbour facility at Nigg Bay, immediately south of the existing harbour. The purpose of the new facility is to complement and expand the capabilities of the existing harbour, accommodate larger vessels, retain existing custom, and attract increased numbers of vessels and vessel types to Aberdeen.

The new harbour development shall include but is not limited to:

- Dredging the existing bay to accommodate vessels up to 9 m draft with additional dredge depth of 10.5 m to the east quay and entrance channel;
- Construction of new North and South breakwaters to form the harbour;
- Provision of approximately 1500 m of new quays and associated support infrastructure. The quay will be constructed with solid quay wall construction and suspended decks over open revetment;
- Construction of areas for development by others to facilitate the provision of fuel, bulk commodities and potable water;
- Land reclamation principally through using materials recovered from dredging operations and local sources, where possible;
- Provision of ancillary accommodation for the facility;
- Off-site highway works to the extent necessary to access the facility and to satisfy statutory obligations;
- Diversions and enabling works necessary to permit the development.

It is noted that a number of these activities may involve the generation of man-made underwater noise and this has the potential to impact on the marine life found in the vicinity of the development.

The purpose of the report is to provide an assessment of the impact of man-made underwater noise arising during the construction process. The extent of the Aberdeen Harbour Expansion Project site is indicated in Figure 1.1.

It is noted that the quantification of an acoustic impact draws on a 3-stage process:

(i) Characterisation of noise source;

(ii) Acoustic propagation of sound;

(iii) Acoustic impact on receptor.

Each potential noise source is reviewed from an acoustic perspective and likely values for their overall source level and frequency spectrum are assigned using data from the peer-reviewed literature.

Previously commissioned client studies indicate that a number of species of marine life are found in and around the Development area and are of concern to the Development. An overview of the species is given and this is followed by an introduction to the acoustic impact criteria against which the significance of a man-made sound may be assessed.

Acoustic propagation using environmental data relating to Nigg Bay and involving sound from each noise source is discussed. The resulting cumulative sound pressure levels at a given receptor location arising from a spread of noise sources are compared with threshold values relating to lethality, auditory injury, temporary deafness and behavioural reactions. Hence the significance of each construction activity is assessed in terms of its acoustic impact.

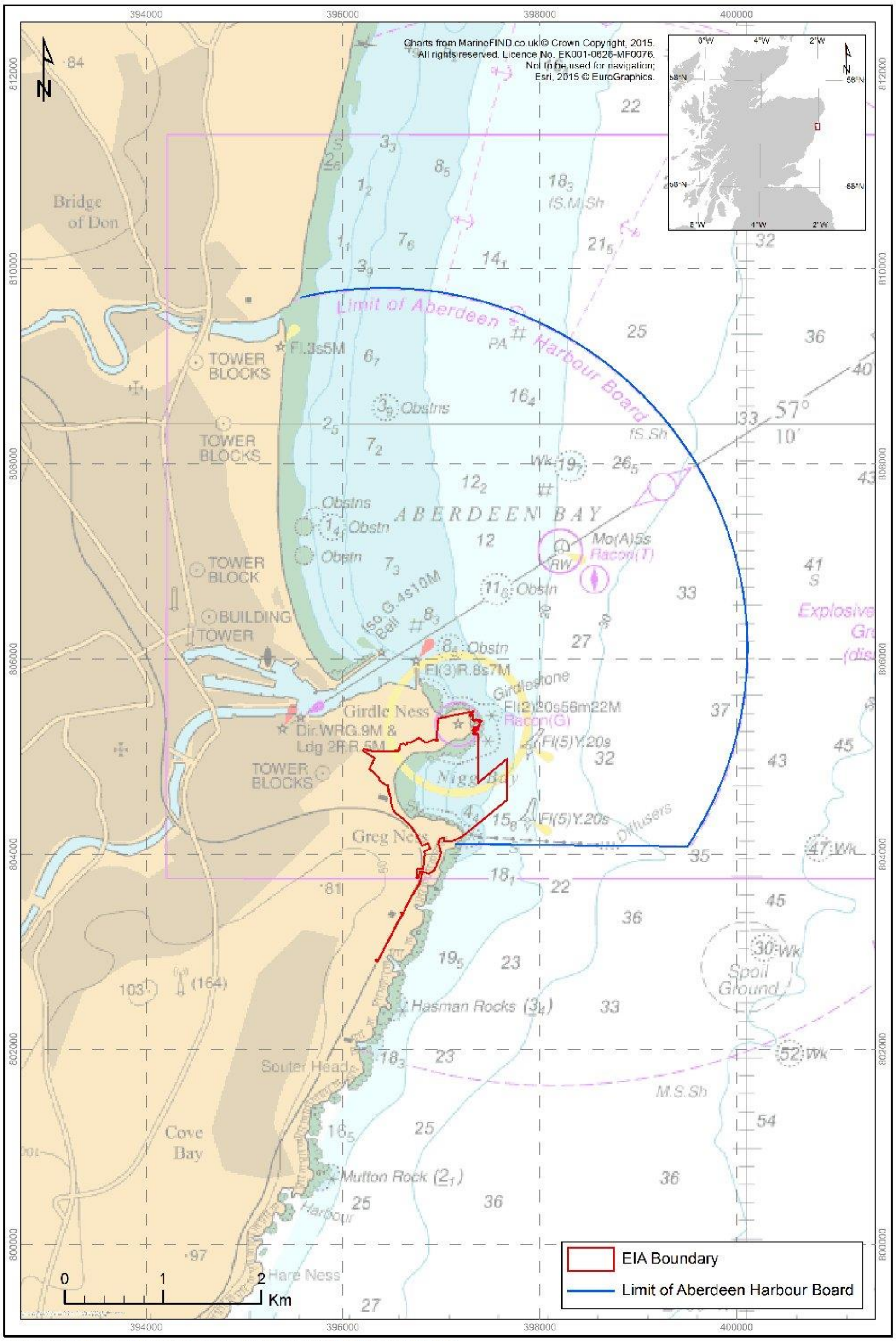

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Figure 1.1: Approximate location of Aberdeen Harbour Expansion Project site

2. DESCRIPTION OF UNDERWATER NOISE AND ASSESSMENT METRICS

2.1 Introduction

Studies by Thomsen *et al.*[1] and Southall *et al.*[2] (2007) for example, provide detailed reviews of the metrics used to measure and assess the impact of underwater noise in the marine environment. A detailed review has not therefore been provided here, although a brief overview is provided to assist the reader. It is noted that a number of these definitions and parameters draw on the advice given in American National Standards Institute (ANSI) S12.7-1986[3].

Sound may be defined as the periodic disturbance in pressure from some equilibrium value. The unit of pressure is given in Pascals (Pa) or Newton per square metre (N/m^2). The measurements however cover a very wide range of pressure values, typically from 1×10^{-3} Pa for the hearing threshold value of a human diver at 1 kHz to 1×10^{7} Pa for the sound of a lightning strike on the sea surface. For convenience therefore, sound levels are expressed in decibels (dB) relative to a fixed reference pressure commonly 1 μPa for measurements made underwater.

2.2 Peak Sound Level

For transient pressure pulses such as an explosion or a single discharge of an airgun, the peak sound level is the maximum absolute value of the instantaneous sound pressure recorded over a given time interval. Hence:

$$\text{Peak Level (zero-to-peak)} = 20 \times \log_{10} (P_{peak}/P_{ref}) \qquad \text{eqn. 2.1}$$

When the pulse has approximately equal positive and negative parts to the waveform, the peak-to-peak level is often quoted and this is equal to twice the peak level or 6 dB higher.

2.3 RMS Sound Pressure Level

The Root-Mean-Square (RMS) Sound Pressure Level (SPL) is used to quantify noise of a continuous nature. Underwater sound sources of this type include shipping, sonar transmissions, drilling or cutting operations, or background sea noise. The RMS Sound Pressure level is the mean square pressure level measured over a given time interval (t), and hence represents a measure of the average sound pressure level over that time. It is expressed as:

$$\text{RMS Sound Pressure Level} = 20 \times \log_{10} (P_{RMS}/P_{ref}) \qquad \text{eqn. 2.2}$$

where RMS Sound Pressure Levels are used to quantify the noise from transients, the time period over which the measurements are averaged must be quoted as the RMS value will vary with the averaging time period. When the noise is continuous, as in the examples given above, the time period over which measurements are taken is not relevant as the measurement will give the same result regardless of the period over which the measurements are averaged.

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[1] Thomsen F., Luedemann K., Kafemann R. and Piper W., (2006). ”Effects of wind farm noise on marine mammals and fish”. Biola, Hamburg, Germany on behalf of COWRIE Ltd. (Coll. Offshore Wind Res. Environ.) Ltd.

[2] Southall B.L., Bowles A.E., Ellison W.T., Finneran J.J., Gentry R.L., Greene Jr. C.R., Kastak D., Ketten D.R., Miller J.H., Nachtigall P.E., Richardson W.J., Thomas J.A., Tyack P.L., (2007), “Marine mammal noise exposure criteria: initial scientific recommendations”. Aquatic Mammals 33, 411–521.

[3] ANSI S12.7-1986, “Methods for measurement of impulse noise”, Issued by the American National Standards Institute, 20 February 1986

2.4 Sound Exposure Level

The problems associated with the time period over which the Sound Pressure Levels are averaged, as highlighted above, can be overcome by describing a transient pressure wave in terms of the Sound Exposure Level (SEL). The Sound Exposure Level is the time integral of the square pressure over a time window long enough to include the entire pressure-time history. The Sound Exposure Level is therefore the sum of the acoustic energy over a measurement period, and effectively takes account of both the level of the sound, and the duration over which the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$\mathrm{SE} = \int_0^T p^2(t)dt \qquad \text{eqn. 2.3}$$

where *P* is the acoustic pressure in Pascals, *T* is the duration of the sound in seconds and *t* is time. The Sound Exposure is a measure of the acoustic energy and therefore has units of Pascal squared seconds (Pa^2-s).

To express the Sound Exposure as a logarithmic decibel, it is compared with a reference acoustic energy level of 1 $\mu\mathrm{Pa}^2$.s. The Sound Exposure Level (SEL) is then defined by:

$$\mathrm{SEL} = 10\log_{10}\int_0^T \frac{p^2(t)dt}{\mathrm{P}_{ref}{}^2} \qquad \text{eqn. 2.4}$$

When a sound time period is less than 1 second, the RMS Sound Pressure Level will be greater than the Sound Exposure Level. For signals of greater than 1 second, the Sound Exposure Level will be greater than the RMS Sound Pressure Level where:

$$\mathrm{SEL} = \mathrm{SPL} + 10\log_{10} T \qquad \text{eqn. 2.5}$$

2.5 Cumulative Sound Exposure Level

Where multiple transient pressure wave events occur, the total or cumulative Sound Exposure Level from multiple events can be calculated by summing the Sound Exposure Level from a number of individual events. The events themselves may be separated in time or space or both. For instance, the events could be consecutive from foundation drilling at adjacent sites or concurrent from vessels operating in close proximity at the same time.

2.6 Source Level

The source level (SL) is the apparent strength of a sound source at a reference distance, usually 1 m, from the source. For example, a source may be quoted as having a source Sound Pressure Level of 180 dB re.1μPa at 1 m. In practise the parameters of the source are rarely measured at such a close range, and the source level is inferred by back-propagating the noise from a number of far field measurements

2.7 Transmission Loss

The transmission loss (TL) represents the loss in intensity or pressure of the acoustic field strength as the sound propagates from source to a receptor. In general, terms the transmission loss is given by:

$$\mathrm{TL} = N\log(r) + \alpha r \qquad \text{eqn. 2.6}$$

where r is the range from the source, N is a factor for attenuation due to geometric spreading, and α (in dB.km^{-1}) is a factor for the absorption of sound in water. Rarely is transmission loss as simply described as this; a more rigorous discussion is given in Section 4.

2.8 Received Level

The Received level (RL) is the strength of the acoustic field at a given depth and range relative to the source. At a range r from a source, this is given by:

$$RL = SL - TL \qquad \text{eqn. 2.7}$$

From eqn 2.6, this can be written in the form:

$$RL = SL - N \log(r) - \alpha r \qquad \text{eqn. 2.8}$$

As the sound varies with range, it is important to state the range at which the measurement has been taken or the estimate has been made.

3. SOUND SOURCE CHARACTERISTICS

3.1 Overview of construction scenarios

Aberdeen Harbour Board (AHB) have appointed Arch Henderson LLP as the civil engineering consultant for the Aberdeen Harbour Expansion Project. A meeting, held at the Aberdeen office of Arch Henderson on 17 April 2015, was attended by members of the Aberdeen Harbour Expansion Project (EIA) team including representatives from Fugro EMU and Kongsberg Maritime.

During the ensuing discussions and at that stage in the project, it became clear that the precise construction scenario was undecided. One of the objectives of the discussions therefore was to discuss all likely options that would be expected under the flexibility of the Design and Build contract.

The discussions highlighted the main features that will be constructed during the project. These include preparation of the seabed, construction of the south and north breakwaters and construction of the pier structures. A notional timetable of construction events was reviewed and this led to the establishment of the likely anticipated phasing of the works. The programme of activities for the project is described in the project Environmental Statement[4] and an outline of events is given in Table 3.1.

Construction Activity	Details	Start Date	Duration	Completion Date
Dredging (including drilling and blasting)	Dredging – Trailing Suction Hopper Dredger (TSHD) Dredging – Backhoe Dredger (BHD) Drilling and Blasting Vessel Spread	Q1 2017	19 months	Q4 2018
Breakwater construction	Dredging – Trailing Suction Hopper Dredger (TSHD) Dredging – Backhoe Dredger (BHD) Drilling and Blasting Rock Placement Vessel Spread	Q1 2017	21 months	Q4 2018
Quay piling operations	Piling Vessel Spread	Q2 2017	23 months	Q2 2019
Quay construction and infilling	Vessel Spread	Q2 2017	31 months	Q4 2019

Table 3.1: Overview of engineering tasks to be undertaken during construction of the Aberdeen Harbour Expansion Project

3.2 Introduction of sound sources

From the perspective of the emission of man-made noise into the marine environment, it became clear that a number of sources needed to be considered in the current acoustic impact study. These include drilling; blasting; dredging; material transport; and vessel movements. The sources themselves tend not to act in isolation: a spread of platforms or vessels deployed during each task is the most likely scenario. The underwater noise modelling scenarios considered in the acoustic impact study therefore will cover the drilling/blasting/dredging/vessel spread with and without the breakwaters in place as appropriate.

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[4] Fugro EMU (2015), Aberdeen Harbour Expansion Project Environmental Statement: Chapter 3: Description of the Development.

A discussion of the acoustic characteristics of each source type is given below.

3.3 Drilling noise

Drilling will be undertaken in Nigg Bay in preparation for subsequent explosive blasting. A number of holes of 0.125 m diameter will be drilled in to the bedrock and these will be packed with explosive charge.

Noise is generated during drilling principally through the action of the drill bit on the surrounding rocks. The level of noise created is dependent therefore not only on the size of the drill bit but also on the degree to which the seabed rock is consolidated; a soft clay will produce lower levels of sound compared to that generated by a granite layer. Client discussions indicate that sediment coverage of the seabed in the Aberdeen Harbour Expansion Project area consists of sandy gravel overlying glacial till with a granitic schist type of basement rock. As a result it is expected that considerable variation in levels of sound may arise during the drilling task.

Sound generated at the drill head is likely to be transmitted into the water through two mechanisms. The first is where the noise is transmitted from the drill bit-sediment interface and into the surrounding seabed layers before becoming refracted back into the water column while the second is where vibrations travel up the drill shaft and then become transmitted into the water.

A review of the literature on underwater drill noise revealed that there is little useful data that has been released into the public domain: invariably the noise measurement units are ambiguous; the drill diameter is not quoted; or there is no information on sediment or seabed rock type.

Two reports however were discovered that contained sufficient data such that useful source levels and frequency spectra for underwater drilling could be estimated. The first report[5] discussed underwater noise recordings made in the vicinity of a site where a 4.2 m diameter foundation socket was being drilled through a metamorphic basement rock having little or no sediment cover. For this scenario, the source level was estimated at 153.4 dB_{peak} re 1 μPa at 1 m. The second report related to small scale drilling off southwest Wales using a 20 cm diameter drill[6]. Measurements of noise were made at distances of 7.5 m, 23 m and 179 m from the site while drilling into sedimentary mudstone or shale. Analysis of the data led to an estimated source level of 135.8 dB_{peak} re 1 μPa at 1 m.

From these data, it is possible to estimate likely source levels associated with drilling in Nigg Bay. Assuming the noise levels to vary linearly with drill diameter (note that there is insufficient published data on drilling noise to test this hypothesis), source levels for the drilling in Nigg Bay are estimated at 136.3 dB_{peak} re 1 μPa at 1 m. The source frequency spectrum shown in Figure 3.1 is based on the data given by Willis *et al.*[6] with spectral levels adjusted to give the requisite source level.

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[5] Ward P. D., Needham K., "Modelling the vertical directivity of noise from underwater drilling". Proceedings of the 11th European Conference on Underwater Acoustics (ECUA 2012) and Acoustical Society of America Proceedings of Meetings on Acoustics (POMA), Vol 17, 070068, December 2012.

[6] Willis M. R., Broudic M., Bhurosah M., Masters I., "Noise Associated with Small Scale Drilling Operations", Proceedings of the 3rd International Conference on Ocean Energy, 6 October, Bilbao, 2010.

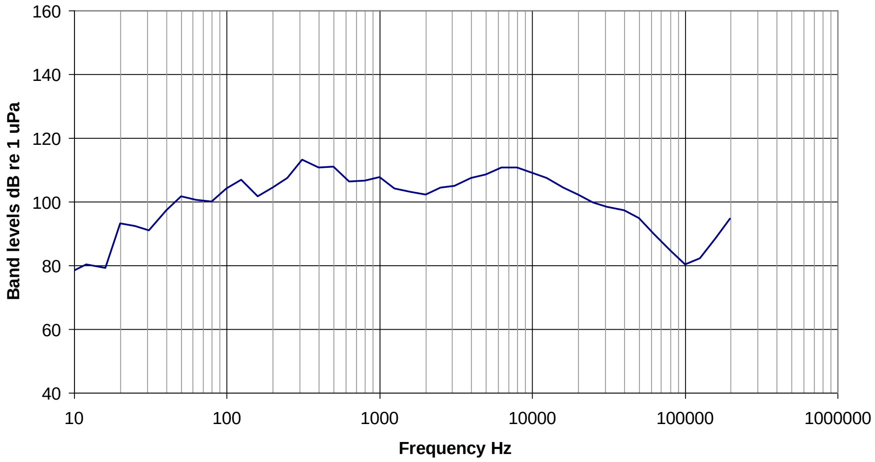


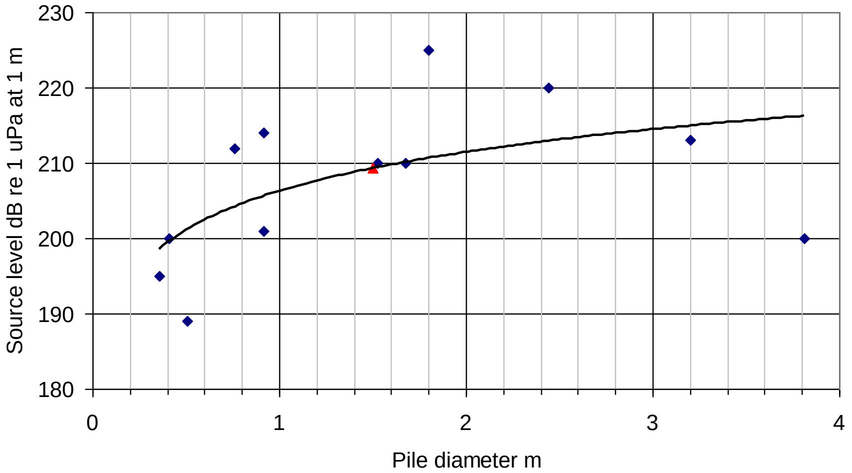
Figure 3.1: Source frequency spectrum for drilling noise

3.4 Piling noise

Piling noise is generated through the impacting of a hydraulically powered hammer onto the end surface of a foundation pile. The noise is dependent on the force applied and the dimensions of the impacting hammer which, in turn, are related to the engineering properties of the sediment in which piling is taking place.

Piling is widely used to construct foundations for offshore marine projects and a number of reports are available where underwater noise levels have been recorded during piling activities in connection with offshore wind farms[7,8]. In addition, underwater noise levels have been recorded for a number of marine construction activities in USA[9]. As a result, sufficient data exists such that an approximate relationship between pile diameter and resulting piling noise levels may be proposed.

From the scatter plot shown in Figure 3.2, it is estimated therefore that the peak source level associated with the 1.5 m diameter pile used in the Aberdeen Harbour Expansion Project construction is likely to be 209.3 dB_{peak} re 1 μPa at 1 m.



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[7] Nedwell J., Howell D., (2004), "A review of offshore windfarm related underwater noise sources", Subacoustech Report No 544R0308.

[8] Nedwell, J.R., Workman, R., Parvin, S.J., (2005). "The assessment of likely levels of piling noise at Greater Gabbard and its comparison with background noise, including piling noise measurements made at Kentish Flats", Subacoustech Report No 633R0115.

[9] "Compendium of Pile Driving Sound Data" (2007), Prepared by Illinworth & Rodkin for The California Department of Transportation. Accessed at http://www.dot.ca.gov/hq/env/bio/files/pile_driving_snd_comp9_27_07.pdf

Figure 3.2: Scatter plot of piling source levels for various offshore projects together with estimated level for 1.5 m pile at Nigg Bay (red triangle)

3.5 Blast noise

It is planned to drill holes 0.125 m diameter and in groups of 2 or 3 down to a depth of 2.5 m below dredge level. Each drill hole will be loaded with 20 kg of high explosive and then wired together with time delays between each hole in order to effect a staged sequence of blasts. Pentolite-based detonators initiate the explosions and the fractured rock is then removed using the backhoe dredger.

In open water, the signature of an underwater explosion consists of an initial outgoing shock wave which eventually collapses in on itself before oscillating a number of times[10]. The peak value, which occurs around a microsecond after detonation is given by the empirical expression[11]:

$$P_{peak} = 5.24 x 10^{13} \left[\frac{W^{1/3}}{R} \right]^{1.13} \mu Pa \qquad \text{eqn 3.1}$$

Very little published data is available that allows for an estimation of peak levels underwater following detonations from confined explosions. A study by Nedwell and Thandavamoorthy[12] involved measurements in water from detonations in bore holes. These indicated that the peak pressure could be as low as 6% of that generated in equivalent, open water conditions. During the Miami harbour deepening project, Hempen *et al.*[13] showed levels of blast pressure in water following borehole detonations, falling to 19% to 41% of that recorded in open water

For a 20 kg charge, the peak pressure in open water is 259 dB re 1 μPa. The peak pressure underwater is expected to be significantly less. The propagation of explosive blast in shallow water is discussed further in Section 5.3.

3.6 Material disposal noise

Material dredged from the seabed will be disposed of either at a designated disposal ground offshore or else used to form the infill for various of the constructions in the Aberdeen Harbour Expansion Project. In either case, a dredger split-hopper will transit to the designated area then open up and allow the material to fall to the seabed.

Only one set of acoustic data relating to rock placement operations was found in the published literature[14]. Measurements of the fall-pipe vessel *Rollingstone*, placing rock at a depth of 60-70 m near the Shetland Islands, UK, showed no evidence that rock placement contributed to the noise level. It is assumed therefore that noise levels associated with rock placement operations were equal to background noise levels (thus see Section 5.7).

3.7 Vessel noise

The deployment of vessels plays a large part in the Aberdeen Harbour Expansion Project activities. From discussions with Project engineers, a number of classes of

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[10] Urick, Robert J. (1983), Principles of Underwater Sound, 3rd Edition. New York. McGraw-Hill.

[11] Cole, R. H. (1948). *Underwater Explosions*. Princeton University Press, Princeton, New Jersey. 437 pp.

[12] Nedwell, J. R., Thandavmoorthy, T. S., 1992. The Water Borne Pressure Wave from Buried Explosive Charges, An Experimental Investigation, Applied Acoustics, 37, 1-14

[13] Hempen, G.L., T.M. Keevin, and T.L. Jordan. (2007). Underwater Blast Pressures from a Confined Rock Removal During the Miami Harbor Deepening Project. International Society of Explosives Engineers, 2007G Volume 1, 12 pp.

[14] Galloper Wind Farm Project, Environmental Statement – Technical Appendices 3, Royal Haskoning Report 9V3083/R01/303424/Exet, October 2011. Downloaded from http://www.galloperwindfarm.com/

vessels required for deployment on the Project have been identified and these include, amongst others, dredgers, survey vessels, crew boats and other general purpose vessels for logistical support, and tugboats. Specific vessels have been tentatively identified where possible but their use on the project is subject to availability. A review of the published literature on vessel noise indicates that relatively little acoustic data specific to the identified vessels are available. Both these factors make the assessment of potential acoustic impacts due to noise from the Project vessels somewhat challenging. In order to be able to provide an indicative assessment of the acoustic impact from vessel noise it is necessary to use instead data from surrogate or proxy vessels and to caveat the results accordingly (see Section 7).

Noise from shipping is a major contributor to the overall noise in a given sea area due principally to the large numbers of ships present, their wide distribution and their mobility. Sound levels and frequency characteristics are related approximately to ship size, vessel speed, engine power and even the age of the engine where through wear and tear, additional noises are generated. However, it is noted that even amongst vessels of similar classes, there is considerable variation[15].

From an acoustic perspective, vessel noise is a combination of sounds having energy spread over a wide range of frequencies, superimposed with tonals at specific frequencies. Such broadband noise can be attributed to propeller cavitation and flow noise and may extend up to 100 kHz peaking in the range 50-150 Hz[16]. The narrowband sound or tonal components arise from the propeller blade rate, engine cylinder firing and crankshaft rotation. Typical frequencies for these components lie in the range 10 - 100 Hz.

A limited set of acoustic data for noise ranged vessels are available[15,17,18,19] and extensive use of these data has been made in the current assessment. The data itself consists of broadband levels and 1/3rd octave band levels measured over a given bandwidth. In all cases there is no high-frequency noise data at frequencies above 10 kHz. This represents a considerable shortfall in the published data particularly with regards to assessing the noise impact on marine species that are known to be responsive to sound at such frequencies. To address this issue for the current study, the noise levels for each vessel were noted over the frequency range 1 kHz to 10 kHz. The mean slope of the data points over this range was determined and the resulting trendline was then extended up to a frequency of 160 kHz. This resulted in there being applied to the data a roll-off of -3 dB/octave band frequency, ie. from a frequency of 10 kHz, the noise level is reduced by 3 dB for each doubling of frequency. Until such time that measured noise levels become available at these elevated frequencies, the uncertainty in these projected figures remains unknown.

Broadband source levels for each of the vessels used in the impact analysis are given in Table 3.2. Indicative frequency spectra for the vessels are shown in Figure 3.3.

Vessel type	**Proxy vessel**	**Broadband source sound pressure level dB re 1 μPa at 1 m**
Survey vessel	*Pompei*	184.0
Tugboat	*DN43*	180.3
Tugboat	*Tug_4500*	200.8

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[15] Richardson W. J., Green Jr, C. R., Malme C. I., Thomson, D. H., (1995), *Marine Mammals and Noise*. Academic Press, New York.

[16] Ross D., (1987) Mechanics of underwater noise, Los Altos: Peninsula Publishing.

[17] Hannay, D.E. 2004. Noise. In Comparative Environmental Analysis (CEA), Chapter 4. Sakhalin Energy Investment Corporation. Available at: http://www.sakhalinenergy.com/documents/doc_33_cea_chp4.pdf

[18] Kiggavik Tug and Barge Noise Modelling, JASCO Applied Sciences, June 2011.

[19] Johansson A. T., Andersson M. H., "Ambient Underwater Noise Levels at Norra Midsjöbanken during Construction of the Nord Stream Pipeline", Report for Nord Stream AG and Naturvårdsverket, 2012.

Table 3.2: Estimated broadband source levels for various classes of vessel

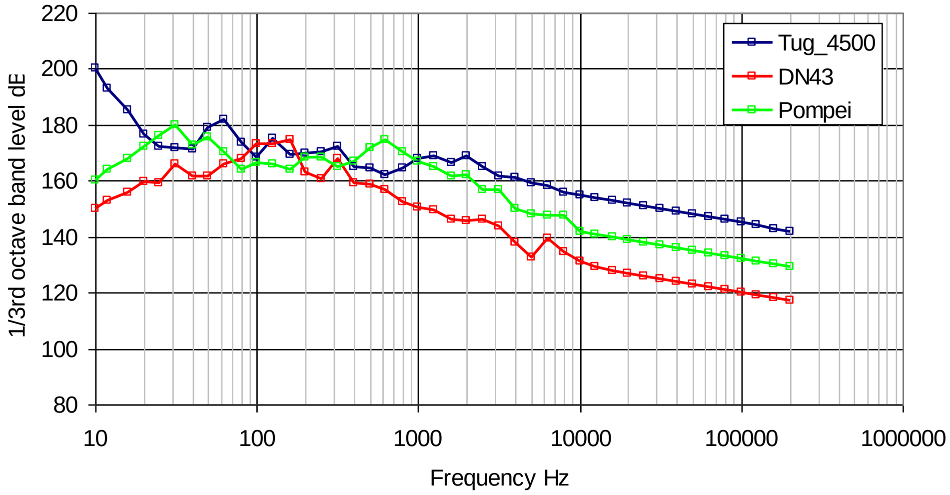

Figure 3.3: Source spectra for classes of vessels used in the Aberdeen Harbour Expansion Project

3.8 Dredging noise

Dredgers are seagoing vessels fitted with specialist equipment for removing seabed material[20]. There are a number of different types; of relevance to the Aberdeen Harbour Expansion Project are the backhoe dredger and the trailing suction hopper dredger.

The backhoe dredger consists of a barge fitted with a mechanically powered excavator. This is lowered over the side of the barge and scoops up the seabed sediment prior to depositing it into a hopper barge nearby. The sound arising from a dredging vessel consists of a number of discrete sources: the digging or scraping sound of the excavator on the seabed; the engine noise driving the excavator; and the noise of the barge engine or else the engines of the tug boat that has pulled the barge into position.

The trailing suction hopper dredger is a fully powered sea-going vessel fitted with one or more large diameter suction pipes which descend to the seabed. A trailing draghead is connected to the end of the suction pipe. The seabed material is sucked up into the pipe then into a hopper installed on the vessel. The sources of noise include the draghead being trailed across the seabed; the suction pump; the seabed material being drawn up the suction tube; the ship's engine; propeller and the dynamic positioning systems fitted to the hull.

The Development engineers indicate that the *Nordic Giant*[21] is indicative of one that could be used for the TSHD activity while no vessel has been identified for the backhoe task. *Nordic Giant* has not been noise-ranged so its acoustic footprint is unknown. A suitable proxy source for this is *TSHD Taccola*[17]. In terms of engine power the two vessels are very similar hence it is assumed that radiated noise levels are also similar. For the backhoe vessel, *BH New York* is assigned the proxy source[20]. A literature search indicated that this was the only backhoe dredging vessel for which published noise data is currently available. Accordingly, data from *TSHD Taccola* and *BH New York* are thus taken forward for use in the analysis contained in the current study.

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[20] Reine K. J., Clarke D., "Characterization of underwater sounds produced by hydraulic and mechanical dredging operations", Journal of the Acoustical Society of America, 135 (6), June 2014, 3280-3294.

[21] Royal Boskalis Westminster N.V. Accessed at http://www.boskalis.com/uploads/media/Nordic_Giant_01.pdf

Source levels for both proxy sources are given in Table 3.3 and 1/3rd octave band levels for both vessels are shown in Figure 3.4. Published noise levels for both vessels were available over only a limited frequency range: up to 10 kHz for *New York* and up to 2 Khz for *Taccola*. Extrapolated data for each was generated following the procedure discussed in Section 3.7 and using roll-offs of -12 dB and – 3 dB per octave doubling for *New York* and *Taccola* respectively. It is noted that the source level for *New York* is around 7 dB higher than that for *Taccola* while *Taccola* has substantially higher levels of high frequency sound (>6 kHz) compared with *New York*.

Vessel type	**Proxy vessel**	**Broadband source sound pressure level dB re 1 μPa at 1 m**
Dredger (Trailing Suction Hopper Dredger)	*Taccola*	180.4
Dredger (Backhoe)	*New York*	187.2

Table 3.3: Estimated broadband source levels for various classes of dredging vessel

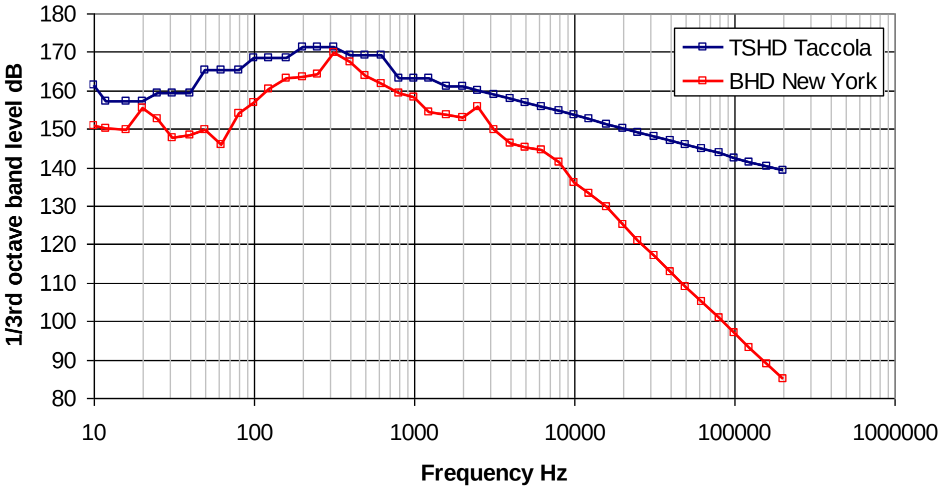

Figure 3.4: Source spectra for dredging vessels used in the Aberdeen Harbour Expansion Project

3.9 Material movement noise

The transport of building materials and equipment associated with the construction phases may take place by sea rather than by road. In this case, a number of powered vessels or barges pulled by tugs may be used. No specific vessels have as yet been identified for these tasks hence the acoustic noise levels subsequently emitted are unknown and it is necessary to use proxy noise sources instead. Hence, for the purpose of the current acoustic assessment the noise associated with marine material movements is based on the noise emitted by the vessel spread for the seabed material disposal activity.

4. CRITERIA FOR ASSESSING IMPACTS UPON MARINE FAUNA

4.1 Introduction

This section of the report describes the assessment criteria proposed by various investigators to assess the impact of underwater sound upon species of interest to the Aberdeen Harbour Expansion Project area. These criteria may be used to estimate impact zones about the sound sources using the results from underwater sound propagation modelling.

4.2 Species of interest to the Aberdeen Harbour Expansion Project area

4.2.1 Introduction

Studies previously commissioned by the client have identified a number of species of fish, invertebrates and marine mammals as being present in and around the Aberdeen Harbour Expansion Project area. This section provides an overview of the susceptibility of the species to underwater sound as far as is known and also notes their conservation status according to the Red List of the International Union for Conservation of Nature (IUCN)[22] and the presence of any other legislation covering their environmental sensitivity or denoting a relevant management plan.

4.2.2 Mammals

A number of species of mammal are regularly found in and around the Aberdeen Harbour Expansion Project area. Table 4.1 notes the species especially of concern to this study along with their conservation status.

Cetaceans make extensive use of underwater sound and have hearing that is highly tuned for the undersea environment[15]. Their susceptibility to impacts arising through the introduction of man-made noise into the marine environment is subsequently well-documented. The cetacean species of concern to the development are bottlenose dolphin and harbour porpoise. Bottlenose dolphin are a feature of the Moray Firth Special Area of Conservation (SAC)[23] and may be found around the mouth of Aberdeen harbour throughout the year. White beaked dolphin, Risso's dolphin and minke whale are also seen from time to time in and around Aberdeen Bay.

The pinniped species present in the development area are harbour seals and grey seals. Although seals are classed as marine mammals they spend considerable periods of time on land. As a consequence, seals are known to hear very well in-air as well as underwater. When diving or swimming, they may be susceptible to impacts arising from high levels of underwater sound. Equally, when on land, they may be liable to impacts arising through the emission of sound in-air such as construction noise.

The only other species of concern to the development is the otter. The European otter (*Lutra lutra*) is a terrestrial mammal that also spends time in coastal seas. It is not to be confused with the sea otter (*Enhydra lutris*) which is classified as a marine mammal and is found around the coasts of the north and eastern Pacific Ocean. There is no hearing data on the European otter however audiograms have been obtained for the

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[22] The IUCN Red List of Threatened Species™ 2012, http://www.iucn.org/about/work/programmes/species/red_list/index.cfm. Accessed May 2015. (CR - Critically Endangered, EN – Endangered, VU – Vulnerable, NT - Near Threatened, LC - Least Concern, DD - Data Deficient, NE - Not Evaluated).

[23] Joint Nature Conservation Committee (JNCC) website accessed at http://jncc.defra.gov.uk

sea otter[24]. These indicate that the otter's peak underwater hearing sensitivity lies in the range 7 kHz to 16 kHz while overall sensitivity levels are somewhat reduced compared with pinniped species.

Mammals	**Legal / Conservation Status**
Cetacea	
Harbour porpoise (*Phocoena phocoena)*	IUCN Least Concern, Annex II, IV of Habitats Directive, EPS
Common bottlenose dolphin *(Tursiops truncatus)*	IUCN Least Concern, Annex II, IV of Habitats Directive, EPS
White beaked dolphin (*Lagenorhynchus albirostris*)	IUCN Least Concern, Annex IV of Habitats Directive, EPS
Risso's dolphin (*Grampus griseus*)	IUCN Least Concern, Annex IV of Habitats Directive, EPS
Minke whale (*Balaenoptera acutorostrata*)	IUCN Least Concern, Annex IV of Habitats Directive, EPS
Pinnipedia	
Common or Harbour seal (*Phoca vitulina*)	IUCN Least Concern, Annex II, V of Habitats Directive
Grey seal (*Halichoerus grypus*)	IUCN Least Concern, Annex II, V of Habitats Directive
Other species	
European otter (*Lutra lutra*)	IUCN Near Threatened, EPS

Table 4.1: Marine mammal species found in the Aberdeen Harbour Expansion Project area

4.2.3 Fish

Table 4.2 lists the species of fish of conservation concern found in and around the Aberdeen Harbour Expansion Project area. Also noted is the sensitivity of the fish to sound where this draws on discussions by Fay and Popper[25] and Popper and Fay[26]. It was observed that the relative sensitivity of fish to underwater sound is dependent on their internal physiology. Some fish species lack a swimbladder (e.g. dab, plaice) and as a consequence they have poor sensitivity to sound and thus relatively poor hearing. By contrast, a number of fish species do possess a swimbladder. This gas-filled sac performs several different functions such as acting as a float which gives the fish buoyancy; as a lung; and as a sound-producing organ. In addition, the swim bladder can enhance the hearing capability of the fish species through the amplification of underwater sound although this alone, would not necessarily make such a fish highly sensitive to sound. These fish would be deemed to have a moderate level of auditory sensitivity. For some species (e. g. herring) there is a connection between the inner ear and the swim bladder and it is this feature which results in them being the most sensitive to underwater noise. Subsequently, there is the potential for such species to be more susceptible to acoustic impacts than fish with low or medium hearing sensitivity.

Of all the fish species of interest to the Aberdeen Harbour Expansion Project only herring and cod may be classed as having high auditory sensitivity and this is borne out by audiogram data[27]. Eel, sea trout and salmon all have a gas-filled swimbladder but nevertheless lack the connection between the swim bladder and the internal ear. These species are all moderately sensitive to underwater noise[28]. By contrast, there is a general lack of information on hearing in lamprey and no audiograms have been

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[24] Ghoul A.,·Reichmuth C., (2014), "Hearing in the sea otter (*Enhydra lutris*): auditory profiles for an amphibious marine carnivore", *Journal of Comparative Physiology A*; **200**(11):967-81. Sage Journals OnlineFirst.

[25] Fay R.R. & Popper A.N. (eds) (1999) *Comparative Hearing: Fish and Amphibians*. New York: Springer-Verlag.

[26] Popper A. N. & R. .R. Fay (2009). "Rethinking sound detection by fishes". Hearing Research.

[27] Enger, P.S., (1967), "Hearing in herring". *Comp. Biochem. Physiol*. 22:527-538

[28] Popper, A. N., Fay, R. R., Platt, C. & Sand, O. (2003). "Sound detection mechanisms and capabilities of teleost fishes". In *Sensory Processing in Aquatic Environments* (Ed Collin, S. P. & Marshall, N. J.), pp. 3–38. New York, NY: Springer-Verlag.

reported. They lack any specialist hearing structures hence they are considered to have low sensitivity to underwater sound[29].

Fish	**Legal / Conservation status[30]**	**Hearing sensitivity**
Sea lamprey (*Petromyzon marinus*)	IUCN Least Concern	Low
River lamprey (*Lampetra fluviatilis*)	IUCN Least Concern	Low
Eel (*Anguilla anguilla*)	IUCN Critically Endangered, CITES App II	Medium
Sea trout (*Salmo trutta trutta*)	IUCN Least Concern BAP, PMF,	Medium
Cod (*Gadus morhua*)	IUCN Vulnerable	High
Herring (*Clupea harengus*)	IUCN Least Concern, BAP, NERC PI, EU MP	High
Atlantic salmon (*Salmo salar*)	IUCN Least Concern, Ann II, V Hab Dir, BAP, PMF, OSPAR, NERC PI,	Low

Table 4.2: Fish species found in and around the Aberdeen Harbour Expansion Project area

4.3 Acoustic impact criteria

The degree to which a given species might be affected by underwater sound emissions depends on a number of factors, these being the sensitivity of the species or individual to the sound, the level of sound on the receptor, its frequency content and the duration of the sound.

This section of the report describes briefly the assessment criteria proposed by various investigators in order to assess the impact of underwater sound upon species of interest to the Aberdeen Harbour Expansion Project area. These criteria are then used to estimate impact zones about the noise sources using the results from high level underwater acoustic propagation modelling.

All impact criteria considered for the Aberdeen Harbour Expansion Project have been developed in accordance with best scientific practice and best available scientific knowledge and have been discussed extensively in the international peer-reviewed literature. It should be noted however that for marine mammals, in many cases, the criteria have had little or no validation under open water conditions. Data from controlled tests with a few captive animals have been used as the basis for developing the auditory injury criteria. Observations of behavioural avoidance with concurrent acoustic measurements are sparse, and hence the behavioural avoidance criteria are speculative. With regards to fish, relatively few of the 30,000+ species have been auditory tested. Of those however, the sample sizes have been such that the results may be considered statistically significant. Nevertheless, the precautionary principle requires that use be made of the criteria subsequently developed while noting the merits or shortfalls of each approach where relevant.

4.3.1 Lethality and physical injury

When marine animals are exposed to very high levels of underwater sound, lethality can ensue. Mortality or direct physical injury from the noise and vibration generated by a particular sound source is associated with very high peak pressure or impulse

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[29] Popper A. N., (2005), “A Review of Hearing by Sturgeon and Lamprey”, Report submitted to the US Army Corps of Engineers, Portland District.

[30] Ann II, IV Hab Dir – Annex II, IV Habitats Directive (1992); BAP – UK Biodiversity Action Plan (1994); PMF – Priority Marine Feature in Scottish waters; OSPAR – OSPAR Convention (1992); BC App II, III – Bern Convention Appendix II, Appendix III; CITES App II (1963), EU MP – European Union Management Plan, NERC PI – Principle Importance under Section 41 of NERC Act 2006

levels. Typically, these effects would be associated with blasting operations or in the immediate vicinity of an impact piling operation where the pile is being driven into the seabed, and is therefore in direct contact with water allowing efficient sound radiation.

In order to investigate this, Yelverton *et al.*[31] carried out explosive blast studies on various species of terrestrial mammals and fish and demonstrated that mortality rates were related to body mass of the subject and the magnitude of the impulsive wave. The work indicates that there are levels below which a sound would cease to be lethal to a creature of a certain weight. It is shown that the upper limit for No-Injury ranges from 26 Pa s for rats (0.2 kg) to 210 Pa s for sheep (45 kg). The work concluded that fatalities increasingly occur in species of fish and marine mammal when the incident peak to peak sound level exceeds 240 dB re. 1 μPa and as the time period of the exposure increases. It is noted that the experiments undertaken by Yelverton *et al.*[31] involved explosions in open water. Due to lack of data, it is uncertain whether blast following confined detonations (such as that likely during construction work in Nigg Bay) would have the same effect on marine life.

Wright and Hopky[32] reviewed a number of studies involving the effects of explosive blast on marine life. It was found that maximum waterborne pressures in excess of 100 kPa led to damage to the internal organs of fish. Hence a limiting threshold for physical injury of 100 kPa (corresponding to a peak to peak level of 220 dB re 1 μPa) was subsequently adopted for use during blasting work in Canadian waters.

Popper *et al.*[33] speculated that mortality could occur in fish when exposed to pile driving noise having a cumulative SEL at least 7-10 dB higher than that which indicated the onset of physiological effects at an SEL of 207 dB re 1 μPa^2.s. It was further noted however, that fish without a swim bladder showed no effects even when exposed to piling noise having a cumulative SEL of 216 re 1 μPa^2.s. The variability of the lethality threshold for fish suggests that investigations are incomplete.

4.3.2 Auditory damage

Marine Mammals

Permanent and temporary hearing loss may occur when marine animals are exposed to sound pressure levels lower than those which give rise to lethality and physical injury. Permanent hearing loss in mammals results from the death of the sensory hair cells of the inner ear. This gives rise to a permanent increase in threshold sensitivity over the affected frequencies and is known as Permanent Threshold Shift (PTS). By contrast, Temporary Threshold Shift (TTS) is a temporary hearing impairment and is not considered an injury[2]. While experiencing TTS, the hearing threshold rises and a sound must be stronger in order to be heard. At least in terrestrial mammals, TTS can last from minutes or hours to (in cases of strong TTS) days. For sound exposures at or somewhat above the TTS threshold, hearing sensitivity of both terrestrial and marine mammals recovers rapidly after exposure to the sound ends. Few data on sound levels and durations necessary to elicit mild TTS have been obtained for marine mammals. Available data on TTS in marine mammals are reviewed in some detail by Southall *et al.*[2].

Southall *et al.*[2] grouped marine mammals according to the frequency response of their hearing. It was suggested that thresholds for injury (and behavioural responses) should be examined separately for five functional hearing groups: low-frequency

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[31] Yelverton, J. T., Richmond, D. R., Hicks, W., Saunders, K., and Fletcher, E. R. (1975). "The Relationship Between Fish Size and Their Response to Underwater Blast." Report DNA 3677T, Director, Defense Nuclear Agency, Washington, DC.

[32] Wright D.G., Hopky G.E., (1998), “Guidelines for the Use of Explosives In or Near Canadian Fisheries Waters”, Canadian Technical Report of Fisheries and Aquatic Sciences 2107, Department of Fisheries and Oceans, Canada.

[33] Popper A.N., M.B. Halvorsen, T.J. Carlson, M.E. Smith, B.M. Casper, (2013), "Effects of pile driving on fishes", J. Acoust. Soc. Am. **134**, 4059.

cetaceans (mysticetes, for which the functional hearing range is concluded to be 7 Hz to 22 kHz); mid-frequency cetaceans (the majority of odontocetes, 150 Hz to 160 kHz); high-frequency cetaceans (remaining odontocetes, 200 Hz to 180 kHz); pinnipeds in water (75 Hz to 75 kHz), and pinnipeds in air (75 Hz to 30 kHz). Hence minke whale are classified as M_{lf}, bottlenose dolphin, white-beaked dolphin and Risso's dolphin amongst others are classified as M_{mf} and harbour porpoise are classified as M_{hf} where lf, mf and hf denote low-, medium- and high-frequency respectively. Similarly, pinnipeds in water are denoted by M_{pw}.

Studies reviewed in Southall *et al.*[2] have indicated that hearing damage can occur following a single exposure to a loud sound or to multiple exposures of lower level sound. In the first case, the threshold is given by the peak sound pressure level while in the second case; the threshold is given by the sound exposure level (SEL) indicating a build-up of energy over a period of time.

Assessment criteria were also based on the type of noise e.g. multiple pulses such as those arising from impact piling; and nonpulse or continuous noise such as that from shipping, dredging or underwater drilling. Specific thresholds using peak-level metrics indicate that, based on current evidence, the onset of PTS and TTS are not dependent on the animal species while thresholds using energy-level metrics are dependent. Summaries of thresholds for PTS and TTS as a function of noise type and animal species are given in Tables 4.3 and 4.4 respectively.

Work carried out by Lucke *et al.*[34] determined that the harbour porpoise appeared to be somewhat more sensitive to underwater sound than indicated by Southall *et al.*[2] Accordingly, the TTS limit was set at 199.7 dB re 1μPa and 164.3 dB re 1μPa^2 s in both cases using un-weighted Sound Pressure Level (SPL).

The US National Marine Fisheries Services (NMFS) propose non-injury limits of 190 dB re 1 μPa (RMS) and 180 dB re 1μPa (RMS) for pinnipeds and cetaceans respectively[35].

Marine mammal group	**Weighting**	**Multiple pulses**	**Nonpulses**
Cetaceans – low frequency	Unweighted	230 dB re 1 uPa	230 dB re 1 uPa
	Mlf	198 dB re 1 μPa^2-s	215 dB re 1 μPa^2-s
Cetaceans – medium frequency	Unweighted	230 dB re 1 uPa	230 dB re 1 uPa
	Mlf	198 dB re 1 μPa^2-s	215 dB re 1 μPa^2-s
Cetaceans – high frequency	Unweighted	230 dB re 1 uPa	230 dB re 1 uPa
	Mlf	198 dB re 1 μPa^2-s	215 dB re 1 μPa^2-s
Pinnipeds	Unweighted	218 dB re 1 uPa	218 dB re 1 uPa
	Mlf	186 dB re 1 μPa^2-s	203 dB re 1 μPa^2-s

Table 4.3: Summary of PTS levels for noise types and marine mammal groups

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[34] Lucke K., Siebert U., Lepper P. A., Blanchet M., (2009), "Temporary shift in masked hearing thresholds in a harbour porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli", Journal of the Acoustical Society of America 125(6), 4060-4070, June 2009

[35] This was based on findings at the High-Energy Seismic Workshop held at Pepperdine University in 1997 as updated by the NMFS' Acoustics Workshop held in Silver Spring, MD in 1999.

Marine mammal group	**Weighting**	**Multiple pulses**	**Nonpulses**
Cetaceans – low frequency	Unweighted	224 dB re 1 uPa	224 dB re 1 uPa
	Mlf	183 dB re 1 μPa^2-s	195 dB re 1 μPa^2-s
Cetaceans – medium frequency	Unweighted	224 dB re 1 uPa	224 dB re 1 uPa
	Mlf	183 dB re 1 μPa^2-s	195 dB re 1 μPa^2-s
Cetaceans – high frequency	Unweighted	224 dB re 1 uPa	224 dB re 1 uPa
	Mlf	183 dB re 1 μPa^2-s	195 dB re 1 μPa^2-s
Pinnipeds	Unweighted	212 dB re 1 uPa	212 dB re 1 uPa
	Mlf	171 dB re 1 μPa^2-s	183 dB re 1 μPa^2-s

Table 4.4: Summary of TTS levels for noise types and marine mammal groups

Fish

Acoustic impact criteria for fish appear somewhat less well developed. The California Department of Transportation (Caltrans) in coordination with the US Federal Highways Administration (FHWA) and the state departments of transportation in Oregon and Washington, USA, established a Fisheries Hydroacoustic Working Group (FHWG)[36]. The purpose of this was to provide guidance on fishery impacts due to underwater sound pressure caused by underwater pile driving. Subsequently, interim criteria for injury to fish from pile driving noise were proposed. This is a dual criteria including a peak level of 206 dB re 1 μPa (peak) and a cumulative SEL level of 187 dB re 1 μPa^2 s (SEL) for fish 2 grams and heavier; or a cumulative SEL of 183 dB re 1 μPa^2 s (SEL) for fish smaller than 2 grams with the peak SPL remaining unchanged. In the absence of any other guidance, these criteria will also be used to assess the impact of continuous noise.

A similar programme of work to that of Southall *et al.*[2] has been completed by Popper *et al.*[37] and from which sound exposure guidelines for fish have been introduced. The published literature was reviewed and from the available data on auditory and behavioural responses when fish are subjected to various classes of underwater sound, a number of impact threshold levels were subsequently defined. The work is ongoing and a number of priority areas have been identified for further research. Nevertheless, of relevance to the Aberdeen Harbour Expansion Project underwater noise impact assessment, threshold levels are available for fish exposed to explosive blast and piling noise. No data is available on suitable thresholds for exposure to vessel noise.

A summary of impact criteria and threshold levels for fish is given in Table 4.4.

4.4 Behavioural reactions – Introduction

At still lower sound pressure levels, it has been observed that fish and marine mammals may exhibit changes in their normal behaviour. These changes range from a startle reaction to the sound, a cessation of their current activities (e.g. feeding, nursing, breeding) or the animals may leave the area for a period of time. Often the behavioural effects are context-dependent and very subtle. Painstaking experimental procedures and much analysis are required to determine whether the observed results are statistically significant. A number of studies supporting behavioural changes are cited below.

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[36] California Department of Transport (DOT) website, http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm

[37] Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D., Bartol, S., Carlson, T., Coombs, S., Ellison, W. T., Gentry, R., Halvorsen, M. B., Løkkeborg, S., Rogers, P., Southall, B. L., Zeddies, D., and Tavolga, W. N. (2014). "Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report," ASA S3/SC1.4 TR-2014 prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. Springer and ASA Press, Cham, Switzerland.

Koschinski *et al*[38]. reported on a series of playback experiments where free-ranging porpoises were exposed to underwater operational noise from a wind turbine. It was found that the animal's closest point of approach to the turbine increased from 120 m when no noise was present to 182 m when the noise was present. At this distance, the sound pressure levels are estimated at 125-130 dB re 1 μPa.

Porpoises exposed to seal scarers were found to turn around and swim directly away at distances between 1.6 km and 2.4 km from the noise source. At these ranges, sound pressure levels were recorded around 119 dB re 1 μPa[39].

Before, during and after a seismic survey in the Irish Sea, Goold[40] (1996) observed an avoidance reaction in the common dolphin (*Delphinus delphis*) at distances of 1 to 2 km from the survey vessel. In this case however, sound pressure levels that gave rise to the observed reactions were not provided but it may be estimated that sound pressure levels were 60 – 80 dB down on source levels – perhaps around 120 -130 dB re 1 μPa.

In a series of experiments, Nedwell *et al*.[41] found that caged brown trout (*Salmo trutta*) were seen to exhibit no behavioural responses when exposed to vibro-piling at a distance of 25 m from the source The sound pressure level at this range was not recorded. Similarly no behavioural changes were observed in the fish when exposed to impact pile driving at a distance of 400 m from the source. At this range, sound pressure levels were estimated at 134 dB re 1 μPa.

Analysis of behavioural responses coupled with measurements of sound levels at receptor locations has led to the development of impact criteria for assessing the significance of behavioural impacts. These fall into two groups making use of un-weighted metrics - where the thresholds do not take into account the hearing sensitivity of the target species; and weighted metrics – where sensitivity is allowed for.

4.4.1 Behavioural reactions – un-weighted metrics

Behavioural thresholds using un-weighted metrics consist of:

- Level B Harassment (defined by the 1994 amendment to the US Federal law Marine Mammal Protection Act of 1972) states that sound has "*the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild*". For impulsive sounds, this threshold has been set at 160 dB re 1 μPa (RMS) while for continuous sounds the threshold is 120 dB re 1 μPa (RMS)[42];

- Low Level Disturbance to impulsive sounds where the threshold has been set at 140 dB re 1 μPa (RMS)[42].

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[38] Koschinski S., Culik B. M., Damsgaard Henriksen O., Tregenza N., Ellis G., Jansen C., Kathe G., (2003), "Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator", Marine Ecology Progress Series Vol. 265: 263–273, 2003

[39] Brandt M. J., Höschle C., Diederichs A., Betke K., Matuschek R., Witte S., Nehls G., (2012), "Effectiveness of a sealscarer in deterring harbour porpoises (*Phocoena phocoena*) and its application as a mitigation measure during offshore pile driving", BioConsult SH, Husum, March 2012. Downloaded from www.bioconsult-sh.de/pdf/report_Sealscarer_20120320.pdf

[40] Goold, J.C. (1996). Acoustic assessment of populations of common dolphin (*Delphinus delphis)* in conjunction with seismic surveying. Journal of the Marine Biology Association. 76, 811-820.

[41] Nedwell, J, Turnpenny, A., Langworthy, J., and Edwards, B. (2003). Measurements of underwater noise during piling at the Red Funnel Terminal, Southampton, and observations of its effect on caged fish. Subacoustics Ltd. Report 558R0207.

[42] National Marine Fisheries Service (NMFS). (1995). Small takes of marine mammals incidental to specified activities; offshore seismic activities in southern California. Fed. Regist. 60(200, 17 Oct.):53753-53760.

4.4.2 Behavioural reactions – weighted metrics (dB$_{ht}$)

Behavioural response and auditory injury from underwater sound is often assessed by comparing the received sound level with the auditory threshold of marine mammals. A number of researchers[1,15,43,44,45] all use critical bands, normally octave or third octave band received levels of noise in comparison with the corresponding marine mammal hearing threshold in order to estimate the range of audibility and zones of influence from underwater sound sources.

This form of analysis has been taken a stage further[46],[47] where the underwater noise is compared with receptor hearing threshold across the entire receptor auditory bandwidth in the same manner that the dB(A) is used to assess noise source in air for human subjects. This dB$_{ht}$ criteria, used in these studies is behavioural based, where received sound levels of 90 dB above hearing threshold (analogous but not equal to 90 dB(A) in air) are considered to cause a strong behavioural avoidance, and levels of 75 dB above hearing threshold invoke a mild behavioural response. It is noted however, that these levels are derived from a small number of studies, involving few species of fish in very particular environments[47,48]. Furthermore the fish were exposed to swept tonal sounds which are rather different to the types of sounds likely to be generated during the Aberdeen Harbour Expansion Project construction task such as vessel, piling and dredging noise. Hawkins and Popper[49] note that defining response criteria to all species when exposed to such diverse noises may be too simplistic an approach hence care must be taken in applying the dB$_{ht}$ technique. In short, the dB$_{ht}$ impact criterion has not been validated by either rigorous peer-review or extensive experimental study. For this reason, it is decided to not take it forward in to the current study.

4.5 Summary of acoustic impact thresholds

A number of species of marine life have been identified in connection with the Aberdeen Harbour Expansion Project. These include dolphins, seals and various fish species. Many of the species are known to be sensitive to sound emitted underwater. In addition a number are legally protected under various guidelines, agreements and directives. Therefore, it is important to provide a rigorous methodology for quantifying the potential risk that the animals face following exposure to sound. The criteria used to assess the significance of the acoustic impact on the marine species found in the Aberdeen Harbour Expansion Project area are summarised in Tables 4.3 and 4.4 below. It is noted that impact criteria for marine mammals are different to those for fish. For marine mammals, the impact criteria are based on both unweighted sound pressure levels and sound exposure levels weighted to take into account hearing sensitivities. By contrast, those for fish are based solely on

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[43] Erbe C., Farmer D. M., (2000), “Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea”, *The Journal of the Acoustical Society of America* **108**(3), 1332-1340

[44] Madsen, P.T., Wahlberg, M., Tougaard, J., Lucke, K. and Tyack, P. (2006). “Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs”. *Mar. Ecol. Progr. Ser*. 309, 279-295.

[45] David, J.A. (2006), “Likely sensitivity of bottlenose dolphins to pile-driving noise”. *Water and Environment Journal*, 20: 48–54.

[46] Nedwell J R (2005) 'A metric for estimating the behavioural effects of noise on marine mammal species'. Subacoustech Report Reference: 59R0303, Presented at the National Physics Laboratory Seminar on Underwater Acoustics, Teddington, UK, October 2005.

[47] Nedwell, J. R., Turnpenny, A. W. H., Lovell, J., Parvin, S. J., Workman, R., Spinks, J. A. L., Howell, D. (2007). Subacoustech Report No 534R1231, Subacoustech, Bishop’s Waltham, UK.

[48] Maes, J., Turnpenny, A. W. H., Lambert, D. L., Nedwell, J. R., Parmentier, A., and Ollevier, F. (2004). “Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet,” *Journal of Fish Biology* 64, 938- 946.

[49] Hawkins A. D., Popper A. N., (2014). “Assessing the Impact of Underwater Sounds on Fishes and Other Forms of Marine Life”, *Acoustics Today*, Spring 2014, 30-41.

unweighted sound pressure levels and sound exposure levels. In addition there are no threshold levels indicating the onset of behavioural reactions.

Exposure limit	Effect
240 dB re 1 µPa Peak	Lethality
229 dB re 1 µPa Peak	Potential mortal injury in fish exposed to explosions
219 dB re 1 µPa^2 s SEL	Potential mortal injury in fish with low hearing sensitivity exposed to piling noise
213 dB re 1 µPa Peak	Potential mortal injury in fish with low hearing sensitivity exposed to piling noise
210 dB re 1 µPa^2 s SEL	Potential mortal injury in fish with medium hearing sensitivity exposed to piling noise
207 dB re 1 µPa Peak	Potential mortal injury in fish with medium hearing sensitivity exposed to piling noise
207 dB re 1 µPa^2 s SEL	Potential mortal injury in fish with high hearing sensitivity exposed to piling noise
207 dB re 1 µPa Peak	Potential mortal injury in fish with high hearing sensitivity exposed to piling noise
210 dB re 1 µPa^2 s SEL	Potential mortal injury in fish eggs and larvae exposed to piling noise
207 dB re 1 µPa Peak	Potential mortal injury in fish eggs and larvae exposed to piling noise
216 dB re 1 µPa^2 s SEL	Recoverable injury in fish with low hearing sensitivity exposed to piling noise
213 dB re 1 µPa Peak	Recoverable injury in fish with low hearing sensitivity exposed to piling noise
207 dB re 1 µPa Peak	Recoverable injury in fish with medium hearing sensitivity exposed to piling noise
207 dB re 1 µPa Peak	Recoverable injury in fish with high hearing sensitivity exposed to piling noise
206 dB re 1 µPa Peak	Onset of injury in fish
203 dB re 1 µPa^2 s SEL	Recoverable injury in fish with medium hearing sensitivity exposed to piling noise
203 dB re 1 µPa^2 s SEL	Recoverable injury in fish with high hearing sensitivity exposed to piling noise
187 dB re.1µPa^{2}s SEL	Onset of injury in fish with body weight greater than 2 g
186 dB re 1 µPa^2 s SEL	TTS in fish with low hearing sensitivity exposed to piling noise
186 dB re 1 µPa^2 s SEL	TTS in fish with medium hearing sensitivity exposed to piling noise
186 dB re 1 µPa^2 s SEL	TTS in fish with high hearing sensitivity exposed to piling noise
183 dB re.1µPa^{2}s SEL	Onset of injury in fish with body weight smaller than 2 g

Table 4.3: Summary of underwater noise impact criteria for fish species

Exposure limit	**Effect**
240 dB re 1 µPa Peak	Lethality
230 dB re 1 µPa Peak	Auditory injury (PTS) onset in cetaceans
224 dB re 1 µPa Peak	Temporary deafness (TTS) onset in cetaceans
218 dB re 1 µPa Peak	Auditory injury (PTS) onset in pinnipeds
215 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in cetaceans exposed to nonpulses
212 dB re 1 µPa Peak	Temporary deafness (TTS) onset in pinnipeds
203 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in pinnipeds exposed to nonpulses
199.7 dB re 1 µPa Peak	TTS onset in harbour porpoise
198 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in cetaceans exposed to multiple pulses
195 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in cetaceans exposed to nonpulses
190 dB re 1 µPa RMS	Level A - Auditory injury criterion for pinnipeds
186 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in pinnipeds exposed to multiple pulses
183 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in pinnipeds exposed to nonpulses
183 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in cetaceans exposed to multiple pulses
180 dB re 1 µPa RMS	Level A - Auditory injury criteria for cetaceans
171 dB re.1µPa^{2}s SEL M-Weighted	PTS onset in pinnipeds exposed to multiple pulses
164.3 dB re 1 µPa^{2}s SEL	TTS onset in harbour porpoise
174 dB re 1 µPa Peak	Aversive behavioural reaction in harbour porpoise
160 dB re 1 µPa RMS	Level B - Harassment in cetaceans and pinnipeds exposed to impulsive sounds
145 dB re 1 µPa^{2}s SEL	Aversive behavioural reaction in harbour porpoise
140 dB re 1 µPa RMS	Low level disturbance in cetaceans and pinnipeds exposed to impulsive sounds
120 dB re 1 µPa RMS	Level B - Harassment in cetaceans exposed to continuous sounds

Table 4.4: Summary of underwater noise impact criteria for cetacean and pinniped species

5. UNDERWATER ACOUSTIC PROPAGATION MODELLING

5.1 Introduction

In order to assess the impact of underwater sound on marine life, it is necessary to model its propagation through the underwater environment from the source location to a point in the far field. For accuracy, the process invariably requires the use of sophisticated modelling techniques and site-specific data. This section discusses the acoustic models used and the geoacoustic and oceanographic data required as input parameters for the models. The modelling processes themselves are divided into those for (i) non-explosive sources; and (ii) explosive sources reflecting the different methodologies developed.

5.2 Non-explosive sources

These include such noise sources as dredging, drilling, piling and shipping. For these sources, a very simple approach to modelling underwater propagation is to consider geometrical spreading laws given by

$$TL = N \log_{10}(r) \qquad \text{eqn. 5.1}$$

where TL is the propagation loss in dB, N is a constant: 20 for spherical spreading and 10 for cylindrical spreading; and r is the distance in metres from the source to the receptor.

When sound propagates uniformly in all directions, spherical spreading applies. When the propagation of sound is constrained by the water surface and the seabed, then cylindrical spreading is most applicable (see e.g. Urick[10]). Although computing the propagation loss in this way is very quick, the biggest drawback is that it fails entirely to take into account the influence of both the environment and of signal frequency on the propagation of sound and hence the propagation loss may be under- or over-estimated, often by a considerable amount. The solution to this is to make use of more sophisticated modelling techniques and these are described briefly below.

The calculation of propagated, underwater sound fields is based on a solution to the Helmholtz equation having appropriate boundary conditions (see e.g. Brekhovskikh and Lysanov[50]). The boundary conditions used and the modelling regime to be considered logically lead to one or other solution to the Helmholtz equation and this has given rise to a number of classes of models that employ similar techniques. The models are based on ray theory, normal mode, parabolic equation and full-field techniques[51],[52]. Each set of solutions are valid and computationally efficient over a limited frequency, depth and range regime. For instance, ray theory is most suited to short range and high frequency scenarios while normal mode and parabolic equations are applied to long range and low frequency models. Full-field models are applicable to many scenarios but are often computationally intensive and require a large level of user-experience to ensure that the mathematical iterative processes have reached convergence[53].

In general the models were developed to operate at narrow-band frequencies and do not therefore easily lend themselves to applications involving broadband sound sources and assessment metrics such as peak level and Sound Exposure Level. To cover the broad range of frequencies of interest to the current study, it is acceptable however to use more than one type of model. For the Aberdeen Harbour Expansion

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[50] Brekhovskikh, LM & Lysanov, Y (1991), *Fundamentals of Ocean Acoustics*. Springer-Verlag, Berlin.

[51] Buckingham M. J., (1992), “Ocean-acoustic propagation models”, *Journal d’Acoustique*: 223-287.

[52] Etter Paul C. (2003), *Underwater Acoustic Modeling and Simulation*, 3rd edition, Spon Press, New York, ISBN 0-419-26220-2.

[53] Jensen F., Kuperman W., Porter M., Schmidt H., (2000), *Computational Ocean Acoustics*, Springer-Verlag.

Project underwater noise study, it is proposed to use a range of models. At low frequencies, the propagation modelling relies on the fully range-dependent parabolic equation model RAM[54]. At high frequencies, RAM becomes too cumbersome to use so a ray-trace model is used instead. The switchover frequency is dependent on the wavelength of the signal and the water depth in which the source is located. When the water depth reaches approximately 8 wavelengths (the wavelength of sound is equal to c_w/f where c_w is the sound speed in water and f is the frequency of the propagating signal); then it becomes more computationally efficient to use an alternative modelling technique. The wider region outside the immediate Aberdeen Harbour Expansion Project area is a shallow water site with typical water depths increasing to 40-50 m (although see Section 5.4 below) along propagation paths radiating from the survey regions. For these shallow water depths, the changeover frequency occurs around 1000 Hz. Subsequently, the ray-trace model Bellhop[55] will be used.

As the sound propagates with range through the water, generally it loses energy. There are a number of mechanisms by which this happens. Urick[10] provides a detailed explanation of these and an overview is given as follows. The first mechanism is due to spreading over range and is a process whereby acoustic energy is converted into heat which is subsequently dissipated in the ocean. The second is due to the interaction of the sound wave with various dissolved salts in the water. This is proportional to the frequency of the propagating signal and the associated losses become considerable at frequencies in excess of 100 kHz. The third mechanism involves reflection and refraction of acoustic energy at the water/seabed interface. The means by which this is modelled starts with the depiction of the water and seabed layers in an idealised representation given below.

Both computer models make use of a shallow water depth- and range-dependent layer overlying two lossy, fluid layers representing the seabed sediment and the underlying basement. This is shown schematically in Figure 5.1 below. It is noted that the classic 3-layer acoustic model as represented in RAM and Bellhop assumes a basement rock that is semi-infinite in thickness. The data that is used to parameterise each layer is discussed below.

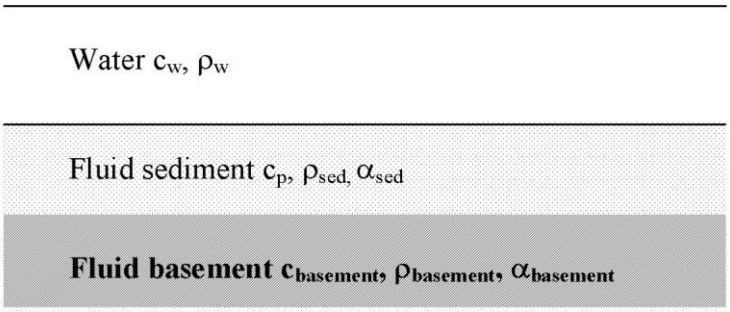

Figure 5.1: Schematic of acoustic model

It is noted that the modelling techniques relied upon by both RAM and Bellhop are based on mature and rigorous scientific methodologies that have been reviewed extensively in the international literature over a number of years. It is considered of fundamental importance that acoustic modelling is not based on "in-house" solutions using non peer-reviewed techniques as this could compromise the developer in the event that the environmental impact assessment documents become subject to

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[54] Collins M. D., (1993), "A split-step Padé solution for the parabolic equation method", *Journal of the Acoustical Society of America*, **93**:1736-1742.

[55] Porter M. B., Y-C Liu,"Finite-Element Ray Tracing", Proceedings of the International Conference on Theoretical and Computational Acoustics, Eds. D. Lee and M. H. Schultz, pp. 947-956, World Scientific (1994).

scrutiny. Such techniques[56] rely on simple geometrical spreading arguments or empirical techniques and fail to incorporate the complex mechanisms required to explain fully how underwater sound propagates through the environment.

The quality of the output data is highly dependent on obtaining site-specific oceanographic and geo-acoustic data. The sources of data used as inputs to the propagation modelling process are discussed below.

5.3 Explosive sources

The acoustic propagation models discussed in the previous section are all ultimately derived from the wave equation[57]. This starting point requires that the underlying acoustics should be linear in nature i.e. all fluctuations in pressure and displacement are of small amplitude.

By contrast, the outgoing waves of acoustic energy from an explosive source are non-linear especially in the near-field. Fundamentally, the change in density of water caused by pressure fluctuations from a passing sound wave is not linearly proportional to the change in pressure. The wave equation as a basis for further analysis is no longer valid and some other mathematical treatment is necessary. A number of techniques have been explored for analysing the propagation of non-linear waves[58,59,60,61,62] but these are necessarily complex and time-consuming and do not easily lend themselves for inclusion in the Aberdeen Harbour Expansion Project studies.

The propagation of sound from explosive source in open water has been dealt with by Arons *et al*. [63], Rogers[64] and Gaspin[65]. Application of the methodology derived from such studies will however lead to an over-estimation of sound levels in the water when considering confined explosions. Wright and Hopky[32] present a semi-empirical technique that models the transmission of sound from an explosion in a borehole and hence determines the distance at which sound levels have fallen to given levels. As a result, it is possible to generate a very simple model of the environment in which the waterborne blast wave decays and this is used to model blast propagation in the current study.

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[56] Kongsberg (2010), 2D seismic survey in the Moray Firth: Review of noise impact studies and re-assessment of acoustic impacts, Prepared for Genesis Oil and Gas Ltd. Downloaded from: https://www.og.decc.gov.uk/environment/moray_2dseismic.pdf

[57] Kinsler L. E., A. R. Frey, A. B. Coppens, J. V. Sanders (1982), Fundamentals of Acoustics, 3rd Edition, John Wiley and Sons, New York.

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[59] Novikov, B. K., O. V. Rudenko, V. I. Timoshenko. (1987), *Nonlinear Underwater Acoustics*. Translated by Robert T. Beyer, Acoustical Society of America.

[60] Beaujean P-P, J., A. A. Folleco, F. J. Boulanger, S. A.L. Glegg, (2003), “Non-Linear Modeling of Underwater Acoustic Waves Propagation for Multi-Receiver Channels”, *Proceedings of OCEANS 2003,* Volume:1.

[61] Castor K., P. Gerstoft, P, Roux, W. A. Kuperman, B. E. McDonald, (2004), “Long-range propagation of finite-amplitude acoustic waves in an ocean waveguide”, *Journal of the Acoustical Society of America*. **116**(4), Pt. 1.

[62] Maestas J., L. F. Taylor, J. M. Collis, “Shock wave propagation along constant sloped ocean bottoms”, *Journal of the Acoustical Society of America*. **136**(6): 2987–2997, December 2014.

[63] Arons A. B., Yennie D. R., Cotter T. P., (1949), “Long range Shock Propagation in Underwater Explosion Phenomena II”. *US Navy Dept. Bur. Ord. NAVORD Rep*. 478.

[64] Rogers P. H., (1977), “Weak Shock Solution For Underwater Explosive Shock Waves”. *Journal of the Acoustical Society of America*. **62**(6):1412-1419.

[65] Gaspin J. B., (1983), “Safe Swimmer Ranges from Bottom Explosions”, NSWC/WOL TR-83-84, Naval Surf. Weap. Cent. DTIC AD-B086375.

5.4 Transect bathymetry

Acoustic propagation is very dependent on the bathymetry of the seabed in the vicinity of the area of interest. In deep water areas, sound tends to travel to greater distances than in shallow areas; in regions of decreasing water depth, the noise levels are rapidly attenuated while sand-banks or other similar seabed features may provide a degree of shielding to regions further down-range. Sources of bathymetric data having an appropriate spatial resolution and for specific use in propagation modelling beyond Nigg Bay include the bathymetric database ETOPO1[66] and STRM30[67]. These are both gridded digital elevation model (DEM) databases having spatial resolutions of 1 minute of arc and 30 seconds of arc respectively corresponding to linear distances of approximately 1.8 km and 0.9 km respectively. Due to the relatively small size of Nigg Bay however, it is unlikely to be represented by more than 3 or 4 data points. Therefore these data are supplemented by an additional number of spot depths transcribed from the relevant navigation charts for the wider Aberdeen Bay sea area such that the bathymetry in and around the bay is adequately represented. Although it is recognised that it is often difficult to guarantee the quality of the digitised chart data when the underlying surveys are not the most recent, the level of resolution derived using these supplementary data is sufficient to support the modelling for Nigg Bay itself[68].

Nigg Bay has a gently sloping seabed with the water depth generally increasing in an easterly direction. At a distance of 500 m the depth lies in the range 6-8 m while beyond the limits of the bay, the water depth increases generally uniformly to a depth of 80 m to 100 m at a range of 25 km.

Three modelling locations were selected:

(i) top of Nigg Bay at 57°08.00'N 002°03.35'W in a water depth of 4 m;

(ii) close to projected end of southern breakwater 57°07.833'N 002°02.780'W in a water depth of 10 m; and

(iii) close to projected end of northern breakwater 57°08.004'N 002°02.783'W in a water depth of 12 m.

For each modelling location, water depth data was taken along a number of transects radiating from the nominal centre and at an azimuthal separation of 10° (see Figure 5.2).

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[66] Amante, C. and B. W. Eakins,(2009), ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp, March 2009

[67] NASA Shuttle Radar Topography Mission dataset (2012), http://topex.ucsd.edu/WWW_html/srtm30_plus.html

[68] UKHO Admiralty Chart 210, Newburgh to Montrose, Edition April 2014. Source data for the areas of relevance dated 1965 and 1976.

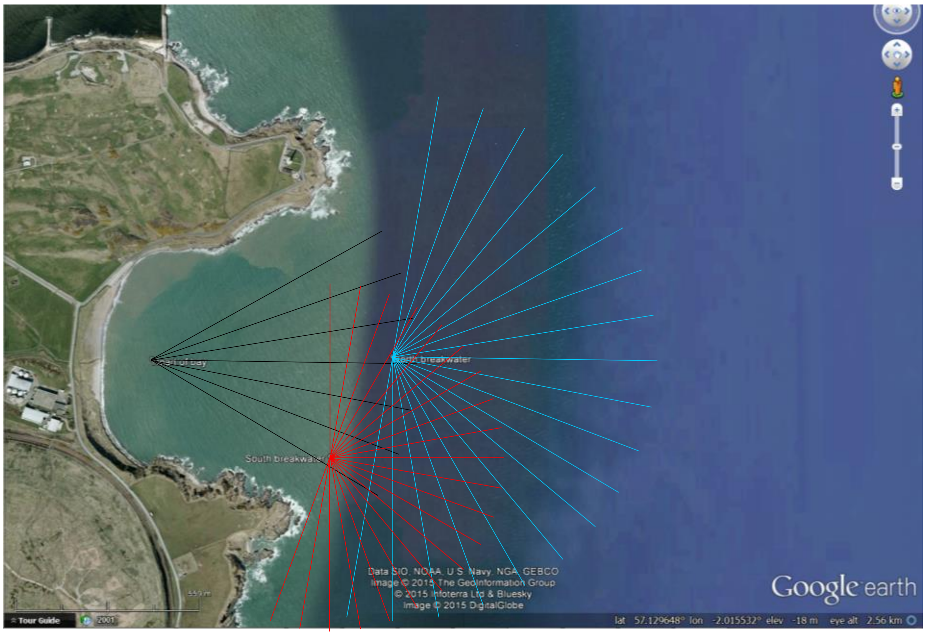

Figure 5.2: Location of three acoustic propagation modelling points around the Aberdeen Harbour Expansion Project area

5.5 Oceanographic data

Oceanographic data was obtained from the World Ocean Atlas[69]. This consists of gridded monthly samples of temperature, salinity and depth and from which sound speed profiles for the Aberdeen Harbour Expansion Project area may be reconstructed.

The notional timetable of engineering tasks discussed in Section 2 indicates that the construction phase of the Aberdeen Harbour Expansion Project will take in excess of 1 year. Hence any of the given tasks such as dredging or piling may take place at any time of the year. From an oceanographic perspective, over the course of a year the sound speed profile in the relatively shallow waters of the UK undergoes a marked change in characteristics and this has a decisive effect on the subsequent propagation of underwater sound. Within the confines of Nigg Bay, the combination of the shallow water and the diurnal tides result in the waters being well mixed and thus isothermal in nature. Beyond the limits of Nigg Bay, the deeper waters lead to some stratification. During the winter months, the topmost 20 m or so of water become well-mixed through the action of the seasonal storms. This results in a profile where the sound speed tends to increase uniformly with depth leading to upwardly refracting profile by the month of February. During late spring and early summer, increased solar heating of the topmost layers produces an increase in the sound speed over the topmost 10-20 m followed by a seasonal thermocline which gives rise to a downwardly refracting profile. This leads to the creation of a surface duct that tends to channel acoustic energy emitted from shallow sources while below this, the energy tends to become directed towards the seabed. As the surface waters cool down and become well-mixed due to the autumnal storms, the surface duct is lost and the profile tends to become increasingly upwardly refracting once again. In order to adequately characterise the environment yet keep the number of acoustic runs to a realistic limit, acoustic propagation modelling was undertaken using the February and August sound speed profiles as these two months are most likely to give rise to the maximum and minimum propagating conditions.

Sound speed profiles for the Aberdeen Harbour Expansion Project area are shown in Figure 5.3. It will be seen that the February sound speed increases with increasing

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[69] WOA (2009), World Ocean Atlas dataset available for download at www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html

water depth. This gives a profile that is upwardly refracting throughout the water column down to the seabed. By August, the surface duct is well developed and the strong negative gradient in the seasonal thermocline down to around 125 m ensures that underwater sound is generally directed towards the sea bed. Given the nature of these profiles, longer range acoustic propagation is more likely to occur during winter than during summer while intermediate conditions will occur during spring and autumn.

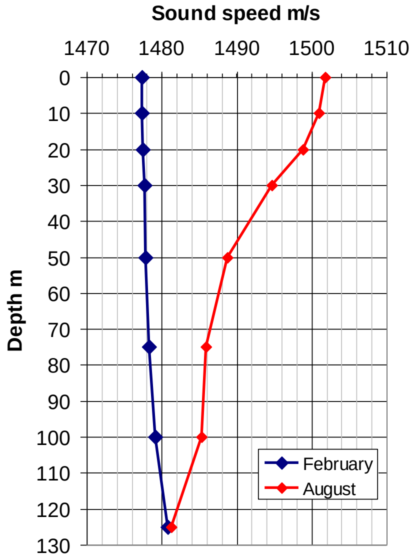

Figure 5.3: Representative sound speed profiles in the Aberdeen Harbour Expansion Project area

5.6 Seabed geoacoustics

Surveys in and around the Aberdeen Harbour Expansion Project area indicate that the seabed sediments consist of a layer of sand or sandy gravel around 2 m to 4 m thick overlying a metamorphic basement[70,71]. Hamilton[72,73,74] provides advice on seabed sediment parameters and from this, the sound speed and attenuation data was obtained. The data is summarised in Table 5.1.

Layer	Compressional wave velocity Vp m/s	Density kg/m³	Attenuation dB/m/kHz	Thickness m
Terrigenous sand	1647	2000	0.454	2
Metamorphic basement	5548	2745	0.095	-∞

Table 5.1: Sediment parameters for acoustic models

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[70] BGS (1987), Seabed sediments around the United Kingdom (North Sheet), British Geological Survey Publications.

[71] Barne, J.H., Robson, C.F., Kaznowska, S.S., Doody, J.P., & Davidson, N.C., eds. 1996. Coasts and seas of the United Kingdom. Region 3 North-east Scotland: Cape Wrath to St. Cyrus. Peterborough, Joint Nature Conservation Committee. (Coastal Directories Series.)

[72] Hamilton E.L., (1963), "Sediment Sound Velocity Measurements made In Situ from Bathyscaph TRIESTE", Journal of Geophysical Research 68 pp. 5991-5998.

[73] Hamilton E.L., (1970), "Sound velocity and related properties of marine sediments", North Pacific, Journal of Geophysical Research 75 pp. 4423-4446.

[74] Hamilton E. L., (1972), "Compressional-wave attenuation in marine sediments", Geophysics 37 pp. 620-646.

5.7 Background noise

An underwater noise remains audible to marine life until one of two conditions are met:

(i) The noise falls so low that it is below the ambient noise level for that locality. It is then said to be masked by the background noise[75]; or

(ii) The noise falls below the hearing threshold of a given marine creature.

The background underwater noise levels are thus a key parameter in attempting to quantify the acoustic impact on marine life. However, no data on underwater background noise specifically in the Nigg Bay area have been found. What follows is a brief discussion of ambient noise in deep and shallow waters and from this, indicative levels for background noise in Nigg Bay have been obtained.

Underwater background noise in deep waters tends to be well defined. The Wenz curves[76] provide indicative spectral levels for shipping, weather-related noise and seismic noise from volcanic and tectonic activity. For these data to be valid the ambient noise field has to be isotropic and homogenous. In shallow waters this assumption is no longer valid. At such locations, underwater background noise is considered to be the sum of three components: shipping and industrial noise; wind and wave noise, including surf; and biological noise and any or all of these may vary significantly over time and location.

A baseline shipping assessment commissioned by the Aberdeen Harbour Board in support of the Aberdeen Harbour Expansion Project[77] indicated that although very little vessel activity occurs within the confines on Nigg Bay, high vessel density may be found close by. Extensive use of the Port of Aberdeen is made by vessels working in the North Sea oil and gas industry as well as those working in the fishing, passenger, military and dredging sectors. In addition, three anchorage areas are found within 5 km of Nigg Bay. Such activity is likely to lead to high background noise levels.

Underwater noise levels have been recorded at a number of similar sites around the UK and these are discussed below in an attempt to estimate the levels that may arise at the Nigg Bay area before any development takes place.

Wille[78], while observing that there appears to be no quantitative relationship between shipping density and noise levels, presented measurements of noise in regions of the North Sea having high levels of vessel traffic where levels were 122 dB re 1 μPa. Background noise levels were recorded at the North Hoyle Offshore Wind Farm (OWF) while the wind farm was being constructed and in the absence of any piling[79]. The wind farm is built on seabed sediments consisting of predominantly gravelly sand. It is located around 6 km off the north Wales coast close to a main shipping route from Liverpool. Noise levels were recorded over the frequency range 10 Hz to 100 kHz and were found to vary between 90 and 150 dB re 1 μPa depending on shipping levels and prevailing weather conditions with a mean level of 112 dB re 1 μPa. Similar measurements were recorded at Scroby Sands wind farm some 3 km off the east

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[75] It is recognized however, that under certain circumstances, narrow-band signals whose levels are below the total noise level across a band of frequencies maybe audible (Richardson *et al*. (1995).

[76] Wenz G. M., (1962) "Acoustic Ambient Noise in the Ocean: Spectra and Sources", *Journal of the Acoustical Society of America*. **34**(12):1936-1956

[77] Anatec (2015), "Nigg Bay Development Baseline Assessment for Shipping and Navigation", Anatec Report Number A3501-FUG-TN-2. Prepared by Anatec Ltd. Presented to Fugro EMU Ltd on behalf of Aberdeen Harbour Board.

[78] Wille P. C., (1984), "Ambient noise: Characteristics of the Noise Field", *Proceedings of the NATO Advanced Study Institute on Adaptive Methods in Underwater Acoustics, Lüneberg, FRG, 1984*, NATO ASI Series, Series C:Mathematical and Physical Sciences Vol. 151, 13-36, Ed H. G. Urban, D Reidel Publishing Company, Holland.

[79] Nedwell J., Langworthy J., Howell D., (2004), "Underwater noise and offshore windfarms", Subacoustech Report No 544R0503.

coast of England and close to the town of Great Yarmouth[79]. Noise levels were mainly between 98 and 130 dB re 1 μPa with a mean of 122 dB re 1 μPa. Full noise spectra were recorded at Yell Sound, Shetland[80]. This is a sheltered location to the south, east and west with deep water to the north. It is used by marine traffic servicing the Schiehallion field to the west of Shetland. Measurements showed that noise levels were highest around 10 Hz at 100 dB re 1 $\mu Pa^2/Hz$ falling to 50 dB re 1 $\mu Pa^2/Hz$ at 10 kHz. It is estimated that this gives an overall broadband noise level of around 130 dB re 1 μPa. Mason[81] concludes that background levels in UK coastal waters of 130 dB re 1 μPa are not uncommon.

The measurements of underwater noise show a considerable variation and it is thus difficult to produce from such data a noise level which may be representative of that at the Aberdeen Harbour Expansion Project area. However, it is proposed that noise levels of 120-130 dB re 1 μPa be used in order to set an upper bound on the levels that may arise at Nigg Bay and to assist in the subsequent quantification of acoustic impacts.

It is unclear what a representative lower noise limit might be - given that low noise levels would only arise at times of relatively calm weather together with little or no passing vessel traffic. From a consideration of the precautionary principle, and in order to set a lower bound on background noise levels, a "worst case" scenario will be discussed when noise levels fall as low as 100 dB re 1 μPa.

5.8 Sound modelling parameters

Due to the limitations of the acoustic propagation techniques[52], it is necessary to assume that the sources are equivalent to acoustic points, for which discrete source depths are required. Typically for the purposes of acoustic propagation in a water channel, the acoustic centre of a vessel is assumed to lie at a water depth of 6 m; while drilling or piling noise is assumed to originate on or very close to the seabed.

The sound sources as discussed in Section 3 all cover a wide range of frequencies. For these, a broadband, time-domain propagation model ideally should be used to represent the source and underwater acoustic environment. However, these tend to be difficult to use and have a considerable time overhead associated with them[53]. An alternative approach is to divide the source frequency bandwidth into 1/3rd octave bands where each band has a given spectral level, centre frequency and bandwidth; and then to use a frequency-domain type program (such as the ones discussed in Section 5.2) for subsequent propagation modelling.

The input parameters for the acoustic propagation modelling as discussed in this section are summarised in Table 5.2.

	Noise source		
Parameter	Vessel	Drilling/Piling	Dredging/ Material disposal
Source depth m	6	At seabed	6
Frequency Hz	10, 12.5, 16, 20, 25, 31, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1k, 1.25k, 1.6k, 2k, 2.5k, 3.15k, 4k, 5k, 6.3k, 8k, 10k, 12.5k, 16k, 20k, 25k, 800, 31.5k, 63k, 80k, 100k, 125k, 160k		
Summer	✓	✓	✓
Winter	✓	✓	✓

Table 5.2: Source parameters for acoustic model inputs

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[80] Nedwell J.R., Edwards B.,(2004), “A review of measurements of underwater man-made noise carried out by Subacoustech Ltd, 1993 – 2003”, Subacoustech Report No 534R0109.

[81] Mason T., (2013), “Modelling of subsea noise during the proposed piling operations at the Dudgeon Wind Farm” Subacoustech Environmental Report: E438R0106.

6. ACOUSTIC PROPAGATION MODELLING RESULTS

6.1 Introduction

This section of the report describes the results of the acoustic propagation modelling undertaken in Section 5. In order to illustrate the effect the environment has on the propagation of construction noise, a number of representative examples are discussed with reference to various noise sources and environmental conditions from each of the construction sites within Nigg Bay.

6.2 TSH dredging noise

Dredging noise arising from *TSHD Taccola* was modelled as a function of range and depth along each of 10 transects centred at the head of Nigg Bay using oceanographic conditions for the months of February and August and a source depth of 6 m. A typical result is given in Figure 6.1 which shows the modelled SPL for the month of February along transect having a bearing of 110° where the water depth increases generally with range from 10 m at the start of the transect to 120 m at a distance of 20 km. It will be seen that the SPL falls with increasing range. At the point of origin the SPL is around 180 dB falling to around 160 dB at 1 km and below 140 dB at 3 km range. Beyond around 3 km, there is a tendency for sound to become focussed at mid water depths leading to lower sound pressure levels close to both the surface and the seabed.

Figure 6.2 shows broadband sound pressure levels as a function of range and depth using oceanographic conditions for the month of August. As before, the SPL appears to fall fairly uniformly with range reaching as low as 120 dB within around 2.5 km. Closer scrutiny reveals that SPLs are somewhat lower at a given range and depth compared with those computed using February conditions. The downwardly refracting nature of the sound speed profile ensures that the sound is directed towards the sediments where it undergoes a loss of energy during subsequent reflection while during the month of February, the sound tends to be directed away from the seabed and thus propagates to longer distances.

The levels of background noise in the Aberdeen Harbour Expansion Project area influence the distance out to which noise from *TSHD Taccola* become inaudible. If background noise is as high as 130 dB re 1 µPa, dredging noise remains audible out to 11 km during the winter months and 8 km during summer. If background noise levels average 120 dB re 1 µPa then vessel noise remains audible beyond 20 km during winter and up to 15 km during summer. A summary of audibility ranges as a function of background noise level is given in Table 6.1.

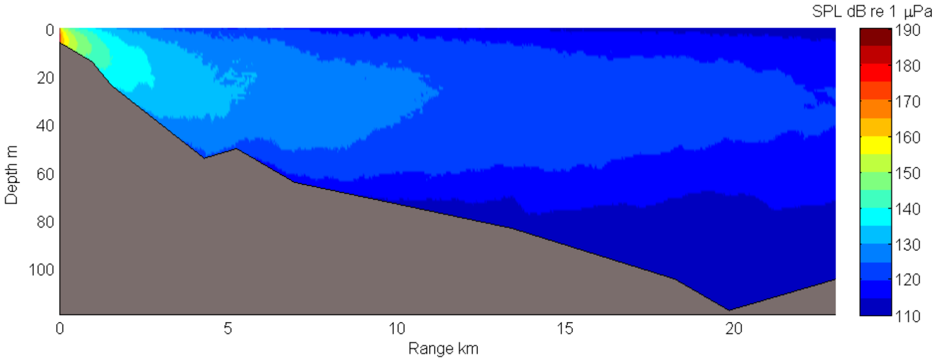

Figure 6.1: Contour plot of broadband SPL as a function of range and depth for vessel noise from TSHD Taccola computed along a bearing of 110° using February oceanographic conditions at the head of Nigg Bay

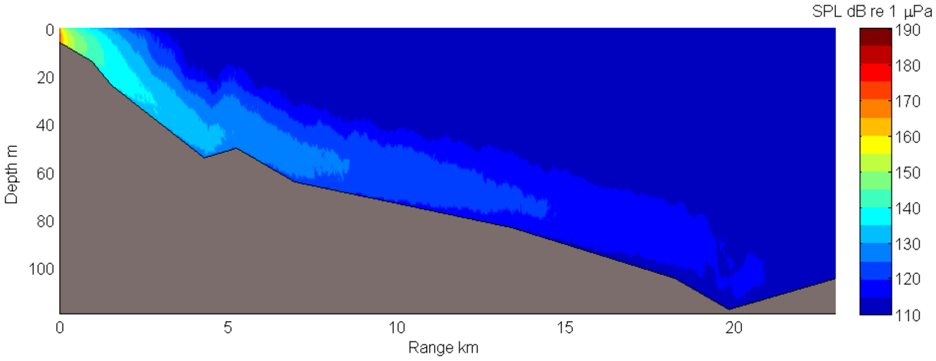

Figure 6.2: Contour plot of broadband SPL as a function of range and depth for vessel noise from *TSHD Taccola* computed along a bearing of 110° using August oceanographic conditions at the head of Nigg Bay

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	11 km	22.5 km	66 km	90 km
Summer	5.2 km	14.6 km	25.5 km	37.4 km

Table 6.1: Audibility ranges for *Taccola* as a function of background noise level

6.3 Backhoe dredging noise

A comparison of may be made of the noise emitted by the backhoe dredger *New York* with that from *TSHD Taccola*.

Figure 6.3 shows SPLs computed using February oceanographic conditions. It will be seen that SPLS at any given location are lower than those in Figure 6.1. For instance at a range of 10 km, the difference amounts to approximately 10 dB. When computed using summer conditions (Figure 6.4), SPLs from the *Taccola* falls in to the background at 8 km but only 5 km from *New York*. The difference in behaviour may be partly attributed to the lower source level where *New York* has a level approximately 7.5 dB down on that of the *Taccola*. However it may be noted that the spectral distribution of energy is different for the two vessels.

The source spectra in Figure 3.4 indicate that *New York* has noise levels lower than *Taccola*, the roll-off at high frequencies is greater for *New York* than for *Taccola* - beyond 10 kHz, band levels are 30 - 40 dB down on those from *Taccola*. *New York* may be considered as a predominantly low frequency noise source. As low frequencies tend to propagate to greater distances than higher frequencies, it might reasonably be expected that noise from *New York* remains at high levels. However, the shallow water channel has the effect of cutting-off the low frequency components (Urick 1985). In this instance, energy in the range 10 Hz to approximately 80 Hz is absorbed into the seabed sediments leaving little energy remaining to propagate.

The audibility of the noise generated by *New York* depends on the prevailing background noise levels. In high background noise conditions, the noise may become inaudible at ranges as short as 2.5 km. By contrast, in low background noise conditions, New York may remain audible out to a range of 76 km. A summary of audibility ranges as a function of noise levels is given in Table 6.2.

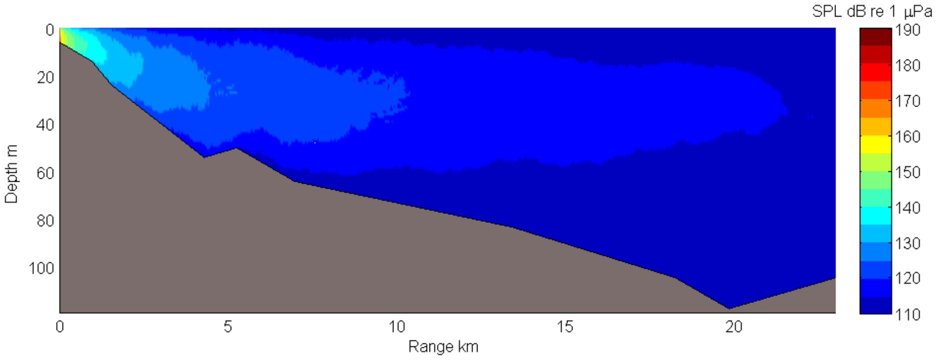

Figure 6.3: Contour plot of broadband SPL as a function of range and depth for vessel noise from *BHD New York* computed along a bearing of 110° using February oceanographic conditions at the head of Nigg Bay

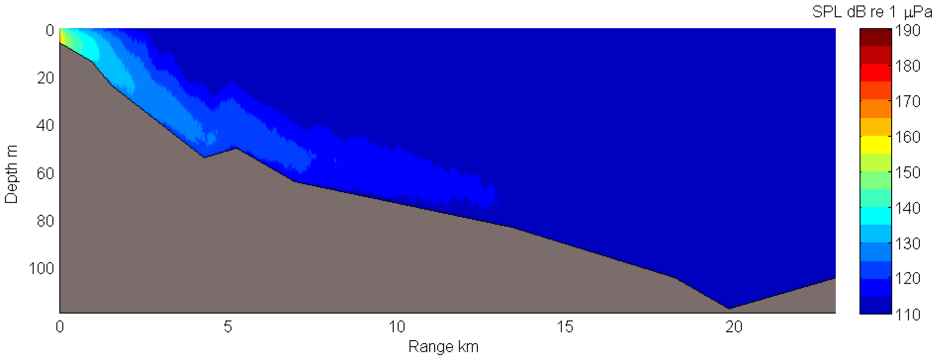

Figure 6.4: Contour plot of broadband SPL as a function of range and depth for vessel noise from *BHD New York* computed along a bearing of 110° using August oceanographic conditions at the head of Nigg Bay

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	2.5 km	11.6 km	33.1 km	76 km
Summer	2.3 km	7.8 km	20.8 km	38.3 km

Table 6.2: Audibility ranges for *New York* as a function of background noise level

6.4 Vessel noise

An example of vessel noise may be seen in Figure 6.5. This shows the noise emitted by the vessel *DN43* modelled using February oceanographic conditions along the 90° transect at the south breakwater construction site. As seen previously, the SPL decreases generally with increasing range. There is the same tendency for the sound to become channelled in mid-water where subsequently, losses due to reflection off either the sea surface or seabed are minimised. It may be noted that SPLs at a given depth and range at this site tend to be slightly higher than those computed at the corresponding location at the head of Nigg bay (Figure 6.1). This may be attributed to the slightly deeper water conditions at the south breakwater construction site where, as a result, the propagation of vessel noise is easier.

When modelled using August oceanographic conditions (Figure 6.6), the sound is channelled into the seabed where it undergoes significant loss. In addition, the effect of the bathymetry has a greater influence on the SPL during the summer months whereby acoustic shadow zones are more likely to become apparent. An example of this is seen around 12-16 km where the sound is directed into the offshore trough. The subsequent decrease in water depth from 16 km to 18 km tends to lead to greater acoustic losses than might otherwise occur. Hence at a given depth and range, the SPL is much lower during summer than during winter.

Comparisons may be made with SPLs computed at the North breakwater site nearby (Figures 6.7 and 6.8). The initial water depth is slightly less than that at the South site and this has an immediate influence on the subsequent acoustic field. At a given depth and range, SPLs tend to be lower than at the South site: this effect is more pronounced during the summer months when the propagating sound is being directed in to the lossy seabed sediments.

The results indicate that SPLs remain above the maximum likely background noise level of 130 dB re 1 μPa out to a range of 12 km during winter and 8 km during summer. For background noise levels of 120 dB re 1 μPa, the corresponding ranges are in excess of 20 km during winter and up to 16 km during summer. In low background noise conditions, the noise emitted by DN43 may remain audible at ranges up to 191 km. A summary of audibility ranges as a function of background noise levels at the south and north breakwater construction sites are are given in Tables 6.3 and 6.4 respectively.

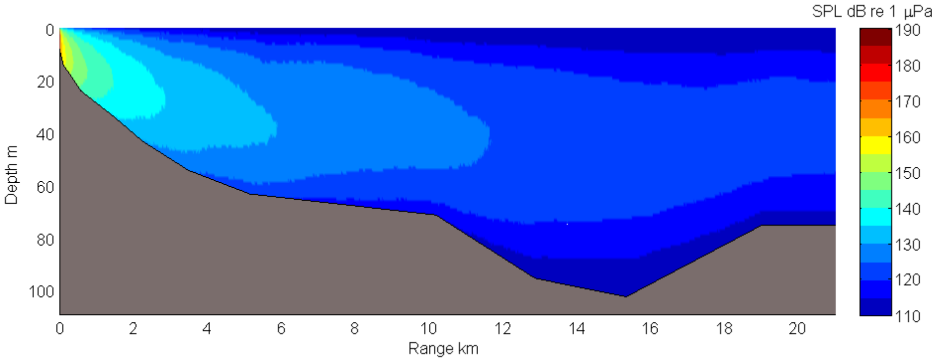

Figure 6.5: Contour plot of broadband SPL as a function of range and depth for vessel noise from *DN43* computed along a bearing of 90° using February oceanographic conditions at the south breakwater construction site in Nigg Bay

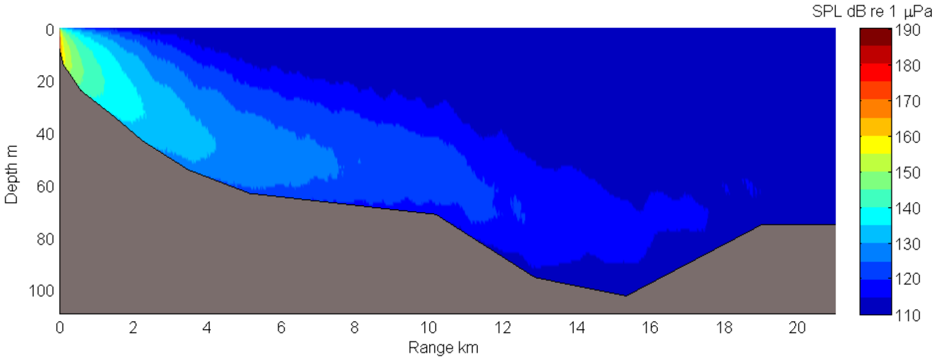

Figure 6.6: Contour plot of broadband SPL as a function of range and depth for vessel noise from *DN43* computed along a bearing of 90° using August oceanographic conditions at the south breakwater construction site in Nigg Bay

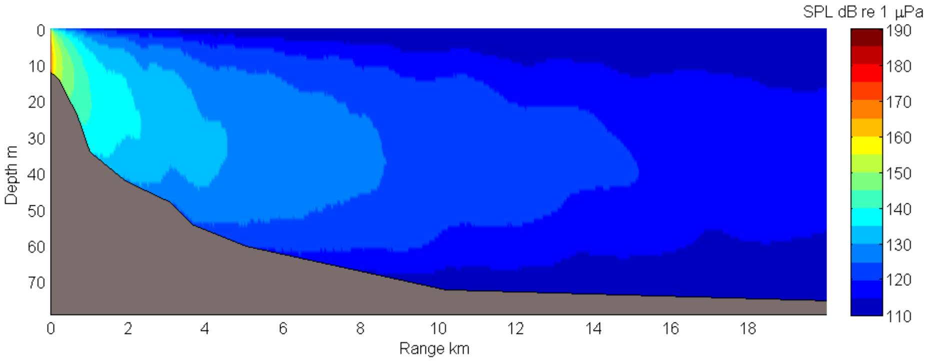

Figure 6.7: Contour plot of broadband SPL as a function of range and depth for vessel noise from *DN43* computed along a bearing of 90° using February oceanographic conditions at the north breakwater construction site in Nigg Bay

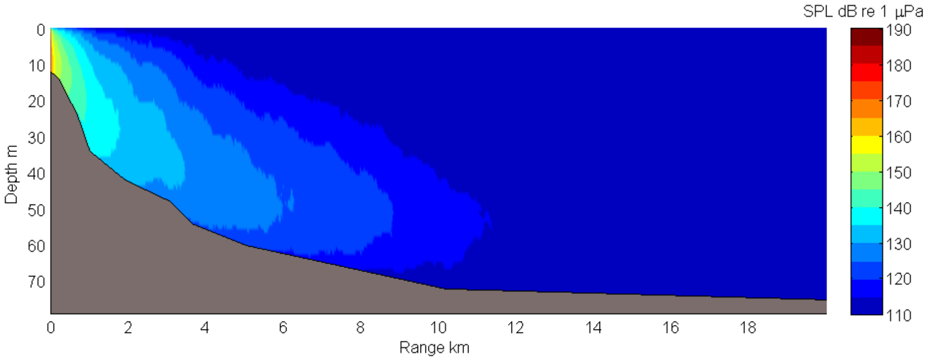

Figure 6.8: Contour plot of broadband SPL as a function of range and depth for vessel noise from *DN43* computed along a bearing of 90° using August oceanographic conditions at the north breakwater construction site in Nigg Bay

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	5.4 km	21 km	60 km	172 km
Summer	4.1 km	11.0 km	25 km	59 km

Table 6.3: Audibility ranges for *DN43* as a function of background noise level at the south breakwater site

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	4.5 km	17.5 km	60 km	191 km
Summer	3.3 km	9.9 km	21 km	55 km

Table 6.4: Audibility ranges for *DN43* as a function of background noise level at the north breakwater site

6.5 Piling noise

Figure 6.9 shows contoured SPL for impact piling noise generated during the month of February where the sound source is located at the seabed. The sound tends to be refracted up towards the sea surface where it is likely to propagate to long range. Sound levels generally fall with increasing range: at 1 km the SPL is around 180 dB re 1 µPa, at 2 km it is around 170 dB and the 160 dB level is reached around 8 km.

By August, the change in sound speed profile has resulted in a marked change in structure appearing in the underwater sound field. Figure 6.10 shows that the sound is directed towards the seabed where it tends to remain. At a range of 14 km, SPLs at the surface fall to 110 dB – around 30 dB down on what may be seen at the same location during winter.

Figures 6.11 and 6.12 show SPL computed using conditions relating to the north breakwater construction site. The shallower water around the noise source leads to lower SPLs at a given range and depth compared with those at the same location at the south site. For instance at the south site, Figure 6.9 shows that SPLs are as high as 160 dB at a range of 19 km while SPLs fall to this level by 13 km at the north site (Figure 6.11). The effect is more pronounced during the summer months where at the north site, surface SPLs remain below 110 dB from 11 km onwards (Figure 6.12).

Piling noise has the potential to remain above background noise levels for very considerable distances. If noise levels are as high as 130 dB re 1 μPa, piling noise is audible to distances of 69 km and 43 km during the winter and summer months respectively. If noise levels are lower than 130 dB re 1 μPa, the audibility ranges may extend to distances in excess of 100 km. In practice this is deemed very unlikely to arise as over such distances, the weather conditions are likely to vary considerably and this influences the environment over which the sound propagates. In regions of high wind and wave action, the disturbed sea surface has a significant dissipative effect with the result that piling noise levels will be greatly attenuated. Summaries of audibility ranges as a function of background noise levels at both construction sites are given in Tables 6.5 and 6.6.

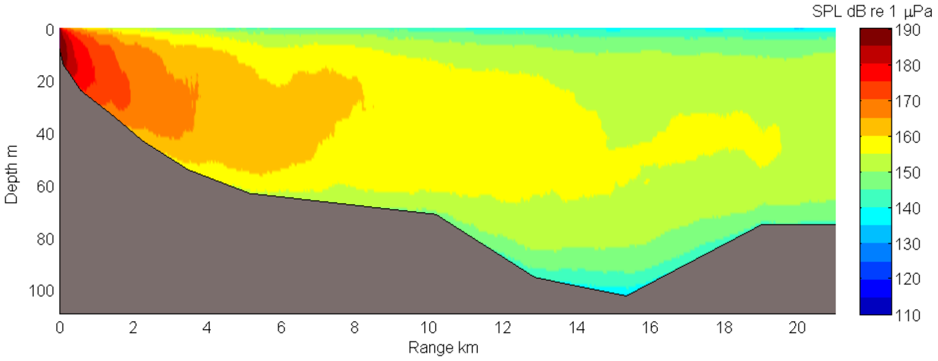

Figure 6.9: Contour plot of broadband SPL as a function of range and depth for piling noise computed along a bearing of 90° using February oceanographic conditions at the south breakwater construction site in Nigg Bay

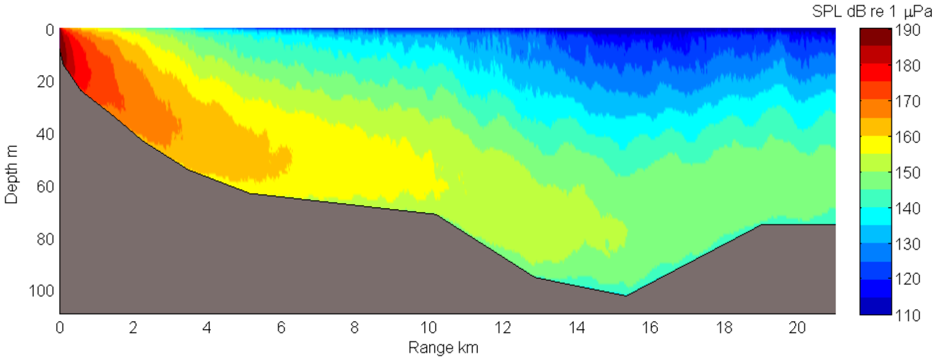

Figure 6.10: Contour plot of broadband SPL as a function of range and depth for piling noise computed along a bearing of 90° deg using August oceanographic conditions at the south breakwater construction site in Nigg Bay

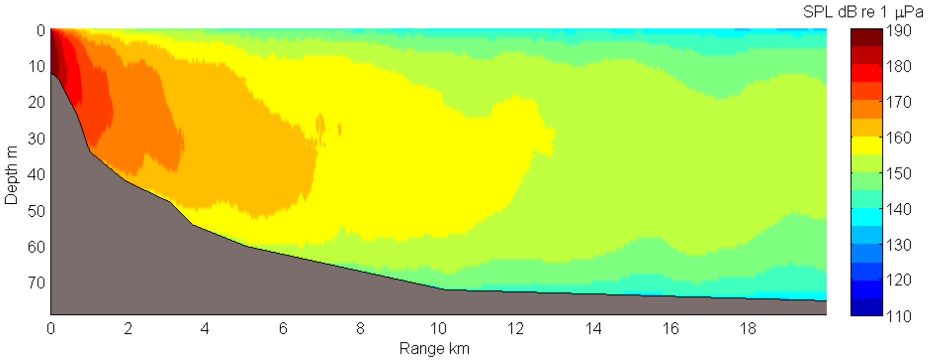

Figure 6.11: Contour plot of broadband SPL as a function of range and depth for piling noise computed along a bearing of 90° deg using February oceanographic conditions at the north breakwater construction site in Nigg Bay

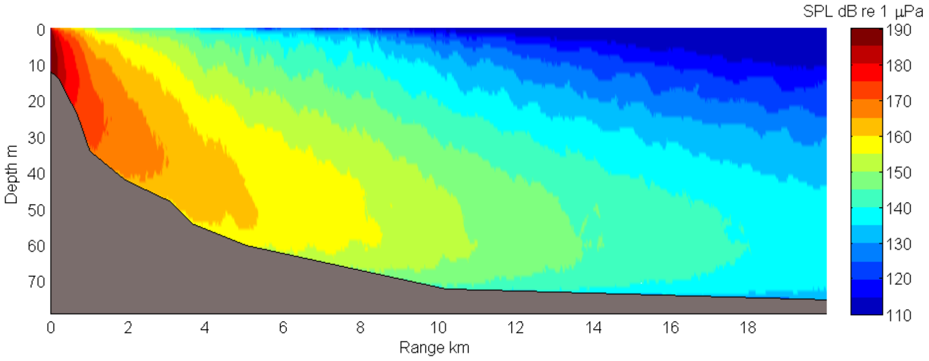

Figure 6.12: Contour plot of broadband SPL as a function of range and depth for piling noise computed along a bearing of 90° deg using August oceanographic conditions at the south breakwater construction site in Nigg Bay

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	69 km	89 km	109 km	128 km
Summer	43 km	55 km	68 km	80 km

Table 6.5: Audibility ranges for piling noise as a function of background noise level at the south breakwater site

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	56 km	73 km	89 km	105 km
Summer	38 km	49 km	60 km	70 km

Table 6.6: Audibility ranges for piling noise as a function of background noise level at the north breakwater site

6.6 Material disposal noise

Underwater noise levels associated with material disposal are so low that generally they fall into the background noise level at relatively short distances - of the order of metres or tens of metres at most. Over such short distances the influence of the environment on the propagation of underwater sound is negligible hence spherical spreading is deemed a valid approach to determining the attenuation of sound over distance. Accordingly, sound pressure levels as a function of range for material disposal was computed – the distances are so short as to be insensitive to environmental conditions and the results are shown in Figure 6.13 below.

The maximum range over which material disposal remains audible depends on the prevailing background noise levels. Section 5 provides guidance on noise levels that may be likely in the Aberdeen Harbour Expansion Project area and a range of values may be considered. When background noise levels are at their highest, around 130 dB re 1 μPa, it is likely that material disposal would be inaudible even at very close range. If background levels lie around 120 dB 1 μPa, the sound of material disposal may be heard out to a few metres. In the event that background noise levels are as low as 100 dB re 1 μPa, then material disposal noise remains audible out to around 35 m. A summary of audibility range as a function of background noise level is given in Table 6.7.

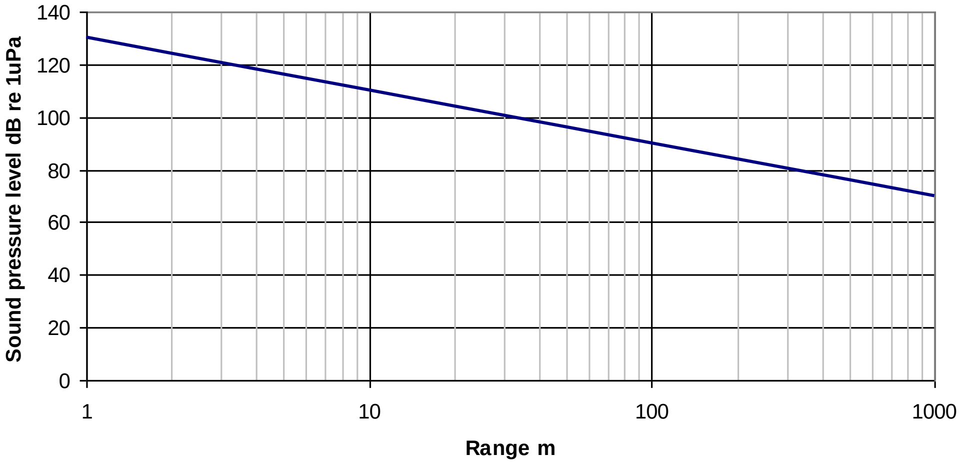

Figure 6.13: Predicted SPLs as a function of range for material disposal

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	< 1 m	3.5 m	15 m	35 m
Summer	< 1 m	3.5 m	15 m	35 m

Table 6.7: Audibility ranges for material disposal noise as a function of background noise level

6.7 Explosive blasting noise

By comparison with the previous noise types, the acoustic modelling undertaken to propagate explosive blasting noise is relatively rudimentary in that the environment is simplified to one of a water channel of constant depth overlying a basement rock.

The propagation of blast noise from explosive sources has been discussed in Section 5. Equations developed by Arons *et al*.**Error! Bookmark not defined.**, and Wright and Hopky[32] allow for the computation of both impulse and peak pressure from a confined explosion as a function of receptor depth and range. For a charge weight of 20 kg and a charge depth of 2.5 m the relationship between peak pressure and range may be modelled. The results are shown in Figure 6.14 where it will be seen that the peak pressure varies logarithmically with range.

Table 6.8 shows the distances at which explosive blasting noise reaches various background noise levels. It is seen that the ranges vary between 14.8 km and 127 km depending on the prevailing background conditions.

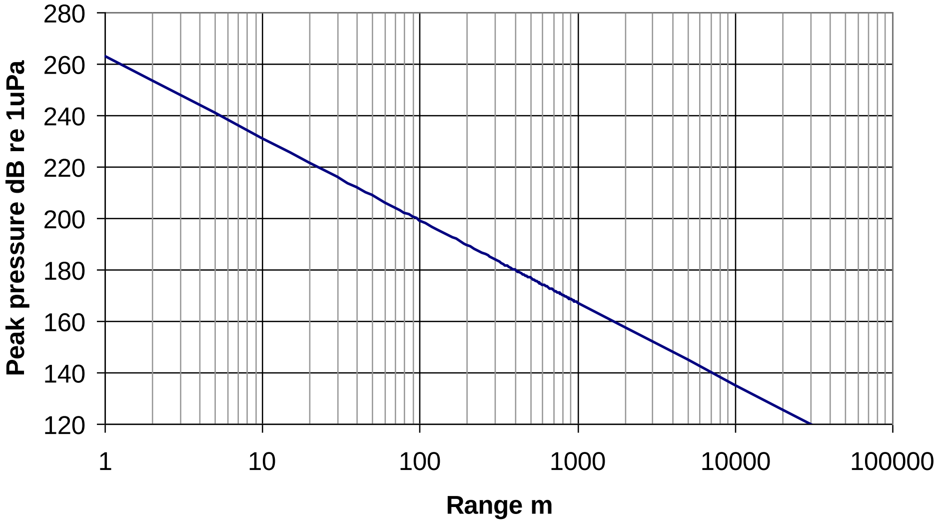

Figure 6.8: Explosive blast peak pressure from a confined detonation as a function of range

Background noise levels dB re 1 μPa			
130	**120**	**110**	**100**
14.8 km	30 km	62 km	127 km

Table 6.8: Audibility ranges for explosive blasting noise as a function of background noise level

6.8 Discussion

For each noise source, propagation modelling was carried out on a number of transects centred on each modelling point. Each transect had a different depth-range profile hence the ease to which sound propagated was different in each case. When the water depth decreased with increasing range, the sound pressure level at a given depth and range was lower than what was observed on transects where the water depth increased. The nature of the sound propagation arising using the bathymetry relating to Nigg Bay means that those transects that skirt the coastline (i.e. those on bearings of 0° to 40° and 160° to 200°) are likely to have the lower sound pressure levels at a given depth and range compared with those whose transects tend to head straight into deep water (i.e. those on bearings generally of 80° to 110°). Accordingly, and with respect to the Precautionary Principle *(q.v.)*, acoustic propagation data from the 90° transects is subsequently taken forward in order to determine the ranges at which lethality, physical injury, hearing damage and behavioural response may become apparent in various species of marine life.

7. ACOUSTIC IMPACT MODELLING RESULTS

7.1 Introduction

The levels of underwater noise generated by each of the Aberdeen Harbour Expansion Project construction activities are used here to estimate impact ranges for a number of target marine species such as cetaceans, pinnipeds and fish. The ranges at which each impact criterion is met may be determined from the acoustic propagation modelling techniques discussed in Sections 6 and 7.

For the purpose of the analysis contained in this report, it is assumed that detonation of the explosive charges occur in isolation of any other noise source. By contrast, the construction activities of dredging, piling, drilling and material disposal all occur as a result of a number of vessels working together in relatively close proximity to each other. The acoustic impact for each construction task is discussed in detail below.

7.2 Impact of explosive sources

The acoustic propagation modelling of blast noise described in Section 6 shows that the sound pressure level falls to the lethality threshold represented by the 240 dB re 1 μPa level (Section 4) at a range of approximately 5 m while the limiting range for Physical Injury in fish (given by the 220 dB re 1 μPa level) is reached at 23 m. The Level A-Auditory Injury thresholds for pinnipeds and cetaceans (given by the 190 dB re 1 μPa and 180 dB re 1 μPa levels) are met at ranges of 200 m and 820 m respectively.

Richardson *et al.*[15] comments that the defining experimental work of explosive blast on marine animals undertaken by Yelverton *et al*.[31] used impulse rather than peak pressure as a parameter. Using the techniques developed by Yelverton *et al.*[31] and discussed in Section 4, it is possible therefore to estimate limiting ranges at which fish and marine mammals may survive following exposure to explosive blast. A number of results are given in Tables 7.1 and 7.2 below. The range of body weights modelled encompass approximately the maximum body weights for each of the species discussed in Section 4.

Table 7.1 shows the limiting ranges at which fish of various body weights may survive explosive blast. For a fish of body weight 5 kg, the 50% mortality criterion lies at a range of 4 m while the No-injury impact range is 12 m. For mammals, using data in Table 7.2, the corresponding ranges are 6 m and 16 m. The modelled results indicate therefore that mammals are more sensitive than fish to the effects of explosive blast.

Based on the criteria for assessing the impact of exposure to explosive blast on fish and as summarised in Table 4.3, potential mortal injury may exist out to a distance of 12 m from the blast site.

	50% lethality			**1% lethality**			**No injury**		
Body weight kg	Impulse (Pa s)	Range (m)	Peak pressure (dB)	Impulse (Pa s)	Range (m)	Peak pressure (dB)	Impulse (Pa s)	Range (m)	Peak pressure (dB)
0.2	202.3	8	234.4	112.9	12	228.8	39.5	24	219.2
0.5	271.2	6	238.4	151.4	10	231.3	52.9	20	221.7
1	338.6	5	241.0	189.0	8	234.4	66.1	18	223.2
2	422.7	5	241.0	236.0	7	236.3	82.5	15	225.7
5	566.8	4	244.1	316.5	6	238.4	110.6	12	228.8
10	707.6	3	248.1	395.1	5	241.0	138.1	11	230.0
20	883.4	2	253.7	493.2	4	244.1	172.4	9	232.8
50	1184.5	2	253.7	661.3	3	248.1	231.2	7	236.3
100	1478.7	1	263.3	825.6	3	248.1	288.6	6	238.4

Table 7.1: Impact ranges for lethality and no injury criteria for fish

	50% lethality			**1% lethality**			**No injury**		
Body weight kg	Impulse (Pa s)	Range (m)	Peak pressure (dB)	Impulse (Pa s)	Range (m)	Peak pressure (dB)	Impulse (Pa s)	Range (m)	Peak pressure (dB)
5	278.9	6	238.4	176.0	9	232.8	73.8	16	224.8
10	364.3	5	241.0	230.0	7	236.3	96.4	14	226.6
20	476.0	4	244.1	300.5	6	238.4	125.9	11	230.0
50	677.8	3	248.1	427.9	4	244.1	179.3	9	232.8
80	812.5	3	248.1	512.9	4	244.1	214.9	8	234.4
100	885.6	2	253.7	559.0	4	244.1	234.2	7	236.3
150	1035.5	2	253.7	653.7	3	248.1	273.9	6	238.4
200	1157.0	2	253.7	730.4	3	248.1	306.0	6	238.4

Table 7.2: Impact ranges for lethality and no injury criteria for mammals

7.3 Discussion

A number of caveats must be applied to the blast modelling results.

Modelling the propagation of sound from explosive blast in open water is well developed: by comparison, that from confined detonations is rudimentary and there is relatively little data against which to compare results. Munday *et al.*[82] states that buried charges produce maximum pressures that are 2 orders of magnitude lower; and mean values for impulse that are 20-30 times lower than those predicted in each case for mid-water explosions. Comparisons of impact ranges calculated using open – water conditions (not presented here) generally support this statement.

No specific data is currently available on underwater noise levels from explosive blast in confined holes and from which more conservative ranges could be estimated. It is noted that blasting is also scheduled to take place onshore. It is possible that ground-based vibrations could propagate underwater. The potential impact of this, based on the modelling undertaken for mid-water based blast and taking into account the comments by Munday *et al*.[82], are deemed to be minimal.

The main criticism of the work carried out by Yelverton *et al.*[31] is that the test subjects themselves were all terrestrial (e.g. sheep, goats), of relatively small size - the effect

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[82] Munday D. R., G. L. Ennis, D. G. Wright, D. C. Jefferies, E. R. McGreer, J. S. Mathers, (1986), "Development and evaluation of a model to predict effects of buried underwater blasting charges on fish populations in shallow water areas", Can. Tech. Rept. Fish Aquat. Sci. 1418: x+49p.

of blast on animals greater than around 60 kg was not explored; and that only gross injuries evident *post-mortem* were considered. It is thought unlikely that this sort of work would ever be repeated or extended due to ethical constraints.

It is noted that the potential mortal injury range determined using the Popper *et al.*[37] criterion does not take into account the body weight of the fish. Further, it is somewhat longer than that determined using the No-Injury range based on the Yelverton *et al*.[37] criterion. The Popper *et al*.[37] criterion may therefore be considered precautionary.

7.4 Impact of non-explosive sources

7.4.1 Introduction - Non explosive sources

The following sections discuss the impact of sound generated during specific operations relating to the construction of the Aberdeen Harbour Expansion Project involving non-explosive sources of noise. The construction tasks are dredging, piling, drilling and material disposal and these activities are all undertaken by a number of vessels working together in relatively close proximity to each other. The impacts arise therefore as a result of exposure to multiple noise sources.

Multiple exposure may be considered in two ways. The first one occurs from multiple noise sources all operating in close proximity to one another and from which the individual noise footprints overlap. This may be referred to as an additive exposure. The second one arises when a receptor is exposed to an underwater noise for an extended period of time. This is often referred to as cumulative exposure. Both concepts are reviewed below. It is noted that acoustic impacts may only be assessed for multiple non-explosive noise sources. No data is available that supports the modelling of impacts from multiple explosive blasts.

7.4.2 Additive exposure

Additive acoustic impacts arise on a marine species when it is exposed to multiple sound sources operating concurrently. The acoustic propagation techniques discussed earlier are used to determine the size of the region over which sound from each source extends. When the separation of the individual noise sources is such that the acoustic footprints overlap, a receptor in the overlap region is susceptible to the sum of the noise fields. While individual noise sources may generate noise levels that are insufficient to meet a given threshold, the noise levels in the overlap region may meet or even exceed the threshold.

Additive exposure to the noise emitted during each of the construction activities and at three locations within Nigg Bay are discussed in detail below. The locations are:

1. Western end of Nigg Bay;
2. Close to the end of the southern breakwater; and
3. Close to the end of the northern breakwater

7.5 Nigg Bay – Head of the bay

7.5.1 Scenario 1 – Trailing suction hopper dredging

This scenario is concerned with trailing suction dredging in the shallow waters at the eastern end of Nigg Bay. For this task, it is assumed that a total of three vessels will be involved.

The trailing suction hopper dredger (TSHD) is assumed to be *TSHD Crestway* and this is to be accompanied by a survey vessel and a workboat which is used for personnel transfer and logistical support. The survey vessel monitors the dredged area around

150 m behind the dredger while the workboat remains around 250 m behind the dredger. A summary of the vessel spread is given in Table 7.3.

With regards to underwater acoustic signatures, none of the vessels involved in the TSH dredging activities have been noise-ranged. The indicative TSH dredger *Crestway* has a power output of approximately 6,700 kW. The nearest TSHD vessel for which noise data exists is *Taccola*[17] and this has a power output of 6,300 kW. It is assumed therefore that the noise levels used to model the impacts based on *Taccola* are likely to be close to those emitted by *Crestway*. As a result, any errors arising as a result of using the proxy noise source are expected to be minimal. Neither the survey vessel nor the workboat have been identified by name. For the acoustic analysis, the vessels *DN43* and *Pompei* have been selected as proxy noise sources[17]. *DN43* is a 335 GRT work vessel 28 m in length and 12.3 m in breadth while *Pompei* is a 1482 GRT barge of dimension 65 m x 16 m. Both vessels have been used in support of shallow water operations in the Sakhalin oil fields.

Project Vessel	**Task**	**No.**	**Length x breadth**	**Gross registered tonnage GRT**	**Power kW**	**Proxy source**
Crestway	Dredging	1	97.5 x 21.6	5,005	6,700	*Taccola*[17]
Unknown	Surveying the sea floor in front or behind the dredging vessel	1	Unknown			*DN43*[17]
Unknown	Logistical support	1	Unknown			*Pompei*[17]

Table 7.3: Summary of vessel spread for trailing suction hopper dredging operations

7.5.2 Impact modelling results

Lethality and injury range

The noise levels generated by the spread of vessels associated with the TSH dredging operations are insufficient to cause lethality (represented by the 240 dB re 1 μPa threshold) in fish or marine mammals even at close range. Noise levels generated by the vessel spread are insufficient to cause auditory injury (indicated by PTS) in cetaceans (represented by the 224 dB re 1 μPa threshold) or in pinnipeds (represented by the 218 dB re 1 μPa threshold). The no-injury limit for fish (given by a threshold of 206 dB re 1 μPa) is not met for TSH dredging involving the vessels included in the given spread. The conservative Level A-Injury criterion for PTS in pinnipeds (represented by the 190 dB re 1 μPa threshold) is met at 1.5 m while for PTS in cetaceans (represented by the 180 dB re 1 μPa threshold) is met at 4.5 m.

Hearing impairment range

Temporary deafness (indicated by TTS) is given by the PTS thresholds reduced by 6 dB. In this case, the noise levels generated by the TSHD vessel spread are insufficient to cause temporary deafness in either cetaceans or pinnipeds. The Lucke *et al.*[34] limit for TTS in harbour porpoises (199.7 dB re 1 μPa (Peak)) is not met.

Behavioural impact range

Aversive behaviour in harbour porpoises (given by the 174 dB re 1 μPa peak-peak threshold) may be seen at distances up to 23 m from any of the vessels involved in the spread. Only the Level B-Harassment criterion for exposure to continuous noise may be observed at significant distances from the vessel spread. The distance at which this criterion is met extends to 44.4 km in winter and 26.4 km during summer. The variation of impact ranges due to seasonal effects is seen to be minimal for all other impacts.

It is noted that the threshold for the Level B impact for continuous noise is set at 120 dB re 1 μPa while background noise levels may lie in the range 100 - 130 dB re 1 μPa (see Section 5). If the background noise levels tend towards the higher end of this range then they will exceed the threshold level for the given impact criterion: the noise levels will never fall as low as 120 dB re 1 μPa. As a result, the potential exists for any marine life found in the area for long periods of time to have become habituated to the prevailing high noise levels. The significance of the Level B - Harassment criterion in such an environment is therefore unclear. It must be emphasised however that the Level B-Harassment criterion relates to sound pressure levels which are not considered injurious to the animal (see Section 4). The use of such a criterion in an impact assessment may therefore be deemed especially precautionary given the expected high background noise from nearby vessel activity in Aberdeen harbour.

Due to the similarity in auditory characteristics, the impact criteria for otters are assumed to be the same as for pinnipeds although this approach may be deemed precautionary (see Section 4.2.4).

The ranges for each acoustic impact using unweighted metrics for the TSH dredging vessel spread are summarised in Table 7.4. A summary of audibility ranges of the TSHD vessel spread as a function of background noise levels is given in Table7.5.

Exposure limit	Effect	Winter	Summer
240 dB re 1 µPa pk	Lethality	<1 m	<1 m
224 dB re 1 µPa pk	Auditory injury (PTS) onset in cetaceans	<1 m	<1 m
218 dB re 1 µPa pk	Auditory injury (PTS) onset in pinnipeds	<1 m	<1 m
218 dB re 1 µPa pk	Temporary deafness (TTS) onset in cetaceans	<1 m	<1 m
212 dB re 1 µPa pk	Temporary deafness (TTS) onset in pinnipeds	<1 m	<1 m
206 dB re 1 µPa pk	Onset of injury in fish	<1 m	<1 m
199.7 dB re 1 µPa pk	Temporary deafness (TTS) onset in harbour porpoise	<1 m	<1 m
190 dB re 1 µPa (RMS)	Level A-Auditory injury in pinnipeds	1.5 m	1.5 m
180 dB re 1 µPa (RMS)	Level A-Auditory injury in cetaceans	4.5 m	4.5 m
174 dB re 1 µPa pk-pk	Aversive behavioural reaction in harbour porpoise	23 m	23 m
120 dB re 1 µPa (RMS)	Level B-Harassment in cetaceans exposed to continuous noise	44.4 km	26.4 km

Table 7.4: Summary of acoustic impacts for TSHD vessel spread

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	18.4 km	43 km	68 km	93 km
Summer	12.1 km	26 km	41 km	55 km

Table 7.5: Audibility ranges for TSHD vessel spread as a function of background noise level

7.5.3 Scenario 2 – Backhoe dredging

This vessel spread is associated with backhoe dredging. For this task, it is assumed that a total of five vessels will be involved.

The backhoe dredger (BHD) is assumed to be *BD Nordic Giant* and this is to be accompanied by a split hopper into which the seabed material is deposited. The split hopper does not have its own propulsion system so it will be towed by two tugs each of which are assumed to be 100 m fore and aft of *Nordic Giant*. *Nordic Giant* itself does not have its own propulsion system so two tugs are required to tow it into position as well. A survey vessel 250 m behind the dredger and a workboat around 150 m behind the dredger completes the vessel spread. A summary of the vessel spread is given in Table 7.6.

None of the indicative vessels in the spread have been noise-ranged so it is necessary to use proxy noise sources for modelling purposes. The acoustic signature has been derived from measurements of dredging noise carried out by *BHD New York.* From the limited information currently available it would appear that this is of similar overall dimension to *Nordic Giant* and has a broadly similar dredging capacity. It is assumed therefore that noise levels generated by the two backhoe dredgers will be broadly similar. The proxy noise source labelled Tug_4500 is based on measurements of noise made from a 6600 Brake Horse Power (BHP) tug and scaled according to an empirical model relating ship noise to speed, length and power[18]. The proxy noise sources for the remaining vessels in the spread are *DN43* and *Pompei* (see Section 3).

Project Vessel	**Task**	**No.**	**Length x breadth**	**Gross registered tonnage GRT**	**Power kW**	**Proxy source**
Nordic Giant	Dredging	1	55 x 17	1090	2085	*New York*[20]
Sand Carrier 101	Material transport	1	134 x 26		300	N/A
Unknown	Tug boat	2				*Tug_4500*[18]
Unknown	Surveying sea floor in front or behind the dredging vessel	1	Unknown			*DN43*[17]
Unknown	Logistical support	1	Unknown			*Pompei*[17]

Table 7.6: Summary of vessel spread for backhoe dredging operations

7.5.4 Impact modelling results

Lethality and injury range

The noise levels generated by the spread of vessels associated with the BH dredging operations are insufficient to cause lethality (represented by the 240 dB re 1 μPa threshold) in fish or marine mammals even at close range. Noise levels generated by the vessel spread are insufficient to cause auditory injury (indicated by PTS) in cetaceans (represented by the 224 dB re 1 μPa threshold) or in pinnipeds (represented by the 218 dB re 1 μPa threshold). The no-injury limit for fish (given by a threshold of 206 dB re 1 μPa[36]) is not met for BH dredging involving the vessels included in the given spread. The Level A-Injury criterion for PTS is met at 2.2 m for pinnipeds and at 24 m for cetaceans.

Hearing impairment range

Noise levels generated by the BD vessel spread are insufficient to cause temporary deafness in either cetaceans or pinnipeds. Similarly the Lucke *et al.*[34] limit for TTS in harbour porpoises is not met.

Behavioural impact range

Aversive behaviour in harbour porpoises may be seen at distances up to 390 m from any of the vessels involved in the spread. The Level B-Harassment criterion for exposure to continuous noise may be observed at significant distances from the vessel spread. The distance at which this criterion is met extends to 56.5 km in winter and 34 km during summer. The variation of impact ranges due to seasonal effects is seen to be minimal for all other impacts. The significance of the Harassment impact for continuous noise in an environment where background noise levels may exceed the impact threshold is unclear (see Section 7.5.2).

The ranges for each acoustic impact using unweighted metrics for the BH dredging vessel spread are summarised in Table 7.7. Audibility ranges for the BHD vessel spread as a function of background noise levels are summarised in Table 7.8.

Exposure limit	Effect	Winter	Summer
240 dB re 1 μPa pk	Lethality	<1 m	<1 m
224 dB re 1 μPa pk	Auditory injury (PTS) onset in cetaceans	<1 m	<1 m
218 dB re 1 μPa pk	Auditory injury (PTS) onset in pinnipeds	<1 m	<1 m
218 dB re 1 μPa pk	Temporary deafness (TTS) onset in cetaceans	<1 m	<1 m
212 dB re 1 μPa pk	Temporary deafness (TTS) onset in pinnipeds	<1 m	<1 m
206 dB re 1 μPa pk	Onset of injury in fish	<1 m	<1 m
199.7 dB re 1 μPa pk	Temporary deafness (TTS) onset in harbour porpoise	<1 m	<1 m
190 dB re 1 μPa (RMS)	Level A-Auditory injury in pinnipeds	2.2 m	2.2 m
180 dB re 1 μPa (RMS)	Level A-Auditory injury in cetaceans	24 m	24 m
174 dB re 1 μPa pk-pk	Aversive behavioural reaction in harbour porpoise	390 m	390 m
120 dB re 1 μPa (RMS)	Level B-Harassment in cetaceans exposed to continuous noise	56 km	34 km

Table 7.7: Summary of acoustic impacts for BH dredging vessel spread

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	31 km	56 km	81 km	106 km
Summer	19.7 km	34 km	48 km	62 km

Table 7.8: Audibility ranges for BHD vessel spread as a function of background noise level

7.6 Nigg Bay – Southern and Northern Breakwater

7.6.1 Scenario 1 – Trailing suction hopper dredging

The vessel spread associated with this operation is assumed to be the same as that deployed at the head of Nigg Bay – see Section 7.5.1.

7.6.2 Impact modelling results

Lethality and injury range

The noise levels generated by the spread of vessels associated with TSH dredging operations in relation to the southern breakwater are insufficient to cause lethality in fish or marine mammals even at close range. Similarly, noise levels generated by the vessel spread are insufficient to cause PTS in cetaceans or in pinnipeds. The no-injury limit for fish is not met for TSH dredging involving the vessels included in the given spread. The conservative Level A-Injury criterion for PTS in pinnipeds (represented by the 190 dB re 1 μPa threshold) is met at a maximum range of 5.3 m while for PTS in cetaceans (represented by the 180 dB re 1 μPa threshold) is met at 18 m.

Hearing impairment range

Noise levels generated by the TSHD vessel spread are unlikely to cause temporary deafness in either cetaceans or pinnipeds. Similarly the Lucke *et al.*[34] limit for TTS in harbour porpoises is not met.

Behavioural impact range

Aversive behaviour in harbour porpoises may be noted at a maximum range of 38 m from any of the vessels involved in the spread. The Level B-Harassment criterion for exposure to continuous noise may be observed at significantly longer distances from the vessel spread. The distance at which this criterion is met extends to 59.8 km in winter and 28.7 km during summer. The variation of impact ranges due to seasonal effects is seen to be minimal for all other impacts. If background noise levels are as high as 130 dB re 1 μPa then dredging noise falls in to the background at 39.3 km during winter and 27.2 km during summer. The significance of the Harassment impact for continuous noise in an environment where background noise levels may exceed the impact threshold is unclear (see Section 7.5.2).

The ranges for each acoustic impact using unweighted metrics for the BH dredging vessel spread are summarised in Table 7.9. Audibility ranges as a function of background noise level at both construction sites are given in Tables 7.10 and 7.11.

		Southern breakwater		**Northern breakwater**	
Exposure limit	**Effect**	**Winter**	**Summer**	**Winter**	**Summer**
240 dB re 1 μPa pk	Lethality	<1 m	<1 m	<1 m	<1 m
224 dB re 1 μPa pk	Auditory injury (PTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
218 dB re 1 μPa pk	Auditory injury (PTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
218 dB re 1 μPa pk	Temporary deafness (TTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
212 dB re 1 μPa pk	Temporary deafness (TTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
206 dB re 1 μPa pk	Onset of injury in fish	<1 m	<1 m	<1 m	<1 m
199.7 dB re 1 μPa pk	Temporary deafness (TTS) onset in harbour porpoise	<1 m	<1 m	<1 m	<1 m
190 dB re 1 μPa (RMS)	Level A-Auditory injury in pinnipeds	5.3 m	1.6 m	1.3 m	1.2 m
180 dB re 1 μPa (RMS)	Level A-Auditory injury in cetaceans	18 m	17 m	8 m	4 m
174 dB re 1 μPa pk-pk	Aversive behavioural reaction in harbour porpoise	38 m	33 m	100 m	100 m
120 dB re 1 μPa (RMS)	Level B-Harassment in cetaceans exposed to continuous noise	59 km	28 km	39 km	27.2 km

Table 7.9: Summary of acoustic impacts for TSH dredging vessel spread

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	34 km	59 km	84 km	109 km
Summer	16 km	28 km	41 km	53 km

Table 7.10: Audibility ranges for TSH dredging vessel spread as a function of background noise level at the south breakwater site

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	22 km	39 km	56 km	72 km
Summer	16 km	27 km	38 km	49 km

Table 7.11: Audibility ranges for TSH dredging vessel spread as a function of background noise level at the north breakwater site

7.6.3 Scenario 2 – Backhoe dredging

The vessel spread associated with this operation is assumed to be the same as that deployed at the head of Nigg Bay – see Section 7.5.3.

7.6.4 Impact modelling results

Lethality and injury range

The noise levels generated by the spread of vessels associated with BH dredging operations are insufficient to cause lethality in marine animals. Similarly, PTS in cetaceans and pinnipeds is unlikely to arise. The no-injury limit for fish is not met for BH dredging involving the vessels included in the given spread. The Level A-Injury criterion for PTS in pinnipeds is met at a maximum range of 2.9 m while for PTS in cetaceans is met at 82 m.

Hearing impairment range

Noise levels generated by the BH dredging vessel spread are unlikely to cause temporary deafness in either cetaceans or pinnipeds. Similarly, the Lucke *et al.*[34] limit for TTS in the harbour porpoise is not met.

Behavioural impact range

Aversive behavioural reactions in porpoise may be seen out to distances of 357 m from the vessel spread while Level B-Harassment reactions may be seen at distances of 58.6 km from the spread in winter and 36.7 km during summer. If background noise levels are as high as 130 dB re 1 μPa then dredging noise falls into the background at 47.7 km during winter and 32.9 km during the summer months. The significance of the Harassment impact for continuous noise in a high natural noise environment must be noted (see Section 7.5.2).

The ranges for each acoustic impact using unweighted metrics for the BH dredging vessel spread are summarised in Table 7.12. Audibility ranges for the noise emitted from the BHD Bessel spread as a function of background noise levels at both breakwater construction sites are given in Tables 7.13 and 7.14.

		Southern breakwater		**Northern breakwater**	
Exposure limit	**Effect**	**Winter**	**Summer**	**Winter**	**Summer**
240 dB re 1 µPa pk	Lethality	<1 m	<1 m	<1 m	<1 m
224 dB re 1 µPa pk	Auditory injury (PTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
218 dB re 1 µPa pk	Auditory injury (PTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
218 dB re 1 µPa pk	Temporary deafness (TTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
212 dB re 1 µPa pk	Temporary deafness (TTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
206 dB re 1 µPa pk	Onset of injury in fish	<1 m	<1 m	<1 m	<1 m
199.7 dB re 1 µPa pk	Temporary deafness (TTS) onset in harbour porpoise	<1 m	<1 m	<1 m	<1 m
190 dB re 1 µPa (RMS)	Level A-Auditory injury in pinnipeds	2.9 m	2.8 m	3.3 m	3.3 m
180 dB re 1 µPa (RMS)	Level A-Auditory injury in cetaceans	82 m	82 m	80 m	80 m
174 dB re 1 µPa pk-pk	Aversive behavioural reaction in harbour porpoise	357 m	357 m	340 m	340 m
120 dB re 1 µPa (RMS)	Level B-Harassment in cetaceans exposed to continuous noise	59 km	37 km	47 km	33 km

Table 7.12: Summary of acoustic impacts for BH dredging vessel spread

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	38 km	59 km	78 km	98 km
Summer	24 km	37 km	49 km	61 km

Table 7.13: Audibility ranges for BHD dredging vessel spread as a function of background noise level at the south breakwater site

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	31 km	47 km	64 km	81 km
Summer	22 km	33 km	44 km	55 km

Table 7.14: Audibility ranges for BHD dredging vessel spread as a function of background noise level at the north breakwater site

7.6.5 Scenario 3 – Drilling

This scenario is concerned with drilling the charge holes in the sea bed around the location of the southern and northern breakwaters. For this task, it is assumed that a total of three vessels will be involved.

Drilling will be undertaken by a jack-up platform with up to 3 drilling heads. It is assumed that this will be towed into position using a tug boat while a workboat will be on hand for personnel transfer and logistical support. A summary of the vessel spread is given in Table 7.15.

With regards to underwater acoustic signatures, none of the vessels involved in the drilling activities have been noise-ranged. Drilling noise is based on measurements made of activities undertaken by the jack-up barge *Mowjack*[6]. For the purpose of the acoustic analysis, the vessels *Tug_4500* and *Pompei* have been selected as proxy noise sources. Further details of these platforms are given in Section 3.

Project Vessel	**Task**	**No.**	**Length x breadth**	**Gross registered tonnage GRT**	**Power kW**	**Proxy source**
Drilling vessel	Drilling	1	Unknown			*Mowjack*[6]
Unknown	Tug boat	1	Unknown			*Tug_4500*[18]
Unknown	Logistical support	1	Unknown			*Pompei*[17]

Table 7.15: Summary of vessel spread for drilling operations

7.6.6 Impact modelling results

Lethality and injury range

The noise levels generated by the spread of vessels associated with drilling operations are insufficient to cause lethality in all species or, more specifically, PTS in cetaceans and pinnipeds. The no-injury limit for fish is not met for drilling involving the vessels included in the given spread. The Level A-Injury criterion for PTS is met at maximum ranges of 10 m and 21 m for pinnipeds and cetaceans respectively.

Hearing impairment range

Noise levels generated by the BH dredging vessel spread are unlikely to cause temporary deafness in either cetaceans or pinnipeds. Similarly, the Lucke *et al.*[34] limit for TTS in harbour porpoises will not be met.

Behavioural impact range

Aversive behavioural reactions in harbour porpoise may be noted at distances up to 52 m from any vessel in the spread. Level B-Harassment reactions may be seen at maximum distances of 46.2 km in winter and 30.3 km in summer. When background noise levels are as high as 130 dB re 1 μPa, the noise from the vessel spread associated with drilling may fall below the background level at a distance of 37 km in winter and 26 km in summer.

The ranges for each acoustic impact using unweighted metrics for the drilling vessel spread are summarised in Table 7.16. Audibility ranges as a function of background noise levels at both breakwater construction sites are given in Tables 7.17 and 7.18.

		Southern breakwater		**Northern breakwater**	
Exposure limit	**Effect**	**Winter**	**Summer**	**Winter**	**Summer**
240 dB re 1 μPa pk	Lethality	<1 m	<1 m	<1 m	<1 m
224 dB re 1 μPa pk	Auditory injury (PTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
218 dB re 1 μPa pk	Auditory injury (PTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
218 dB re 1 μPa pk	Temporary deafness (TTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
212 dB re 1 μPa pk	Temporary deafness (TTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
206 dB re 1 μPa pk	Onset of injury in fish	<1 m	<1 m	<1 m	<1 m
199.7 dB re 1 μPa pk	Temporary deafness (TTS) onset in harbour porpoise	<1 m	<1 m	<1 m	<1 m
190 dB re 1 μPa (RMS)	Level A-Auditory injury in pinnipeds	10 m	10 m	3.6 m	3.6 m
180 dB re 1 μPa (RMS)	Level A-Auditory injury in cetaceans	21 m	21 m	25 m	25 m
174 dB re 1 μPa pk-pk	Aversive behavioural reaction in harbour porpoise	52 m	52 m	50 m	50 m
120 dB re 1 μPa (RMS)	Level B-Harassment in cetaceans exposed to continuous noise	46 km	30 km	37 km	26 km

Table 7.16: Summary of acoustic impacts for drilling vessel spread

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	26 km	46 km	66 km	86 km
Summer	16.1 km	30 km	42 km	55 km

Table 7.15: Audibility ranges for the drilling vessel spread as a function of background noise level at the south breakwater site

	Background noise levels dB re 1 μPa			
Season	**130**	**120**	**110**	**100**
Winter	20 km	37 km	53 km	70 km
Summer	14.8 km	26 km	37 km	48 km

Table 7.16: Audibility ranges for the drilling vessel spread as a function of background noise level at the north breakwater site

7.6.7 Scenario 4 - Piling

This scenario is concerned with piling the deck supports into the seabed. For this task, it is assumed that a total of three vessels will be involved.

It is assumed that piling will be carried out from a piling barge. This is likely to be towed into position using a tug boat and a workboat will be on hand for personnel transfer and logistical support. A summary of the vessel spread is given in Table 7.17.

For the purpose of the acoustic impact analysis, a number of proxy noise sources have been selected. Piling noise is based on an analysis of underwater noise measurements made of activities undertaken on various project in Northern California[9]. Details of the vessels *Tug_4500* and *Pompei* are given in Section 3.

Project Vessel	**Task**	**No.**	**Length x breadth**	**Gross registered tonnage GRT**	**Power kW**	**Proxy source**
Unknown	Piling barge	1	Unknown			*Pile noise*
Unknown	Tug boat	1	Unknown			*Tug_4500*[18]
Unknown	Logistical support	1	Unknown			*Pompei*[17]

Table 7.17: Summary of vessel spread for piling operations

7.6.8 Impact modelling results

Lethality and injury range

Overall noise levels generated by the spread of vessels associated with piling operations are strongly influenced by the noise from the impact piling task. Even so, noise levels are insufficient to cause lethality in all species or, more specifically, potential mortal injury in fish, recoverable injury in fish and PTS in cetaceans and pinnipeds. The no-injury limit for fish is met at a range of 1.5 m from the vessels included in the given spread. The Level A-Injury criterion for PTS is met at maximum ranges of 246 m and 651 m for pinnipeds and cetaceans respectively.

Hearing impairment range

Noise levels generated by the piling vessel spread are insufficient to cause temporary deafness in either cetaceans or pinnipeds. By contrast, the Lucke *et al.*[34] limit for TTS in harbour porpoises is met at a distance of 3.2 m.

Behavioural impact range

The maximum range over which aversive behavioural reactions may be seen in harbour porpoise extends to 1344 m. There is a small seasonal variation associated with this impact with the longer range being likely during the winter months. Level B-Harassment for exposure to impulsive noise occurs at a threshold of 160 dB re 1 μPa compared with 120 dB re 1 μPa for continuous noise. For piling noise, this is met at a maximum distance of 10.5 km. Low level disturbance reactions given by the 140 dB re 1 μPa threshold may be seen at a maximum range of 49.2 km from the vessel spread. The higher overall noise levels associated with the piling vessel spread mean that the sound has to propagate much further before it falls into the background. For background noise levels of 130 dB re 1 μPa and 120 dB re 1 μPa then, during the winter months, the inaudibility range lies at 69.2 km and 89.2 km respectively. During summer the corresponding ranges are 43.2 km and 55.7 km.

The ranges for each acoustic impact using unweighted metrics for the piling vessel spread are summarised in Table 7.18. Audibility ranges for piling noise as a function of background noise level at the south and north breakwater construction sites are given in Tables 7.19 and 7.20 respectively.

		Southern breakwater		Northern breakwater	
Exposure limit	**Effect**	**Winter**	**Summer**	**Winter**	**Summer**
240 dB re 1 µPa pk	Lethality	<1 m	<1 m	<1 m	<1 m
224 dB re 1 µPa pk	Auditory injury (PTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
218 dB re 1 µPa pk	Auditory injury (PTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
218 dB re 1 µPa pk	Temporary deafness (TTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
213 dB re 1 µPa pk	Potential mortal injury in fish with low hearing sensitivity	<1 m	<1 m	<1 m	<1 m
213 dB re 1 µPa pk	Recoverable injury in fish with low hearing sensitivity	<1 m	<1 m	<1 m	<1 m
212 dB re 1 µPa pk	Temporary deafness (TTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
207 dB re 1 µPa pk	Potential mortal injury in fish with medium hearing sensitivity	<1 m	<1 m	<1 m	<1 m
207 dB re 1 µPa pk	Potential mortal injury in fish with high hearing sensitivity	<1 m	<1 m	<1 m	<1 m
207 dB re 1 µPa pk	Potential mortal injury in fish eggs and larvae	<1 m	<1 m	<1 m	<1 m
207 dB re 1 µPa Peak	Recoverable injury in fish with medium hearing sensitivity	<1 m	<1 m	<1 m	<1 m
207 dB re 1 µPa Peak	Recoverable injury in fish with high hearing sensitivity	<1 m	<1 m	<1 m	<1 m
206 dB re 1 µPa pk	Onset of injury in fish	1.5 m	1.5 m	1.5 m	1.5 m
199.7 dB re 1 µPa pk	Temporary deafness (TTS) onset in harbour porpoise	3.2 m	3.2 m	3.2 m	3.2 m
190 dB re 1 µPa (RMS)	Level A-Auditory injury in pinnipeds	246 m	242 m	244 m	236 m
180 dB re 1 µPa (RMS)	Level A-Auditory injury in cetaceans	651 m	609 m	600 m	560 m
174 dB re 1 µPa pk-pk	Aversive behavioural reaction in harbour porpoise	1344 m	1239 m	1220 m	1060 m
160 dB re 1 µPa (RMS)	Level B-Harassment in cetaceans exposed to impulsive noise	10.5 km	7.3 km	8.2 km	6.0 km
140 dB re 1 µPa (RMS)	Low level disturbance in cetaceans exposed to impulsive noise	49.2 km	30.7 km	40 km	27 km

Table 7.18: Summary of acoustic impacts for piling vessel spread

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	69 km	89 km	109 km	129 km
Summer	43 km	55 km	68 km	80 km

Table 7.19: Audibility ranges for the piling vessel spread as a function of background noise level at the south breakwater site

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	56 km	73 km	89 km	106 km
Summer	38 km	49 km	60 km	71 km

Table 7.20: Audibility ranges for the piling vessel spread as a function of background noise level at the north breakwater site

7.6.9 Scenario 5 – Seabed material disposal

This scenario is concerned with disposing of the seabed material either at an offshore disposal site or else using the material to act as landfill at various locations within Nigg Bay. For this task, it is assumed that up to five vessels could be involved.

Disposal of the material is likely to take place from a hopper barge. As these are unlikely to have their own propulsion system, they need to be towed by up to three tug boats. It is assumed that two tug boats 100 m in front of the hopper barge and one tug 100 m behind. In addition, a survey vessel and a workboat will provide support. For the purpose of the acoustic impact analysis, it is assumed that these two lie some 150 m off the hopper barge. A summary of the vessel spread is given in Table 7.21.

With regards to underwater acoustic signatures, Section 3 notes that seabed material disposal in itself is a low noise activity. However when disposal involves a number of vessels, then the noise form the resulting spread becomes significant. In this case, the tug boats are based on the vessels identified as *Tug_4500* and while the workboats are based on *Pompei*. Further details of these platforms are given in Section 3.

Project Vessel	Task	No.	Length x breadth	Gross registered tonnage GRT	Power kW	Proxy source
Unknown	Hopper barge for holding seabed material	1	Unknown	Unknown	Unknown	*N/A*
Unknown	Tug boat	3	Unknown	Unknown	Unknown	*Tug_4500*[18]
Unknown	Logistical support	2	Unknown	Unknown	Unknown	*Pompei*[17]

Table 7.21: Summary of vessel spread for seabed material disposal operations

7.6.10 Impact modelling results

Lethality and injury range

The noise levels generated by the spread of vessels associated with disposal operations are insufficient to cause lethality in marine animals or PTS in cetaceans and pinnipeds. The no-injury limit for fish is not met during disposal operations involving the vessels included in the given spread. The Level A-Injury criterion for PTS in pinnipeds may be met at a range of 18 m from the vessel spread while for PTS in cetaceans it is met at 234 m.

Hearing impairment range

Noise levels generated by the disposal vessel spread are insufficient to cause temporary deafness in either cetaceans or pinnipeds. The Lucke *et al.*[34] limit for TTS in harbour porpoise is met at 2 m from the vessel spread.

Behavioural impact range

The harbour porpoise may show signs of aversive behaviour at a maximum range of 462 m when exposed to disposal noise from the given vessel spread. There is a small seasonal variation associated with this impact with the range during the summer months being 30 m shorter. The Level B-Harassment reactions may be seen out to 62.5 km from the vessel spread during winter reducing to 40 km during summer. If noise levels are as high as 130 dB re 1 μPa then disposal noise become inaudible at 51.3 km during winter and 27.5 km during summer.

The ranges for each acoustic impact for the seabed material disposal vessel spread are summarised in Table 7.22. Audibility ranges for the noise emitted by the vessel spread as a function of background noise level at each construction site are summarised in Tables 7.23 and 7.24.

		South breakwater		North breakwater	
Exposure limit	**Effect**	**Winter**	**Summer**	**Winter**	**Summer**
240 dB re 1 µPa pk	Lethality	<1 m	<1 m	<1 m	<1 m
224 dB re 1 µPa pk	Auditory injury (PTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
218 dB re 1 µPa pk	Auditory injury (PTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
218 dB re 1 µPa pk	Temporary deafness (TTS) onset in cetaceans	<1 m	<1 m	<1 m	<1 m
212 dB re 1 µPa pk	Temporary deafness (TTS) onset in pinnipeds	<1 m	<1 m	<1 m	<1 m
206 dB re 1 µPa pk	Onset of injury in fish	<1 m	<1 m	<1 m	<1 m
199.7 dB re 1 µPa pk	Temporary deafness (TTS) onset in harbour porpoise	1.8 m	1.8 m	1.8 m	1.8 m
190 dB re 1 µPa (RMS)	Level A-Auditory injury in pinnipeds	17 m	17 m	17 m	17 m
180 dB re 1 µPa (RMS)	Level A-Auditory injury in cetaceans	234 m	122 m	234 m	239 m
174 dB re 1 µPa pk-pk	Aversive behavioural reaction in harbour porpoise	462 m	432 m	441 m	441 m
120 dB re 1 µPa (RMS)	Level B-Harassment in cetaceans exposed to continuous noise	62 km	40 km	51 km	35 km

Table 7.22: Summary of acoustic impacts for seabed material disposal vessel spread

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	43 km	62 km	82 km	102 km
Summer	27 km	40 km	52 km	65 km

Table 7.23: Audibility ranges for the material disposal vessel spread as a function of background noise level at the south breakwater site

	Background noise levels dB re 1 µPa			
Season	**130**	**120**	**110**	**100**
Winter	34 km	51 km	67 km	84 km
Summer	24 km	35 km	46 km	57 km

Table 7.24: Audibility ranges for the material disposal vessel spread as a function of background noise level at the north breakwater site

7.6.11 Scenario 6 – Material movements

This scenario is concerned with transporting building materials and equipment to the Aberdeen Harbour Expansion Project site by sea rather than by land.

The spread of vessels likely for this activity is considered to be the same as those for the seabed material disposal task *viz*. one hopper barge, three tugs and one additional vessel providing logistical support.

7.6.12 Impact modelling results

The ranges at which each impact criterion is met are the same as those for the seabed material disposal scenario. Accordingly, the ranges for each acoustic impact for the material movements vessel spread are summarised in Table 7.22 and the audibility ranges given differing levels of background noise are given in Tables 7.23 and 7.24..

7.6.13 Discussion of results

The results indicate that none of the construction activities dredging, drilling, piling, material disposal or material movements are likely to cause lethality (represented by the 240 dB re 1 μPa threshold), potential mortal injury in fish (given by a range of thresholds from 229 dB re 1 μPa to 207 dB re 1 μPa depending on fish hearing sensitivity), auditory injury in cetaceans (indicated by the 224 dB re 1 μPa threshold) or auditory injury in pinnipeds (given by the 218 dB re 1 μPa threshold). Neither temporary deafness in cetaceans and pinnipeds (represented by the 218 dB re 1 μPa and 212 dB re 1 μPa thresholds) nor recoverable injury in fish (given by thresholds from 213 dB re 1 μPa to 207 dB re 1 μPa depending on auditory sensitivity) are likely to arise. With the exception of the piling vessel spread, no other construction activity generates noise levels that are likely to lead to the onset of injury in fish (given by the 206 dB re 1 μPa threshold). Similarly only piling is likely to generate noise levels high enough to cause temporary deafness in harbour porpoise (given by the 199.7 dB re 1 μPa threshold). For all activities other than piling, the auditory injury criteria for pinnipeds and cetaceans (given by the 190 dB re 1 μPa and 180 dB re 1 μPa thresholds respectively) do not exceed a maximum distance of 82 m while aversive behaviour in harbour porpoise may be noted at a maximum distance of 390 m. For piling, the corresponding ranges are 650 m and 1344 m.

It is noted that with the exception of the Level B-Harassment impact, the criteria are generally short range and therefore in the immediate vicinity of the given vessel spread. Whether the Level B-Harassment criterion is relevant however depends largely on prevailing background noise levels. If the background level is as high as 130 dB 1 μPa, then the vessel spread noise slips into the background at distances varying between 12 km and 69 km depending on the season and vessel spread considered. The significance of the Harassment impact for vessel spread noise in an environment where background noise levels may exceed the impact threshold is unclear (see Section 7.5.2). When the background noise levels drop as low as 100 dB re 1 μPa, the vessel spread noise may become audible out to 129 km.

If the breakwaters are built before either dredging operations take place then the breakwater walls will tend to reflect the vessel spread noise back into the bay. The result of this is that the region of the North Sea beyond Nigg Bay will not be subsequently impacted by man-made noise and the Level B-Harassment criterion will no longer apply.

In the event that the actual noise levels from each of the platforms are greater than those assumed then the ranges to any given impact may be greater than those indicated above. Until such time as the vessels and platforms have been noise-ranged then any errors arising as a result of this approach are unquantifiable.

7.7 Cumulative Exposure

7.7.1 Introduction

Acoustic impacts may also occur when an animal is exposed to a sound which, in itself, may not be sufficiently loud to give rise to either permanent or temporary deafness or to induce a behavioural reaction but which will do so when exposure to the sound is allowed to build up over a period of time. Southall *et al.*[2] provides the metric of sound exposure level (SEL) in order to quantify this impact and M-weighted thresholds for this are given in Tables 4.4 and 4.5 for fish, cetaceans and pinnipeds.

The cumulative build-up of noise is explored using a fleeing–animal model[83] where the animal moves around through the noise field at various distances from the noise source and over a period of time. For each noise source – animal separation, the corresponding sound pressure level is computed. The SEL or the cumulative sound pressure level as a function of time is compared with threshold levels given in Tables 4.4 and 4.5 at which various acoustic impacts are met.

7.7.2 Noise source - animal scenarios

The cumulative dose on an animal is dependent not only on its audiological sensitivity to the noise but also on its proximity and duration of exposure to a sound source. Any result arising from a given noise - animal scenario therefore is unique to that specific model scenario only. Nevertheless the modelling results provide some insight into the build up of acoustic exposure level and the time thus required to meet a specific threshold level.

For the noise – animal scenarios considered, it is assumed that the noise source is stationary at the construction site within Nigg Bay and an animal swims from a given start location within Nigg Bay on a constant bearing of 90° and at a constant speed of 1.5 m/s.

As the animal moves through the acoustic field, it experiences an instantaneous SPL and also an SEL both of which vary over time. This relationship is illustrated in Figure 7.1 for each of three typical paths a, b, and c over which the animal travels for a total exposure duration of 600 seconds. The three paths each represent a different start location with Path a being the furthest from the noise source and Path c being the nearest. It will be seen that for Paths b and c, the SEL exceeds the 160 dB re 1 μPa^2 s level.

The scenario was run many times each with a different start location, for each animal grouping, and for the construction activities involving each vessel spread. The maximum SEL was noted for each start location and the results are compiled in Tables 7.15 through to 7.21. Due to the proximity and similarity of the two sites, the results from the south and north breakwaters are presented together but separately from those for the head of Nigg Bay. It is noted that there are two different threshold levels representing the onset of TTS for harbour porpoise – the 195 dB re 1 μPa^2 s threshold is derived from the M-weighting criteria developed by Southall *et al*.[2] while the more conservative 164.3 dB re 1 μPa^2 s threshold comes from the work of Lucke *et al*.[34] where it was observed that the harbour porpoise appeared more sensitive to man-made noise than originally indicated.

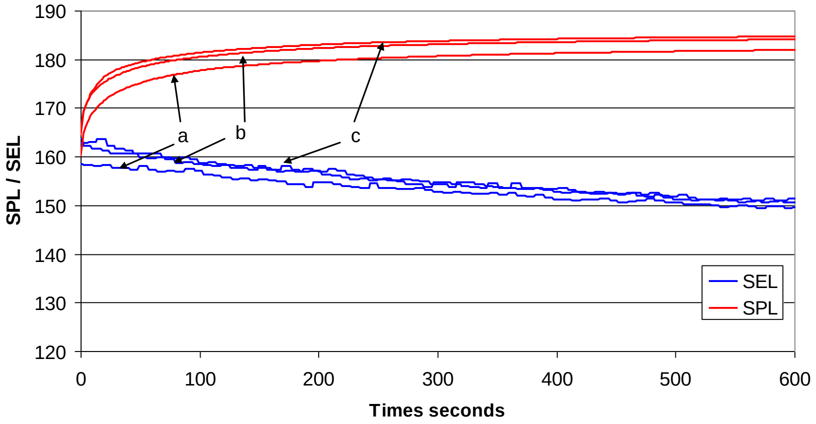

Figure 7.1: Typical instantaneous SPL and cumulative SEL for a 600 second exposure duration

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[83] Theobald P., Lepper P., Robinson S., Hazelwood D., (2009), "Cumulative Noise Exposure Assessment For Marine Mammals Using Sound Exposure Level As A Metric", UAM Conference Proceedings 2009.

7.7.3 Impact modelling results

Table 7.15 shows that Hf cetaceans (see Section 4) will meet the audiological injury (PTS) impact criterion (represented by the 215 dB re 1 μPa^2 s threshold) if the animal commences swimming from the backhoe dredging vessel spread at a distance of 20 m or less. In order to avoid TTS, the same animal must get no closer than 350 m from the vessel spread. Fish of body weight greater than 2 g must get no closer than 680 m to the vessel spread in order to avoid meeting the no-injury impact criterion while smaller fish, i.e. less than 2 g body weight, must get no closer than 1150 m. Based on the Lucke *et al.* criterion[34], harbour porpoise are significantly more sensitive to noise from the vessel spread. In order to avoid the thresholds for TTS and aversive behaviour, they must remain further than 10 km from the vessel spread.

In order to avoid a given impact, each target species must remain further away from the backhoe dredging spread than from the TSHD vessel spread (*cf*. Tables 7.15 and 7.16 or Tables 7.17 and 7.18).

When the animals are exposed to the noise emitted by the vessel spread for drilling, the initial start ranges are 210 m for all the cetacean groupings (see Tables 7.19 and 7.20). However, when the animals are exposed to material disposal noise (and material movements noise – see Section 3.9), the initial start ranges increase from 300 m for Hf cetaceans through 320 m for Mf cetaceans to 490 m for Lf cetaceans. This indicates that Lf cetaceans are more sensitive to the low frequency noise emitted by the vessels likely to form part of the spread for this activity.

When animals are exposed to the noise arising from the piling vessel spread, the initial start ranges shown in Table 7.21, are the longest of all the scenarios modelled. In order to avoid TTS, Hf cetaceans must get no closer to the spread than 2500 m while the corresponding ranges for Mf and Lf cetaceans are 3150 m and 5610 m respectively. As noted above, these data indicate that the noise emitted by the piling vessel spread is more likely to impact on Lf cetaceans than Mf and Hf cetaceans due to their increased sensitivity to the low frequency acoustic energy emitted by this spread.

Additional criteria may be used to assess the impact of piling noise on fish. Potential mortal injury (PMI) and recoverable injury (RI) are all relatively short range impacts varying between 90 m and 200 m depending on fish auditory sensitivity and season. For fish having low, medium and high auditory sensitivities, temporary hearing damage indicated by the TTS impact criterion, may occur at a maximum range of 3110 m. The maximum no-injury limit varies between 2560 m and 5630 m depending on the body weight of the fish considered.

In general, for the longer range impacts it is noted that there is some seasonal variation with the longer ranges occurring during the winter months.

7.7.4 Impact ranges - Head of Nigg Bay

Species	Impact	Threshold dB re 1 μPa^2 s	Feb	Aug
Hf cetaceans	PTS	215	20 m	20 m
	TTS	195	350 m	350 m
Mf cetaceans	PTS	215	20 m	20 m
	TTS	195	350 m	350 m
Lf cetaceans	PTS	215	20 m	20 m
	TTS	195	350 m	350 m
Pn pinniped	PTS	203	270 m	260 m
	TTS	183	1040 m	950 m

Fish >2g	No-injury	187	680 m	610 m
Fish <2g	No-injury	183	1150 m	1080 m
Harbour porpoise	TTS	164.3	> 10 km	> 10 km
	Aversive	145	> 10 km	> 10 km

Table 7.15: Summary of cumulative acoustic impacts for backhoe dredging vessel spread

Species	**Impact**	**Threshold dB re 1 μPa^2 s**	**Feb**	**Aug**
Hf cetaceans	PTS	215	20 m	20 m
	TTS	195	230 m	230 m
Mf cetaceans	PTS	215	20 m	20 m
	TTS	195	230 m	230 m
Lf cetaceans	PTS	215	20 m	20 m
	TTS	195	230 m	230 m
Pn pinniped	PTS	203	150 m	150 m
	TTS	183	480 m	410 m
Fish >2g	No-injury	187	300 m	270 m
Fish <2g	No-injury	183	530 m	440 m
Harbour porpoise	TTS	164.3	8730 m	6500 m
	Aversive	145	> 10 km	> 10 km

Table 7.16: Summary of cumulative acoustic impacts for TSH dredging vessel spread

7.7.5 Impact ranges – South and North breakwater

Species	Impact	Threshold dB re 1 μPa^2 s	South breakwater		North breakwater	
			Feb	**Aug**	**Feb**	**Aug**
Hf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	320 m	320 m	300 m	300 m
Mf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	320 m	320 m	300 m	300 m
Lf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	340 m	330 m	310 m	300 m
Pn pinniped	PTS	203	240 m	240 m	220 m	220 m
	TTS	183	1840 m	1820 m	1400 m	1370 m
Fish >2g	No-injury	187	1340 m	1280 m	1000 m	960 m
Fish <2g	No-injury	183	2460 m	2430 m	2060 m	1910 m
Harbour porpoise	TTS	164.3	>10 km	>10 km	>10 km	>10 km
	Aversive	145	>10 km	>10 km	>10 km	>10 km

Table 7.17: Summary of cumulative acoustic impacts for backhoe dredging vessel spread

Species	Impact	Threshold dB re 1 μPa^2 s	South breakwater		North breakwater	
			Feb	**Aug**	**Feb**	**Aug**
Hf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	230 m	230 m	220 m	220 m
Mf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	230 m	230 m	220 m	220 m
Lf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	230 m	230 m	220 m	220 m
Pn pinniped	PTS	203	150 m	150 m	140 m	140 m
	TTS	183	730 m	670 m	540 m	500 m
Fish >2g	No-injury	187	440 m	400 m	370 m	340 m
Fish <2g	No-injury	183	930 m	850 m	700 m	650 m
Harbour porpoise	TTS	164.3	>10 km	>10 km	>10 km	8760m
	Aversive	145	>10 km	>10 km	>10 km	>10 km

Table 7.18: Summary of cumulative acoustic impacts for TSH dredging vessel spread

Species	**Impact**	**Threshold dB re 1 μPa^2 s**	**South breakwater**		**North breakwater**	
			Feb	**Aug**	**Feb**	**Aug**
Hf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	210 m	210 m	200 m	200 m
Mf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	210 m	210 m	200 m	200 m
Lf cetaceans	PTS	215	20 m	20 m	20 m	20 m
	TTS	195	210 m	210 m	200 m	200 m
Pn pinniped	PTS	203	210 m	210 m	200 m	200 m
	TTS	183	580 m	560 m	450 m	430 m
Fish >2g	No-injury	187	420 m	400 m	380 m	350 m
Fish <2g	No-injury	183	870 m	830 m	690 m	660 m
Harbour porpoise	TTS	164.3	>10 km	>10 km	>10 km	8670m
	Aversive	145	>10 km	>10 km	>10 km	>10 km

Table 7.19: Summary of cumulative acoustic impacts for drilling vessel spread

Species	**Impact**	**Threshold dB re 1 μPa^2 s**	**South breakwater**		**North breakwater**	
			Feb	**Aug**	**Feb**	**Aug**
Hf cetaceans	PTS	215	280 m	280 m	270 m	270 m
	TTS	195	300 m	300 m	280 m	280 m
Mf cetaceans	PTS	215	280 m	280 m	270 m	270 m
	TTS	195	320 m	310 m	290 m	290 m
Lf cetaceans	PTS	215	280 m	280 m	270 m	270 m
	TTS	195	490 m	450 m	440 m	410 m
Pn pinniped	PTS	203	300 m	300 m	280 m	280 m
	TTS	183	2550 m	2540 m	2120 m	2070 m
Fish >2g	No-injury	187	1830 m	1790 m	1530 m	1490 m
Fish <2g	No-injury	183	3390 m	3180 m	2940 m	2740 m
Harbour porpoise	TTS	164.3	>10 km	>10 km	>10 km	>10 km
	Aversive	145	>10 km	>10 km	>10 km	>10 km

Table 7.20: Summary of cumulative acoustic impacts for seabed material disposal vessel spread

Species	**Impact**	**Threshold dB re 1 μPa^2 s**	**South breakwater**		**North breakwater**	
			Feb	**Aug**	**Feb**	**Aug**
Hf cetaceans	PTS	198	210 m	210 m	200 m	200 m
	TTS	183	2500 m	2360 m	2030 m	1880 m
Mf cetaceans	PTS	198	210 m	210 m	200 m	200 m
	TTS	183	3150 m	2810 m	2590 m	2260 m
Lf cetaceans	PTS	198	280 m	250 m	250 m	230 m
	TTS	183	5610 m	4080 m	4650 m	3510 m
Pn pinniped	PTS	186	2490 m	2180 m	2080 m	1800 m
	TTS	171	>10 km	>10 km	>10 km	9870 m
Harbour porpoise	TTS	164.3	>10 km	>10 km	>10 km	>10 km
	Aversive	145	>10 km	>10 km	>10 km	>10 km
Fish – low sensitivity	PMI	219	90 m	90 m	90 m	90 m
	RI	216	100 m	100 m	100 m	100 m
Fish – medium sensitivity	PMI	210	110 m	110 m	100 m	100 m
	RI	203	200 m	200 m	190 m	190 m
Fish – high sensitivity	PMI	207	110 m	110 m	100 m	100 m
	RI	203	200 m	200 m	190 m	190 m
Fish eggs, larvae	PMI	210	110 m	110 m	100 m	100 m
Fish – all sensitivities	TTS	186	3110 m	2620 m	2670 m	2190 m
Fish >2g	No-injury	187	2560 m	2180 m	2190 m	1860 m
Fish <2g	No-injury	183	5630 m	4110 m	4680 m	3540 m

Table 7.21: Summary of cumulative acoustic impacts for piling vessel spread

8. SUMMARY AND CONCLUSIONS

This report provides an assessment of the impact on the environment of man-made underwater noise generated during the construction stages of the Aberdeen Harbour Expansion Project. The main sources of noise have been identified as dredging using both trailing suction hopper dredgers and backhoe dredgers; drilling, material disposal, piling and explosive blasting.

Specific data on the sound characteristics of each noise source does not exist. In order to be able to carry out the assessment, generic values of source levels and frequency spectra were obtained from the published literature and used as proxy data erring wherever possible, on the precautionary side so as not to under-estimate the resulting ranges over which each impact criterion is met.

The acoustic propagation modelling has been carried out using computer programmes based on rigorous mathematical models and peer-reviewed techniques combined with high temporal and spatial resolution site-specific data relating to the bathymetry, oceanography and geoacoustics of the Development area. Initial results indicated that the environment influence the propagation of sound. During the winter months, sound is directed towards the sea surface where it has the potential to propagate to considerable distance. By contrast, during the summer months, the downward refracting sound speed profile directs the sound into the seabed. The outcome is that sound pressure levels at a given range and depth tend to be lower in summer than in winter.

Acoustic impact modelling draws on blast impact modelling, M-weighting criteria for marine mammals and fish hearing sensitivity where relevant.

For blast impact modelling from confined detonations, the results are given in terms of the range at which a specific impact criterion is met as a function of animal body weight. Mortality may arise during blasting. In order to survive the blast from a 20 kg explosive charge, a fish of body weight 0.2 kg must be greater than 24 m from the detonation site. This distance falls to 11 m for a 10 kg fish. The results indicate that for the same body weight, a mammal is more sensitive to the impact of explosive blast. The more precautionary Level A-Auditory Injury criteria for pinnipeds and cetaceans are met at ranges of 200 m and 820 m respectively.

For each of the remaining activities e.g. dredging, drilling, piling and material disposal, it is assumed that a number of vessels are acting together in close proximity to one another. The acoustic footprint from the resulting vessel spread is compared with threshold levels known to give rise to various acoustic impacts.

The modelling results indicate that none of the activities are likely to give rise to either fatality or auditory damage indicated by PTS. The piling vessel spread generates the highest level of noise. The onset of TTS in harbour porpoise is nevertheless a short range impact occurring at 3 m from the piling site. Level A – Auditory injury criteria for pinnipeds and cetaceans are met at distances of 250 m and 650 m. The corresponding ranges for all other construction activities are much lower. Aversive behavioural reactions in harbour porpoise may be noted at distance of 1.3 km from the piling vessel spread but only 460 m for the material disposal vessel spread and 52 m for the drilling vessel spread.

It is noted that with the exception of the Level B-Harassment impact, the criteria are generally short range and therefore in the immediate vicinity of the given vessel spread. Whether the Level B-Harassment criterion is relevant however depends largely on prevailing background noise levels. If the background level is as high as 130 dB 1 μPa, then the vessel spread noise slips into the background at a distances varying between 12 km and 69 km depending on the season and vessel spread considered. The significance of the Harassment impact for vessel spread noise in an environment where background noise levels may exceed the impact threshold is unclear – the animals may have become habituated to the prevailing high noise levels.

When the breakwaters are built, these will tend to reflect vessel spread noise back into the bay. The result of this is that the region of the North Sea beyond Nigg Bay will not be subsequently impacted by man-made noise and the Level B-Harassment criterion will no longer apply.

The SEL metric was used to assess the impact of acoustic dose using a simple model involving an animal swimming through the sound field generated by each vessel spread. The maximum SEL experienced by an animal was determined as function of the distance at which the animal commenced moving away from the noise source. Using the M-weighted impact criteria proposed by Southall *et al.*[2], the modelling indicates the minimum distance at which an animal may attain before a given impact threshold is met. In order to avoid PTS, a harbour porpoise must get no closer than 20 m from either the dredging or piling vessel spreads. The minimum distance increases to 210 m and 280 m when exposed to piling and material disposal noise. Aversive behavioural reactions may be seen in the harbour porpoise at distances beyond 10 km when exposed to noise from any of the vessel spreads considered.

In the event that the actual noise levels from each of the platforms are greater than those assumed then the ranges to any given impact may be greater than those indicated above. Until such time as the vessels and platforms have been noise-ranged then any errors arising as a result of this approach are unquantifiable.