Appendix D
Underwater construction noise assessment

R.D. McCauley & A.J. Duncan (September 2008) *Prediction of underwater noise and associated environmental impacts from a proposed ocean outfall on the northern Tasmanian coast.*

Curtin
UNIVERSITY OF TECHNOLOGY

Centre for Marine Science and Technology

PREDICTION OF UNDERWATER NOISE AND ASSOCIATED ENIVIRONMENTAL IMPACTS FROM A PROPOSED OCEAN OUTFALL ON THE NORTHERN TASMANIAN COAST

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Abstract

Predictions of the underwater noise to be generated from construction of an ocean outfall pipe extending 2.9 km offshore of northern Tasmania and environmental predictions of the noise have been made. Noise sources included vessels likely to be used in construction, the noise produced by non-explosive rock fracturing charges set in-water and noise produced inside of a dry berm and transmitted into surrounding water via the seabed from sheet piling and small explosive charges. These noise sources were considered to be those which reached highest levels in the water or were likely to be the most persistent in the ocean outfall construction. Vessel noise estimates were made using source signatures emulating a noisy working barge and various states of vessel manoeuvring noise mated with sound transmission modelling. Predictions of sheet piling and explosive noise produced inside a berm pumped dry and transmitted via the seabed into surrounding waters were made using many assumptions, all erring on the high side. High frequency energy of the land based sources were rapidly attenuated by the seabed thus all signals appearing in the water column outside the berm had most energy below a few hundred Hz. The source signature of 100, 200 and 500 g slow-burn, non-explosive rock fracturing cartridges were estimated using a physics based model and mated with sound transmission modelling to give estimated received levels for the cartridges used in 36 m depth water on eight headings. The range at which most great whales may avoid the area of offshore construction is estimated to lie between 200 m to 3 km from typical construction activities, with the higher ranges correlating with periods of the noisiest activities. With only a barge operating the range for great whale avoidance is estimated at 200 m to one km. Some great whales may approach close to construction activities due to curiosity or habituation to the construction activities. For fish only the highest levels of noise generated during offshore construction may lead to avoidance and this only from a few hundred metres about the noise source. It is believed that toothed whales, penguins and pinnipeds will be little impacted by offshore construction as most of the noise sources will poorly overlap their hearing capability. During periods of sheet piling inside the berm great whales may keep away from the berm out to 2 km and fish behaviour may be altered out to 800 m from the berm. No marine animals will receive sound loadings sufficient to cause physiological harm from sheet piling noise. Small explosive charges used inside the berm to fracture rock may cause temporary threshold shifts in marine mammals out to 500 m outside of the berm and would not be sufficient to harm fish except any immediately adjacent the berm wall and then only in worst case scenarios (all the assumptions used are met and the explosive signal shape remains suitable). All behavioural impacts on animals outside of the berm from the use of explosive charges inside the berm will be of short duration and given the low duty cycle of use, of little to no long term significance to the animals concerned. The rock fracturing cartridges used outside the berm wall in the water, will not be capable of producing any serious physiological impacts on nearby marina animals, except possibly at very short (< 10 m) range. Cetaceans will need to be within 20 m of a large cartridge to receive a sound loading sufficient to cause any temporary hearing impairment. Like the use of explosives inside the berm, the frequency of use of the non-explosive rock-fracturing cartridges will be low with long breaks (many hours to days) between consecutive use. Hence the significance of any behavioural response to the rock fracturing cartridges will be low to negligible.

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1 Introduction

Gunns Ltd. Propose to construct an ocean outfall on the northern Tasmania coast, in the area defined on Figure 1. The Centre for Marine Science and Technology (CMST) of Curtin University has been contracted to define the levels and environmental implications of underwater noise produced during the construction of this ocean outfall. Specifically, the CMST was to:

1. Estimate the likely upper limits of the underwater sound impacts at 50 m, 100 m, 250 m, 500 m and 1000 m from potential noise sources involved in construction of the ocean outfall;
2. At each of the calculation distances, describe the potential impacts of the calculated sound levels on fish, diving birds (penguins) and marine mammals.

This report presents the results of numerical modelling of underwater sound levels from a variety of sources representative of those to be used in construction of the ocean outfall, with a discussion of the likely impacts of these levels on marine fauna in the area.

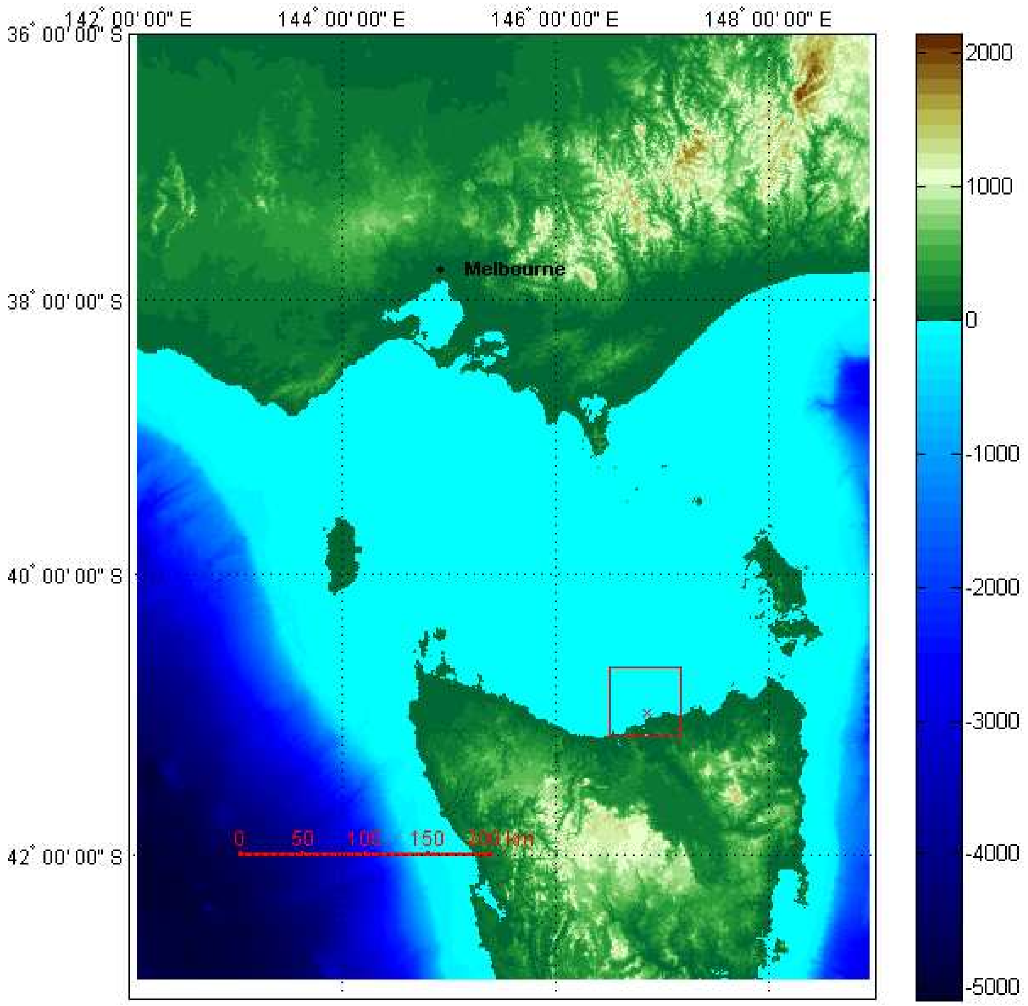

Figure 1. Geographical location of the proposed outfall (red cross). Red square delineates region shown in Figure 4

2 Methods

Construction of the ocean outfall will involve:

- Building a shore-end ‘berm’ or wall to enclose a work area then carrying out typical excavation and construction works within the berm (pumped clear of water). Sound transmission into the ocean from activities occurring inside the berm would be only via ground coupled paths (ie. no direct water coupled paths). The seaward end of the berm is proposed to extend 317 m from the shoreline.
- Carrying out underwater dredging (flattening the seabed for the pipe footings) along the pipe route using: 1) primarily a barge mounted backhoe or excavator; and 2) possibly for selected rock outcrops, a chemical charge inserted into drill holes which expands and fractures the rock (using either the NoneX, non-explosive rock popping cartridges or expanding resins)
- Locating a barge seaward of the intended pipe end and using this to pull the steel or high density polyethylene pipe (HDPE) seaward from the berm. The barge is proposed to be located 3.88 km from the shore.

The type of pipe proposed to be used is currently not completely defined, but may be either steel pipe or HDPE. The HDPE pipe may be either laid across the shoreline as for the steel pipe or pulled into a drill hole set below the dunes and entering the water below the high tide mark. The use of the HDPE pipe will entail:

- Directional drilling from land based plant through rock under the fore-dune, shore and surf zone, to approximately 400 m offshore.
- Pulling of approximately 720 m of HDPE pipe through the drilled hole from the seaward end to the landward end using a winch situated on land beyond the fore-dune.
- Towing of 2.9 km of HDPE pipe in 500-600 m sections into position, joining them together, sinking them and securing the pipe to concrete weights.

A variety of small support vessels from dinghies to small tugs will be used in the work. While general specifications of operations and the types of equipment to be used are reasonably well known the actual construction events and hardware cannot be precisely defined. For example the use of the non-explosive rock fracturing charges will depend on how much can be achieved using the barge mounted excavators and is difficult to predict in advance. Thus for underwater noise prediction, what are believed to be ‘typical’ noise signatures from construction or vessel sources have been used with any unknown erring on the environmentally conservative side. Estimates of the radiated underwater noise from impact-sheet piling and small explosive charges used inside a dry berm, and of non-explosive rock fracturing cartridges used in the ocean have been made using various assumptions and modified real or derived source signatures mated with sound transmission modelling.

The various co-ordinates of the ocean outfall are given in Table 1.

2.1 Source modelling

It is not possible to include all underwater noise sources associated with construction activities as: 1) their respective noise signatures are unknown and will likely vary considerably depending on their operational state; and 2) it would be an enormous exercise to accurately predict the underwater noise fields of more than a few sources. Hence here we have used what we consider to be the dominate underwater noise sources of:

- Sheet piling and small explosive charges within the berm as the noisiest activities inside the berm
- The barge noise modelled as a stationary ship, where all the noise is generated by on-board machinery. The source level used in modelling is from a large merchant ship at anchor (actually a floating production storage offloading – FPSO – vessel) and would be expected to be at the high end of what a barge involved in the ocean outfall construction would produce.
- A 24 m vessel involved in manoeuvring operations, as would be expected from small tugs operating around the barge. Manoeuvring noise is typically limited in duration to several minutes except where dynamically positioned vessels are used. No dynamically positioned vessels are believed planned to be used in the construction operations. The source levels of two bursts of manoeuvring noise from the 24 m vessel have been used.
- Simulated cartridge signatures for 100, 200 and 500 g weights of the non-explosive rock-fracturing technique, which uses drilled holes filled with cartridges which fracture the rock via pressure produced from gaseous products of a slow burn chemical reaction (NoneX cartridges, www.nonex.com).

Table 1: Location of sections of the proposed ocean outfall.

	Lat	**Lon**	**E**	**N**
shore	41° 1.708' S	146° 51.890' E	488637	5458058
End of Berm	41° 1.538' S	146° 51.866' E	488603	5458373
Start of Diffuser	41° 0.243' S	146° 51.699' E	488365	5460769
End of Outfall	41° 0.135' S	146° 51.685' E	488345	5460968
Barge	40° 59.621' S	146° 51.602' E	488228	5461918

The noise produced by small dinghies moving around the site is expected to be well below the vessel manoeuvring noise used in the modelling. The noise of the backhoe operating from the barge will be expected to be similar to the barge noise only with some noise spikes where the rock is ground away by the excavator blade. The third octave and power spectra of the vessel noises used in modelling are shown on Figure 2 (third octave) and Figure 3 (power spectra).

The noise produced by underwater drilling for rock fracturing charge placement will involve hydraulic or compressed air driven drilling machines use on the seabed with plant located on a working vessel or barge above. While there will be some noise generated by the underwater component of the drill operations the vessel noise is considered to be the dominant and most consistent noise source in this operation. Thus translating the modelled barge noise to the site of drilling operations would give an outside estimate of the continual noise to be produced by rock drilling for cartridge or resin placement.

If it is carried out, the borehole drilling for the HDPE pipe under the fore-dunes will involve shore based plant and the noise produced by the rotating drill head in the rock below sea level. No noise from the land based drilling plant will enter the ocean, as the plant will be too far away from the water. The drill noise may couple to the seawater with any noise produced depending on the rock type, amount of drilling lubricant used, depth of drill bit, and coupling of the rock to the seawater. If sand overlies the rock being drilled (which it does to some degree) then coupling of the sub-surface drill noise into the seawater can be expected to be poor and to attenuate high frequencies rapidly. We have not modelled the sub-surface drilling noise as in terms of its contribution to highest noise levels and the cumulative noise impact of the project, it is considered to be below the contribution of vessel noise, the non-explosive rock popping cartridges or sheet piling and explosives potentially used inside the berm. The noise from sub-sea drilling will involve increasingly high losses in the high frequencies, as has been shown in section 3.2 for noise produced inside the berm and transmitted into the surrounding water.

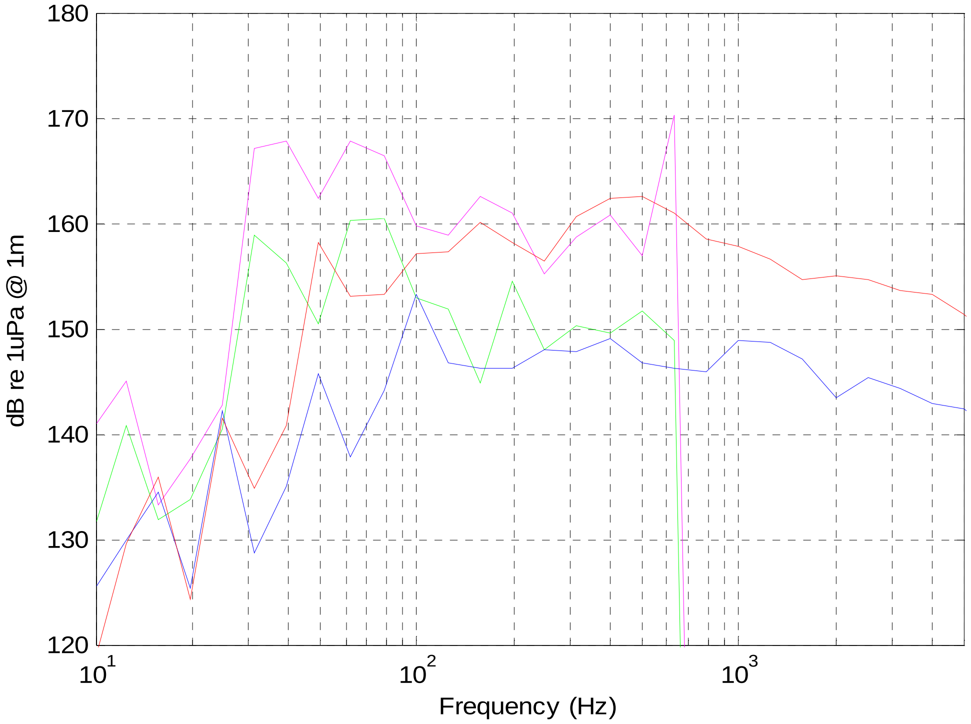

Figure 2. Third octave source spectra for the following sources: blue, vessel manoeuvring noise (quiet); red, vessel manoeuvring noise (loud); green, stationary barge (from ahead); magenta, stationary barge (from beam on).

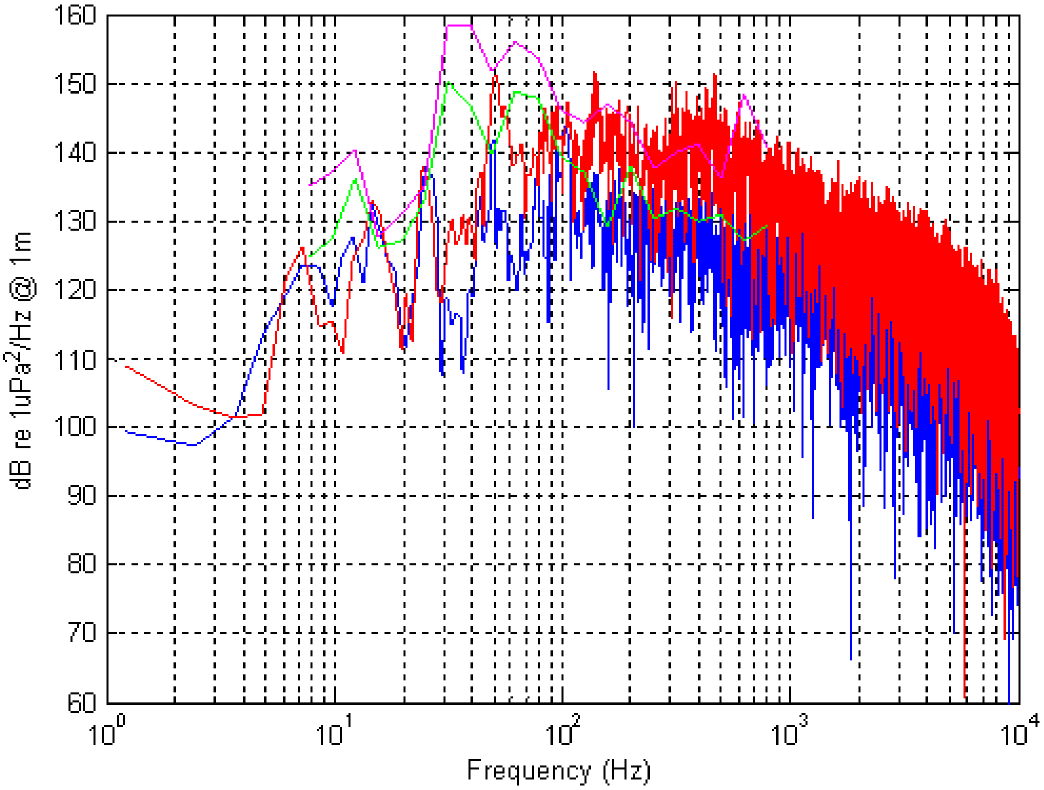

Figure 3. Broadband source spectra for the following sources: blue, vessel manoeuvring noise (quiet); red, vessel manoeuvring noise (loud); green, FPSO (ahead); magenta, FPSO (beam on).

2.2 In-water propagation modelling

The seabed in the area is expected to consist of a layer of sand of variable thickness over limestone or basalt. Sand is more reflective to sound than limestone at the low grazing angles important for horizontal acoustic propagation, so a uniform sand seabed was used for modelling as it represents a worst-case situation. The corresponding geo-acoustic parameters are given in Table 2 (based on tables from Jensen et. al. 2000).

Propagation model runs were carried out using bathymetry profiles corresponding to the eight directions indicated in Figure 4 and plotted in Figure 5. The parabolic equation model RAMGeo , written by Mike Collins from the US Naval Research Laboratory, was chosen for propagation modelling because it works reliably with fluid seabeds such as this and can deal with range dependent water depth. Bathymetry was derived from the Geoscience Australia 0.2' electronic bathymetry grid.

The sound speed profile used for the modelling was obtained from the nearest grid point of the World Ocean Atlas (2005) and is shown in Figure 6.

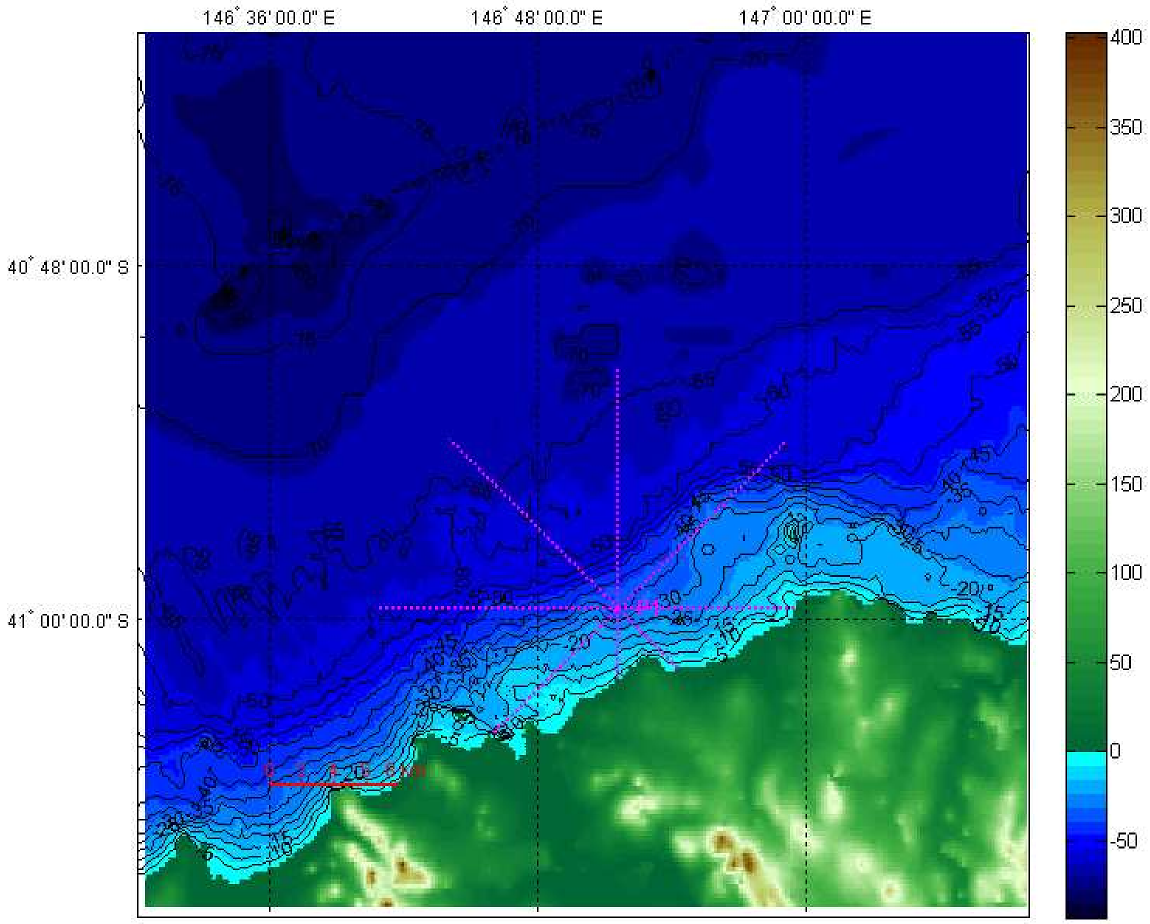

Figure 4. Source location for the barge showing detailed bathymetry. The dotted magenta lines show the bathymetry profiles used for the propagation model runs.

Table 2. Seabed acoustic data used in propagation modelling.

Material	**Density (kg.m^{-3})**	**Compressional wave speed (m/s)**	**Compressional wave attenuation (dB per wavelength)**
Coarse sand	1940	1750	0.8

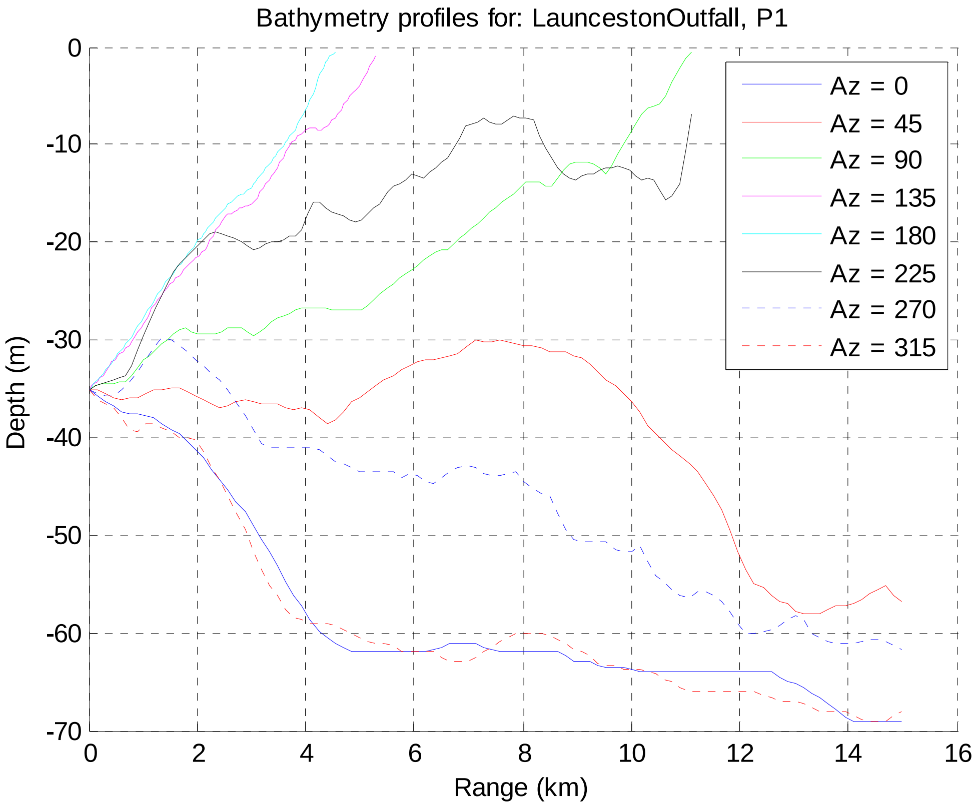

Figure 5. Bathymetry profiles used for propagation modelling for source location P1.

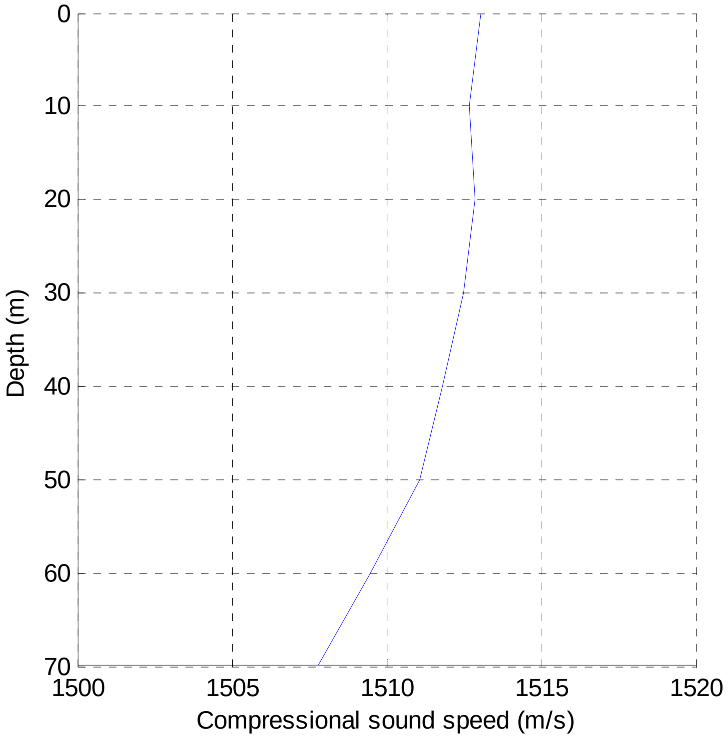

Figure 6. Water column sound speed profile used for propagation modelling.

2.3 In-water source received level calculations

Received levels were calculated for each bathymetry track as follows:

- The propagation model was run to obtain transmission loss as a function of range and depth for frequencies spaced at 1/3 octave intervals from 8 Hz to 1 kHz (ie. at 22, 1/3 octave centre frequencies).
- The source level for the respective sources at each of these frequencies was obtained by integrating the source spectrum over a 1/3 octave frequency band centred on the desired frequency.
- The source level and transmission loss were then combined to compute the received level as a function of range and depth for a grid of points covering the length of the propagation track to a depth of 80 m. The range increment used was 20 m and the depth increment was 2 m. This process first calculated the received levels as a function of frequency then summed the energy across all frequencies at each spatial point to give the estimated broadband received level at each spatial point.

2.4 Sound transmission from inside berm into water

A substantial portion of the pipe preparation work will be carried out in an area surrounded by a berm and kept pumped clear of water. This area will extend into some 320 m seaward of the shoreline. Activities planned to take place inside the berm include ground works for the pipe route and assembling the pipe. Some small explosive charges may be needed in the berm to remove rock.

Any sound generated in the berm will only couple to the surrounding ocean via ground borne transmission paths. Airborne sound energy only enters the ocean at near vertical incidence angles, and even then only a small fraction of the incident energy enters the water. As much of the sound generating activities in the berm will be below water level, then none can enter via this path. Transmission through the ground inside the berm to the ocean may be by two main paths: 1) by interface waves travelling along the seabed / water interface or by energy travelling laterally along the seabed, with some of this energy 'leaking' back into the water column; or 2) by subsea reflections. A schematic of these transmission paths is shown on Figure 7.

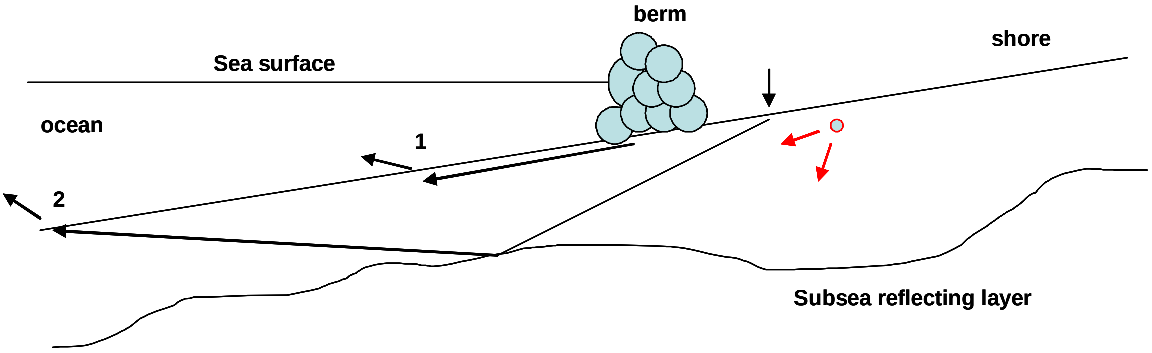

Figure 7: Schematic of main sound transmission paths from inside the berm to the sea water. The paths are: 1) via energy transmitted either laterally through the substrate or along the seabed / water interface and which 'leaks' energy into the water column; or 2) via sub sea reflections passing back into the water. The paths are shown for as a source acting on the substrate but are applicable for a source in the substrate.

The ground will act as a low-pass filter, only allowing low frequency energy to pass and attenuating the signal to some degree. The amount of attenuation and the filtering characteristics of the seabed will depend on the seabed type. An optimal transmission route for noise energy produced inside the berm to transmit into the surrounding water will occur if the seabed under the berm is solid rock with no overlying sand and this rock directly couples to the ocean beyond the berm. The best attenuating seabed would be sand, in which case transmission of sound through the sand in the berm to the sand outside the berm and so the ocean, will involve high losses.

An example of excellent ground to water coupling for sound energy from four sets of pile driving noise measured by the authors is shown on Figure 8 as received signal spectra. In this example two sets of pile driving noise are compared, as per: 1) a pile was being driven on land but within 50 m of a 13 m deep sided channel and the noise measured in-water at 100-165 m range from the pile (blue spectra); and 2) where a pile was being driven in-water and measured at ranges of 60-100 m from the pile (red spectra). These measurements were taken on the same day and were within a few hundred metres of each other in the uniform depth channel. While this example is not transferable to the case here as the pile measurements displayed had a steep 13 m vertical interface between the water and ocean, which allowed the land based signals to couple directly to the water, they do indicate the sharp filtering applied by the land to the piling signals. While the absolute levels of the signals shown on Figure 8 relate more to the piling force and range at which the measurements were taken, there is clear and sharp filtering of the land based signals below 2 kHz. Note that no pile driving is intended to occur inside the berm.

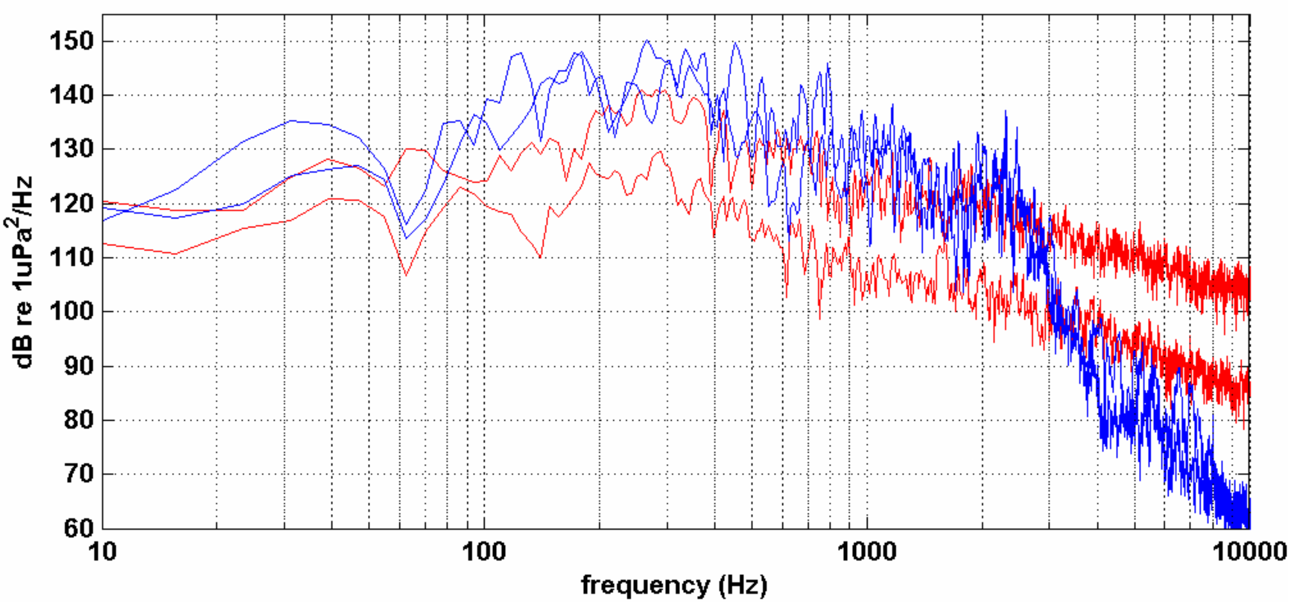

Figure 8: Measured spectra of two sets of piling (each curve is the mean spectra from five impacts). The blue curves were from land based piling measured in the ocean with excellent land-water coupling; and the red curves were from water based piling also measured in the ocean.

In the example shown on Figure 8 the frequency at which the land transmission attenuates the signal is quite high, beginning at around 2 kHz. In a large data set of air gun array signal transmission available to the author from around Australia (McCauley et al in prep.) which have limestone pavement seabeds, including the western end of Bass Strait, the ground borne filtering is typically severe above 200 Hz and at moderate ranges (km) the ground does not pass any energy above 100 Hz. In areas known to have deep sand layers over limestone there is typically comparatively low levels of ground borne air gun array energy detected by seabed coupled hydrophones (ie. on the NW Shelf of Western Australia, McCauley 2008).

It is impossible to precisely predict how well sound will travel from inside the berm to the surrounding water without knowing the exact seabed type in the area and carrying out sophisticated modelling. In order to attempt to estimate received sound levels in the water around the berm we have made the following assumptions:

- The continual seabed which couples the inside of the berm to the outside water is sand. While there are rock outcrops known to be inside the berm these are believed to be scattered and the primary interface between the inside of the berm and the ocean is assumed to be a sand seabed;
- Transmission of airborne sound from sources inside the berm either through the seabed into the surrounding water or through the berm wall itself are ignored due to the poor coupling from airborne sound to substrate borne sound;
- There will be no airborne sound transmitted directly into the water as the transmission paths will not allow this;
- There will be coupling of sound energy transmitted through the substrate into the overlying water assuming a vertical sand \ water interface at a specified range. While this will not be the case it provides a worst case scenario. It is extremely difficult to predict the efficiency of seabed-into-water energy at any range if we assume a sloping seabed.
- That at close range on the ocean side of the berm wall (out to 1 km), the dominant source of sound energy originating from inside the berm at any range will be that transmitted through the seabed. This implies that energy which enters the water column at ranges closer to the source from the range of interest does not transmit laterally. For the low frequencies which the sea bed passes this will be the case in the shallow water around the berm.
- That the seabed sand layer does not support shear waves due to the low shear speed (ie. table 1.3 in Jensen et al 2000). For rock substrates which do support shear waves, these become a significant loss mechanism for the transmission of sound energy at moderate (hundreds m) to long ranges (many km).
- The sources which will transmit through the seabed into the ocean water will only be those well coupled into the seabed inside the berm. Such sources include sheet piling, small explosive charges used inside the berm to fracture rock, or jack-hammering. Any poorly substrate-coupled noise source can be ignored from the point of view of sound transmission into water surrounding the berm.

Using the above assumptions then transmission of substrate-coupled noise sources inside the berm to outside the berm through sand is given by a loss of:

0.8 dB / λ

from table 1.3 in Jensen et al (2000) and where λ is the wavelength. The transferral of sound energy from one media to another for normal (vertical) incidence is given by:

$$T = \frac{2}{1 + \frac{r_1}{r_2}}$$

where T is the ratio of incident and transmitted pressure, and r_1 and r_2 are the respective acoustic impedances (density x sound speed) of the two media. Using values for water saturated sand and sea water this gives a coupling efficiency of 64% or a loss of 3.9 dB going from sand into the water ($20*\log_{10}(0.64)$). In reality the efficiency of conversion of the substrate borne energy into the water will be considerably lower as the sound energy will not leave the sand at normal incidence (near vertical transmission between the sand and water) and so the loss at the interface will be much higher than 3.9 dB.

2.5 Units

As the types of noise to be produced by the ocean outfall are primarily continual industrial noise, the document primarily uses mean squared pressure units of dB re 1µPa. The fact they are mean squared pressure is indicated by (msp) following the units. For the non-explosive cartridge noise estimates the impulse measure of dB re 1µPa^2.s has been used. This is now widely termed sound exposure level and indicated as SEL.

3 Results

3.1 Predicted in-water sound fields

The resulting sound fields for the barge and manoeuvring noise are shown on Figure 9, in units of mean squared pressure. The noise used to emulate the barge was directional in nature hence two headings of the barge were assumed, one which aligned the highest noise level around the barge with the best sound transmission path and one which aligned the highest noise level around the barge with the worst sound transmission path. The plots of transmission of the different sources along all of the bathymetry paths used in modelling are shown on Figure 10. This plot highlights the inherent variability of transmission of the different sources along different headings from the source.

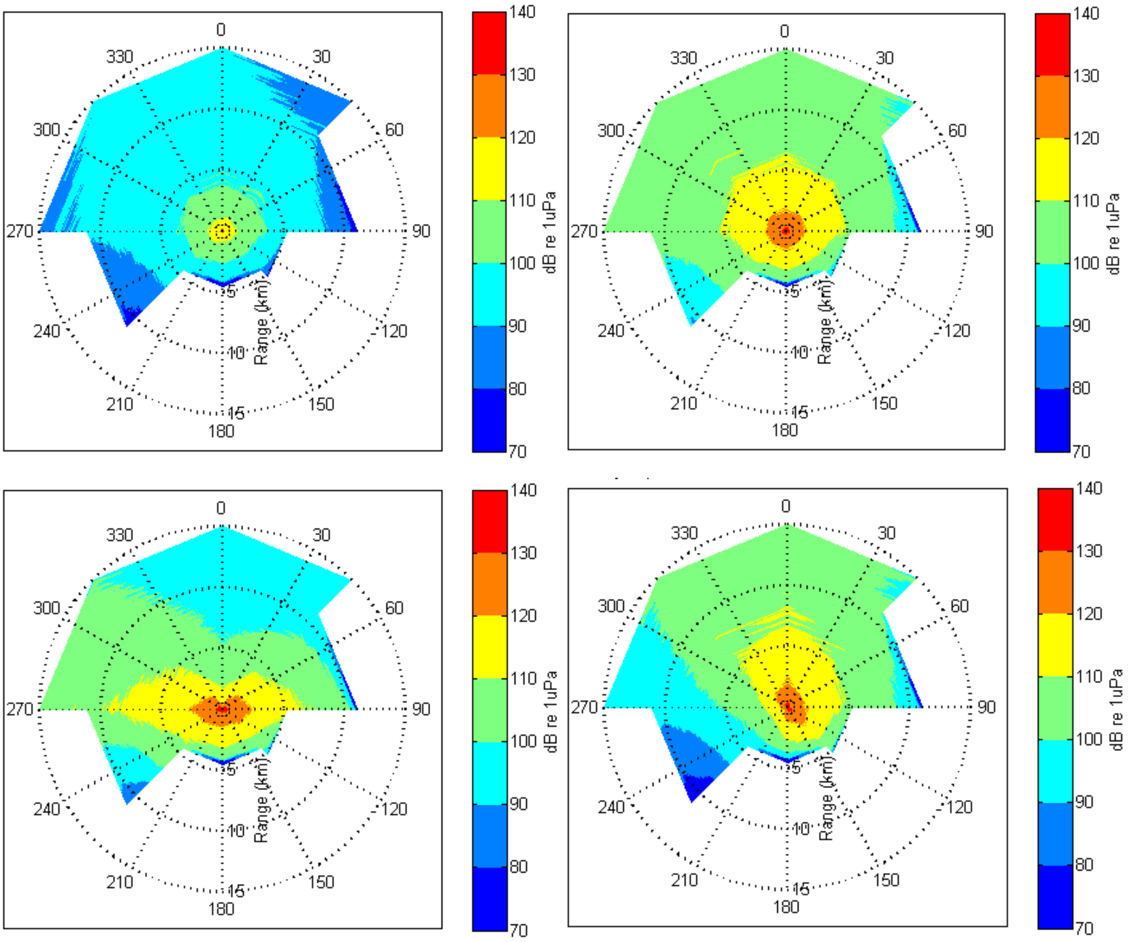

Figure 9. Maximum received level at any depth as a function of range and azimuth for the following sources: Top left, vessel manoeuvring noise (quiet); top right, vessel manoeuvring noise (loud); bottom left, barge noise on 0° heading; bottom right, barge noise on 247° heading.

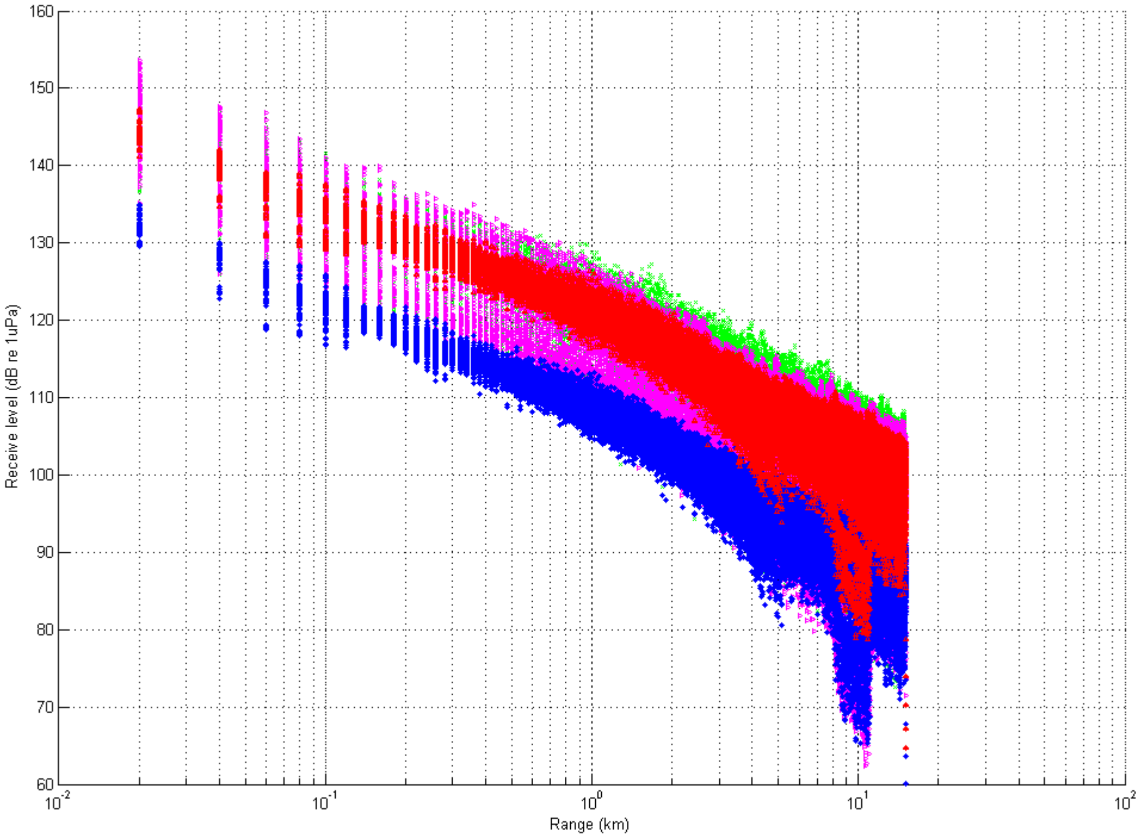

Figure 10. Scatter plots of predicted received level vs. distance from the source for all depths and azimuths for the following sources: blue, vessel manoeuvring noise (quiet); red, vessel manoeuvring noise (loud); green, barge on 0° heading; magenta, barge on 247° heading.

The predicted levels of the barge and higher level vessel manoeuvring noise at several ranges is listed on Table 3 in mean squared pressure units.

Table 3: Spread of received levels (due to different bathymetry paths) at specified ranges for the stationary barge and the higher level manoeuvring noise. The units are mean squared pressure of dB re 1µPa.

	50 m	**200 m**	**500 m**	**1000 m**
Barge	128-148	120-137	115-131	112-127
Higher level manoeuvring noise	130-142	128-135	123-129	117-128

3.2 Predicted transmission from inside berm to surrounding water

The two highest level noise sources proposed to be used inside the berm are only considered. As stated above only noise sources inside the berm which are well coupled to the substrate are expected to stand any chance of being transmitted beyond the confines of the berm. The high source level activities considered are the driving of sheet piling, which will be carried out to make work areas safe and to allow for de-watering, and the use of small explosive charges to facture rocks inside the berm.

The explosive charges modelled used five measured signatures of different 40 g charges (TNT) used to fracture rock near Hobart, with measurements made from a 3 m depth receiver in 10 m of water at 340 m range (McCauley 2006). Two example signature waveforms are shown on Figure 11. The section of explosive signal was excised (based on the time taken for 90% of the signal energy to pass and this bracketed) and the signal adjusted back to source level (level at 1 m range) assuming cylindrical spreading (ie. multiply the received signal by $\sqrt{Ra}$, where Ra was 340 m). This is a simplistic assumption and does not account for multipath transmission but since the remainder of the calculations were carried out in the frequency domain, is considered a first approximation.

To account for losses through the seabed for the explosives used inside the berm it was first considered that all the explosive charge energy coupled to the seabed. The five explosive source level signatures then each had a power spectra made at 40 Hz resolution and were corrected to units of dB re 1µPa. The 40 Hz resolution allowed one FFT sample to encapsulate the full explosive signal. A sound speed of 1510 ms^{-1} was assumed and the wavelengths at the FFT frequencies calculated, the number of wavelengths in 50, 200, 500 and 1000 m calculated, and a loss of 0.8 dB \ λ applied appropriately to each spectra, to give loss through the seabed to the respective range. A further loss of 3.9 dB was then applied to account for the efficiency of converting the sediment borne energy to waterborne energy. The calculations for explosives then gave the estimated received spectra in the water at ranges of 50, 200, 500 and 1000 m, which are shown on Figure 12 along with the estimated mean 40 g explosive source spectra.

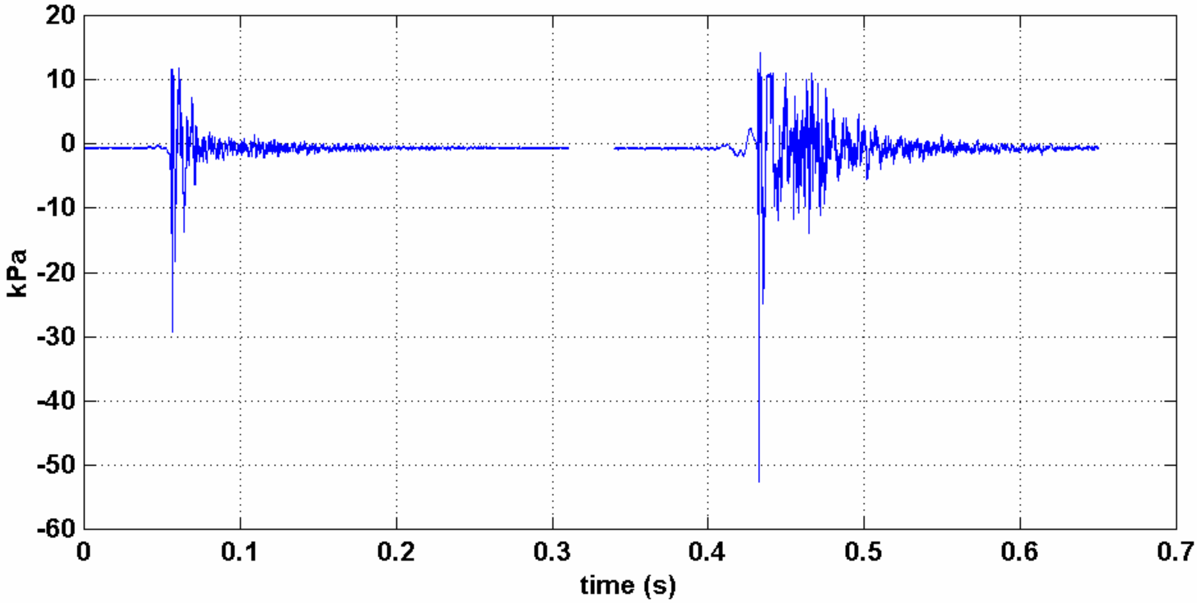

Figure 11: Example of underwater explosions measured at 340 m from 40 g charges used to fracture rock in 10 m water depth over a hard bottom. Data from McCauley (2006).

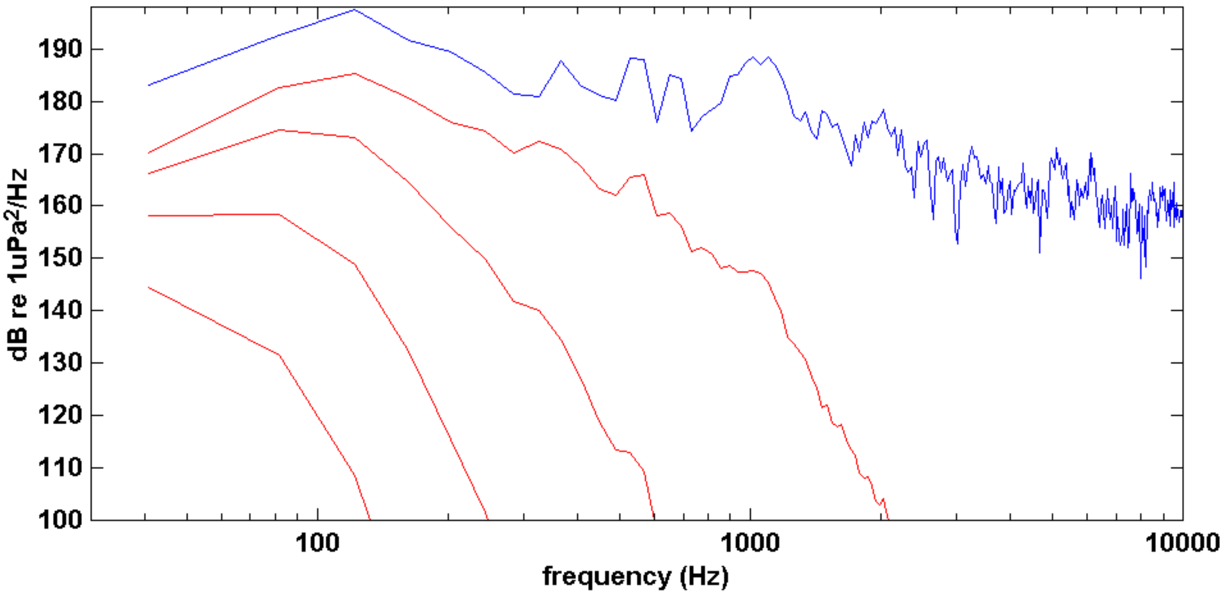

Figure 12:Estimated source spectra for 40 g explosion (blue curve) and estimated received levels at 50, 200, 500 and 1000 m as red curves (becoming progressively weaker with increasing range).

The estimated mean received levels in the water column for small explosive charges used inside the berm wall and received outside it, at 50, 200, 500 and 1000 m range, are 206, 194, 178 and 161 dB re 1µPa respectively. The low-pass filtering of the seabed is evident on Figure 12, where the high frequency energy can be seen to be rapidly stripped away with this effect increasing dramatically as the range increases.

The second activity modelled for noise levels transferred outside the berm wall for activities taking place inside the wall was sheet piling where large sheets of steel are driven into the seabed to form a barrier of some sort. Sheet piles may be driven down by hitting them with a large hammer, in which case a signal similar to pile driving is produced, or by vibratory piling where the sheet is vibrated down. To emulate impact sheet piling a source signature of pile driving was used, as presented in McCauley and Salgado Kent (2008, Figure 13). This can be considered a worst case scenario from the perspective of the highest noise levels produced. It was considered that the energy delivered into the seabed for sheet piling inside the berm was equivalent to the energy delivered into the water column from the measured impact pile driving signal. A power spectra of the pile driving source signature was taken using a 40 Hz bandwidth which encompassed the signal only, this adjusted to units of dB re 1µPa (msp), all the energy considered to couple into the seabed, a loss of 0.8 dB / λ applied appropriately assuming a sound speed of 1510 ms^{-1}, and a 3.9 dB loss applied for coupling the sediment borne energy into the water. The resulting estimates of broad band energy produced at 50, 200, 500 and 1000 m range were 198, 180, 166 and 150 dB re 1µPa (msp) respectively. Like the explosive charge the signal which made it into the water surrounding the berm was stripped of any high frequency energy.

3.3 Noise source signature of Nonex propellant cartridges

The proponents may need to break up some rock on the seaward side of the berm to clear the propose pipe route. In order to avoid having to use underwater explosives they have specified two alternatives, the use of a slow burn chemical rock fracturing technique or expanding resins. The slow burn rock-fracturing technique relies on a cartridge inserted into a hole drilled in the rock, which is sealed over. The cartridge is ‘fired’ and via a chemical reaction produces a high gas pressure within the rock which fractures it. The cartridges are not explosive in nature and do not produce the near instantaneous pressure impulse or shock wave of explosives. They do produce a high pressure over a short time frame and so will produce noise. To establish how much noise they may produce required some detailed calculations, given below.

Apart from the drilling operation, the use of expanding resins will not produce underwater noise, hence this technique has not been discussed here. The efficiency of each technique and the alternative rock removal techniques (barge mounted excavator) will determine if the non-explosive cartridges or expanding resins will be used.

An estimate of the underwater noise produced by the Nonex cartridges and the rationale and physics behind this, follows. The first step involved the difficult task of building source signatures for the Nonex cartridges, the second step involved using modelled sound transmission losses and the source signature to predict sound levels radiating away from the charge.

Gas pressure calculation

Nonex cartridges (Nonex 2008) operate by the chemical reaction of nitrocellulose with ammonium nitrate, resulting in a mixture of water vapour, carbon dioxide, and nitrogen, plus the release of a significant quantity energy in the form of heat. This reaction may be written as:

$$x(C_6N_3H_7O_{11}) + y(NH_4NO_3) \rightarrow a(H_20) + b(N_2) + c(CO_2)$$

The relative values of the constants x, y, a, b and c were determined by the requirement that the number of atoms of each element must be the same on the left side of the equation as on the right side. The result is:

$$2(C_6N_3H_7O_{11}) + 9(NH_4NO_3) \rightarrow 25(H_20) + 12(N_2) + 12(CO_2)$$

From this equation, and the molar weights of the constituent elements given in Table 4 the number of moles of each gas liberated per gram of propellant were calculated. The amount of heat liberated per gram of charge was computed from the difference between the sum of the heats of formation of the reaction products and the sum of the heats of formation of the reactants. The result was

$$E = 4540 \text{ J. g}^{-1}.$$

The initial temperature of the gas mixture was computed under the assumption that all the heat energy produced in the reaction went into raising the temperature of the gas. An effective specific heat (at constant volume) was calculated for the gas mixture by summing the products of the individual specific heats and the number of moles of each individual gas (Table 4). The result was

$$C_{veff} = 0.94 \text{ J.C}^{-1}.\text{g}^{-1}.$$

The temperature rise of the gas was then calculated from:

$$\Delta T = \frac{E}{C_{veff}} = 4830 \text{ °C}, \qquad (1)$$

Note that the temperature rise is independent of the charge weight. The final gas temperature was determined by adding ΔT to the ambient temperature.

Table 4: **Chemical properties of the molecules involved in the deflagration of Nonex cartridges. Data from CRC (1984), and cobweb.ecn.purdue.edu/~propuls/propulsion/comb/propellants.html.**

Molecule	Molar weight (g)	Moles per gram of charge (mol.g^{-1})	Heat of formation (kJ.mol^{-1})	Heat of formation per gram of charge (kJ.g^{-1})	Specific heat at constant volume (J.C^{-1}.mol^{-1})	Ratio of specific heats ($\gamma = C_p/C_v$)
$C_6N_3H_7O_{11}$	297.16	0.00152	-767	-1.17		
NH_4NO_3	80.06	0.00684	-364	-2.49		
H_20 (gas)	18.02	0.0190	-242	-4.60	26	1.3
N_2	28.02	0.00913	0	0	21	1.4
CO_2	44.01	0.00913	-394	-3.60	28	1.3

The initial pressure of the gas was then determined from the ideal gas law:

$$P_0 = \frac{nRT_0}{V_0} \quad \text{(Pa)} \qquad (2)$$

where $n = 0.0373 m_{charge}$ is the number of moles of gas produced in the reaction, m_{charge} is the charge weight (g), $R = 8.3145$ J.K^{-1}.mol^{-1} is the gas constant, T_0 is the initial temperature in Kelvin (°C + 273.15), and V_0 is the initial gas volume (m^3), which was taken as the volume of the unstemmed part of the drill hole.

The change in gas pressure with time was calculated on the assumption that the expansion of the gas was adiabatic, i.e. that there was insufficient time for a significant portion of heat energy to be lost to the surrounding rock. This assumption results in the following equation for the pressure at time t:

$$P(t) = P_0 \left(\frac{V_0}{V(t)} \right)^{\gamma} \quad \text{(Pa)} \qquad (3)$$

where $V(t)$ is the gas volume (m^3) at time t and γ is the ratio of specific heats at constant pressure and constant volume for the gas mixture (taken as 1.3).

Rock Dynamics

To make the calculations tractable a fairly simple model of the rock dynamics was adopted. The following assumptions were made:

1. The rock is assumed to be spherical, with the charge initially contained in a spherical cavity at its centre.
2. The rock is assumed to have zero tensile strength, which allows circumferential forces to be ignored.
3. The rock is assumed to behave as a rigid body under compression.
4. Acoustic radiation is due only to the rigid body motion of the outer surface of the rock.
5. Gas generated by the charge is assumed to move immediately into the cracks formed by the expansion of the rock.
6. The volume of cracks at any given time is taken as the difference between the volume contained by the outer surface of the rock at that time and its initial volume.
7. The outward expansion of the rock is driven by the pressure of the gas produced by the charge acting on the cavity wall, and counteracted by the sum of the hydrostatic pressure and radiation pressure acting on the outer surface of the rock. The effect on expansion of the gas in the cracks is ignored.

8. Once the gas pressure drops below the point at which it is balanced by the hydrostatic pressure it is set equal to this value. This is equivalent to assuming the cracks and cavities flood at that point.
9.

These assumptions allow simple rigid body dynamics to be applied to the problem, which result in the following equation for the radial acceleration of the outer surface of the rock:

$$\frac{d^2r}{dt^2}=\frac{4\pi}{M}\left(r_i^2P-r^2P_r\right) \tag{4}$$

where M is the total mass of the rock, r is its instantaneous external radius, r_i is the instantaneous radius of the cavity, P is the instantaneous gas pressure, and $P_r = P_{hyd} + P_{rad}$ is the sum of the hydrostatic and radiation pressures.

Acoustic radiation

The theory of acoustic radiation from a vibrating sphere is covered in Morse (1976), who shows that the acoustic pressure a distance r_h from the centre of the sphere is given by:

$$p(r_h,t)=\frac{f\left(t-\frac{r_h}{c}\right)}{r_h} \tag{5}$$

where c is the sound speed in the surrounding fluid and the function f satisfies the following differential equation on the surface of the sphere:

$$\frac{1}{r}\frac{df}{dr}-\frac{f}{r^2}=-\rho\frac{d^2r}{dt^2}. \tag{6}$$

Here ρ is the density of the fluid. It is straightforward to show that:

$$\frac{df}{dr}=-\frac{1}{c-u}\frac{df}{dt}, \tag{7}$$

where $u=\frac{dr}{dt}$, so (6) can be written as

$$\frac{1}{r(c-u)}\frac{\partial f}{\partial t}+\frac{f}{r^2}=\rho\frac{\partial^2 r}{\partial t^2} \tag{8}$$

If the displacement of the sphere's surface as a function of time, $r(t)$, is known, then (8) can be numerically integrated to obtain $f(t)$. However, solution of (4) to obtain $r(t)$ requires knowledge of the radiation pressure, $P_{rad}(t)=p(r,t)$, which in turn depends on $f(t)$ through (5). Substituting (5) into (7) gives, after some manipulation:

$$\frac{dP_{rad}}{dt}+\frac{c}{r}P_{rad}=\rho\left(c-\frac{dr}{dt}\right)\frac{d^2r}{dt^2} \tag{9}$$

Equations (4) and (9) were solved simultaneously using a standard numerical differential equation solver (Matlab's ode45 function), to give the sphere radius and radiation pressure as a function of time, from which the acoustic pressure at a distance of 1 m was computed using (5).

Examples of waveforms computed using this method are given in Figure 13. Corresponding broadband and third octave spectra are shown in Figure 14 and Figure 15 respectively. These results are in broad agreement with an example waveform given in MTD (1996).

The chief limitation of this model is its simplistic treatment of the rock dynamics, as a result of which it does not account for sound produced by any shock or acoustic wave that propagates through the rock prior to its bulk motion after fracture. However, shock waves are unlikely due to the relatively slow burn rates of the Nonex cartridges, which makes this effect less significant than for high explosives such as TNT.

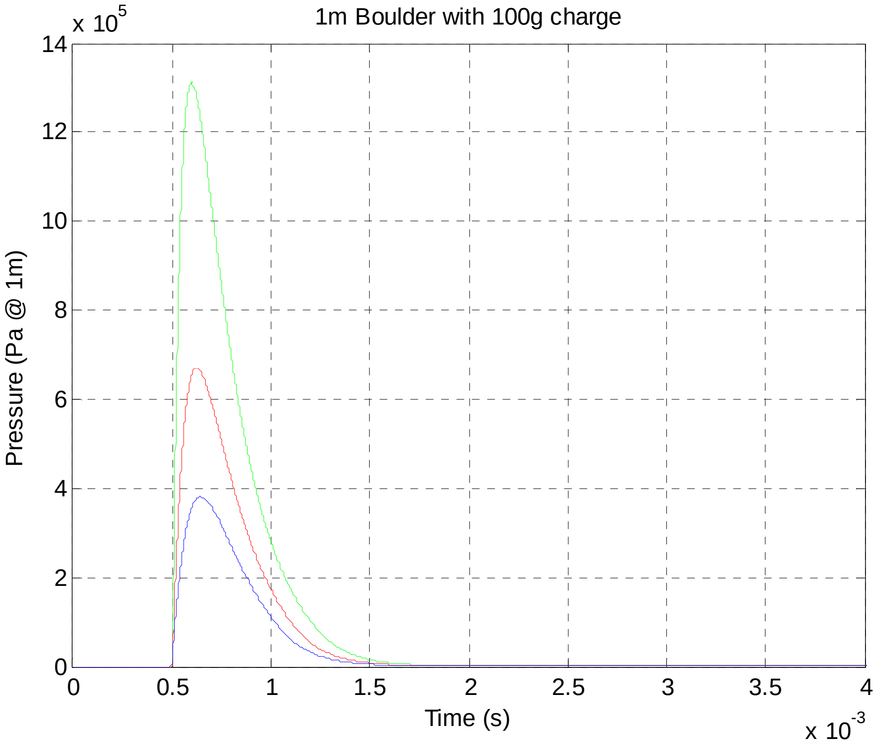

Figure 13. Modelled acoustic source waveforms for demolition of a 1 m diameter basalt rock of density 2700 kg/m^3 at a depth of 33 m using Nonex cartridges of the following weights: blue, 100g (SL = 195.8 dB re 1 µPa^2.s @ 1m); red, 200g (SL = 200.4 dB re 1 µPa^2.s @ 1m); green, 500g (SL = 205.7 dB re 1 µPa^2.s @ 1m)

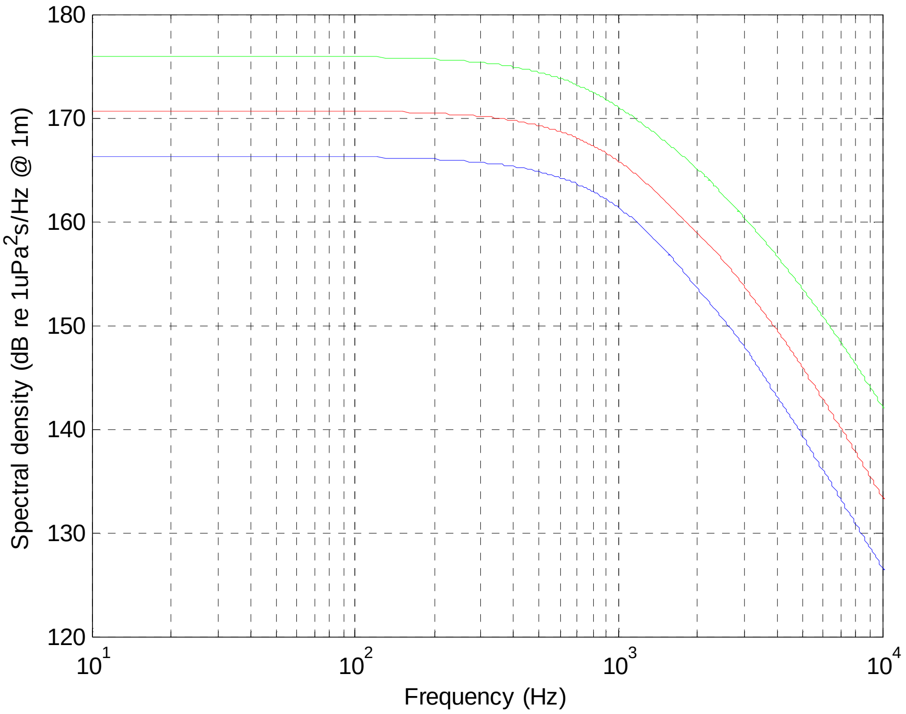

Figure 14. Modelled broadband source spectra for demolition of a 1 m diameter basalt rock of density 2700 kg/m^3 at a depth of 33 m using Nonex cartridges of the following weights: blue, 100g; red, 200g; green, 500g

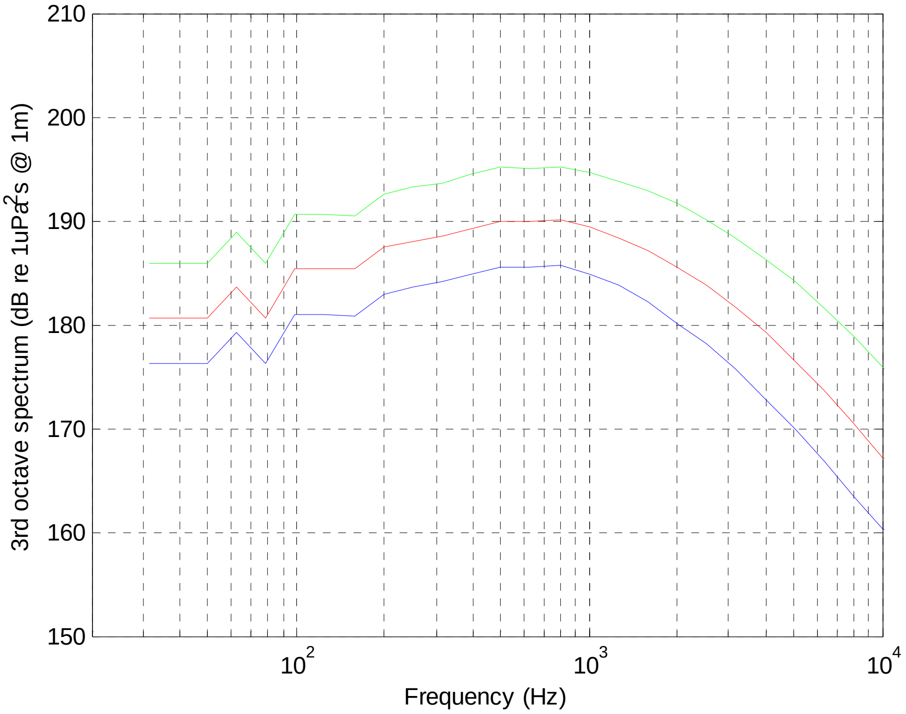

Figure 15. Modelled third octave source spectra for demolition of a 1 m diameter basalt rock of density 2700 kg/m^3 at a depth of 33 m using Nonex cartridges of the following weights: blue, 100g; red, 200g; green, 500g

3.4 Transmission of Nonex cartridge type noise

The sound transmission model RAMGeo was run as per the set up defined in section 2.2 but with the source placed on the seabed and the model run at 1/3 octave centre frequencies up to 8 kHz, since the source signature had considerable high frequency energy. The location was taken at the seaward end of the pipe route, although at short ranges (within a km of the cartridge) these results will be directly transferable to cartridges used in shallower waters. Again the model was set up and run along eight headings from the nominal cartridge location. The respective source levels integrated across each 1/3 octave band were then used with the modelled transmission loss to give the received level at range and depth for each 1/3 octave centre frequencies and the energy integrated across the bandwidth used to give the estimated broadband level of the cartridges. This was done for source cartridge weights of 100, 200 and 500 g weight.

The resulting sound fields produce are shown on Figure 16 for a 100 g cartridge, Figure 17 for a 200 g cartridge and Figure 18 for a 500 g cartridge. The estimated levels with range for each cartridge weight and along the different headings (bathymetry paths) are shown on Figure 19. The spread of estimated received levels at various ranges for the different cartridge sizes are listed in Table 5 in sound exposure level units which best describe impulse measures, of dB re 1µPa^2.s .

Table 5: Spread of received levels (due to different bathymetry paths) at specified ranges for different cartridge weights. The units are sound exposure level of dB re 1µPa^2.s, which best describe impulse signals.

	50 m	**200 m**	**500 m**	**1000 m**
100 g	162-166	155-158	148-153	145-151
200 g	166-171	159-164	154-158	149-155
500 g	172-176	165-168	159-163	155-160

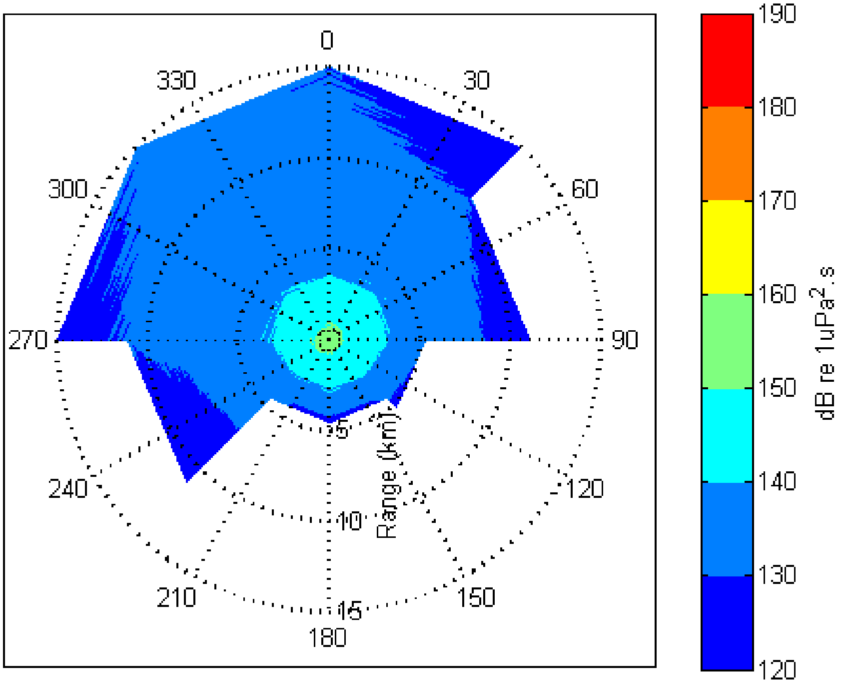

Figure 16: Estimated sound field produced by a 100 g Nonex like cartridge. (Maximum received level at any depth.)

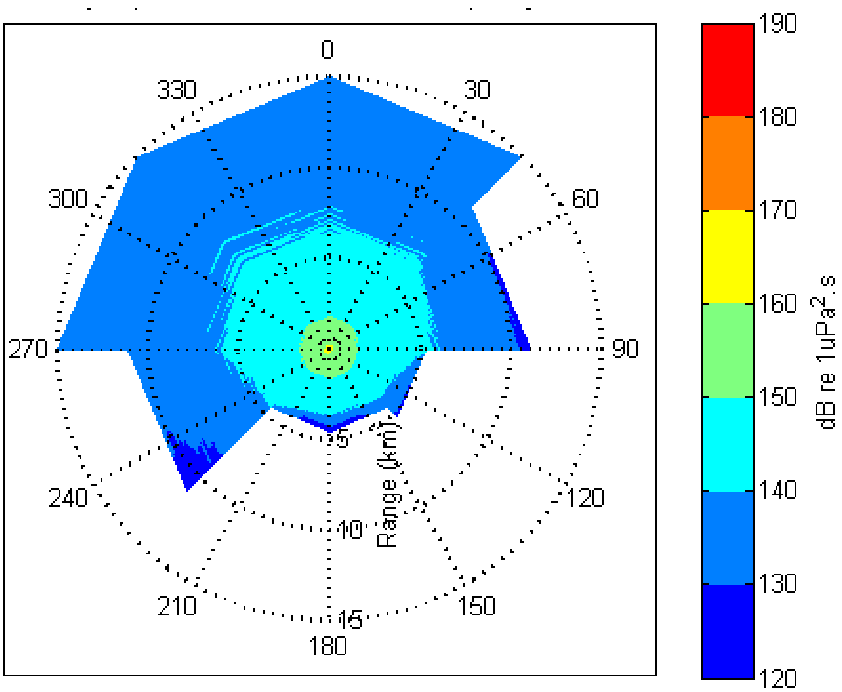

Figure 17: Estimated sound field produced by a 200 g Nonex like cartridge

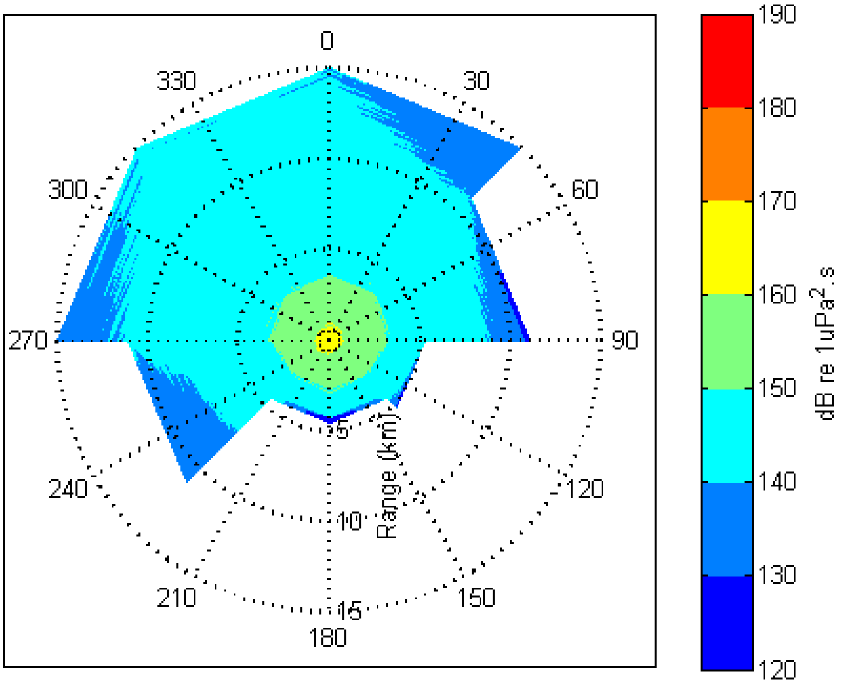

Figure 18: Estimated sound field produced by a 500 g Nonex like cartridge

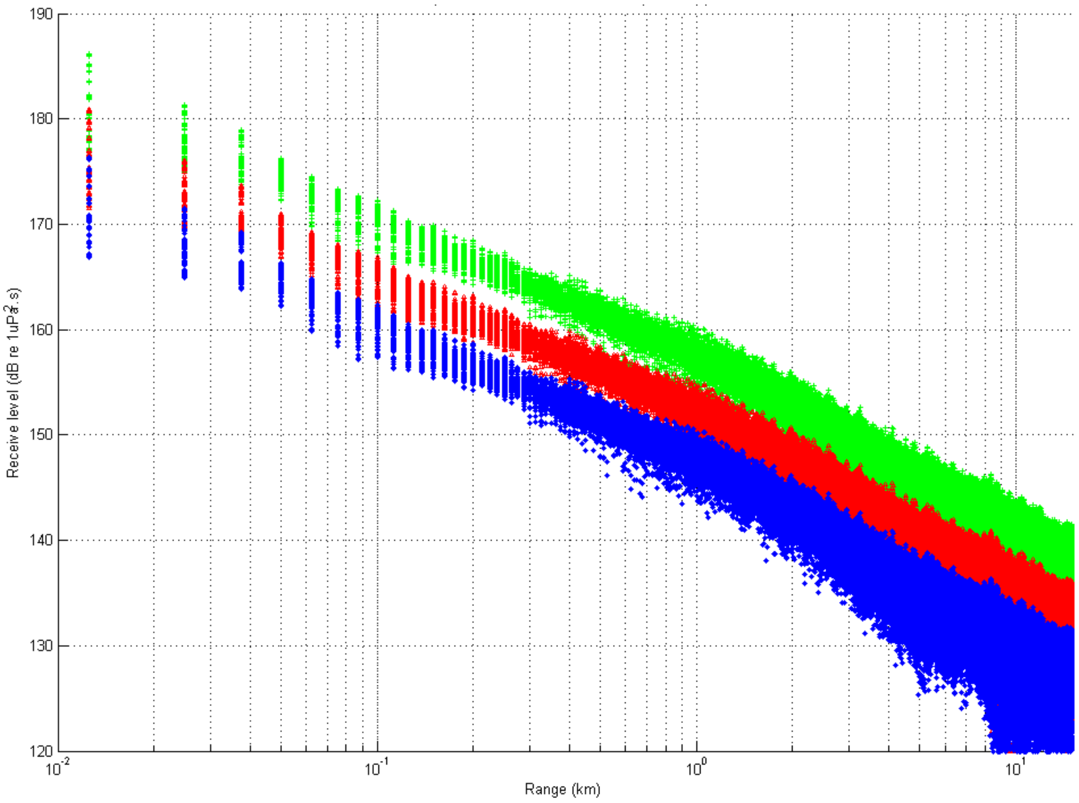

Figure 19: Predicted transmission of the Nonex style cartridges at the ocean outfall site. The colours represent: blue = 100 g cartridge; red = 200 g cartridge; green = 500 g cartridge.

4 Discussion

4.1 Hearing response of fish, penguins and marine mammals

Fish

In general terms fish have ‘best’ hearing thresholds in the low kHz range (ie. 100 – 1000 Hz) although many species show responses to signals in the infrasound (low Hz range) and some species can detect signals in the many kHz range. Typically at best sensitivity those fish with good hearing sensitivity can hear down to just below the lowest expected ocean ambient noise conditions across their frequency band of best hearing (ie. down to 60-90 dB re 1µPa in the hearing range 100-800 Hz) while those fish with poor hearing may only hear sounds many 10’s of dB above lowest expected ambient noise conditions. The variability in hearing sensitivity in fish is related to the physiology of the hearing anatomy of different species. Fish have been divided into two broad groups based on hearing sensitivity, ‘hearing specialists’ and ‘hearing generalists’. Distinctions between the groups are based on whether the species have specialised organs for improving sound reception. Fish that have morphological adaptations that link the otolithic hearing end organs to their swimbladders or a gas filled bullae are considered ‘hearing specialists’. Audiograms of ‘hearing specialists’ show high sensitivity to sounds with sound levels as low as 60 dB re 1µPa (tones) across a broad frequency range into several kHz. Fish with specialist hearing systems are generally those adapted to function at night, in dark, deep or dirty water, or for whom sound plays a critical role in reproductive purposes or predator detection.

The dominant sounds which will be produced by the ocean outfall construction directly overlap the hearing range of fishes. For the purposes of assessing environmental impacts of the ocean outfall noise, fish in the vicinity of the ocean outfall are considered to hear down to expected ambient noise conditions over 100 Hz – 1 kHz.

Penguins

A single penguin species is common in southern Australia. This is the fairy or little penguin, *Eudyptula minor*. Little information is available on the hearing of penguins in-air and underwater. In general, it is thought that penguins are sensitive to frequencies over the range of 100 Hz to 15 kHz (ie see discussion in McCauley, 1994). For example a study of the hearing of the Blackfooted penguin (*Sphenikcus demersus)* in terms of the cochlear potentials showed best sensitivity in the region of 600 to 4000 Hz (Wever *et al*., 1969). Generally the hearing of penguins appears to be similar to the hearing of other smaller birds, with greatest sensitivity between 1-3 kHz, although for conservative purposes here penguins are considered to hear well into low frequencies down to 500 Hz.

Marine Mammals

Richardson et al (1995) summarise the many studies of marine mammal hearing. In general terms the toothed whales, or Odontocetes, are known to communicate at frequencies from 1 kHz to greater than 20 kHz and to echolocate from a few kHz to typically 30-50 kHz although some species can produce higher frequency signals. Most Odontocetes have best hearing sensitivity in the many kHz range with their optimal hearing band dependant on species. Most of the underwater noise sources likely to be detected near the ocean outfall construction will have dominant frequencies in the low kHz region, and for the signals produced inside the berm in the low hundred Hz region, thus will overlap poorly with Odonotocete hearing. The most common dolphin likely to be found in the vicinity of the ocean outfall, the bottlenose dolphin (*Tursiops sp.*) has an optimal hearing frequency range of ~15 kHz to 50 kHz. Thus the ocean outfall noise sources will not overlap well with the hearing range of Odontocetes.

The hearing response of the larger baleen whales has not been determined by any experimental means, due to their size and the inherent problem of working with such large animals. But, the baleen whales are known to produce signals over the frequency range of tens Hz to many kHz and thus for most environmental noise assessment purposes are considered to hear down to lowest expected ocean ambient noise conditions in the 10 Hz to 1000 Hz range.

4.2 Types of noise impacts

In terms of noise impact, there are several categories of impacts to consider. Listed in increasing order of severity, impacts include:

- masking of signals of interest (which can lead to behavioural responses);
- behavioural response including aversion or attraction
- temporary threshold shift where hearing sensitivity is temporarily reduced (TTS);
- permanent threshold shift where hearing sensitivity is permanently reduced (PTS);
- physiological damage including hearing impairment or organ damage;
- death.

All ‘noise’ can mask signals or make them more difficult to detect. Assessing how this will impact animals in the vicinity of the ocean outfall construction site is difficult and depends on many factors, such as:

- the respective time history of the masking noise and the signals being masked – do the times of sound production / detection by animals potentially impacted overlap with the times of masking noise (ie. daytime)?
- The use made by animals in the vicinity of the ocean outfall of noise cues;

- The frequency overlap of the masking noise and the signals of interest. Of note here is that most Odontocete signals will not be masked at all by noise produced by the ocean outfall construction as their frequency content is well above that of most noise produced.

Behavioural responses may range from attraction to aversion. There are many marine animals which are attracted towards underwater sounds. Examples include sharks (Myrberg et al 1976) and some humpback whales to air gun signals (McCauley et al 2003). There are many documented instances of aversion of marine animals to sounds with are considered to be intense or obnoxious. For example McCauley et al (2003) found that above 156 dB re 1μPa (msp) (or 145 dB re 1μPa^2.s SEL) fish showed obvious behavioural responses to an approaching air gun (impulsive noise) and at around 160 dB re 1μPa (msp) (or 150 dB re 1μPa^2.s SEL) the behaviour of caged fishes suggested they would flee an approaching air gun. Values of the levels of continual underwater noise sources which may produce avoidance in fishes are not known. While many fishes have been shown to flee the noise of approaching vessels, the noise levels involved have not been accurately documented. Hence for this document the lower threshold level of McCauley et al (2003) of 156 dB re 1μPa (msp) for impulse noise (an air gun) is considered to apply for avoidance of fishes to continuous noise.

For continuous, industrial noises Richardson et al (1995) considered the underwater disturbance threshold for great whales to be around 120 dB re 1μPa (msp) based on various studies by Malme *et al.* 1984 (as cited in Richardson et al, 1995) for whales moving around construction facilities in the Canadian Arctic. McCauley et al (2003) found that for travelling great whales the tolenace levels of the whales to impulse noise was generally around 144-151 dB re 1μPa^2.s (SEL).

Assessing the behavioural response of fish and some marine mammals to the ocean outfall generated noise will be complicated by other impacts produced by the outfall activities and the highly variable response to noise amongst different individuals of the same species. For example offshore dredging operations associated with clearing the pipe route will attract many fish species as the seabed disturbance will throw benthic invertebrates into the water column, so attracting fish predators. It is known that many cetaceans show what can only be considered as curious behaviour and are attracted to situations not normally found in the ocean, and so may show an initial attraction to offshore operations. The nature of the ocean outfall construction in that it is fixed spatially and will not move around pursuing animals is a mitigating factor and may lead to many animals habituating to the noise type.

There are mixed data on noise levels that cause TTS or PTS in marine mammals (temporary or permanent hearing threshold shifts). The National Marine Fisheries Service in the US (NMFS) considers that levels above 190 dB re 1μPa (msp) for impulse signals may could cause temporary hearing impairment in harbour seals and sea lions and levels above 180 dB re 1μPa (msp) for impulse signals may cause temporary hearing impairment in whales (Vagle 2003). Based on this, the NMFS has established a safety zone of 180 dB re 1μPa (msp) for impulse signals for grey (baleen) whales.

Lethal impacts on marine animals are only known to occur either from underwater explosives, from nearby pile driving for fish, or for certain marine mammal species from sound induced behavioural responses (ie. beaked whales and military sonars). No underwater explosives are to be used in the water (although they may be used on land or inside the cleared berm, and a non-explosive rock fragmentation technique may be used in the ocean). No pile driving will be used in the construction although driving of sheet piling will occur inside the berm and may be transmitted into the surrounding water. No beaked whales will occur in the area of the ocean outfall and none of the vessels involved will have anywhere near the high powered sonar capability matching the military sonars implicated in beaked whale strandings.

For explosives Hastings and Popper (2005) have attempted to estimate the impulsive noise level likely to cause fish kills from underwater explosives or pile driving impulses. They have used data from a variety of sources and using idealised explosive waveforms standardised the measurement units to estimate the likelihood of fish kills for impulse measures in sound exposure units (dB re 1µPa^2.s) for different sized fish. While the levels vary with fish size no lethal effects were estimated for levels below 190 dB re 1µPa^2.s. McCauley (2006) characterised the five received explosive signals from 40 g charges at 340 m from which we can compare units. The five explosive charges had mean squared pressure units on average 15 dB higher than the sound exposure level units. Extrapolating this to the values presented by Hastings and Popper implies that no fish kills will occur for levels below 205 dB re 1µPa (msp).

For this document the received threshold levels for continuous noise at which set impacts occur, are considered to be:

- 120 dB re 1µPa (msp) the level at which baleen whales will largely avoid the area for continual noise although some individuals may tolerate higher levels for some periods
- 144-151 dB re 1µPa^2.s (SEL) the level at which great whales may avoid continual and approaching impulse noise
- 156 dB re 1µPa (msp) for continual noise or 145 dB re 1µPa^2.s (SEL) for repetitive and approaching impulse noise, the level at which fish will avoid the area
- 180 dB re 1µPa (msp) the level at which TTS may begin to occur in cetaceans
- 190 dB re 1µPa (msp) the level at which TTS may begin to occur in pinnedpeds
- 205 dB re 1µPa (msp) for continual noise or 190 dB re 1µPa^2.s (SEL) for impulse noise the level at which we may begin to expect to see fish kills from explosive or pile driving like signals

4.3 Noise impacts of offshore construction

The predicted underwater sound levels for offshore construction activities are primarily believed to be produced by vessel operations. The most persistent noise sources will be those associated with vessel either manoeuvring or from the stationary barge or work vessels. Figure 10 gives the estimated transmission of a variety of noise sources from the ocean outfall vicinity which are likely to be encountered during construction.

From the predicted transmission of noise likely to be produced by offshore operations we can predict that for baleen whales the 120 dB re 1µPa (msp) level, or that at which a proportion of baleen whales may avoid the area, may be reached at anywhere between 200 m to 3 km from the operations. It should be noted that the highest noise levels in the estimated sound transmission curves and thence the highest ranges for baleen whale avoidance, derive from vessel manoeuvring noise. The amount of time vessels are engaged in manoeuvring noise is typically low, they manoeuvre to carry out some function then either leave or go to anchor. While service vessels are idle or at anchor the noise signature from the ocean outfall operations will be dominated by the barge noise, which will have an underwater sound field as shown on the two lower plots of Figure 9. The barge only noise has an expected 120 dB re 1µPa (msp) contour occurring at around a few hundred m to one km. Thus if we consider that in an average working day the manoeuvring noise takes place for an hour out of a ten hour working day, then the range at which most whales will tolerate the ocean outfall construction will be from a few hundred m to a km, with perhaps during 10% of daylight hours when works are in progress this range increasing to as much as 3 km. These ranges of avoidance ignore initially curious whale encounters (ie. whales which may move closer to operations out of curiosity). The expected density of baleen whales in the vicinity of the ocean outfall will be low even if the construction activities occur during the known period of baleen whale visitation of late Autumn to early Spring for southern right and perhaps humpback whales.

Thus taken together the range of tolerance of most baleen whales to the ocean outfall offshore construction activities will normally be from a few hundred m to perhaps one km, with the range possibly increasing for short durations during periods of intense vessel activity. There is expected to be a comparatively low interaction rate of baleen whales with the ocean outfall construction.

For fish the normal underwater signals produced during outfall offshore construction activities are not believed sufficient to produced continual avoidance except within 100 m of the higher level noise sources. The 156 dB re 1μPa (msp) threshold will only be found at around 100 m for the highest level activities modelled (vessel manoeuvring) and will not occur for the stationary barge activities. Thus for fish the modelled sound field suggest little avoidance of the area due to underwater noise and in all probability some fish will be attracted into the area due to disturbances of the seabed increasing prey availability.

Toothed whales nearby to the ocean outfall construction will be little impacted by underwater noise as all of the dominant noise sources likely to be used have little energy above one kHz and so overlap poorly with their hearing capability.

While penguins and pinnipeds will detect the noise generated during ocean outfall offshore underwater construction activities the comparatively low levels of even the highest noise types (ie. Figure 10) suggest they will be little impacted directly. The suggestion that their hearing capabilities tend to have an optimal frequency range tending into the kHz suggests they will have a comparatively poor overlap with the energy content of most sources associated with the ocean outfall further suggesting they will be little impacted.

Given the low potential for avoidance of the ocean outfall offshore construction activities by fish then toothed whales, penguins and pinnipeds are unlikely to be influenced by any shift in their fish prey availability due to ocean outfall construction activities.

4.4 Noise impacts of berm construction

Non explosive activities

The estimates of maximum likely levels of sound in the water column produced by impact sheet piling carried out inside the berm and transmitted via the seabed into the water column surrounding the berm are 198, 180, 166, 150 and 123 dB re 1μPa (msp) at 50, 200, 500, 1000 and 2000 m range (respectively). These ranges assume optimum coupling of the sheet piling noise into the seabed and maximum efficiency in conversion of the seabed transmitted energy into waterborne noise energy. The range for the signal to reach various levels suggests:

- During periods of impact sheet piling baleen whales may keep away from the berm by near to 2 km (2.1 km according to the decay curve);
- Fish behaviour may be altered out to 780 m from the berm (range to reach 156 dB re 1μPa msp);
- Great whales within 200 m of the sheet piling (ie. immediately adjacent the berm wall) may receive levels sufficient to cause TTS
- No animals will receive signal levels sufficient to cause any serious physiological impacts

It is unlikely that penguins, pinniped and Odontocetes will respond overtly to sheet piling as so much of the signal’s high frequency energy is stripped away so rapidly by the seabed that the high frequency hearing of these animals will overlap poorly with the received signal energy content.

Impact sheet piling is the only activity to be carried out inside the berm, apart from explosives (discussed below), which is believed to create significant noise levels in waters surrounding the berm.

Explosives used inside the berm

The estimates of maximum likely levels of sound in the water column produced by small explosive rock breaking charges set inside the berm and transmitted via the seabed into the water column surrounding the berm are 206, 194, 178 and 161 dB re 1µPa (msp) at ranges of 50, 200, 500 and 1000 m respectively. These estimates are considered to be high as the efficiency of transferring sound energy travelling in the seabed into the water column was not known and considered to be a worst case scenario of the sound leaving the seabed at normal incidence (ie. perpendicular to the seabed / water interface) which will not be the case.

The estimated levels of explosives used inside the berm and transmitted outside the berm exceed the thresholds at which TTS may begin to occur for marine mammals at around 500 m or less. Thus it would be prudent for a marine mammal watch to be kept when using explosives inside the berm and these used only if no marine mammals are within 500 m of the berm wall.

The estimated received levels suggest fish outside the berm wall may be injured at 50 m or less from the explosive charge (received levels exceeding 205 dB re 1µPa). Given that most charges will be back inside the berm some distance (that is they may be 20 – 100 m from the water anyway), the overly conservative estimates of received noise level (erring on the high side), and that the ground will act to alter the explosive signal shape (which plays a significant part in the ability of explosive or pile driving signals to cause physical damage) then while there is some probability of injury to fish found close to the berm wall, this is considered to be low.

The frequency of the use of explosive charges inside the berm will be so low (a handful of charges used over several days) that although each charge detonation may induce some behavioural changes in nearby marine animals, the significance of these behavioural shifts in the long term will be negligible.

4.5 Noise impacts of in-water rock fracturing using non-explosive cartridges

The use on the non-explosive rock fracturing cartridges outside of the berm is currently not known and will depend on how well conventional techniques with a barge mounted excavator can deal with the rock. Conversations with the proponents has led us to believe that if these cartridges are used they will only involve a small number of rocks to be removed and so a small number of cartridges.

The predicted received levels of the rock fracturing cartridges were given in Table 5 and the trend of received level with range shown on Figure 19. Even at the highest levels predicted at 10 m range from the cartridge the predicted impulse levels are below the maximum impulse measures expected to cause fish kills. For cetaceans the range at which TTS or hearing threshold shifts may begin to occur is within 20 m of the cartridge and this only for the 500 g cartridge. The 100 g cartridge will not produce an impulse sufficient to cause TTS (according to the thresholds specified) and the 200 g cartridge may only reach levels sufficient to cause TTS at < 10 m range from the cartridge firing point.

The rock fracturing cartridges may produce modest impulse pressures for comparatively long ranges. For example the signals do not decay to 144-145 dB re 1μPa^2.s until 1-10 km from a cartridge (pending cartridge size and the respective bathymetry path, Figure 19). At this level for a continual (pulse every ~10 s) and approaching impulse source, fish and great whales have been observed to show behavioural changes culminating in avoidance. But, the use of the rock fracturing cartridges will not involve repetitive nor approaching signals. It is likely only a handful of cartridges will be fired within a short space of time, then none until the following day (if required) when excavation of debris from the previous cartridge firing and drilling preparation for the next, have taken place. This is a considerably different scenario to that at which avoidance behaviours have been seen for approaching impulsive signals of air guns. Thus the behavioural responses of nearby animals to the use of the cartridges will likely consist of short term startle responses only, with the levels reached not sufficient to cause any physiological impacts.

5 Summary

The results are summarised as:

- Estimates of transmission of vessel and barge noise, non-explosive rock popping charges used in the water and the noise of sheet piling and explosives to be used inside a dry berm have been calculated. These sources are considered to be the primary noise sources involved in the ocean outfall construction, from the point of view of maximum levels likely to be encountered (explosive and non-explosive charges, sheet piling) and persistence (vessel noise). While other noise sources will be involved in the construction process they either will not be as persistent in time or produce lower overall sound levels. Thus the ranges and recommendation for the noise sources modelled can be considered as covering all scenarios involved in the outfall construction.
- Vessel noise sound transmission estimates were made using a source emulating a noisy working barge and various states of vessel manoeuvring noise, for the offshore ocean outfall site on eight equally spaced headings about the source. The levels of the stationary barge reached at 50, 200, 500 and 1000 m were 128-148, 120-137, 115-131 and 112-127 dB re 1μPa respectively, with the level ranges due to differing bathymetry paths. The levels of modest manoeuvring noise reached at 50, 200, 500 and 1000 m were 130-142, 128-135, 123-129 and 117-128 dB re 1μPa respectively with the ranges given by differing bathymetry paths.
- Predictions of sheet piling and explosive noise produced inside a berm pumped dry and transmitted via the seabed into surrounding waters were made. These levels were considered high given the assumptions made. The levels of 40 g explosive charges reached in the surrounding water at 50, 200, 500 and 1000 m were 206, 194, 178 and 161 dB re 1μPa respectively. The levels of impact sheet piling reached in the surrounding water at 50, 200, 500 and 1000 m were 198, 180, 166 and 150 dB re 1μPa respectively. High frequency energy of the source was rapidly attenuated by the seabed thus all signals appearing in the water column outside the berm had most energy below a few hundred Hz.
- The source signature of 100, 200 and 500 g slow-burn, non-explosive rock fracturing cartridges were predicted using a physics based model. These source signatures were mated with sound transmission modelling to give estimated received levels for the cartridges used in 36 m depth water. The levels of the cartridges reached at 50, 200, 500 and 1000 m were 172-176, 165-168, 159-163 and 155-160 dB re 1μPa^2.s respectively, with the level ranges due to differing bathymetry paths. Levels of the smaller cartridge weights are given in Table 5.
- The range at which most great whales may avoid the area of offshore construction is estimated to lie between 200 m to 3 km from typical construction activities, with the higher ranges correlating with periods of the noisiest activities. With only the barge operating the range for

great whale avoidance is estimated at 200 m to one km. Some great whales may approach close to construction activities due to curiosity or habituation to the construction activities.

- For fish only the highest levels of noise generated during offshore construction may lead to avoidance and this only from a few hundred m about the noise source.
- It is believed that toothed whales, penguins and pinnipeds will be little impacted by offshore construction as most of the noise source swill poorly overlap their hearing capability
- During periods of sheet piling inside the berm great whales may keep away from the berm out to 2 km and fish behaviour may be altered out to 800 m from the berm during sheet piling. No marine animals will receive sound loadings sufficient to cause physiological harm from sheet piling noise.
- Small explosive charges used inside the berm to fracture rock may cause temporary threshold shifts in marine mammals out to 500 m outside of the berm and would not be sufficient to harm fish except any immediately adjacent the berm wall and then only in worst case scenarios (all the assumptions used are met and the explosive signal shape remains suitable). All behavioural impacts on animals outside of the berm from the use of explosive charges inside the berm will be of short duration and given the low duty cycle of use, of little to no long term significance to the animals concerned.
- The rock fracturing charges used outside the berm wall in the water, will not be capable of producing any serious physiological impacts on nearby marina animals, except possibly at very short (< 10 m) range. Cetaceans will need to be within 20 m of a large cartridge to receive a sound loading sufficient to cause any temporary hearing impairment. Like the use of explosives inside the berm, the frequency of use of the non-explosive rock-fracturing cartridges will be low with long breaks (many hours to days) between consecutive use. Hence the significance of any behavioural response to the cartridges will be low to neglible.

6 Recommendations

The following recommendations are made based on the findings presented:

- For certainty and allowing for the many unknowns in estimating the noise levels of the Nonex cartridges, to allow a buffer range of 50 m around the site of any cartridge firing point, within which no penguins, pinnipeds or marine mammals occur. Some allowance may need to be made for any individual pinnipeds which persist in keeping in close proximity to cartridge operations for whatever reasons.
- That a marine mammal watch be organised during periods when sheet piling or explosive activities are to be carried out inside the berm and that these activities are suspended if great whales are within 500 m of the berm.
- A large portion of the authors time has been spent in attempting to estimate noise levels for various sources not previously measured. This included the non-explosive rock fracturing charges and the use of equipment and explosives inside a breakwater but potentially coupled via the seabed to the ocean. A large number of potentially dubious assumptions (always environmentally conservative) have had to be made in order to estimate received sound levels from these sources. It would be of considerable benefit if such activities could be measured in-situ to assist in future assessments of environmental impacts of similar activities. This could be done relatively easily by deploying a noise logger near the site and simply letting it run over the duration of construction activities (ie. un-attended),

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