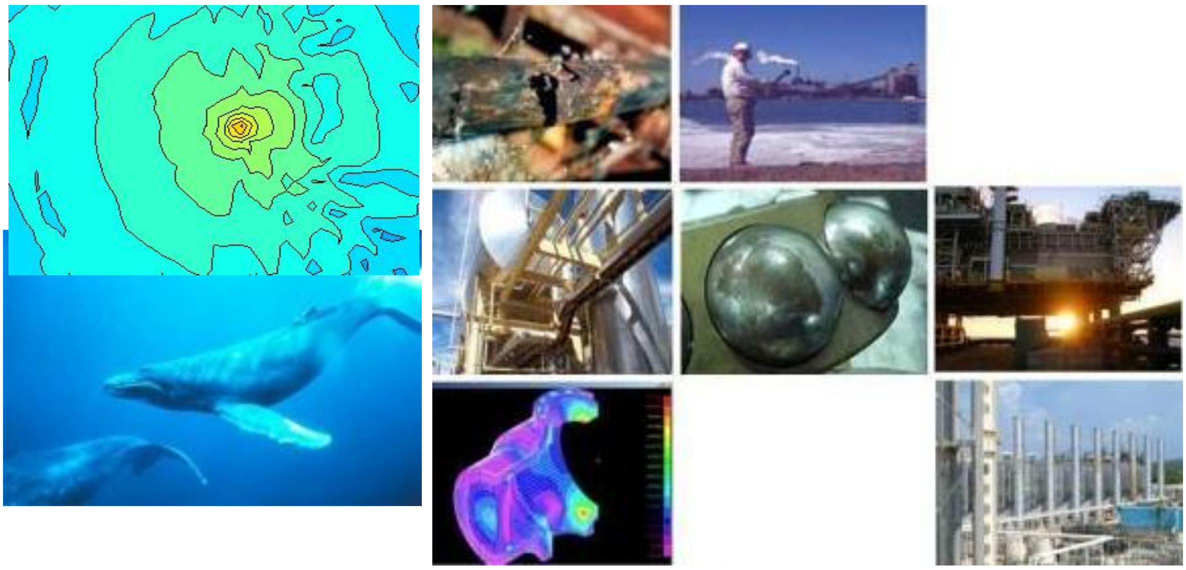
SVT ENGINEERING CONSULTANTS

TECHNICAL NOTE

Woodside Browse Downstream Development

UNDERWATER NOISE MODELLING: PILE DRIVING



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1. INTRODUCTION

SVT was commissioned by Environmental Resources Management (ERM) under the Consolidated Environmental Services (CES) contract for Woodside Energy Limited (Woodside) to perform underwater noise modelling for activities associated with the Browse Liquefied Natural Gas (BLNG) Precinct Development in 2010. The modelling was presented in the Strategic Assessment Report (SAR) for the BLNG Precinct Development (DSD 2010)[1]. Two errors have since been identified with the pile driving modelling conducted for the SAR. The errors identified are as follows:

1. An error in the presentation of the pile-driving source level as a Power Spectral Level (dB re 1 µPa/Hz) was incorrectly implemented as third octave band levels in the SAR modelling. This resulted in an under-estimation of predicted received levels at ranges >100 metres.
2. A curve fitting error in the SAR modelling resulted in the over-estimation of predicted levels at closer ranges (<100 m). Curve fitting was necessary during the SAR modelling as the model resolution at the time was not fine enough to predict close range levels.

The errors in the pile driving scenarios did not occur in the other scenarios modelled for the SAR (i.e. blasting, dredging and shipping). The errors are therefore localised to the pile driving scenarios only and the other modelling scenarios presented in the modelling conducted for the SAR are accurate.

The purpose of this technical note is to present revised underwater noise modelling for pile driving associated with the proposed Browse LNG Downstream Development (Downstream Development). The modelling outputs will be used by Woodside to inform the underwater noise assessment for the proposed Downstream Development, to be assessed through a Referred Proposal.

The modelled pile driving scenario in this technical note is comparable to the pile driving scenario used in the modelling conducted for the SAR. However, the revised modelling uses updated seabed geotechnical and bathymetry data and a revised source level based on a wider literature review to best reflect the predicted sound levels from pile driving associated with the proposed Downstream Development.

1.1 Background

Woodside is the foundation proponent of the proposed BLNG Development on behalf of the Browse Joint Venture. The BLNG Development will recover natural gas and condensate resources from the Browse Basin gas fields (Torosa, Brecknock and Calliance) that are located offshore, approximately 450 km north-north-west of Broome, in the Kimberley region of Western Australia. Subject to government approvals, onshore site investigations and other technical studies, Woodside plans to build an onshore gas processing facility within a State-Government-approved gas-processing LNG Precinct near James Price Point, 60 km north of Broome on the Dampier Peninsula. The BLNG Precinct is designed to be a multiple-user Kimberley gas hub and has been defined in a Strategic Assessment Report (SAR) released by the Department of State Development (DSD) in 2010.

Marine facilities required for the proposed Downstream Development include product loading berths, a material offloading facility, a small vessel harbour, product and utility pipelines and other

[1] Department of State Development (DSD) 2010, *Browse Liquefied Natural Gas Precinct —Strategic Assessment Report, Part 1 through to Part 6 inclusive,* Department of State Development, Perth, Western Australia, December 2010.

facilities supporting the offshore Browse gas infrastructure. Construction activities may involve the use of marine piling, blasting, dredging, rock dumping and various work vessels.

In 2010 SVT developed an underwater model for the DSD Strategic Assessment Report (SAR). The modelling completed for the SAR simulated marine piling, blasting, dredging and vessel movements.

1.2 Aim

The aim of this study was to perform revised underwater noise modelling for pile driving associated with the proposed Browse LNG Downstream Development.

1.3 Quantifying Sound Levels

A variety of parameters are used in underwater acoustics to define steady-state and impulsive signals. Some of the important definitions (See also Appendix B) are as follows:

- Sound Pressure Level (SPL) Root Mean Square (RMS) - units dB re 1 µPa. The RMS pressure is the decibel value of the root mean of the squared pressure over a defined period of a signal.
- Sound Pressure Level (SPL) Peak - units dB re 1 µPa (0-Pk). Peak pressure is the maximum recorded pressure and is measured from the mean of the signal to the maximum excursion from the mean.
- Sound Exposure Level (SEL) - units dB re 1 μPa^2.s. Sound exposure level is a measure of energy with the dB level of the time integral of the squared-instantaneous sound pressure normalized to a 1-s period. For impulsive signals, such as pile-driving noise, the averaging time is a significant consideration. Impulsive signals are better described by a measure of SEL and a measure of the signal peak pressure.

1.4 Pile Driving Description

Piles can be driven using various methods, such as vibration, gravity and hammer. The method that is used depends on the size of the pile and the substrate into which the pile is being driven. It is anticipated that piles will be driven by hydraulic impact hammers for the construction of the proposed Downstream Development.

Pile-driving operations involve hammering a pile into the seabed. The noise emanating from a pile during a pile-driving operation is a function of its material type, its size, the force applied to it and the characteristics of the substrate into which it is being driven. The duration of the noise that is generated by an impact hammer hitting the top of the pile is short. It lasts approximately 100 ms and can, therefore, be described as impulsive noise. It is assumed that the acoustic centre of the noise source is at the mid-point of the water column, due to the implied directional propagation of radiated energy from in-phase modal excitation along the pile.

The action of driving the pile into the seabed will excite bendy waves in the pile that will propagate along the length of the pile and then into the seabed. A bendy wave consists of a compression wave and a transverse wave. The transverse wave component of the waves will create compressional waves that will propagate into the ocean, and the compressional component of the bendy waves will propagate into the seabed. There will also be some transmission of the airborne acoustic waves into the sea. It can be expected that most of the energy from the hammering

action of the pile driver will transfer into the seabed. Once in the seabed, the energy will then propagate outwards as compressional and shear waves. Some of the energy may be transferred into Rayleigh waves, which are seismic waves that form on the water/seabed interface, but it is expected that these will account for a small portion of the total wave energy.

2. METHODOLOGY

2.1 Underwater Noise Modelling

Underwater noise propagation models use bathymetric data, geoacoustic information and oceanographic parameters as inputs to produce estimates of the acoustic field in the water column at any depth and distance from the source. The accuracy of the environmental information used in the model is critical for the model's predictions. The geoacoustic parameters of the seabed, particularly the seabed layer structure, the compressional and shear sound velocities for each layer material, and the corresponding sound attenuation coefficients, can affect the acoustic propagation and can, therefore, affect the accuracy of the model's predictions.

2.1.1 Model Selection

Various numerical techniques are used to develop underwater acoustic propagation models, including wavenumber integration, ray theory, normal modes, parabolic equation (PE) and finite differences/finite elements. When determining which model is to be used for the modelling prediction, it is necessary to define the application for which it is to be used and the type of underwater environment it is going to simulate. For the model applied in this assessment, the underwater environment has the following characteristics:

- strong range dependence
- a shallow water ocean environment
- differing bottom types.

Parabolic Equation (PE) models are capable of making predictions in various conditions: shallow water, areas that have changing bottom types and under environmental conditions that are range dependent. A PE model called the Monterey Miami Parabolic Equation (MMPE) model was selected. This was selected because it has been benchmark-tested for shallow water environments at the Shallow Water Acoustic Modelling (SWAM 99) Workshop, where the performance of numerous models in a variety of shallow water environments were tested. The PE model is a well recognized algorithm for transmission loss prediction and is widely used in the field of underwater acoustics. SVT have validated the model in multiple instances, for example: seismic survey modelling in Bassett Field (SVT for Total, 'Underwater Noise Modelling Validation and Results for 3D Seismic Survey in Bassett Field', 2010, Job Ref: 1052786-3-200), pile driving in Cape Lambert B (SVT for SKM, 'Underwater Measurements of CLB Pile Driving', 2011, Job Ref: 1052908-1-200) and Shark Bay Resources in Shark Bay.

The MMPE is a broadband model, and makes use of transmission loss calculations at multiple frequencies. With higher frequency comes greater computational overhead, and therefore to speed up the modelling process an upper-bound on frequency must be chosen. SVT chose to consider from 63 Hz to 8 kHz, which is viewed considered as being very reasonable since most of the pile energy is in the first 2 kHz. This is a standard approach that has been followed by others such as the Centre for Marine Science and Technology (CMST) at Curtin University.

Furthermore, the absorption of sound in sea water increases significantly with high frequencies. Jensen et al[2]. provide the well-recognised expression for the frequency dependence of attenuation (see equation 1), where α is the attenuation in dB/km and f is the frequency of the sound in kHz.

$$\alpha = (3.3)(10^{-3}) + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + (3.0)(10^{-4}) \qquad (1)$$

Using this equation will result in 4.1 dB/km attenuation for a sound wave at 20 kHz, compared to 0.8 dB/km at 8 kHz and 0.1 dB/km at 2 kHz.

2.1.2 Data and Model Limitations

The following data and model limitations need to be noted:

1. **Rough Surface Scattering**. Acoustic wave scattering due to the roughness of sea surface and seabed is not accounted for in the model.

2. **Salinity and Sound Speed Profiles**. Sound speed profiles in a water column are a function of temperature, salinity and pressure. As the water depth in the modelling area is relatively shallow it has been assumed that the water column is isothermal. Salinity is expected to have negligible effect on the sound speed profile. Variation in the model's sound speed profile has therefore been limited to the effects of water column pressure

2.2 Modelling Inputs

2.2.1 Environmental Inputs

The following environmental conditions were entered into the model:

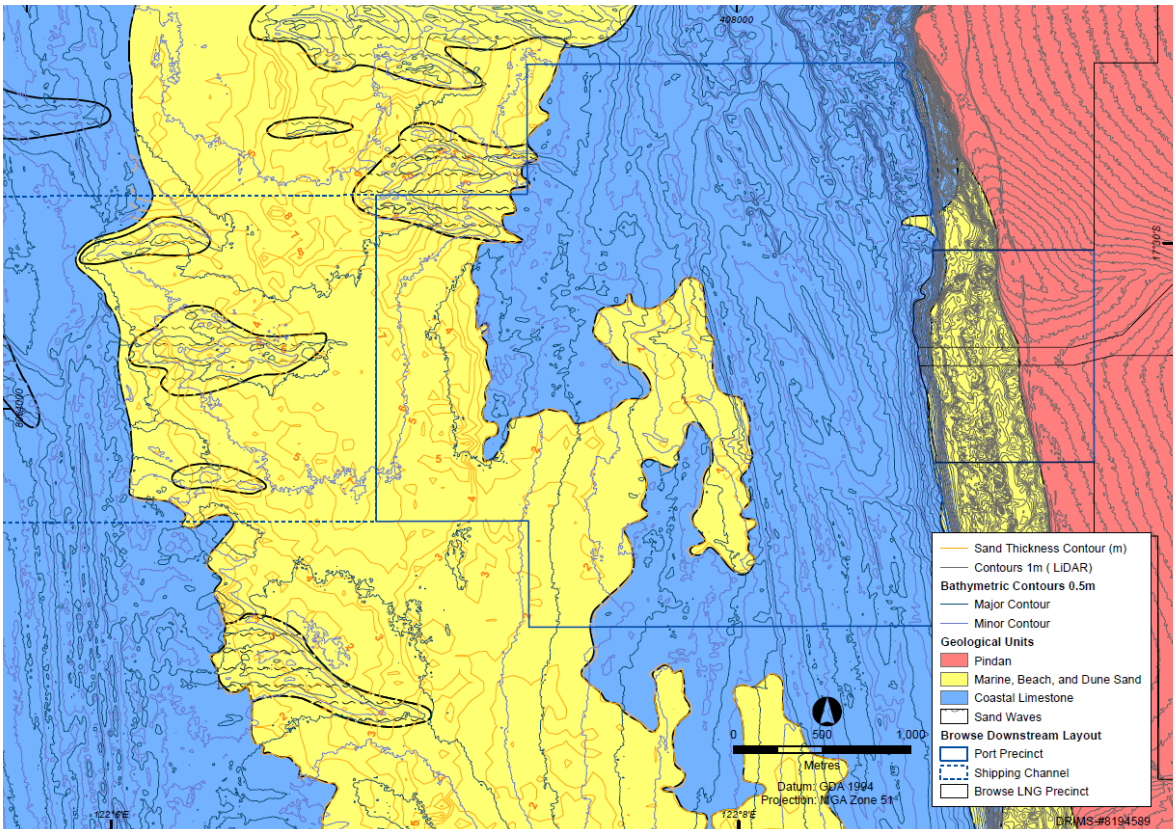
1. **Tide Level**. Tides near the James Price Point coastal area are semi-diurnal (two highs and two lows each day), with tidal sea-surface height variability in excess of plus or minus (±) 4 m. In all cases for this study the Highest Astronomical Tide (HAT) was used. Depth has a strong correlation with received sound levels underwater and the use of HAT is conservative given that HAT occurs very infrequently.

2. **Seabed Types**. Based on geophysical survey results supplied to SVT by Woodside (Figure 2-1), the seabed features in the nearshore survey area off James Price Point are mainly coastal limestone (calcanerite), marine, beach and dune sands, and pindan rock (see Figure 2-1). The geoacoustic properties of the seabed types used in the model are as described in Table 2-1.

3. **Sound Speed Profile.** Shallow water (i.e. < 20 m) in the Pilbara area has been found to be more or less isothermal for the entire water column. As a result, the sound speed profile in the nearshore James Price Point coastal area is assumed to be isothermal with a constant temperature of 23 ºC and a constant salinity of 35 ppt. An isothermal temperature change of a few degrees Celsius in a shallow water environment less than 30 m is assumed to have a negligible effect on the received levels of sound. For instance, increasing the isothermal water temperature from 23 ºC

[2] Jensen et al. *Computational Ocean Acoustics,* Springer, New York, 2000.

to 28 ºC would result in an increase in the sound speed below the surface but not a change in the sound speed gradient.



Geological Units: Pindan; Marine, Beach and Dune Sands; Coastal Limestone; Sand Waves

Figure 2-1 Bottom type data provided to model with Downstream Development overlay.

Table 2.1 Geophysical seabed properties used in the model for each seabed type

Type	Sound speed (m/s)	Density (g/cm^3)	Compressional Attenuation (dB/m/kHz)	Shear Attenuation (dB/m/kHz)	Shear Speed (m/s)
Basalt[3]	5250	2.70	0.100	0.200	1500
Coastal Limestone (calcanerite)[4]	2850	2.79	0.100	0.200	1400
Marine, beach and dune sands (silty sand)4	1600	1.80	0.900	2.5	100
Pindan (rock)3	374	2.05	150	150	374

[3] Jensen et al. *Computation Ocean Acoustics*, Springer, New York, 2000.

[4] C P Salagado Kent, R D McCauley, A J Duncan, 'Environmental impacts of underwater noise associated with harbor works, Port Hedland', Centre for Marine Science and Technology Curtin University, 2009.

2.2.2 Modelling Scenario

Pile-driving barges are expected to be operating at berths and access jetties in the integrated marine facility (IMF) with up to three piling barges operating simultaneously. The modelling assumes that the pile barges are approximately 400 m apart. A pile-driving scenario of three 900-1500 mm diameter piles being driven by hydraulic impact hammers of up to 470 kJ was modelled as a conservative estimate for a 40 t hammer. The pile-driving scenario is consistent with the SAR, with the exception of a slight increase in pile diameter and a revised source level – both of which are based on updated information (see 2.2.3).

2.2.3 Estimation of Piling Source Level

To predict received noise levels from pile driving, the underwater noise model (which calculates transmission loss) requires source levels of the noise source and the source locations.

Source level calculations are an estimation of the sound pressure level at 1 metre from the acoustic centre of the noise source. They are usually extrapolated from a far-field measurement. Accurate source level estimates may require a large set of measured data.

The spectral content and source level of the piling operation was based on published data[5] of measured results for piling using a 49 kJ hammer (recorded at a mid-water receiver depth of 13 m, and a distance of 21 m); this was scaled to 470 kJ using an energy relationship. The variables that may affect the source level estimation of a pile are pile wall thickness, hammer energy, pile diameter, resistivity of seabed material, pulse repetition rates and pulse duration. Each of these variables remained consistent with the modelling conducted for the SAR, except for the pile diameter, which increased slightly from 900–1200 mm in the SAR, to 900–1500 mm in the revised modelling to best reflect potential engineering parameters to be applied in construction.

It is assumed that the hammer energy level rather than the pile diameter, will dominate the source level, and therefore the source level for 900-1200 mm diameter piles (as presented in the SAR) or 900-1500 mm diameter piles (as modelled in this report) are considered comparable. The resulting single pulse SEL source level used in the model in this report is 209 dB re 1 μPa^2.s, compared to 205 dB re 1 μPa^2.s in the SAR. This revised source level is based on a wider review of available literature on noise levels from pile driving5.

2.2.4 Noise Source Locations

Pile-driving barges are expected to be operating at berths and access jetties in the integrated marine facility (IMF). The assumed locations of three simultaneously operating piling operations for the purposes of the modelling are outlined in Table 2-2 and Figure 2-3. The locations were chosen to be consistent with the locations modelled in the SAR and provide only an approximate location of proposed pile driving barges.

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[5] C P Salagado Kent, R D McCauley, A J Duncan, 'Environmental impacts of underwater noise associated with harbor works, Port Hedland, Centre for Marine Science and Technology Curtin University, 2009'.

Table 2.2 Noise source locations for pile-driving barges

Source	Easting	Northing
Pile Driving 1 – Near IMF	407069 m	8064082 m
Pile Driving 2 – Near IMF	406952 m	8064457 m
Pile Driving 3 – Near IMF	407285 m	8064849 m

2.2.5 Modelling Source Depths and Characteristics

The depths of the noise sources were determined by estimating their acoustic centre, and the source level and spectrum taken from the available literature or an empirical formula.

The depths of the pile-driving noise sources were determined by estimating their acoustic centre, as listed in Table 2-3. The depth of the acoustic centre level for each pile varies due to a dependence on water depth. The source spectrum levels of the source used in the model are given in Appendix A.

Table 2.3 Noise source depths and characteristics for pile-driving barges

Source	Source Depth	Source Characteristics
Pile Driving 1 – Near IMF	7 m above seabed	See Figure A-1 in Appendix A
Pile Driving 2 – Near IMF	7.5 m above seabed	See Figure A-1 in Appendix A
Pile Driving 3 – Near IMF	6.7 m above seabed	See Figure A-1 in Appendix A

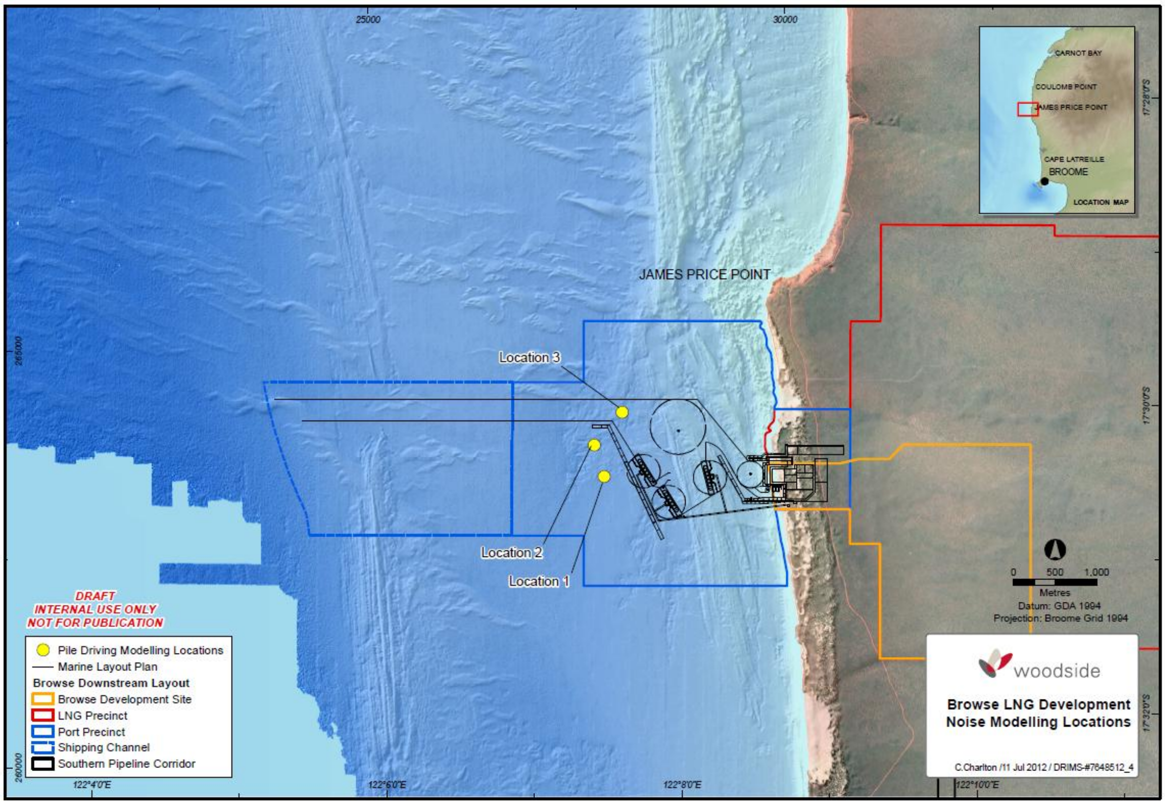

Figure 2-2 BLNG Development Precinct Port Area with conceptual port layout and locations of pile driving modelling in this report.

2.3 Frequency Range

The frequency range used in the model was from 63 Hz to 8 kHz. This frequency range was chosen as most of the pile energy is in the first 2 kHz. This frequency range is consistent with what has been used by others such as CMST at Curtin University[6]. Absorption of sound in sea water also increases significantly with higher frequencies. Noise sensitive receptors including cetaceans and dugongs have broad frequency ranges however, the range used in the model is expected to cover the expected frequency range of the major noise energy produced by pile driving operations that might impact these species. More information on the auditory sensitivity of marine mammals is provided below.

2.3.1 Auditory Sensitivity of Marine Mammals

Cetaceans (whales, dolphins) and dugongs have typical mammalian ears that consist of a middle ear and cochlea. Ears are the organs most sensitive to pressure and, therefore, to injury. Severe damage to the ears can include damage of the tympanic membrane, fracture of the ossicles, cochlear damage, haemorrhage, and cerebrospinal fluid leakage into the middle ear.

[6] C P Salagado Kent, R D McCauley, A J Duncan, 'Environmental impacts of underwater noise associated with harbor works, Port Hedland, Centre for Marine Science and Technology Curtin University, 2009'.

As low-frequency cetaceans, humpback whales produce a complex set of vocalised song patterns. The spectrum of the patterns has been measured to be between 20 Hz and 24 kHz, with a maximum peak-to-peak source level of 184 dB re 1 μPa @ 1m [7]. In the absence of more detailed information on the hearing of humpback whales from the literature, it can be assumed that this bandwidth and source level is indicative of the whales' auditory bandwidth and auditory sensitivities.

Dolphins are mid-frequency cetaceans, which have hearing over a wide range of low to very high frequencies. According to the combined available research results, mid-frequency cetaceans have lower and upper frequency limits of nominal hearing at approximately 150 Hz to 160 kHz respectively[8].

Dugongs are also mid-frequency marine species. The hearing frequency range for dugongs is from 400 Hz and 46 kHz[9], with the most sensitive range between 1 kHz and 8 kHz.

Frequency-selective weighting may be employed to measure sound pressure or energy in a specific frequency band of sound, with emphasis or de-emphasis on particular frequencies as a function of the relative sensitivity of a receiver. A frequency M-weighting will be applied to the modelled spectra at the receiver based on the species classification (low, mid or high-frequency)[8]. The result will represent the effective received sound level for that species. The M-weightings are shown graphically in Figure 2-3. When applied, these weightings will reduce the received level by reducing levels in frequency bands which species are not as sensitive to (by the amount dictated in the M-weighting curve) – in a similar manner to the A-weighting curve for humans.

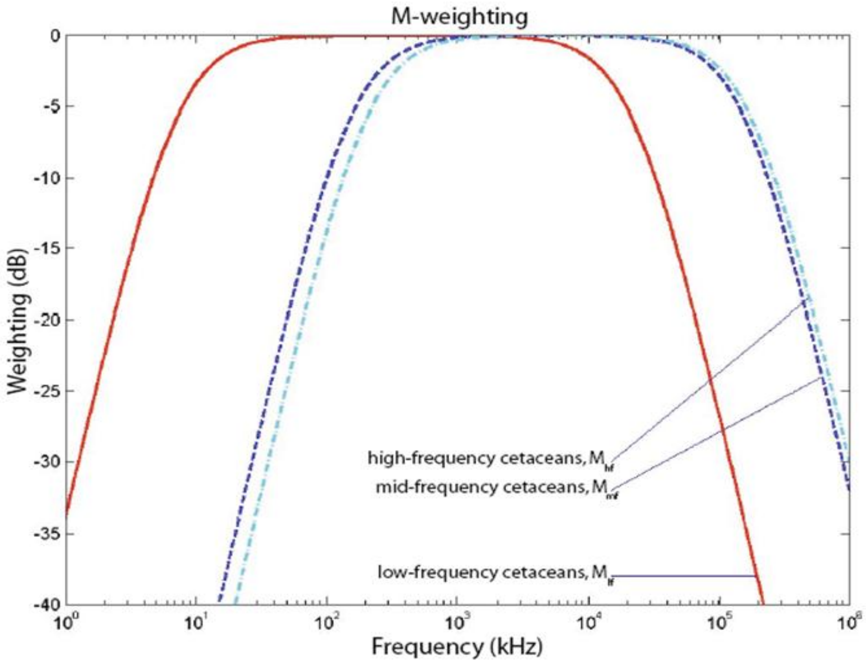

Figure 2-3 The M-weighting functions for low-, mid-, and high-frequency cetaceans.

[7] Whitlow *et al*, 'Acoustic properties of humpback whale songs', JASA, 120(2), Aug 2006.

[8] Southall *et al*, 'Marine mammal noise exposure criteria: initial scientific recommendations', *Aquatic Mammals*, Volume 33, Number 4, 2007, ISSN 0167-5427

[9] J Nedwell, 'Fish and Marine Mammal Audiograms: A summary of available information', Subacoustech Ltd. 2004.

3. MODELLING RESULTS

Contour plots of received levels are provided for a depth of two metres, which was chosen under the assumption that noise sensitive receptor species such as cetaceans and dugongs will spend most of their time within the first couple of metres of the water column. For pile driving, the cumulative SEL level is presented as a function of the exposure duration in addition to the single strike SEL. Therefore, the range changes with the length of exposure. All plots shown have an M_{lf} (low frequency cetacean) weighting applied to the received level as this is the worst-case scenario for the given noise sources (see Section 2.3).

Figure 3-1 and Figure 3-2 show the predicted SEL for a single pulse with all three piling barges operating simultaneously. Figure 3-2 and Figure 3-3 present the SEL noise contour for 10 seconds of continuous pile-driving operation using three pile barges. Figure 3-5 and Figure 3-6 present the SEL noise contour for 10 minutes of continuous pile-driving operation using three pile barges. Figure 3-7 and Figure 3-8 present the SEL noise contour for 3 hours of continuous[10] pile-driving operation in 24 hours using three pile barges. As can be seen from these figures the longer that a marine mammal is exposed to pile-driving pulses the higher the SEL value will be. As a result the time of exposure must be considered when determining the zones of possible injury and behavioural disturbance. An intermittent piling operation of three hours total piling has the equivalent SEL contour as three hours of continuous piling, since in each case the same amount of sound energy accumulates.

Figure 3-9 and Table 3.1 present the predicted SEL as a function of distance and exposure time for the operation of three piles.

[10] Due to the nature of SEL the same level will be achieved over a 24 hour period if the piling is not continuous.

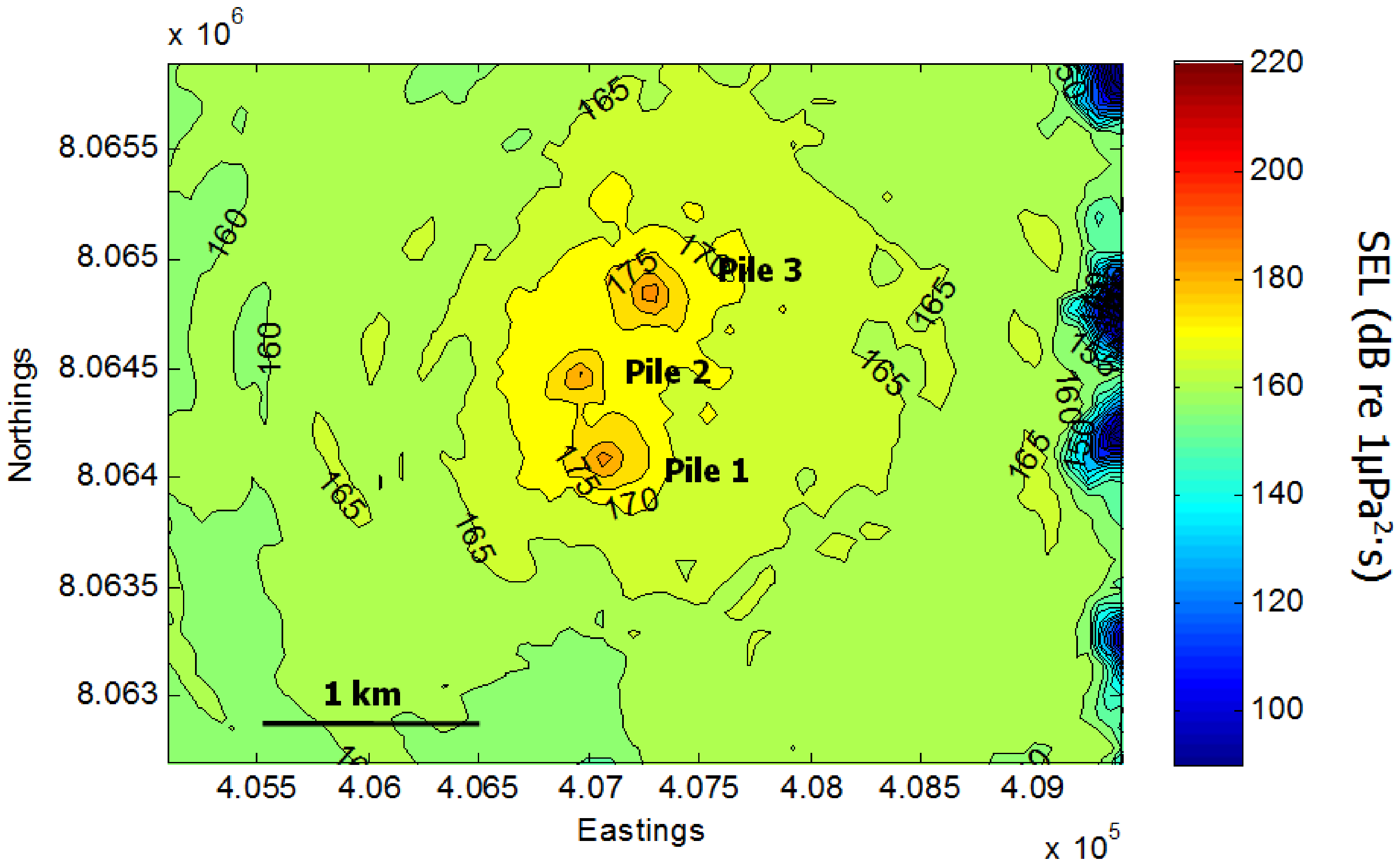

Figure 3-1 Single pulse SEL contour plot for three pile barges operating simultaneously.

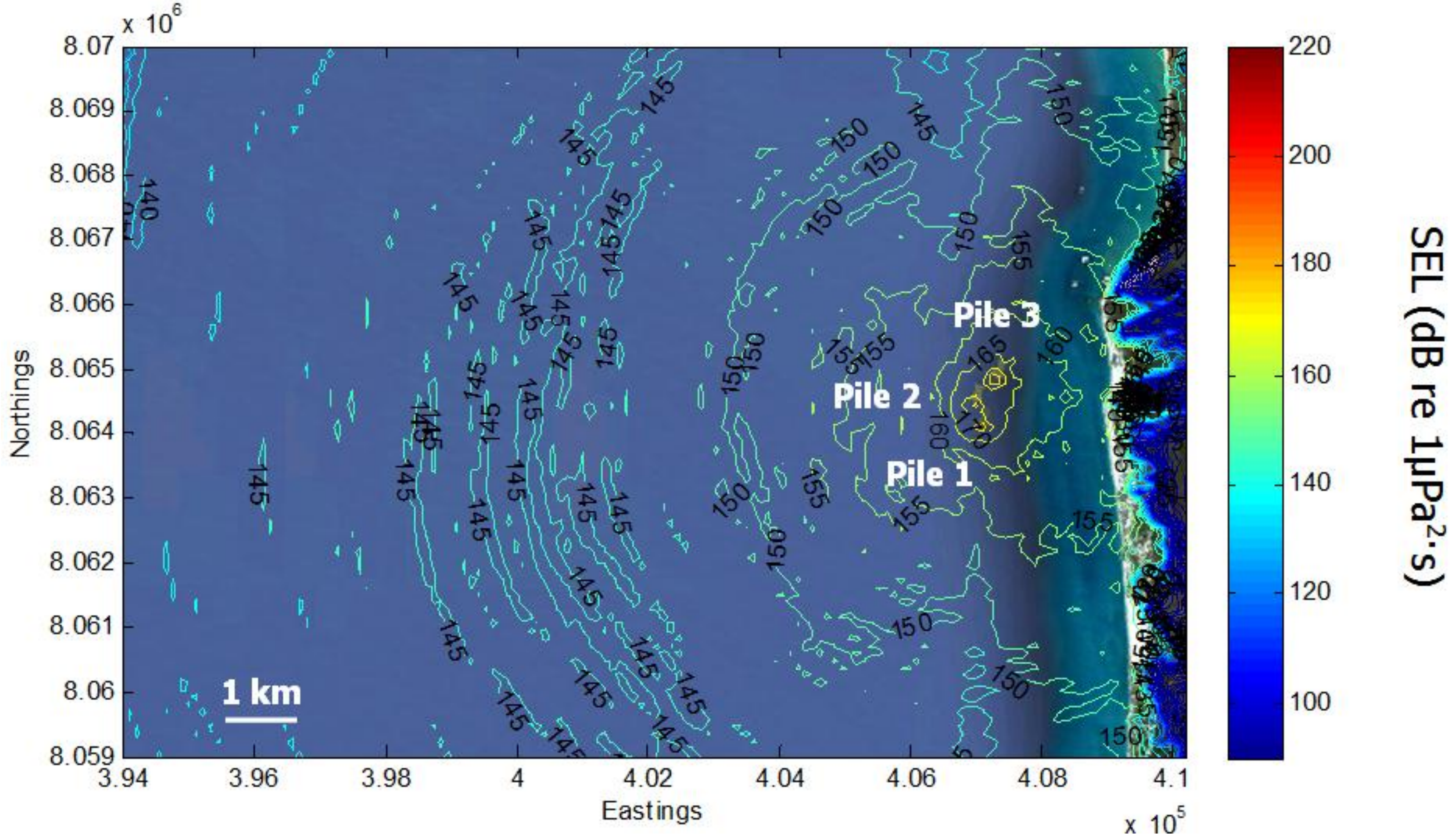

Figure 3-2 Overview of single pulse SEL contour plot (15 km) for three pile barges operating simultaneously.

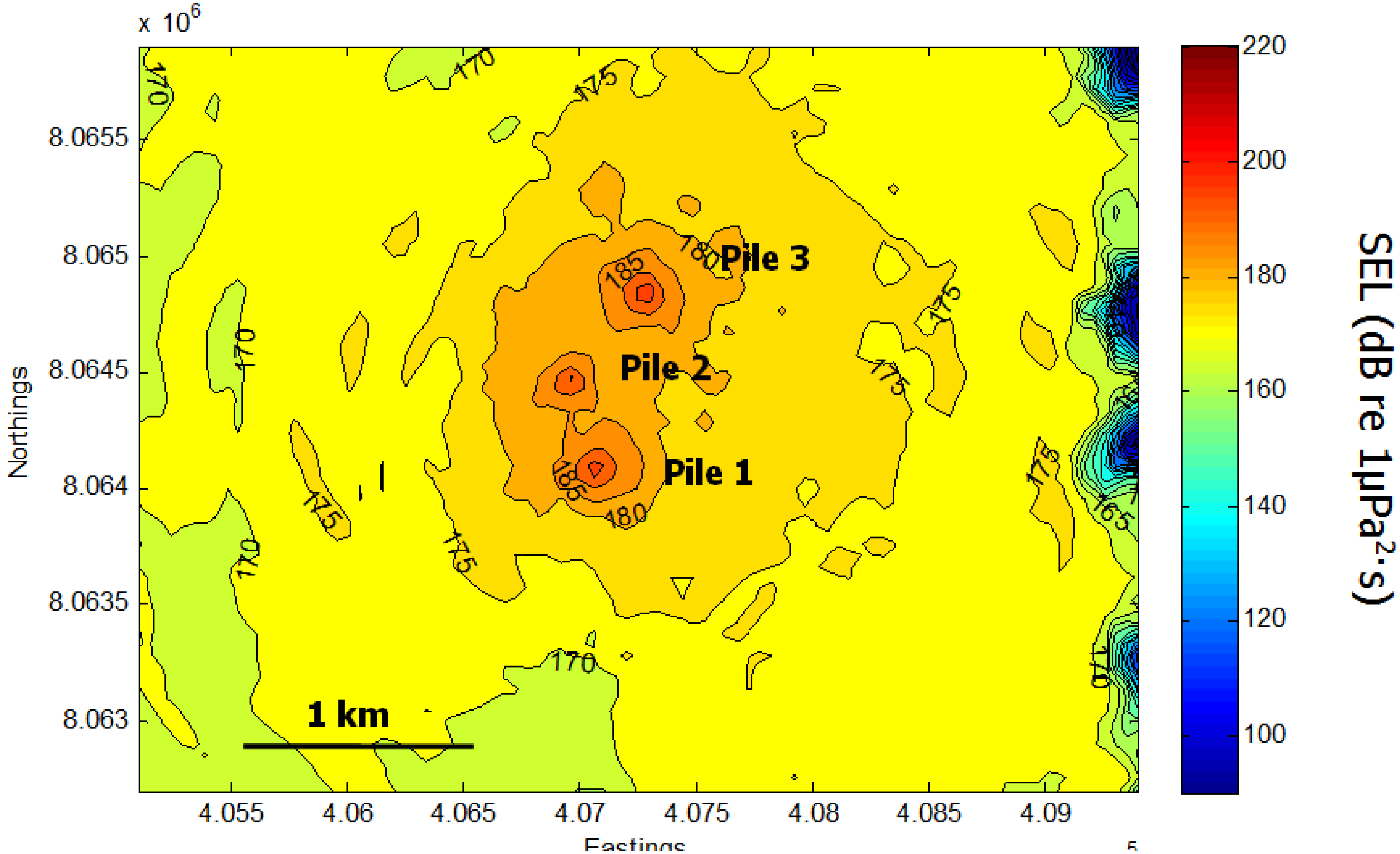

Figure 3-3 SEL contour plot for three pile barges operating simultaneously for a 10 second period.

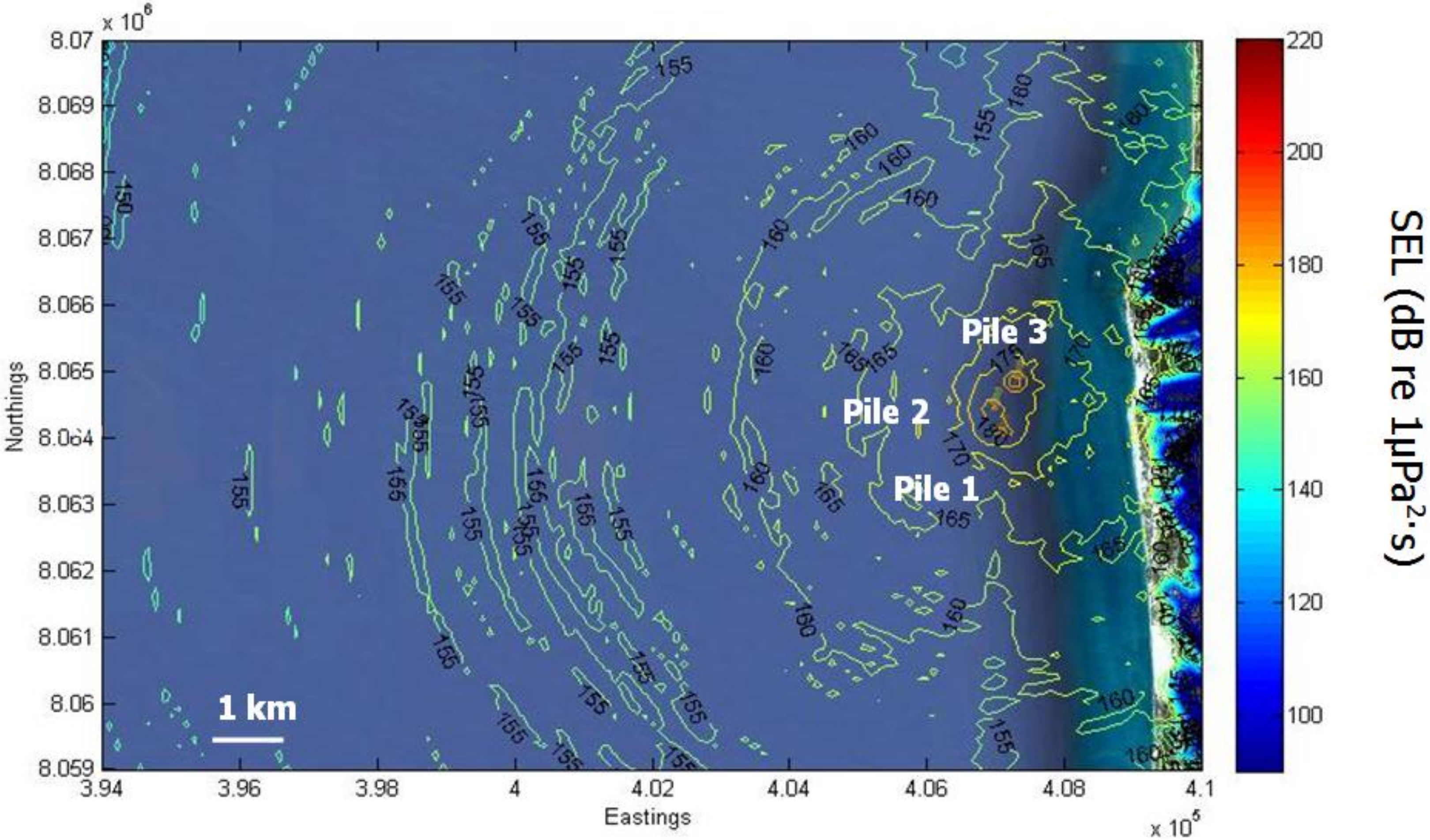

Figure 3-4 Overview of SEL contour plot (15 km) for three pile barges operating simultaneously for a 10 second period.

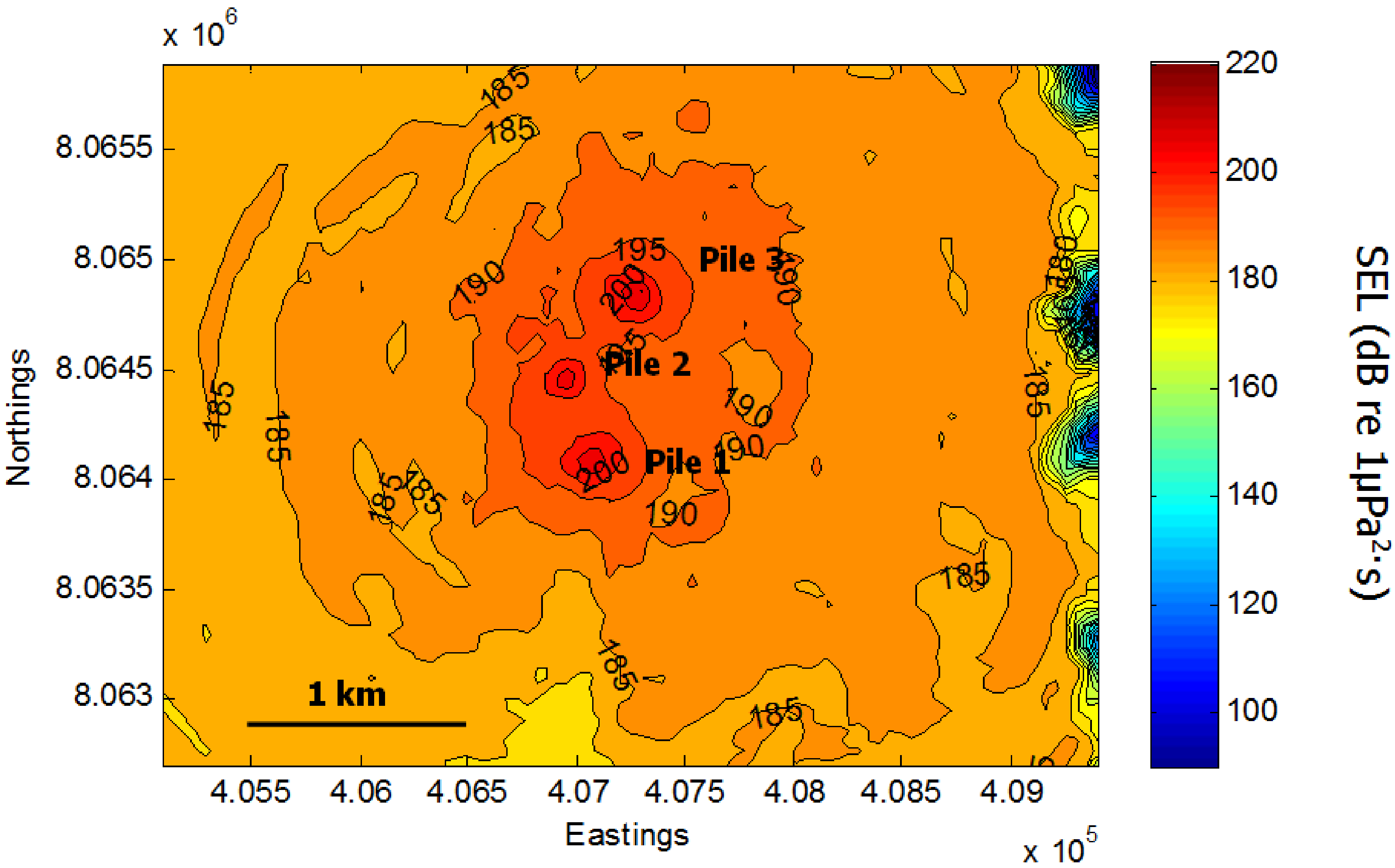

Figure 3-5 SEL contour plot for three pile barges operating simultaneously for a 10 minute period.

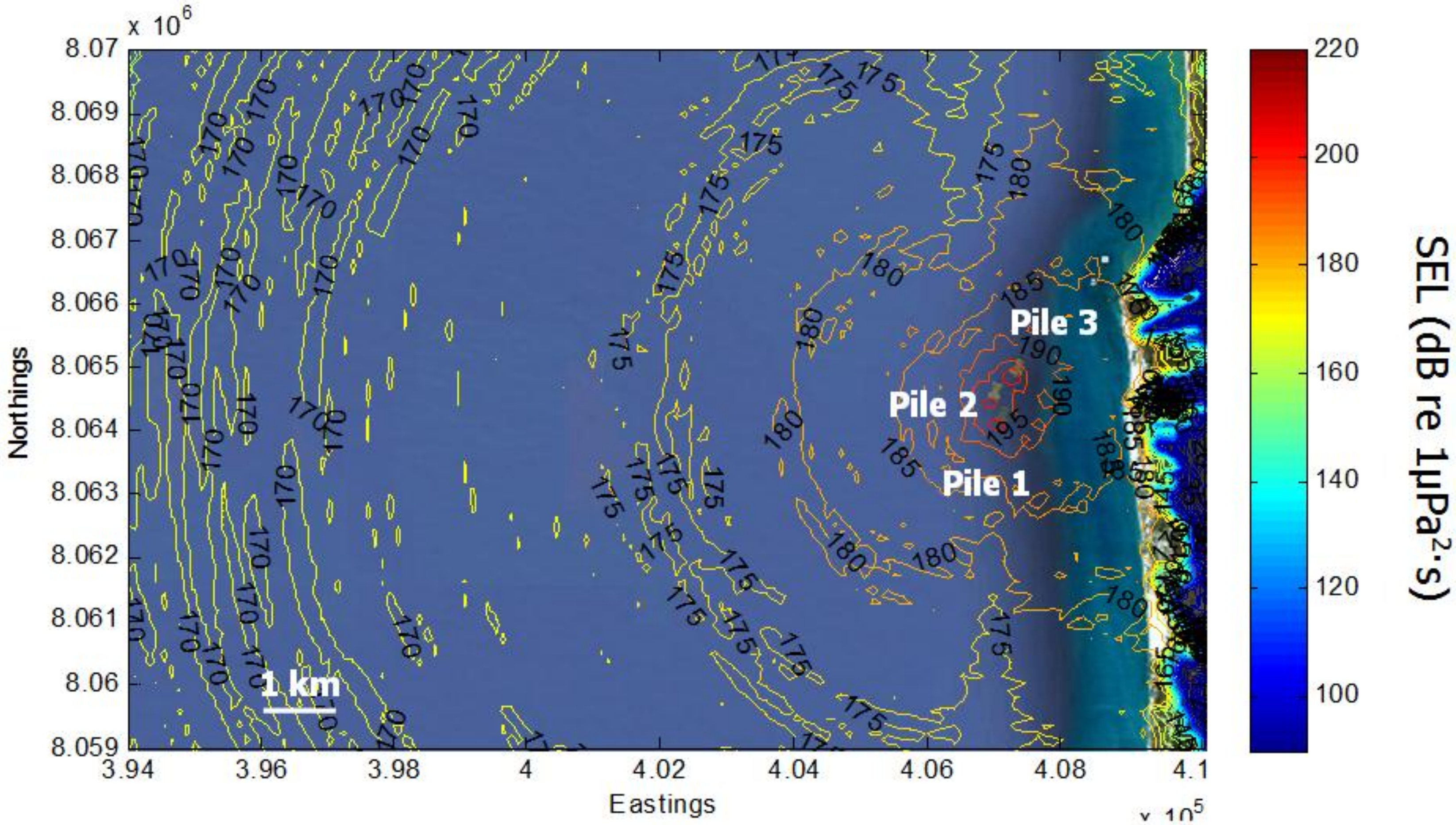

Figure 3-6 Overview of SEL contour plot (15 km) for three pile barges operating simultaneously for a 10 minute period.

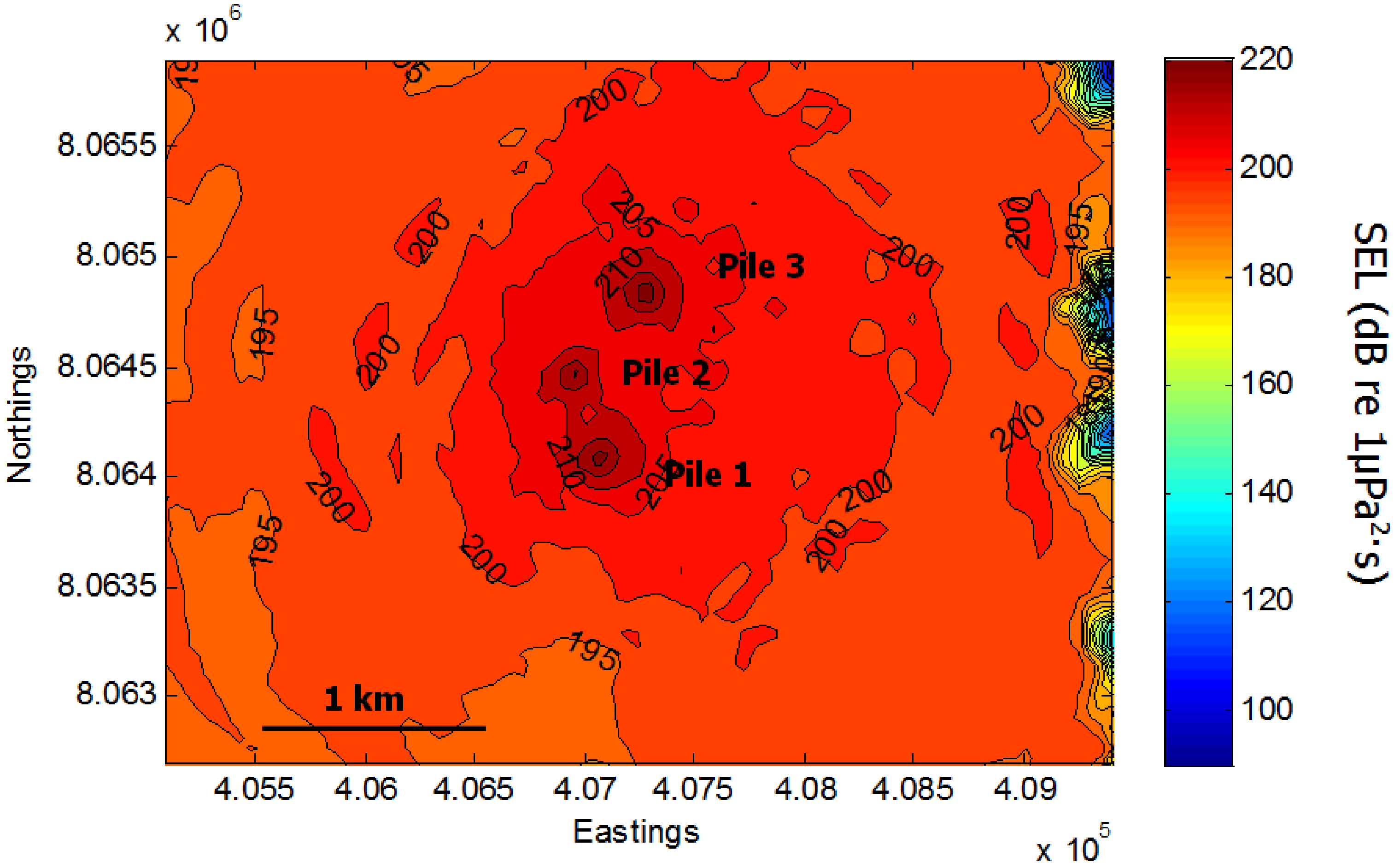

Figure 3-7 SEL contour plot for three pile barges operating simultaneously for 3 hours in a 24 hour period.

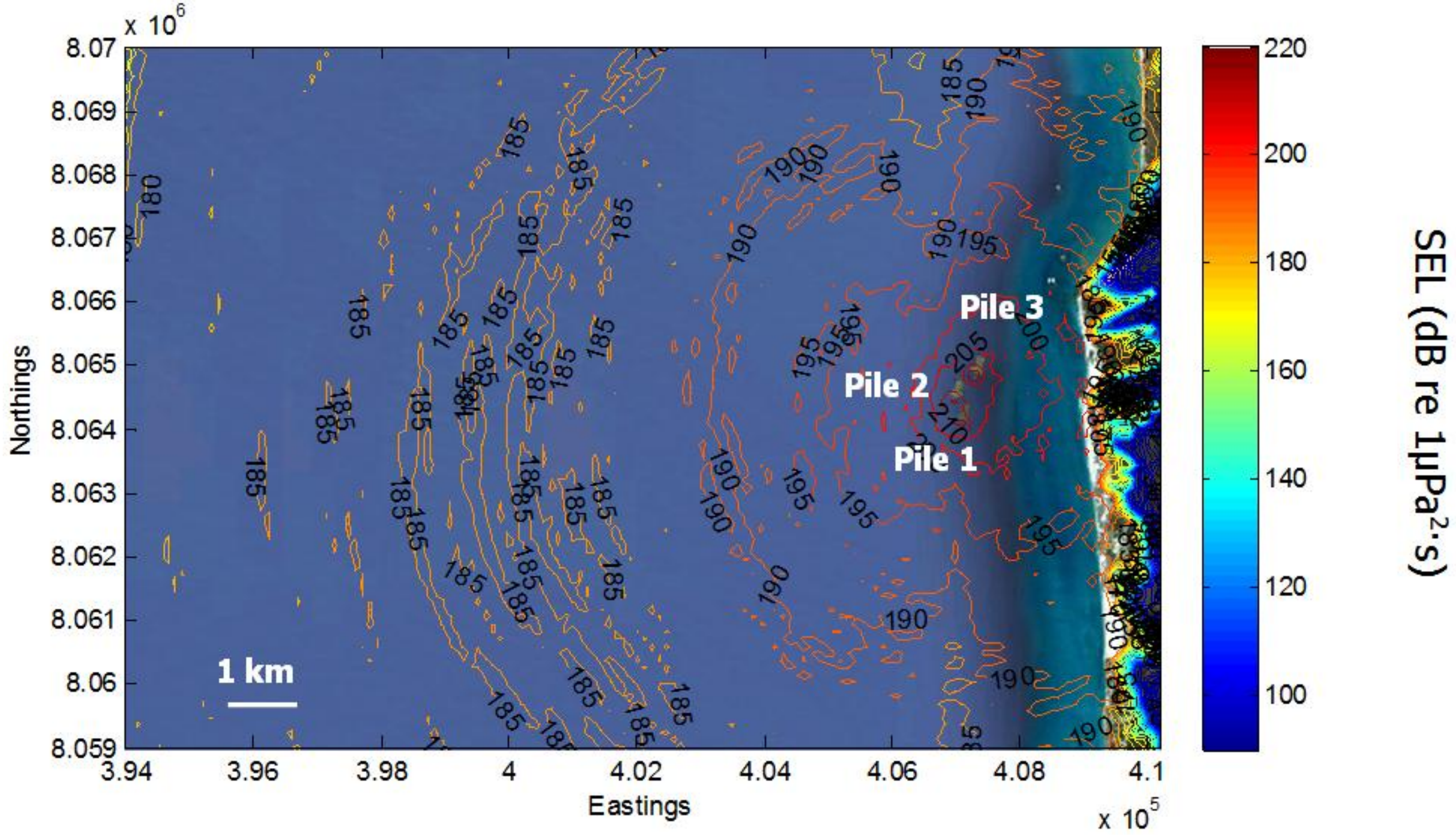

Figure 3-8 Overview of SEL contour plot (15 km) for three pile barges operating simultaneously for 3 hours in a 24 hour period.

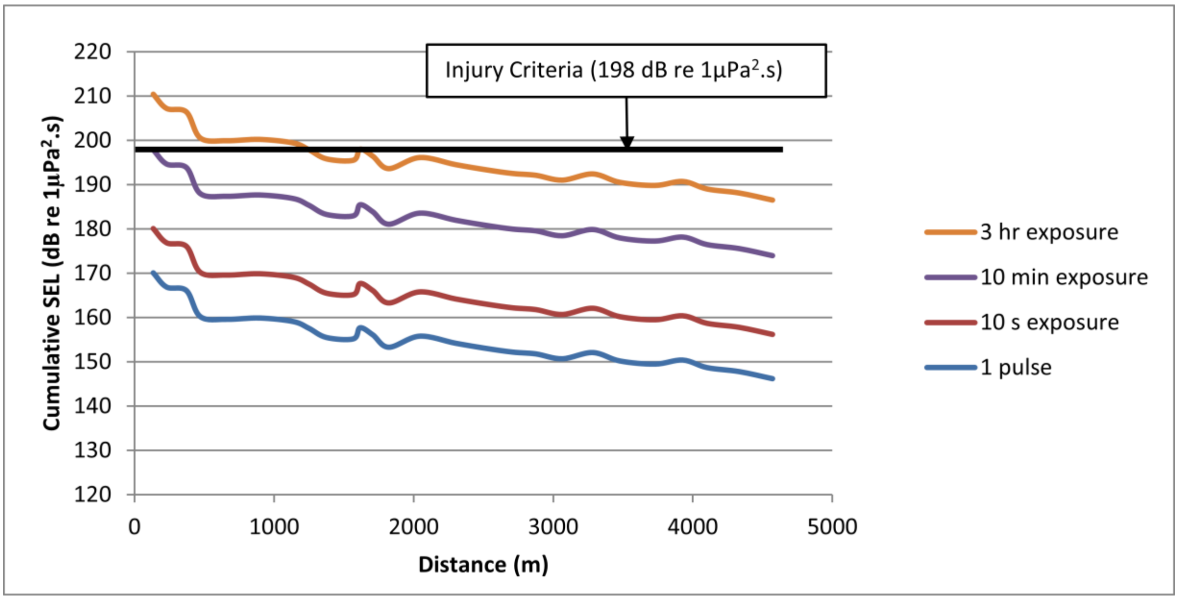

Figure 3-9 Predicted SEL (M_{lf}) values under different exposure durations as a function of distance, at a depth 2 m below the sea surface for three 1.5 meter diameter piles operating simultaneously.

Table 3.1 Predicted SPL peak and SEL (M_{lf}) from 3 piling barges as a function of distance from the source.

Distance from Source (km)	Peak SPL (dB re 1 µPa)	SEL (dB re 1 µPa^2·s) for a single piling strike	SEL (dB re 1 µPa^2·s) for a 10 s period	SEL (dB re 1 µPa^2·s) for a 10 min period	SEL (dB re 1 µPa^2·s) for a 1 hr period	SEL (dB re 1 µPa^2·s) for a 3 hr period	RMS_{pulse} (dB re 1 µPa)
0.05	195	178	188	206	214	219	188
0.1	190	174	183	201	209	214	184
0.2	186	169	179	197	205	209	179
0.5	180	163	173	191	199	203	173
1	175	158	168	186	194	199	168
2	171	154	164	182	190	194	164
5	165	148	158	176	184	188	158
10	160	143	153	171	179	184	153
15	158	141	151	168	176	181	151

4. DISCUSSION

The pile driving modelling for the Browse LNG Precinct was re-modelled post submission of the SAR to correct the identified errors in the SAR modelling and present the accurate results. In addition, the revised modelling used updated seabed and bathymetry data as well as a revised source level. The modelling results in this report show that the sound levels associated with pile driving exceed sound levels that were predicted in the modelling conducted for the SAR for a comparable piling scenario. The updated seabed and bathymetry data and the revised source level had a minor effect on the revised modelling results, as demonstrated below. The difference in results between the SAR modelling and the revised modelling can be attributed to the errors in the modelling conducted for the SAR. The influence of each of these parameters on the modelling outputs are described below.

4.1 Comparison of Revised Pile-Driving Modelling Results with the SAR modelling for the BLNG Precinct

4.1.1 Seabed

As accurate geophysical data was not available at the time of the SAR, it was assumed that the James Price Point area consisted of a sandy bottom. Sand, not limestone was considered as the worst case, as an acoustic wave is absorbed faster into a limestone (i.e. calcanerite) seabed at shallow grazing angles than it is for a sandy bottom. Since the SAR, more accurate geophysical surveys have been undertaken which have resulted in a better understanding of the seabed types in the area (see section 2.2.1). A comparison between the received levels of the modelling presented in the SAR compared to the revised modelling showed that, close to the pile, the effect of the seabed has resulted in an approximate decrease in received levels of 5 dB re 1 uPa^2.s as a result of parts of the seabed consisting of limestone (i.e. calcanerite).

The modelling found that shallow grazing angles between 10 and 30 degrees over the calcanerite layer resulted in higher absorption of up to 5 dB of the radiated energy into the seabed. As the pile noise sources were placed over the calcanerite, higher absorption was observed in the near-field when compared to the SAR modelling, which assumed a worst-case scenario of uniform sand.

4.1.2 Source Levels

A literature review of pile-driving source levels was undertaken (see Section 2.2.3). This review resulted in the revised modelling using a more representative source level of 209 dB re 1 uPa^2.s for the proposed hammer energy. A source level of 205 dB re 1 uPa^2.s was used in the modelling presented in the SAR. The lower source level in the SAR modelling would result in lower predicted received levels. However due to the technical error in the SAR modelling (see section 4.1.3) the difference is not apparent.

4.1.3 Errors in the Pile Driving Modelling Presented in the SAR

An error in the presentation of the pile-driving source level as a Power Spectral Level (dB re 1 µPa/Hz) was incorrectly implemented as third octave band levels in the SAR modelling. This resulted in an under-estimation of predicted received levels at ranges > 100 metres as shown in Table 4.1.

In addition, a curve fitting error in the SAR modelling resulted in the over-estimation of predicted levels at closer ranges (<100 m). Curve fitting was necessary during the SAR modelling as the model resolution at the time was not fine enough to predict close range levels. This error explains why the results of the revised modelling show that the close range predicted received levels are lower than those presented in the SAR.

Table 4.1 Comparison of the revised Predicted Received Levels in for pile driving compared with the SAR Modelling (SEL, dB re 1 µPa^2.s)

Range (km)	Revised modelling					SAR				
	Single pulse	10 s	10 m	1 hr	3 hr	Single pulse	10 s	10 m	1 hr	3 hr
0.05	178	188	206	214	219	196	207	225	234	239
0.1	174	183	201	209	214	173	184	202	211	216
0.2	169	179	197	205	209	155	166	184	193	198
0.5	163	173	191	199	203	143	154	172	181	186
1	158	168	186	194	199	134	145	163	172	177
2	154	164	182	190	194	126	137	155	164	169
5	148	158	176	184	188	114	125	143	152	157

APPENDIX A : NOISE SOURCE SPECTRUM LEVEL DATA

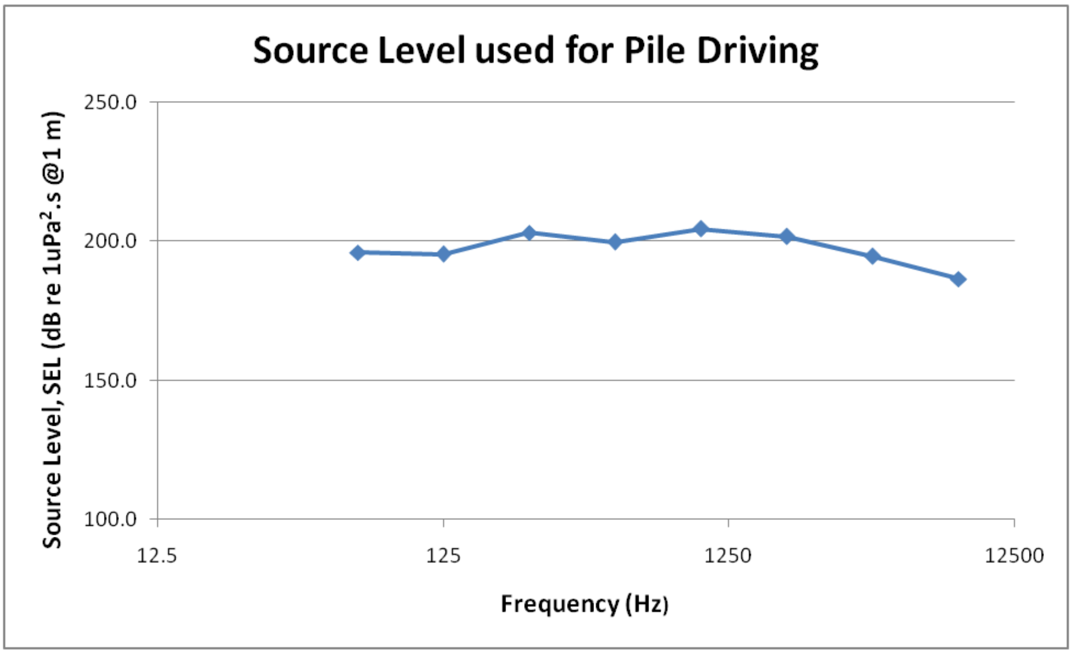

Figure A-1 Source characteristics of Pile-driving in octave bands.[11]

[11] Source Level (SEL) has been derived from: C P Salagado Kent, R D McCauley, A J Duncan, 'Environmental impacts of underwater noise associated with harbor works, Port Hedland, Centre for Marine Science and Technology Curtin University, 2009.

APPENDIX B : BASIC PRINCIPLES

Appendix B-1 : Equivalent continuous sound pressure level, L_{eq}

The L_{eq}, also known as the RMS (root mean squared) level is defined as the average pressure at a point relative to some reference pressure p_{ref} defined over some time period T. For underwater acoustics, the reference pressure is generally taken to be p_{ref} = 1 µPa. This is far more descriptive representation of sound pressure level than an instantaneous measurement due to the time dependent nature of sound.

$$L_{eq} = 10\ \log_{10}\left(\frac{1}{T}\int_0^T \frac{p(t)^2}{p_{ref}^2}dt\right) \tag{B.1}$$

Appendix B-2 : Sound Exposure Level (SEL)

The Sound Exposure Level (SEL) is a useful parameter as it does not have to consider specifically the duration of an impulsive source – only the total energy that has been measured, and is expressed as an equivalent level with one second duration. This is especially useful as it can be used in an accumulative context by summing all energy over an extended time period T and then finding the effective level. The disturbance and injury criterion for marine life is conveniently given in SEL for impulsive noise sources such as pile-driving.

$$SEL = 10\ \log_{10}\left(\int_0^T \frac{p(t)^2}{p_{ref}^2}dt\right) \tag{B.2}$$

For *n* pulses, the cumulative SEL can be derived from the single pulse SEL by equation B.3.

$$SEL_{cum} = SEL + 10\log(n) \tag{B.3}$$

Appendix B-3 : Sound Propagation Effects

In underwater acoustics sound propagates both through the water and through the sea bed due to efficient transmission due to their similar acoustic impedances. This is not the case with the air-water boundary at the sea surface. Therefore the effect of airborne propagation can be assumed insignificant, and more importantly the surface will act as a near perfect reflector of underwater sound. Bottom loss must also be considered and is a function of the bottom type and the grazing angle. The limiting frequency f_0 below which no propagation is possible within the sediment is given by Eq. B.4.

$$f_0 = \frac{c_{water}}{4h}\sqrt{\frac{1}{1-(c_{water}/\ c_{sediment})^2}} \tag{B.4}$$

APPENDIX C : ACRONYMS

Acronym	Definition
BLNG	Browse Liquefied Natural Gas
CMST	Centre of Marine Science and Technology
DSD	Department of State Development
HAT	Highest Astronomical Tide
IMF	Integrated Marine Facility
LNG	Liquefied Natural Gas
MMPE	Monterey Miami Parabolic Equation
MSL	Mean Sea Level
PE	Parabolic Equation
RMS	Root Mean Square
SEL	Sound Exposure Level
SPL	Sound Pressure Level